September 2014

BOW RIVER AND ELBOW RIVER

Basin-Wide Hydrology Assessment and 2013 Flood Documentation

Submitted to:
Alberta Environment and Sustainable Resource Development (ESRD), Edmonton
The City of Calgary

REPORT

Report Number: 13-1326-0054-2000

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1.0 INTRODUCTION

1.1 Project Background

The City of Calgary (The City), in partnership with Alberta Environment and Sustainable Resource Development (ESRD), commissioned Golder Associates Ltd. (Golder) to undertake an update of the 2010-2012 Bow and Elbow River Hydraulic Model and Flood Inundation Mapping Project. The overall scope of work includes a basin-wide flood event documentation and hydrology assessment using preliminary 2013 flow data, and a hydraulic model update incorporating surveyed 2013 high watermarks, post-flood bathymetry and topography and re-surveyed river cross sections.

In June of 2013, The City experienced a severe flood estimated to be close to the 100-year event for the Bow River and significantly higher for the Elbow River. The magnitude of 2013 flood peaks throughout the Bow and Elbow River basins, including at The City, warrant a re-analysis of the flood frequency statistics computed in 2010 (Golder, 2010). Post-flood observations on the both rivers suggest that the characteristics of the river bed and banks at many key locations were significantly altered due to erosion, scour and deposition. The hydraulic model and flood inundation mapping completed in 2012 (Golder, 2012) for the Bow and Elbow Rivers through The City, using pre-2013 flood channel bathymetry and cross section data, may not currently be as representative as desired for emergency response, and the model and mapping are being updated.

1.2 Study Scope

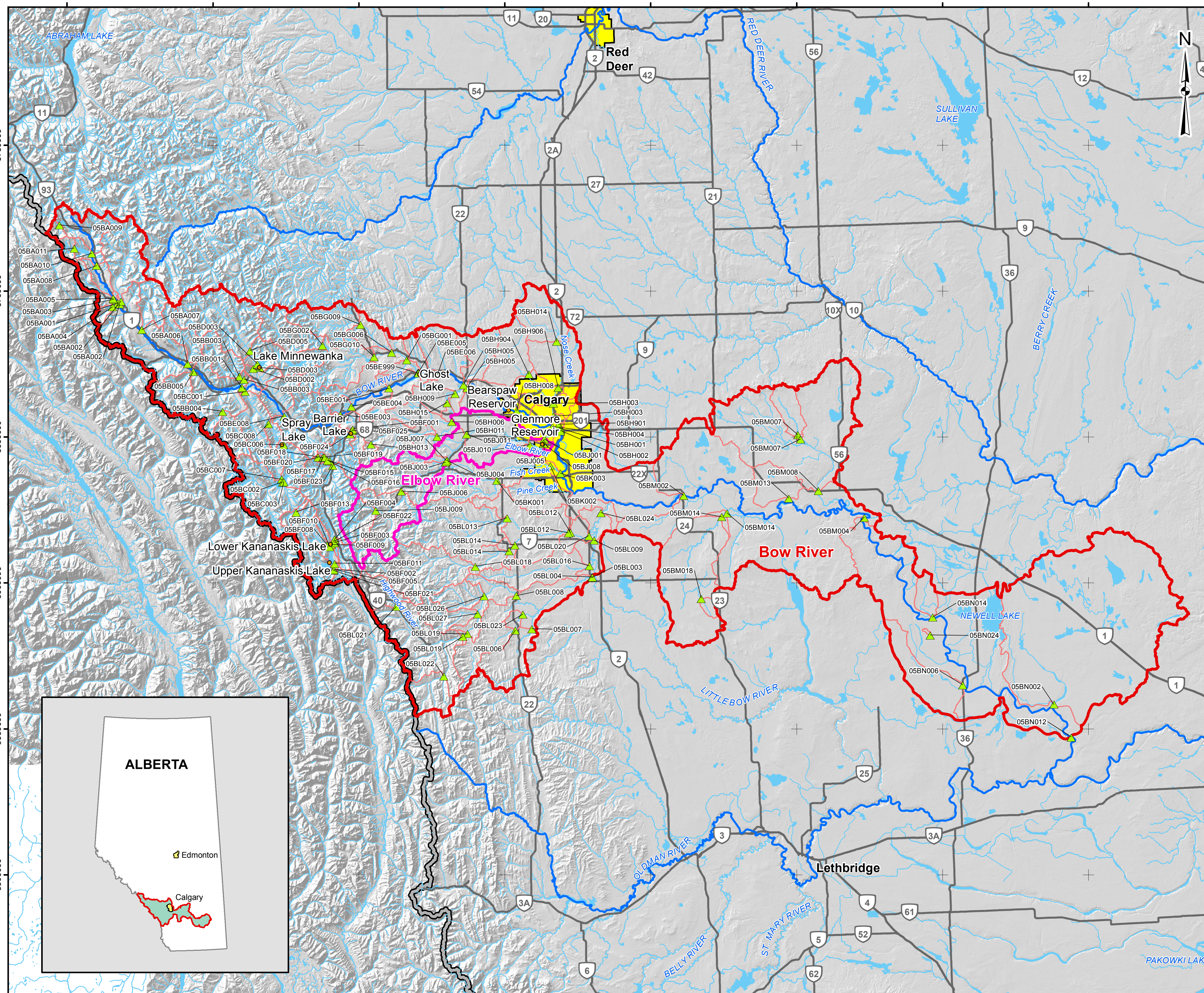
The primary objective of the project is to update the 2012 HEC-RAS hydraulic model and flood inundation mapping for the Bow and Elbow rivers through The City. Given the magnitude and impact of the 2013 flood throughout the Bow and Elbow River basins, and the critical hydrologic importance of the 2013 flood event, ESRD also required a basin-wide hydrologic assessment and a stand-alone hydrology report to put the 2013 floods into context. The scope of the basin-wide hydrologic assessment was to document the magnitudes of June 2013 flood peaks at various locations, and to undertake an updated frequency analysis to determine flood magnitudes for a range of return periods for information and use in flood inundation mapping and other projects.

The City and ESRD provided historic Water Survey of Canada (WSC) and preliminary 2012 and 2013 flow data for gauges on the Bow River, Elbow River and their tributaries. TransAlta Corporation (TransAlta) provided flow and reservoir level data up to 2013 at their hydropower developments on the Bow River and its tributaries.

It is important to note that the 2012 and 2013 flow data used in the present study are preliminary and subject to change following finalization by WSC. As such, the preliminary 2013 flood peaks and any corresponding flood frequency statistics presented in this report should be used with caution and reviewed again when final data are available. This report should be read in conjunction with “Important Information and Limitations of This Report”.

1.3 Study Area

The study area, shown in Figure 1.1, includes the Bow River and its tributaries upstream of its confluence with the Highwood River. The drainage area of Bow River at Calgary (WSC Station 05BH004) is 7,868 km^2. The upstream reach of the Bow River and its tributaries are controlled by several hydropower structures. Within the City, the Bow River is joined by several streams, including Elbow River, Nose Creek, Fish Creek and Pine Creek. The Elbow River is the most significant tributary to the Bow River within The City, and flows into the Glenmore Reservoir before discharging into the Bow River just downstream of downtown. The drainage area of the Elbow River below Glenmore Dam (WSC Station 05BJ001) is 1,236 km^2. Table 1.1 provides a summary of the basic hydrologic information available from WSC for Bow River and its tributaries within the study area.



LEGEND

- HYDROMETRIC STATIONS
- STORAGE STRUCTURE
- BOW RIVER BASIN
- ELBOW RIVER BASIN
- PFRA SUB-BASIN
- MAJOR RIVER
- PRIMARY HIGHWAY
- WATERCOURSE
- WATERBODY
- PROVINCIAL BOUNDARY
- POPULATED PLACE

REFERENCE

HYDROMETRIC STATIONS, HYDROLOGIC REGIONS, BASIN AND SUB-BASIN DATA OBTAINED FROM PRAIRIE FARM REHABILITATION ADMINISTRATION (PFRA). BASE HYDROLOGY, POPULATED PLACES AND PROVINCIAL BOUNDARY OBTAINED FROM IHS ENERGY INC. HILLSHADE AND ROADS OBTAINED FROM GEOBASE ®.
DATUM: NAD 83 10TM AEP FOREST

40 0 40
SCALE 1:1,350,000 KILOMETRES

PROJECT

Alberta Government

BOW RIVER AND ELBOW RIVER BASIN-WIDE HYDROLOGY

TITLE

BOW RIVER AND ELBOW RIVER BASINS

Golder Associates

PROJECT No. 13-1326-0054			SCALE AS SHOWN	REV. 0
DESIGN	AB	21 Apr. 2014	FIGURE: 1-1	
GIS	JE	02 Jun. 2014		
CHECK	AB	25 Jul. 2014		
REVIEW	AB	25 Jul. 2014		

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Table 1.1: Summary of Existing Hydrologic Data

WSC Station ID	Station Name	Gross Drainage Area (km^2)	Period of Record	Length of Record (Years)	Type of Recorded Hydrologic Data	Condition of Recorded Hydrologic Data
05BA001	Bow River at Lake Louise	422	1910-2013	104	Flow	Natural
05BB001	Bow River at Banff	2,210	1909-2013	105	Flow	Natural
05BE004	Bow River near Seebe	5,170	1923-2011	89	Flow	Regulated
05BE006	Bow River below Ghost Dam	6,550	1933-1989	57	Flow	Regulated
05BH005	Bow River near Cochrane	7,412	1916-2013	98	Flow	Regulated
05BE005	Ghost Lake near Cochrane	6,480	1929-2013	85	Level	Regulated
05BH008	Bow River below Bearspaw Dam	7,770	1983-2013	31	Flow	Regulated
05BH004	Bow River at Calgary	7,868	1911-2013	103	Flow	Regulated
05BD003	Lake Minnewanka near Banff	647	1916-2013	98	Level	Regulated
05BC006	Spray Reservoir at Three Sister Dam	N/A	1949-2013	65	Level	Regulated
05BC002	Spray River near Spray Lakes	360	1915-1939	25	Flow	Natural
05BC001	Spray River at Banff	751	1910-2013	104	Flow	Regulated since 1951
05BF005	Upper Kananaskis Lake	151	1932-2013	82	Level	Regulated
05BF009	Lower Kananaskis Lake	359	1932-2013	82	Level	Regulated
05BF025	Kananaskis River below Barrier Dam	899	1975-2013	39	Flow	Regulated
05BF001	Kananaskis River near Seebe	933	1911-1962	52	Flow	Regulated starting 1932
05BJ004	Elbow River at Bragg Creek	791	1934-2013	80	Flow	Natural
05BJ010	Elbow River at Sarcee Bridge	1,190	1979-2013	35	Flow	Natural
05BJ005	Elbow River above Glenmore Dam	1,220	1933-1977	45	Flow	Natural
05BJ008	Glenmore Reservoir at Calgary	1,224	1976-2013	38	Level	Regulated
05BJ001	Elbow River below Glenmore Dam	1,236	1908-2013	106	Flow	Regulated since 1932
05BH003	Nose Creek at Calgary	893	1911-1986	76	Flow	Natural
05BK001	Fish Creek near Priddis	261	1957-2013	57	Flow	Natural
05BL024	Highwood River near the Mouth	3,952	1970-2013	44	Flow	Regulated
05BM002	Bow River below Carseland Dam	15,660	1956-2013	58	Flow	Regulated
05BM004	Bow River below Bassano Dam	20,250	1916, 1919-1933, 1964-2013	66	Flow	Regulated
05BN012	Bow River near the Mouth	25,280	1965-2013	49	Flow	Regulated

2.0 BASIN-WIDE HYDROLOGY

2.1 General Approach

Golder conducted a hydrologic study for ESRD (then Alberta Environment, AENV) and The City in 2010 to estimate the return period flood estimates for use in the Bow and Elbow Rivers hydraulic model, upon which the 2012 flood inundation maps are based (Golder, 2010 & 2012). According to historic records, major floods occurred on the Bow River in 1879, 1897, 1902, 1929, 1932, 1995 and 2005. Records also indicate that major floods occurred on the Elbow River in 1915, 1923, 1929, 1995, and 2005. As part of the 2010 study, the hydrology of the Bow and Elbow Rivers was examined in detail by reviewing past work (such as the 1983 Calgary Floodplain Study, AENV), utilizing the latest methods of frequency analysis, and considering changes in flows due to flow regulation by hydro infrastructure, water diversions and land use changes.

The 2010 hydrologic study computed naturalized 100-year flood flows on the Bow River above Elbow River of 1,710 m^3/s and on the Elbow River above Glenmore Reservoir of 737 m^3/s. Preliminary data for the 2013 flood event suggest that the peak flow recorded on the Bow River above Elbow River at WSC Station 05BH004 was close to the 2010 100-year flood estimate, while the peak flow on the Elbow River above Glenmore Reservoir at WSC Station 05BJ010 was significantly greater than the 2010 100-year flood estimate.

The scope of work for the present basin-wide hydrology assessment included: generation of to-2013 naturalized daily flow series' at the major storage facilities on the Bow River upstream of Bearspaw Dam and on the Elbow River at Glenmore Dam; and the estimation of 2-, 5-, 10-, 20-, 50-, 100-, 200-, 500-, and 1,000-year flood flows (corresponding to 50, 20, 10, 5, 2, 1, 0.5, 0.2 and 0.1 percent probabilities of annual exceedance, respectively) based on flood frequency analysis of naturalized and/or recorded peak flow series at relevant locations along the Bow River and its tributaries, including the Elbow River.

The general approach of the 2014 hydrology assessment was based on the methodology detailed in the 2010 hydrology report (Golder 2010) prepared for The City and ESRD as part of the 2010-2012 Bow and Elbow River Hydraulic Model and Flood Inundation Mapping Project. The flow naturalization and computation of regulated and natural flow statistics followed the same procedures as in the 2010 study. To satisfy Calgary-specific requirements, flood frequency flows were estimated for the Elbow River above and below Glenmore Dam, the Bow River above and below Bearspaw Dam, as well as above and below the Elbow River and at confluences with major tributaries, including the Highwood River, Fish Creek, Pine Creek, and Nose Creek.

The present assessment also included documentation of preliminary, recorded June 2013 flood peaks at select gauged locations within the study area, and estimation of peaks at select ungauged locations or at gauged locations with incomplete records. Corresponding return periods or frequencies of the June 2013 flood were also computed. In addition to hydrometric gauge sites and the above-noted locations within Calgary, locations of interest to ESRD included the communities of Banff, Canmore, Exshaw, Lac des Arcs, Seebe, Morley, Stoney First Nation, Ghost Lake, Cochrane, Bearspaw, Waiparous, Bragg Creek, Tsuu T'ina First Nation, Siksika First Nation and Bassano, as well as significant tributary locations. The list of selected locations included:

- Elbow River at Bragg Creek (WSC Station 05BJ004);
- Elbow River at Sarcee Bridge (WSC Station 05BJ010);
- Elbow River Inflow into Glenmore Reservoir;
- Elbow River below Glenmore Dam (WSC Station 05BJ001);

- Bow River at Lake Louise (WSC Station 05BA001);
- Bow River at Banff (WSC Station 05BB001);
- Bow River downstream of Spray River;
- Forty Mile Creek upstream of Bow River;
- Spray River at Banff (WSC Station 05BC001);
- Cougar Creek Upstream of Bow River;
- Stoneworks Creek at Highway 1;
- Exshaw Creek at Exshaw;
- Kananaskis River upstream of Bow River;
- Ghost River above Waiparous Creek (WSC Station 05BG101);
- Waiparous Creek near the Mouth (WSC Station 05BG006);
- Ghost Reservoir Inflow;
- Ghost Reservoir Outflow;
- Bow River at Cochrane (WSC Station 05BH005);
- Bearspaw Reservoir Inflow;
- Bearspaw Reservoir Outflow;
- Bow River at Calgary (WSC Station 05BH004);
- Bow River downstream of Elbow River Confluence;
- Bow River upstream of Highwood River Confluence;
- Bow River downstream of Highwood River Confluence;
- Bow River below Carseland Dam (WSC Station 05BM002);
- Bow River at Highway 547;
- Bow River at Highway 842;
- Bow River below Bassano Dam (WSC Station 05BM004);
- Bow River at Highway 539;
- Bow River at Highway 36;
- Bow River at Highway 875; and
- Bow River near the Mouth (WSC Station 05BN012) – at Highway 524.

2.2 Generation of Naturalized Daily Flow Series

The hydrology of the Bow River upstream of Calgary is influenced by the operation of several storage reservoirs on the Bow River (Bearspaw Reservoir, Ghost Lake) and its tributaries (Lake Minnewanka, Spray Lake, Barrier Lake, Lower and Upper Kananaskis Lakes), and the hydrology of the Elbow River and Bow River downstream of the Elbow River confluence is influenced by the operation of Glenmore Reservoir.

Naturalized daily flow series up to 2013 were developed at all major storage facilities on the upper Bow River, including inflows to Bearspaw Reservoir, Ghost Lake, Lake Minnewanka, Spray Lake, Barrier Lake, Lower and Upper Kananaskis Lakes, and Glenmore Reservoir on the Elbow River. The flow naturalization used the same project depletion method and the SSARR channel routing procedures as used by ESRD. The approach is explained in more detail in Appendix A of the 2010 hydrology study (Golder, 2010) and reproduced as Appendix A of this report. Naturalization of daily flows was facilitated by the Natural Flow Computation Program (NFCP) developed for the Prairie Provinces Water Board (Optimal Solutions, 2009). The annual maximum daily flows up to 2013 from each naturalized daily flow series are provided in Appendix A.

2.3 Statistical Tests on Flood Series

An in-house application of Environment Canada's Consolidated Frequency Analysis (CFA) software was used for flood frequency analyses and to conduct statistical tests for independence (not serially correlated), trend, randomness, and homogeneity. This application uses the same parametric probability distribution functions (i.e., Three-parameter Log-Normal, Extreme Value, Log-Pearson Type III and Weibull) as the CFA for fitting the flood flow series. The application incorporates modern boot strapping and two methods for parameter estimation (methods of moments and maximum likelihood), the ability to estimate confidence intervals for a flood estimate of all the standard return periods, and the Anderson-Darling methods (Stephens, 1974) to identify the best-fit probability distribution.

Table 2.1 provides the results of statistical tests on the naturalized and natural annual maximum daily flow series at various key locations on the Bow River and its tributaries. The results of statistical tests indicate that most of the recorded or naturalized daily flow maxima are independent, random, homogeneous, and do not display any significant trends. Inflows to Bearspaw Reservoir display a trend and non-homogeneity at the 1% and 5% level of significance. The non-homogeneity and trends for inflows to Bearspaw Reservoir may be due to a combination of long-term variability in the region's climate regime and alteration of flow patterns following the construction of major storage facilities on the Bow River and its tributaries. Notwithstanding the trend and non-homogeneity in the maximum annual daily flow series, the entire series for the Bow and Elbow Rivers are considered appropriate for frequency analysis.

2.4 Frequency Analysis of Naturalized Peak Flow Series

The City and ESRD provided the historic WSC and preliminary 2012 and 2013 flow data for gauges on the Bow River, Elbow River and their tributaries. TransAlta provided flow and reservoir level data at their hydropower developments on the Bow River and its tributaries. The regulated flows were naturalized and annual maximum daily flow series were developed at these locations.

The purpose of the frequency analysis of naturalized maximum daily flow series was to estimate the instantaneous flood frequency flows from 2-year to 1000-year using the naturalized daily flow series. Frequency analyses on the annual maximum daily flow series at regulated locations were completed for the Bow River above Bearspaw Dam and the Elbow River above Glenmore Reservoir. The results are provided in Table 2.2.

Table 2.1: Statistical Test of Annual Maximum Daily Flows

Station Name	Local Inflow into Lower Kananaskis	Inflow to Upper Kananaskis Lake	Inflow to Lake Minnewanka	Inflow to Spray Lake	Local Inflow to Spray River at mouth	Inflow to Barrier Lake	Bow River at Banff	Inflow to Ghost Reservoir	Inflow to Bearspaw Reservoir without Historic Data	Inflow to Glenmore Reservoir
Serial correlation coefficient test for independence										
S_1	-0.01	0.20	0.21	0.18	0.23	0.31	0.01	0.05	0.18	0.13
t	-0.06	1.20	2.10	1.82	1.84	3.06	0.13	0.45	1.79	1.36
t(α=0.05)	-1.69	1.69	1.66*	1.66*	1.67*	1.66*	1.66	1.66	1.66*	1.66
t(α=0.01)	-2.43	2.44	2.37	2.36	2.39	2.37*	2.36	2.37	2.36	2.36
Spearman rank order correlation coefficient test for no-trend										
r_s	-0.05	0.11	0.11	0.05	0.11	0.21	0.22	0.05	0.25	-0.01
t	-0.32	0.66	1.10	0.46	0.87	1.98	2.25	0.43	2.61	-0.08
t(α=0.05)	-2.03	2.03	1.99	1.98	2.00	1.99	1.98*	1.99	1.98*	-1.98
t(α=0.01)	-2.72	2.72	2.63	2.63	2.66	2.63	2.62	2.64	2.63	-2.62
Mann-Whitney split sample test for homogeneity										
Size of earlier sample	20	20	46	49	30	45	50	20	23	25
z	-0.48	-1.14	-0.44	-0.11	-1.48	-2.27	-1.40	-0.12	-3.48	-1.58
z(α=0.05)	-1.64	-1.64	-1.64	-1.64	-1.64	-1.64*	-1.64	-1.64	-1.64*	-1.64
z(α=0.01)	-2.33	-2.33	-2.33	-2.33	-2.33	-2.33	-2.33	-2.33	-2.33*	-2.33

*: Instances when the criteria for the respective statistical tests were not met.

Table 2.2: Estimated Daily Flood Flows (m^3/s) for Various Return Periods - Derived from Frequency Analysis of Natural or Naturalized Annual Maximum Daily Flows for Streams with Storage Reservoirs

Return Period (Year)	Local Inflow to Lower Kananaskis Lake	Inflow to Upper Kananaskis Lake	Inflow to Lake Minnewanka	Inflow to Spray Lake	Local Inflow to Spray River at Mouth	Inflow to Barrier Lake	Bow River at Banff	Inflow to Ghost Reservoir	Inflow to Bearspaw Reservoir without Historical Data	Inflow to Bearspaw Reservoir with Historical Data	Inflow to Glenmore Reservoir
Drainage Area (km^2)	**151**	**150**	**647**	**520**	**230**	**899**	**2,210**	**6,550**	**7,770**	**7,770**	**1,236**
2	17.4	22.4	53.6	65.2	12.0	70.8	205	348	376	354	58.5
5	21.8	28.2	80.4	87.8	20.0	113	262	471	520	592	108
10	24.7	32.5	101	107	27.0	148	296	573	641	814	156
20	27.4	36.9	124	129	35.8	188	326	688	781	1,060	218
50	30.9	42.9	158	164	50.4	250	361	869	1,000	1,420	331
100	33.5	47.7	187	196	63.8	307	385	1030	1,210	1,720	448
200	36.1	52.8	219	235	79.6	375	407	1,220	1,450	2,040	602
500	39.6	60.1	268	298	105	482	435	1,530	1,840	2,480	885
1,000	42.2	65.6	309	357	127	581	455	1,810	2,210	2,830	1,180

2.5 Routing of Naturalized Daily Flood “Hydrographs” of Various Return Periods

Synthetic inflow flood “hydrographs” at major storage facilities on the Bow River and its tributaries, including the Elbow River at Glenmore Reservoir, were developed for each return period assessed as part of the flood frequency analyses of the naturalized maximum daily flow series. The synthetic inflow “hydrographs” were developed using the same approach as in Golder (2010). The approach is summarized below:

- For a specific computed return period flood (for example, the 100-year daily flood), an analogous actual daily flow of equal or similar magnitude was identified from the naturalized daily flow series;
- The flood volumes, time to peak and the “hydrograph” time base for each selected return period daily flood “hydrograph” were determined based on a recorded naturalized (daily time step) flow series identified as being analogous for each computed return period flood; and
- A dimensionless Gamma function, with its mean, standard deviation and skewness parameters similar to those of the recorded analogous “hydrograph”, was developed for each return period flood event, wherever possible.

It should be noted that these daily flood “hydrographs” are not true hydrographs, but synthetic and idealized representations of actual but unknown flood hydrographs represented as a series of average daily flows.

The flood volumes, along with the estimates of the time base of the daily flood “hydrographs” were used to scale the ordinates of the dimensionless Gamma functions such that the maximum daily flow, the time to peak and the total surrogate “event” flow volume closely matched the target values for a given return period. For example, for the 50-year daily flood inflow to Glenmore Reservoir, with a maximum daily flow of 302 m^3/s, the analogous recorded maximum daily flow of May 23, 1932 (311 m^3/s) was used as a surrogate to derive the 50-year daily flood inflow “hydrograph”. The time to peak for the May 1932 flood was about two days. The mean discharge, standard deviation, hydrograph time base of about seven days, a base flow of 52 m^3/s, and a skewness coefficient of 0.582 were used to determine the parameters for the Gamma function.

It was not always possible to find a surrogate or analogous flood from naturalized, recorded daily data for each return period flood, especially for floods with return periods greater than 50 years. In addition, for some surrogate floods, it was not possible to fit the Gamma function if the skewness coefficient was either small or negative. For those cases, the shape of the Gamma function was assumed to be the same as the daily flood inflow “hydrographs” derived for a different return period. For example, for deriving the daily flood inflow “hydrographs” to Glenmore Reservoir, the only surrogate observed hydrograph that could be identified and fitted to a Gamma function was the one corresponding to the 50 year return period. Hence, the shapes of inflow “hydrographs” for other return periods were assumed to be the same as the 50 year return period.

Naturalized daily flood “hydrographs” for each return period were developed for the following hydropower developments on tributaries to the Bow River: Cascade (Lake Minnewanka), Spray Lake, Upper Kananaskis Lake, Lower Kananaskis Lake, Barrier Lake, Ghost Lake and Bearspaw Reservoir. Naturalized daily flood “hydrographs” were also developed at the WSC gauging station at Banff (WSC Station 05BB001), which records natural flows (unaffected by any man-made regulation) at a location with a drainage area of 2,210 km^2.

The naturalized daily flood “hydrographs” are provided in Appendix B of this report.

2.5.1 Estimation of Annual Peak Instantaneous Flows from Annual Maximum Flows

The maximum daily flows obtained after routing the synthetic naturalized daily inflow "hydrographs" through Bearspaw and Glenmore Reservoirs were transformed into peak instantaneous discharges using updates of the relationships established in 2010 between recorded annual maximum daily and annual maximum instantaneous flows (see Appendix B in Golder 2010). For the Bow River below Bearspaw Dam, this relationship was established in the 2010 study from recorded annual maximum daily and instantaneous flows at WSC Station 05BH004 (Bow River at Calgary) between 1915 and 2007. Based on discussions with ESRD and The City during a project meeting on May 8, 2014, it was decided that the relationship between maximum instantaneous and maximum daily should be based on relatively natural flow records of the Bow River at Calgary between 1915 and 1932, when the effects of TransAlta's reservoirs during that period would have been minimal. The updated relationship is shown in Figure 2.1.

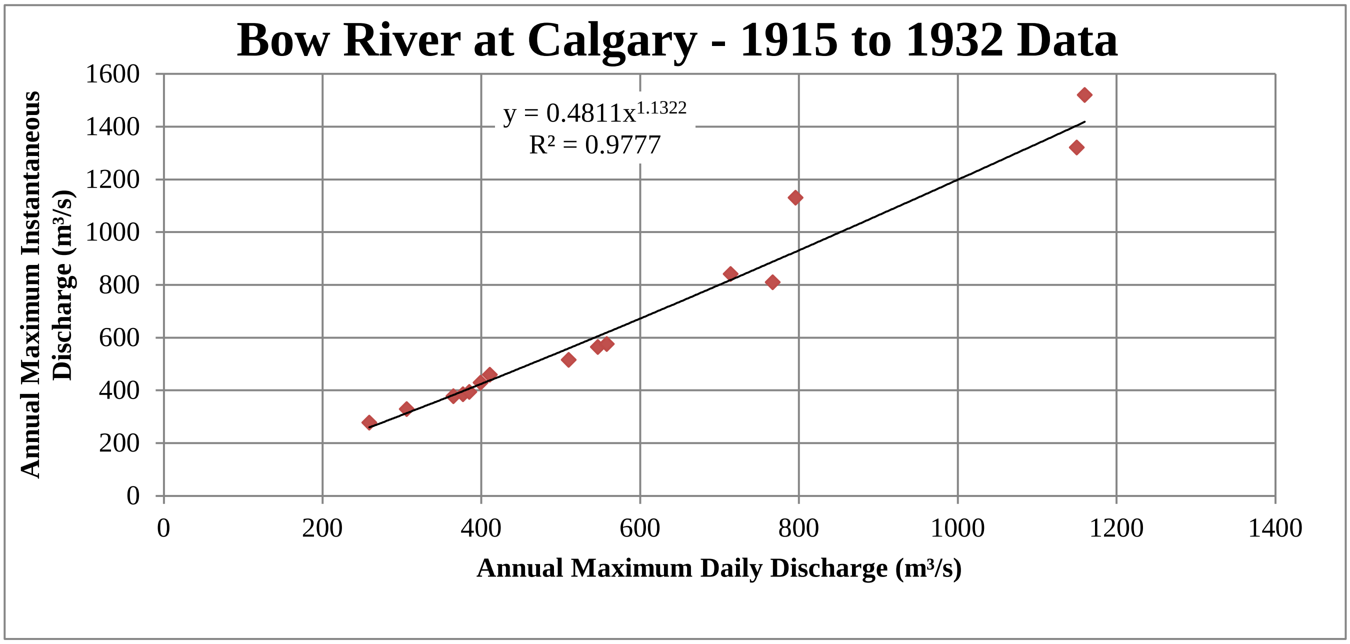


Figure 2.1: Relationship between Maximum Instantaneous and Maximum Daily Flows for the Bow River at Calgary

For the Elbow River below Glenmore Dam, the relationship was established based on recorded maximum daily and maximum instantaneous flows at WSC Station 05BJ001 (Elbow River below Glenmore Dam) and on historic large floods estimated for the Elbow River by T. Blench & Associates (Blench, 1965). The relationship was updated for this study using flow data up to 2013 and is shown in Figure 2.2.

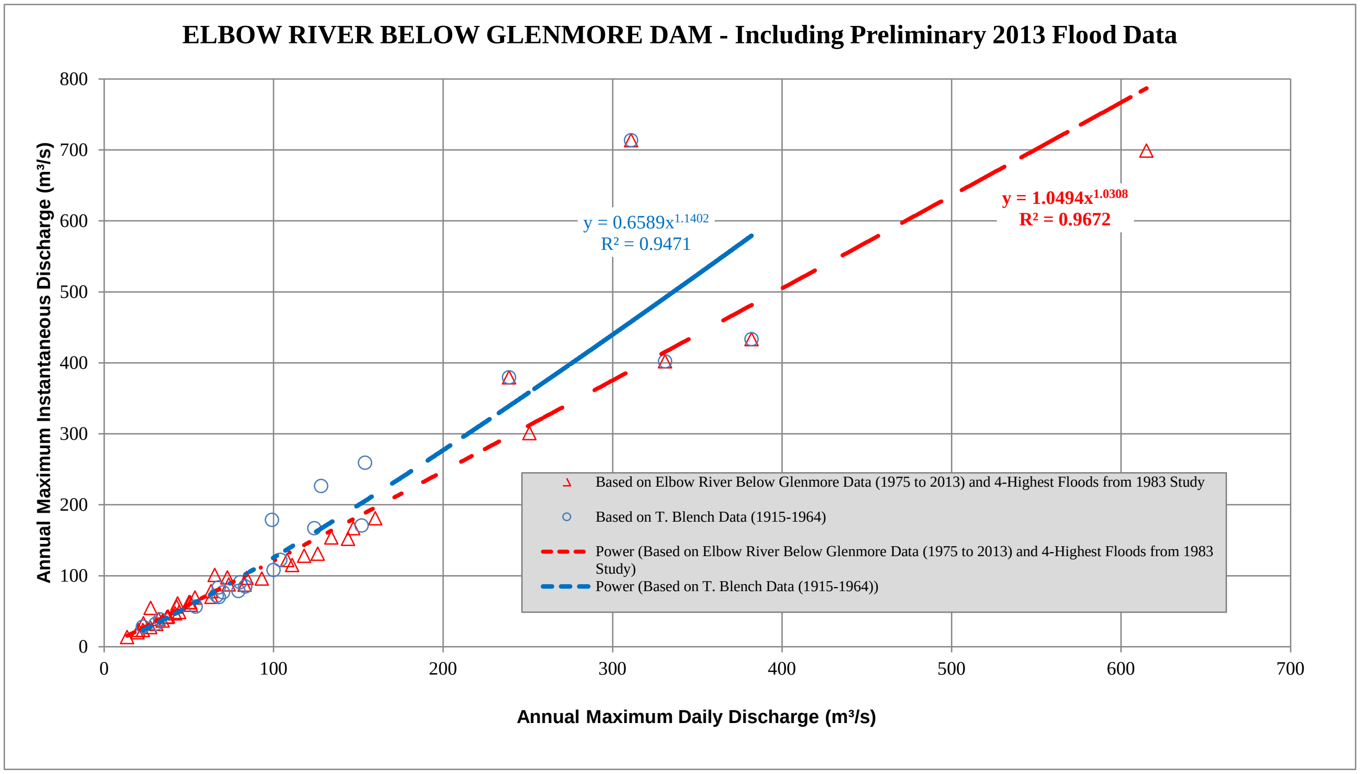


Figure 2.2: Relationships between Maximum Instantaneous and Maximum Daily Flows for the Elbow River below Glenmore Dam

2.5.2 Bow River below Bearspaw Dam

The naturalized maximum instantaneous peak flood flows on the Bow River upstream of its confluence with Elbow River corresponding to the routed naturalized daily flood inflow “hydrograph” for each return period are provided in Table 2.3. The flood routing was based on current operating rules. Table 2.3 also shows the naturalized maximum instantaneous peak flood flows for each return period obtained from the maximum daily flows (Table 2.2) using the updated maximum instantaneous-maximum daily flow relationships (Figure 2.1).

Table 2.3 shows a comparison of flood flows derived for the present hydrology assessment (with data up to 2013, including five more years of data than in the 2010 study) with those in the 2010 study (with data up to 2008).

Analyses carried out during the 2010 study indicated that Ghost Reservoir and Bearspaw Reservoir, on their own, have negligible effects (reductions of between 1% and 2%) on peak flows, as demonstrated by comparing Columns 1 and 5 in Table 2.3. Similar adjustments were made to the peak outflow values at Bearspaw Reservoir (Column 2 of Table 4) obtained during the 2014 update to develop the “Naturalized Flow Data up to 2013, Including Historic Floods, Routed through Bearspaw Reservoir” values shown in Column 6 of Table 2.3.

Table 2.3: Comparison of Instantaneous Flood Flows (m^3/s) for the Bow River Upstream of its Confluence with the Elbow River

Return Period (Years)	(1) Frequency Analyses of Naturalized Flow Data up to 2008 using Method in the 2010 Study for Incorporating Historic Floods (2010 Study)	(2) Frequency Analyses of Naturalized Flow Data up to 2013 using Method in the 2010 Study for Incorporating Historic Floods (2014 Study)	(3) Routing of Naturalized Inflow Hydrographs based on Data up to 2008 and Excluding Historic Floods through Bearspaw and Upstream Reservoirs (2010 Study)	(4) Routing of Naturalized Inflow Hydrographs based on Data up to 2013 and Excluding Historic Floods through Bearspaw and Upstream Reservoirs (2014 Study)	(5) Routing of Naturalized Inflow Hydrographs based on Data up to 2008 and Including Historic Floods Routed through Bearspaw Reservoir ONLY (2010 Study)	(6) Routing of Naturalized Inflow Hydrographs based on Data up to 2008 and Including Historic Floods Routed through Bearspaw Reservoir ONLY (2014 Study)
	(1879-2008)	(1879-2013)	(1912-2008 Excluding Historic Floods)	(1912-2013 Excluding Historic Floods)	(1879-2008)	(1879-2013)
2	423	373	494	385	418	369
5	606	666	614	487	597	659
10	774	937	751	586	763	927
20	983	1,240	842	681	970	1,230
50	1,350	1,680	969	820	1,330	1,660
100	1,710	2,040	1,070	832	1,700	2,020
200	2,170	2,420	1,210	1,050	2,160	2,390
500	2,980	2,950	1,520	1,370	2,970	2,920
1,000	3,810	3,370	1,780	1,680	3,810	3,340

A comparison of the results of the 2010 study and the 2014 update suggests the following:

- There is a significant discrepancy in the naturalized flows routed through Bearspaw Reservoir between the 2010 and 2014 analyses. The discrepancy has been traced to an error in the daily flood inflow “hydrographs” generated in 2010 for Bow River at Banff. Table 4 in Golder (2010) indicates that the 100-year and 1000-year flood flows on the Bow River at Banff (WSC Station 05BB001) were 377 and 450 m^3/s, respectively. However, the synthetic “hydrographs” shown for Bow River at Banff in Appendix B (Plot (f)) of Golder (2010) suggest that the 100-year and 1,000-year flood flows on the Bow River at Banff were 560 and 670 m^3/s, respectively. During the 2014 update, the 100-year and 1000-year flood flows on the Bow River at Banff are estimated as 385 and 455 m^3/s, respectively, and the synthetic hydrographs in Appendix B of this report reflect these values.
- The values in Column 2 of Table 2.3, obtained during the 2014 update, are generally higher than the equivalent values obtained during the 2010 study. The exceptions are for the 2-year, 50-year and 1000-year flood estimates.
- The values in Column 6 of Table 2.3, obtained during the 2014 update, are generally higher than the equivalent values obtained during the 2010 study. The exceptions are for the 2-year, 50-year and 1000-year flood estimates.
- No adjustment, using the method in USGS Bulletin 17B, of the 2014 updated flood flows (shown in Column 6 in Table 2.3) was made during the 2014 update. One of the findings of the Golder (2010) study was that once historic floods were incorporated using the approach described therein, the results from the two approaches were essentially the same.

The differences between the flood estimates reported in the 2010 study and the 2014 update study are due to (1) the significant flood event that occurred in 2013 and (2) the revised relationship between maximum instantaneous flow and maximum daily flow derived from natural flood data recorded between 1915 and 1932.

2.5.3 Elbow River below Glenmore Reservoir

Table 2.4, Columns 1 to 4, shows the return period floods (maximum daily and maximum instantaneous) obtained during the 2010 study based on return period synthetic inflow hydrographs routed through Glenmore Reservoir.

Corrections to peak flood flows routed through Glenmore Reservoir were made during the 2010 study to account for historic floods corresponding to those observed for the Bow River. The corrections were made using a similar procedure as the 1983 study by AENV since there was no historic flood recorded on the Elbow River. In the 1983 study, the frequency plot for the recorded floods for the Elbow River was shifted to mimic the shape of the frequency plots for the Bow River that included historic floods. The resulting increase/decrease in peak flood flows for the Elbow River were about 3% decrease for 2-year flood, 12% increase for 5-year, 24% increase for 10-year, 32% increase for 20-year, 42% increase for 50-year, and 47% increase for 100-year or greater return period floods. The results from the 2010 study are shown in Columns 5 and 6 in Table 2.4.

The equivalent values obtained during the 2014 update are shown in Table 2.5. The flood routing was based on current operating rules at Glenmore Reservoir. The results in Table 2.5 suggest that a significant increase in the 2014 updated flood estimates for all return periods compared to the 2010 results.

Table 2.4: Comparison of Inflows and Outflows Derived from Naturalized Synthetic Daily Flood Inflow "Hydrographs" for the Elbow River below Glenmore Dam – 2010 Study

Return Period (Years)	Based on Naturalized Recorded Flows (Inflow)		Naturalized Flows Routed through Glenmore Reservoir (Outflow)		Naturalized Flows Routed through Glenmore Reservoir and Corrected for Historic Floods (Outflow)	
	(1) Maximum Daily Discharge (m^3/s)	(2) Instantaneous Discharge (m^3/s)	(3) Maximum Daily Discharge (m^3/s)	(4) Instantaneous Discharge (m^3/s)	(5) Maximum Daily Discharge (m^3/s)	(6) Instantaneous Discharge (m^3/s)
2	55.9	66.8	45.1	53.3	43.6	51.5
5	107	132	73.7	89.1	82.2	99.4
10	154	193	126	156	156	193
20	211	267	165	206	219	274
50	302	389	245	313	349	445
100	385	501	366	476	538	699
200	481	633	477	626	701	922
500	632	841	624	830	917	1,220
1,000	766	1,030	757	1,020	1,110	1,490

Table 2.5: Comparison of Inflow and Outflow Flood Flows Derived from Naturalized Synthetic Inflow Hydrographs for the Elbow River below Glenmore Reservoir – 2014 Update

Return Period (Years)	Based on Naturalized Recorded Flows (Inflow)		Naturalized Flows Routed through Glenmore Reservoir (Outflow)		Naturalized Flows Routed through Glenmore Reservoir and Corrected for Historic Floods (Outflow)	
	(1) Maximum Daily Discharge (m^3/s)	(2) Instantaneous Discharge (m^3/s)	(3) Maximum Daily Discharge (m^3/s)	(4) Instantaneous Discharge (m^3/s)	(5) Maximum Daily Discharge (m^3/s)	(6) Instantaneous Discharge (m^3/s)
2	58.5	69.6	55.5	65.9	53.8	63.9
5	108	131	105	127	118	143
10	156	191	153	187	190	234
20	218	270	168	206	222	275
50	331	415	276	344	392	494
100	448	567	442	560	628	803
200	602	769	595	760	875	1,130
500	885	1,140	877	1,130	1,290	1,690
1,000	1,180	1,540	1,170	1,530	1,720	2,270

2.6 Peak Flow Estimates for Major Tributaries

ESRD and The City required updated flood flow estimates with return periods from the 2-year to the 1000-year for each major tributary (i.e., Nose Creek, Fish Creek, Pine Creek, and Highwood River) entering the Bow River between the Bearspaw Dam and the Highwood River confluence. A frequency analysis of the annual maximum instantaneous flow series for each tributary had been performed as part of the 2010 study. The 2010 study investigated two approaches to estimate flood flows for the lower reaches of the Bow River (the reach between its confluences with Elbow River and Highwood River), one based on coincident return period flood events and the other based on adjustments for slightly different timing of actual recorded annual flood peaks. The first approach resulted in conservative estimates of peak flows downstream of tributary confluences and was consistent with the direction provided by ESRD to assume “coincident events for all rivers and streams”. The final recommended flood estimates provided in the 2010 study were based on this approach and the same approach was used for the 2014 update. The flood frequency estimates at the mouth of each major tributary to the Bow River up to the Highwood River are provided in Table 2.6 and the results for each location on the Bow River below a major tributary are provided in Table 2.7.

2.6.1 Nose Creek at Calgary

Flow records for Nose Creek at Calgary (WSC Station 05BH003) are only available for the periods from 1911 to 1919 and from 1973 to 1986. The operation of this station was discontinued after 1986. The annual series of recorded maximum instantaneous discharges, maximum daily discharges and corresponding dates are provided in Appendix B in Golder (2010). A relationship between annual maximum daily discharges and maximum instantaneous discharge was established (shown in Appendix B of Golder (2010)), to estimate annual maximum instantaneous discharge for those years where instantaneous flows were not available. The flood frequency estimates for Nose Creek at Calgary for various return periods, as estimated during the 2010 study, are provided in Table 2.6.

2.6.2 Fish Creek at the Mouth

Flow records for Fish Creek at the mouth (WSC Station 05BK003) are available only for the period from 1989 to 1993. Flood flow estimates for Fish Creek at the mouth were transferred using data recorded at Fish Creek near Priddis (WSC Station 05BK001) based on regional relationships between drainage area and return period floods.

The transfer of flood flows from the upstream station to the mouth was accomplished during the Golder (2010) study using the following steps.

1) Establish a regional relationship between drainage area and flood peaks for various return periods.
2) Establish a relationship between annual maximum daily flows and annual instantaneous flows for Fish Creek near Priddis.
3) Transfer the annual maximum daily flood flows from Fish Creek near Priddis to Fish Creek at the mouth based on the regional relationship established in Step 1.
4) Generate instantaneous flood flows for Fish Creek at the mouth based on the relationship established in Step 2.

Threepoint Creek near Millarville (WSC Station 05BL013) has a drainage area of 507 km^2. A review of recorded flow data at this hydrometric station indicated a high level of similarity with the flow regime at Fish Creek near Priddis (drainage area of 261 km^2). Over a period of 25 years (1967 to 2007) the annual maximum daily flows at the two stations occurred on the same date for 23 of these years, and for the remaining two years the maximum daily flow lagged by one day.

The similarity between these two closely located watersheds (Fish Creek and Threepoint Creek) permitted the establishment of a regional relationship that allowed for the transfer of the flood flow data from Fish Creek near Priddis (drainage area of 261 km^2) to Fish Creek at the mouth (drainage area of 442 km^2). A relationship between annual maximum daily discharges and annual maximums instantaneous discharges was established using the Fish Creek near Priddis data. This relationship was used to derive the annual maximum instantaneous discharges for Fish Creek at the mouth from the maximum daily discharge.

A frequency analysis of annual floods at WSC Station 05BK001, including the preliminary 2013 flood peak value, was carried out as part of an updated regional analysis as described in Section 2.8. The regional flood estimates derived as part of the 2010 study (Golder, 2010) are comparable to the regional flood estimates obtained as part of the 2014 study. For example, the regional equations depicted in Figure 2.3 in Section 2.8 suggest that the 20-year and 100-year flood flow from a drainage area of 442 km^2 (equal to that of Pine Creek at the mouth) are expected to be about 198 and 454 m^3/s, respectively, which are similar to the estimates of 198 and 444 m^3/s reported in the 2010 study report. Hence, the 2010 flood flow estimates for Fish Creek at the mouth were retained for this study and are reproduced in Table 2.6.

2.6.3 Pine Creek at the Mouth

AMEC completed a review and update of flood frequency estimates at several locations on Pine Creek through the Municipal District of Foothills and The City of Calgary for a flood hazard mapping study recently completed for ESRD (AMEC, 2013). AMEC provided two set of flood frequency estimates, one based on application of the HSPF model and the other based on a regression analysis of floods recorded on regional streams. Given the uncertainties associated with estimating flood discharges in Pine Creek, AMEC recommended that the more conservative HSPF estimates be used for the Pine Creek flood hazard study. The HSPF flood frequency estimates used in the flood hazard study are provided in Table 2.6 and were adopted for this study.

2.6.4 Highwood River at the Mouth

Golder completed an update of the flood frequency estimates of the Highwood River at various locations on the river including at its mouth as part of a separate study for ESRD (Golder, 2014). The Highwood River experienced extreme high flows in 2013 and several of the hydrometric stations were not functioning during the peak flow period. The 2013 flood estimates were based on hydrologic model simulations that were then adjusted with peak estimates obtained from extending the incomplete recorded flood hydrographs at those hydrometric stations. The flood frequency estimates were then updated and these values, given in Table 2.6, have been used for the 2014 updates of flood flows on the Bow River below Highwood River.

Table 2.6: Instantaneous Flood Flows (m^3/s) for Tributary Streams to the Bow River at the Mouths

Return Period (Years)	Elbow River	Nose Creek	Fish Creek	Pine Creek	Highwood River
Drainage Area (km^2)	**1,236**	**893**	**442**	**212**	**3,952**
2	63.9	6.15	39.0	3.9	205
5	143	14.2	85.7	12.9	473
10	234	23.0	134	19.8	742
20	275	35.3	198	27.3	1,210
50	494	60.2	317	38.1	1,660
100	803	88.8	444	47.0	2,210
200	1,130	130	618	56.7	2,870
500	1,690	214	946	70.8	3,980
1,000	2,270	310	1,300	82.4	4,940

Table 2.7: Instantaneous Flood Flows (m^3/s) along the Bow River – Assuming Coincident Events for all Rivers and Streams

Return Period (Years)	Bow River above Confluence with Elbow River	Bow River below Confluence with Elbow River	Bow River below Confluence with Nose Creek	Bow River below Confluence with Fish Creek	Bow River below Confluence with Pine Creek	Bow River below Confluence with Highwood River
2	369	433	439	478	482	687
5	659	802	816	902	915	1,390
10	927	1,160	1,180	1,320	1,340	2,080
20	1,230	1,500	1,540	1,740	1,770	2,980
50	1,660	2,150	2,210	2,530	2,570	4,230
100	2,020	2,820	2,910	3,360	3,400	5,610
200	2,390	3,520	3,650	4,270	4,320	7,200
500	2,920	4,610	4,820	5,770	5,840	9,820
1,000	3,340	5,610	5,920	7,220	7,300	12,240

2.7 Flood Frequency Analysis at Gauged Locations with Natural Flows

The City and ESRD provided the historic WSC and preliminary 2012 and 2013 flow data for gauges on unregulated watercourses on the Bow River, Elbow River and their tributaries. Frequency analyses of the annual flood peak series, including the preliminary 2013 flood peaks, at the various gauged locations in the Bow and Elbow River basins were carried out to estimate floods with return periods of 2, 5, 10, 20, 50, 100, 200, 500 and 1,000 years. Probability distributions considered for fitting the annual flood peak series included the Generalized Extreme Value, Log Pearson Type III, 3-parameter Log Normal and Weibull functions. The estimated flood statistics at the gauged locations are provided in Table 2.8.

2.8 Flood Frequency Estimates at Ungauged Locations

The gauged and ungauged locations on streams in the Bow and Elbow River basins where ESRD requested flood peak estimates and flood frequency statistics are listed in Section 2.1. A regional flood frequency approach was used to develop empirical relationships between drainage areas and floods of a given return period, from which flood statistics at ungauged locations could be estimated. The relationships were used to estimate the return periods of the preliminary 2013 recorded flood flows at gauged locations.

The flood frequency statistics at the ungauged locations were estimated as follows:

- Drainage areas at WSC station locations were obtained from WSC hydrometric data. Drainage areas at ungauged locations were estimated from the known drainage areas at upstream or downstream WSC stations by adding or subtracting, respectively, the estimated local areas between the WSC stations and locations of interest. All drainage areas used in the analyses are gross areas.
- The naturalized flood frequency estimates for the Bow River downstream of Spray River were estimated as follows:
  - Return period flood estimates were obtained for the Bow River at Banff from a frequency analysis of natural (unregulated) maximum instantaneous flows at WSC Station 05BB001.
  - Natural (unregulated) flows were recorded for the Spray River at Banff from 1910 to 1949 at WSC Station 05BC001.
  - The annual maximum instantaneous flows at WSC Station 05BC001 (Spray River at Banff) were about 1.15 times the corresponding annual maximum daily flows based on the only two years (1948 and 1949) that maximum instantaneous flows were available.
  - The annual maximum instantaneous flows at WSC Station 05BC001 from 1911 to 1947 were then calculated from the respective maximum daily flows using the 1.15 multiplier, and a frequency analysis carried out on the filled series from 1911 to 1949.
  - Comparison of annual maximum occurrence dates at WSC Stations 05BC001 and 05BB001 over the 1911-1949 period suggests that in most years they occurred within a day of each other. It is unlikely that the maximum instantaneous flows from the two rivers occurred at the same time. But, it is reasonable to assume that a good approximation of the maximum instantaneous flow of the Bow River below Spray River is the maximum instantaneous flow of the Bow River at Banff plus the maximum daily flow of the Spray River at Banff. The instantaneous flood frequency estimates for the Bow River below Spray River were therefore estimated as the instantaneous return period floods at WSC Station 05BB001 (Bow River at Banff) plus the maximum daily return period floods at WSC Station 05BC001 (Spray River at Banff), computed by dividing the instantaneous values by 1.15.

- Regional relationships between drainage area and floods of a range of return periods were developed for the Elbow River and tributaries of the Bow River that were not affected by flow regulation from TransAlta's operations. The at-station flood frequency estimates for various return periods were plotted against the corresponding drainage areas at the WSC stations on log-log graphs and linear lines were fitted visually for each flood return period. The basins included in the regional analysis reflect the hydrologic responses of high elevation catchment areas. The records at Bow River at Banff (WSC Station 05BB001) and Bow River at Lake Louise (WSC Station 05BA001) were removed from the regional analysis because flood flows at these locations are attenuated by Lake Louise and do not in general reflect the headwater hydrologic responses of other high elevation basins. Figure 2.3 shows the linear log-log fits to the empirical relationships between drainage area and the T-year flood estimates for the mostly headwater sub-basins with unregulated flows in the Bow and Elbow River basins.

The regional relationships between drainage area and T-year flood estimates were then used to estimate the 2 year to 1,000-year flood flows at selected ungauged locations. The estimated flood statistics at the ungauged locations are provided in Table 2.9.

Flood estimates at WSC Stations 05BM002, 05BM004 and 05BN012 were based on frequency analyses of recorded annual flood peaks. The gross drainage areas at the ungauged locations between these stations were estimated visually from a 1:1,000,000 scale map. Flood estimates at ungauged locations on the Bow River were determined by interpolation of flood flows at upstream and downstream gauged locations based on ratios of effective drainage area. The ratio of effective drainage area to gross drainage area at an ungauged location was the average of the ratios at the upstream and downstream gauged locations. This approach is basically a linear transfer of return period flood estimates at WSC Stations 05BM002, 05BM004 and 05BN012 to locations on the Bow River that are in between two adjacent stations. The approach, that essentially constrains the flood estimate at a location to a value between those at the upper and lower WSC stations, is considered reasonable as the relationship between effective runoff contributing areas and flood flows at locations in the lower reaches of the Bow River becomes complex.

Table 2.8: Regional Flood Frequency Analysis Results

WSC Station Name	Cataract Creek near Forestry Road	Waiparous Creek near the Mouth	Trap Creek	Highwood River at Diebel's Ranch	Elbow River at Bragg Creek	Fish Creek near Priddis	Pekisko Creek	Threepoint Creek near Millarville	Elbow River at Sarcee Bridge	Highwood River at the Mouth
WSC Station Number	**05BL022**	**05BG006**	**05BL027**	**05BL019**	**05BJ004**	**05BK001**	**05BL023**	**05BL013**	**05BJ010**	**05BL024**
Drainage Area (km^2)	**166**	**332**	**137**	**774**	**791**	**260**	**232**	**507**	**1,189**	**3,952**
2-year	23	29	13	78	64	27	13	42	85	205
5-year	45	70	28	143	129	66	37	111	194	473
10-year	68	117	43	210	198	108	64	185	307	742
20-year	101	179	64	300	290	169	100	281	454	1,210
50-year	164	294	105	473	462	290	168	452	708	1,660
100-year	235	409	150	663	643	431	236	619	954	2,210
200-year	335	555	213	926	883	634	323	827	1,250	2,870
500-year	534	813	336	1,440	1,320	1,050	478	1,190	1,770	3,980
1,000-year	757	1,050	474	2,000	1,780	1,530	619	1,500	2,220	4,940

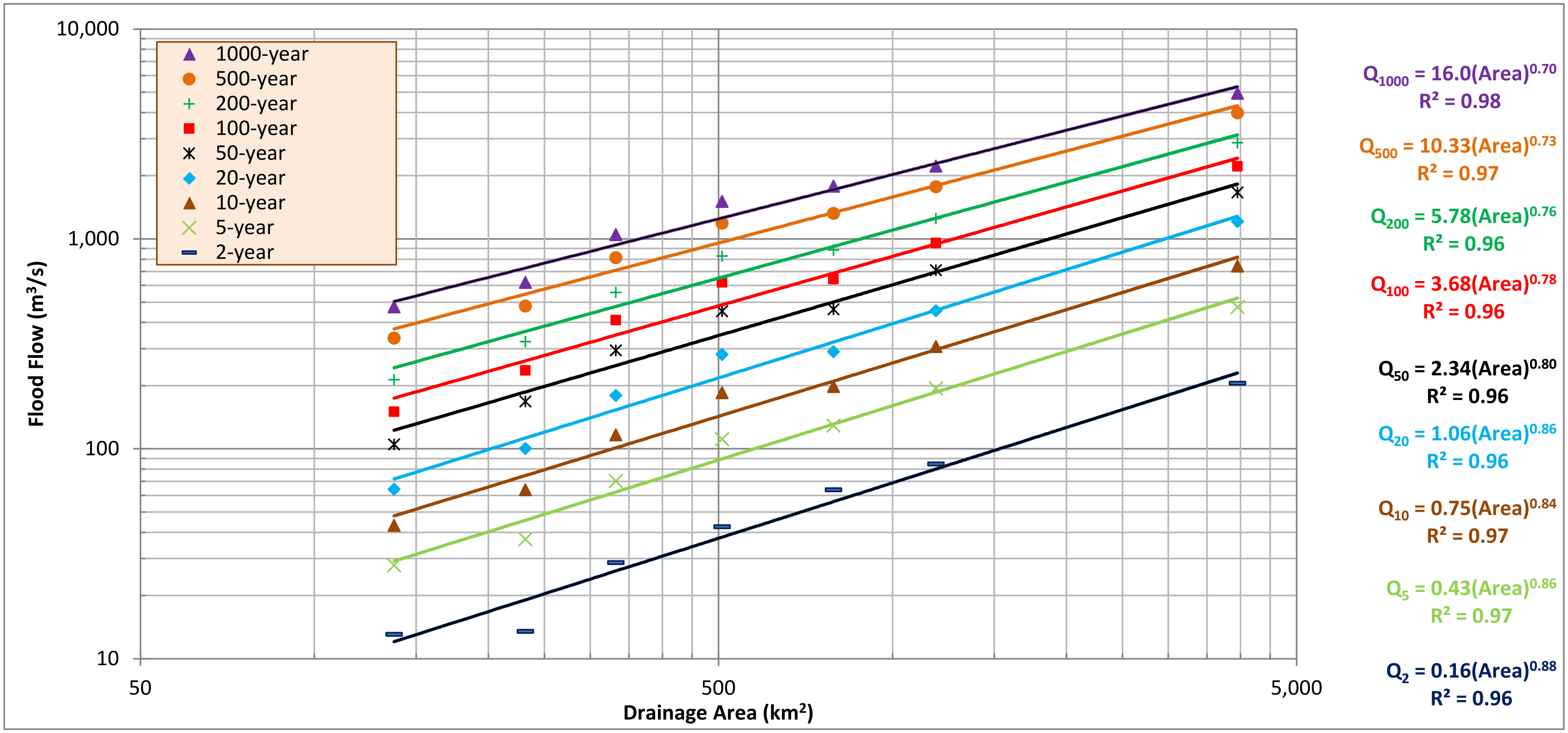


Figure 2.3: Empirical Relationships between WSC Station Drainage Areas and Return Period Flood Estimates – Bow and Elbow River Basins

Table 2.9: Updated Instantaneous Flood Frequency Estimates (Including Preliminary 2013 Flood Flows) at Gauged and Ungauged Locations

WSC Station ID	WSC Station Name or Location of Interest	Gross Drainage Area (km^2)	Effective Drainage Area (km^2)	Flow Series Type[1] and Computed Instantaneous Flood Flows (m^3/s)										Preliminary 2013 Flood Peak (m^3/s)	Approximate Return Period of 2013 Flood Peak
				Type	1000-yr	500-yr	200-yr	100-yr	50-yr	20-yr	10-yr	5-yr	2-yr		
05BJ004	Elbow River at Bragg Creek	791	791	N	1,780	1,320	883	643	462	290	198	129	63.7	1,160 [E]	~ 300-year
05BJ010	Elbow River at Sarcee Bridge - Inflow into Glenmore Reservoir	1,189	1,189	N	2,220	1,770	1,250	954	708	454	307	194	84.6	1,240 [E]	~ 200-year
05BJ001	Elbow River below Glenmore Dam (Including Historic Floods)	1,236	1,236	NZ	2,270	1,690	1,130	803	494	275	234	143	63.9	699	~ 90-year
05BA001	Bow River at Lake Louise	422	422	N	218	184	147	125	105	84.7	71.8	60.6	47.3	61.1	~ 5-year
05BB001	Bow River at Banff	2,210	2,210	N	563	524	471	432	395	345	307	268	210	450	~ 150-year
05BC001	Spray River at Banff (1911-1949)	751	751	N	301	270	232	205	180	150	128	107	79.0	60.1	< 2-year
	Bow River downstream of Spray River	2,961	2,960	N	825	759	673	611	551	476	419	361	279	520 [R]	~ 50-year
	Forty Mile Creek upstream of Bow River	148	148	EQ	102	91	76	66	58	47	40	34	26	~ 76[a]	~ 200-year
	Cougar Creek upstream of Bow River	42.6	42.6	EQ	222	159	100	70	48	26.3	17.8	10.7	4.32	~ 70	~ 100-year
	Stoneworks Creek at Highway 1	6.17	6.17	EQ	57.2	38.9	23.0	15.3	10.1	5.02	3.49	2.03	0.793	~ 15	~ 100-year
	Exshaw Creek at Exshaw	32.3	32.3	EQ	183	130	81.1	56.1	38.3	20.8	14.1	8.42	3.39	~ 70	~ 150-year
	Kananaskis River upstream of Bow River	899	899	R	697	578	450	368	300	226	178	136	85.0	368	~ 100-year
05BG010	Ghost River above Waiparous Creek	485	485	N	1,789	1,174	670	436	282	155	95.1	55.3	20.7	350	~ 50-year
05BG006	Waiparous Creek near the Mouth	333	333	N	1,106	856	581	427	305	185	119	71.1	28.7	320	~ 50-year
	Ghost Reservoir Inflow	6,550	6,550	NZ	3,400	2,980	2,440	2,060	1,700	1,250	945	673	377	1,240	~ 25-year
	Ghost Reservoir Outflow	6,550	6,550	NZ	3,370	2,950	2,420	2,040	1,680	1,240	936	666	373	1,230	~ 25-year
05BH005	Bow River at Cochrane	7,412	7,383	NZ	3,370	2,950	2,420	2,040	1,680	1,240	936	666	373	2,050 [R]	~ 100-year
	Bearspaw Reservoir Inflow	7,770	7,740	NZ	3,370	2,950	2,420	2,040	1,680	1,240	936	666	373	1,900 [R]	~ 100-year
	Bearspaw Reservoir Outflow	7,770	7,740	NZ	3,340	2,920	2,390	2,020	1,660	1,230	927	659	369	1,880 [R]	~ 100-year
05BH004	Bow River at Calgary (IHF[d])	7,870	7,740	NZ	3,340	2,920	2,390	2,020	1,660	1,230	927	659	369	1,720[b] [R]	~ 80-year
	Bow River downstream of Elbow River Confluence (IHF)	9,100	8,950	NZ	5,610	4,610	3,520	2,820	2,150	1,500	1,160	820	433	2,420 [R]	~ 75-year
	Bow River upstream of Highwood River Confluence (IHF)	10,440	10,260	NZ	7,300	5,840	4,320	3,400	2,570	1,770	1,340	915	482	2,820 [R]	~ 75-year
	Bow River downstream of Highwood River Confluence (IHF)	14,390	14,150	NZ	12,240	9,820	7,200	5,610	4,230	2,980	2,080	1,390	687	5,820 [R]	~ 120-year
05BM002	Bow River below Carseland Dam	15,660	14,700	R	6,530	5,100	3,660	2,830	2,180	1,524	1,140	834	495	3,300 [R]	~ 120-year
	Bow River at Highway 547	16,460	15,450	R	6,870	5,370	3,860	3,000	2,310	1,610	1,210	877	514	3,300 [R]	~ 120-year
	Bow River at Highway 842	16,960	15,920	R	7,080	5,540	3,990	3,100	2,390	1,670	1,250	904	526	3,300 [R]	~ 120-year
05BM004	Bow River below Bassano Dam	20,250	17,750	R	7,910	6,220	4,500	3,500	2,710	1,890	1,410	1,010	571	3,340 [R]	~ 90-year
	Bow River at Highway 539	22,250	19,140	R	6,240	4,950	3,620	2,840	2,210	1,560	1,160	842	477	3,340 [R]	~ 150-year
	Bow River at Highway 36	23,050	19,130	R	6,240	4,950	3,620	2,840	2,210	1,560	1,170	842	478	3,340 [R]	~ 150-year
	Bow River at Highway 875	23,850	19,080	R	6,300	5,000	3,660	2,870	2,230	1,570	1,180	849	481	3,340 [R]	~ 150-year
05BN012	Bow River near the Mouth - Highway 524	25,280	19,160	R	6,210	4,930	3,610	2,830	2,200	1,550	1,160	839	476	3,610[c] [R]	~ 200-year

Notes:

1: Series Type: N: Natural Flows; NZ: Naturalized Flows; R: Regulated Flows; EQ: Based on regional regression equations or estimated using results from other site studies.

a: See Section 2.9.4 for discussion

b: At the time when the report for this study was being finalized, WSC estimated this value to be 1,840 m^3/s. This estimate is not expected to change the flood frequency estimates.

c: At the time when the report for this study was being finalized, WSC estimated this value to be 3,450 m^3/s. This estimate is not expected to change the flood frequency estimates.

d: IHF – Including Historic Floods

E: Estimated by WSC and may be different from preliminary recorded value. Estimate used in flood frequency analysis.

R: Regulated Flow

2.9 Estimates of June 2013 Flood Peaks and Return Periods

One of the objectives of this study was to estimate the return period of the June 2013 flood event for streams at several locations in the Bow and Elbow River basins. The locations of interest are listed in Section 2.1. Table 2.9 provides preliminary estimates of the peak flows during the 2013 flood event, as well as flood frequency estimates that take the June 2013 flood into account. Return period estimates for the preliminary June 2013 flood peaks at each location of interest were obtained by comparing the peaks to the frequency analysis results. The preliminary June 2013 flood peak flow estimates were obtained as follows:

2.9.1 WSC Stations and Other Locations on Bow River and Elbow River

WSC and ESRD provided preliminary continuous flow records during the June 2013 flood event at hydrometric stations such as WSC Stations 05BA001, 05BH004, etc. Table 2.9 shows the maximum flow recorded at these stations. These values are considered preliminary until published by WSC.

WSC or The City provided peak flow estimates at hydrometric stations that stopped recording flows during the peak of the flood, such as WSC Stations 05BJ004, 05BJ010, etc. Such values are denoted as [E] in Table 2.9.

The June 2013 peak flow of the Bow River downstream of Spray River was estimated as the recorded instantaneous peak flow of the Bow River at Banff (WSC Station 05BB001) plus the preliminary maximum daily flow recorded of the Spray River at Banff (WSC Station 05BC001) on the same day (see Section 2.8).

2.9.2 Downstream of Hydropower Reservoirs

TransAlta provided preliminary daily discharges recorded below Barrier (Kananaskis River), Ghost (Waiparous River) and Bearspaw (Bow River) Dams. The daily outflow values were increased by ten percent to estimate peak instantaneous values, however, these estimates are considered to be preliminary and approximate.

2.9.3 Locations on Bow River Downstream of Highwood River Confluence

The peak June 2013 flood estimates at WSC Stations 05BM002, 05BM004 and 05BN012 were based on preliminary flows provided by WSC. Peak flood estimates at ungauged locations on the Bow River were then determined by interpolation of flood flows at upstream and downstream gauged locations based on ratios of effective drainage area (following the procedure described in Section 2.8 for flood frequency estimation).

2.9.4 Locations on Tributaries to Upper Reach of Bow River

The peak June 2013 flood estimates for Cougar Creek upstream of Bow River, Stoneworks Creek at Highway 1, Exshaw Creek at Exshaw, and Forty Mile Creek at Banff were of interest to ESRD. Flows on these streams are not recorded and indirect methods to estimate peak flows were required.

The standard approach taken by Golder is based on comparing the regional flood frequency estimates (using the relationships shown in Figure 2.3) with the estimated return period of the June 2013 flood in other upper Bow River tributary watersheds (see Tables 2.8 and 2.10). The regional data suggest that the return period of the June 2013 flood in the upper watersheds ranges from 100 years (Kananaskis River below Barrier Lake and upstream of Bow River), to 150 years (Bow River at Banff, WSC Station 05BB001) and even to 200 years (Redearth Creek near the Mouth, WSC Station 05BB005).

If the regional correlation was considered valid, the relationships depicted in Figure 2.3 and the drainage areas of ungauged streams at a location of interest could be used to estimate preliminary peak 2013 flood flows and corresponding return period flows.

This approach was used for obtain the Cougar, Stoneworks and Exshaw Creek peak 2013 flows and frequency statistics presented in Table 2.9, with additional details presented in the relevant sections below.

- Cougar Creek upstream of Bow River: ~ 70 m^3/s peak 2013 flow ~ 100-year flood;
- Stoneworks Creek at Highway 1: ~ 15 m^3/s peak 2013 flow ~ 100-year flood; and
- Exshaw Creek at Exshaw: ~ 70 m^3/s peak 2013 flow ~ 150-year flood.

An alternate method, also based on regional data but using a specific analogous basin, was used to obtain the Forty Mile Creek estimates presented in Table 2.9, as outlined in the relevant section below.

- Forty Mile Creek upstream of Bow River: ~ 76 m^3/s peak 2013 flow ~ 200-year flood

Several hydrologic studies were undertaken or commissioned by the provincial government, municipalities, private industry and engineering consultants to characterize the June 2103 flood. Some of these study reports were reviewed to assist in providing estimates of the June 2013 peak flows at the above four locations.

Cougar Creek upstream of Bow River

Cougar Creek is a tributary of the Bow River, located on the north side of the river at Canmore.

BGC Engineering Inc. (BGC) recently carried out a forensic analysis of the June 19-21, 2013 debris flood event on Cougar Creek for the Town of Canmore (BGC, 2013a), and provided an assessment of short-term flood mitigation measures. BGC reviewed available photographs taken during the June 2013 flood event and past flooding events as part of their forensic analysis to develop a short-term mitigation design flow. As part of their analysis, BGC provided an estimate of the peak flow during the flood event.

BGC noted that the 100-year flood for Cougar Creek just upstream of its confluence with the Bow River (drainage area estimated to be about 42.6 km^2 at this location) had been previously been estimated at about 16 m^3/s by AMEC (AMEC, 2003 & 2007). However, photographs and videos reviewed by BGC suggested that the peak flow of the 2013 debris flood was much greater than 16 m^3/s. Photographs of the inlet of the Elk Run Boulevard culvert showed the culvert at about two-thirds capacity at the peak of the flood. CH2M HILL (CH2M HILL, 1993) indicated that this culvert has a capacity of 160 m^3/s, suggesting that the 2013 peak flow may have been in excess of 100 m^3/s. However, based on their analysis, BGC suggested that the extent of aggradation at the culvert inlet during the peak of the flood was not known and the wingwalls had been outflanked, reducing the hydraulic efficiency of the culvert. They noted that it was likely that the peak flow was coincident with a reduced culvert capacity.

Therefore, for the purposes of the short-term mitigation design, BGC tentatively assigned a peak flow of 64 m^3/s to the 2013 event. This is four times the previous 100-year flood estimate. BGC is currently conducting hydraulic modelling of the culvert inlet, with various assumed channel geometries, to develop a range of potential peak flows. Results of that sensitivity analysis were not available at the time of writing their 2013 report.

A return period of about 100 years is considered an appropriate estimate of the 2013 flood at Cougar Creek. This corresponds to an approximate 2013 peak flow of about 70 m^3/s for a drainage area of 42.6 km^2, based on the flood frequency estimates provided in Table 2.9. This estimate is close to BGC's preliminary estimate.

Stoneworks Creek at Highway 1

Stoneworks Creek is a tributary of the Bow River, located on the north side of the river at Canmore. The drainage area is estimated to be about 6.17 km^2 at a location just upstream of Highway 1.

BGC recently conducted a preliminary hazard assessment of Stoneworks Creek, including documentation of damage from the June 2013 flood for the Town of Canmore (BGC, 2013b). BGC postulates that the June 2013 event that impacted the Stoneworks Creek alluvial fan is best described as a debris flood rather than a flood.

Referencing a 2009 Stantec design brief, BGC (2013b) describes flows in Stoneworks Creek being routed to upstream of a 1200 mm diameter culvert named Culvert 4, which would convey flows up to a 10-year flood, with higher flows being directed to a 900 mm diameter culvert named Culvert 8. The 100-year flood would see Culvert 8 receiving approximately 65 percent of the total flow, and Culvert 4 receiving the remaining 35 percent. Culvert 4 was noted to have sufficient capacity (2 m^3/s) to convey 70 percent of the design 100-year flood flow (3 m^3/s). Below Culvert 4, Stonework Creek flows would be routed under Highway 1 through an existing 1200 mm diameter culvert. At the outlet of Culvert 8, creek flows would discharge under Highway 1 through a 900 mm diameter concrete culvert. According to BGC's observations, these works were severely impacted and damaged during the 2013 flood. The 1200 mm diameter culverts under Palliser Trail and Highway 1 became blocked, resulting in the creek flowing parallel to Palliser Trail to the northwest.

Based on an analysis of past events, BGC suggests that the June 2013 event was the largest debris flood on record for Stoneworks Creek, dating back to 1940s. However, no frequency for the 2013 event was provided. Nevertheless, it appears that the 2013 peak flow in Stoneworks Creek was much greater than the previous culvert design 100-year flow of 3 m^3/s.

A return period of about 100 years is considered an appropriate estimate of the 2013 flood at Stoneworks Creek. This corresponds to an approximate 2013 peak flow of about 15 m^3/s for a drainage area of 6.17 km^2, based on the flood frequency estimates provided in Table 2.9.

Exshaw Creek at Exshaw

A report prepared by ARA Engineering Ltd. (ARA) for Alberta Transportation in 2013 (ARA, 2013) provides a peak flow estimate of 42 m^3/s in Jura Creek during the June 2013 flood. Jura Creek is adjacent to Exshaw Creek, and has a drainage area of 15 km^2 at the Highway 1A crossing. The June 2013 flood peak estimate computed by ARA was based on the Basin Runoff Potential Method with a precipitation amount of about 200 mm during the flood event, and was checked by comparing the calculated flow depth with photos of high water marks upstream of the crossing. Using the flood-area relationships provided in Figure 2.3, the 100-year and 200-year flood estimates for a basin with a drainage area of 15 km^2 are 31 and 45 m^3/s, respectively. ARA's peak flow estimate of 42 m^3/s in Jura Creek during the June 2013 flood appears to be closer to the 200-year event based on the regional flood frequency estimates.

Exshaw Creek has a drainage area of about 32.3 km^2 near Exshaw. Assuming that 150-year is an appropriate estimate of the return period of the 2013 flood in Exshaw Creek, a peak flow of about 70 m^3/s is considered a reasonable preliminary 2013 peak flow estimate, based on the flood frequency estimates provided in Table 2.9.

Forty Mile Creek

Forty Mile Creek is currently ungauged, and various methods used to estimate both the 2013 peak and flood frequency statistics provide a wide range of results. Table 2.9 presents recommended values, including a preliminary 2013 peak flow of about 75 m^3/s that corresponds to about a 200-year flood, obtained following the approach described below.

WSC reports a preliminary estimate of a peak flow of 450 m^3/s for the Bow River at Banff (WSC Station 05BB001), and Table 2.9 shows that this flow has a return period of about 150 years.

Northwest Hydraulics Consultants (nhc) completed a flood hazard study for the Bow River and Forty Mile and Echo Creeks at Banff for ESRD prior to the June 2013 flood (nhc, 2013). The study computed 100-year and 1,000-year flood estimates for the Bow River at Banff as 378 and 448 m^3/s, respectively, but the frequency analysis was completed prior to the June 2013 flood. This frequency analysis suggests that the June 2013 peak flow had a return period close to 1,000 years. However, this return period is not consistent with those computed for other locations in the upper reaches of the Bow River, and does not include the flood in its analysis.

The nhc study also references an earlier Banff floodplain study done by AENV that included a 100-year flood estimate of 407 m^3/s (AENV, 1980). This is closer to the 100-year flood estimate of 432 m^3/s for Bow River at Banff (WSC Station 05BB001) provided in Table 2.9.

The nhc report provides a 100-year flood estimate of 43.7 m^3/s for Forty Mile Creek at Banff, as noted in Table 2.10. This estimate is based on the results of a regional flood frequency analysis of relatively short peak flow records (most between the 1970s and 1990s) on similarly sized basins close to the Forty Mile Creek basin.

Golder prepared flood frequency estimates for Forty Mile Creek as noted in Table 2.10 using the regional flood frequency relationships shown in Figure 2.3, that were also used for Cougar, Stoneworks and Exshaw Creeks. This analysis suggests that a 100-year peak flow for Forty Mile Creek at Banff is about 185 m^3/s. The analysis included the preliminary estimates of the 2013 flood at a number of locations in the Bow River, Elbow River and Highwood River basins, i.e., over a much wider region than that in the nhc (2013) study.

Golder believes that the 100-year peak flow estimate for Forty Mile Creek by nhc (2013) is an underestimate because it does not include the 2013 event, and that the estimate based on the standard regional analysis used for the other creeks is an overestimate because it is almost half of the flow recorded for the Bow River at Banff.

The differences in flood frequency estimates for Forty Mile Creek were then addressed to some extent by analyzing the annual peak flows recorded at WSC Station 05BB005, Redearth Creek near the Mouth. Redearth Creek is located on the south side of Bow River and approximately across from Forty Mile Creek. Its drainage area at WSC Station 05BB005 is 147 km^2, which is almost the same as that of Forty Mile Creek upstream of Bow River (148 km^2). It is considered an appropriate surrogate basin for analysis and its flow records between 1974 and 1996 were used in the regional flood analysis undertaken by nhc (2013).

The flow records at WSC Station 05BB005, however, only extend from 1974 to 1996. The peak annual flows for this station were correlated with those at WSC Station 05BB001 (Bow River at Banff) for the concurrent period. The resulting regression relationship was used to generate peak flow estimates at WSC Station 05BB005 from 1909 to 2013, corresponding to the available records at WSC Station 05BB001. Based on this regression relationship, the 2013 peak flow on Redearth Creek is estimated as 76 m^3/s using the peak flow estimate of 450 m^3/s at WSC Station 05BB001, Bow River at Banff. A frequency analysis was conducted on the extended Redearth Creek near the Mouth annual peak flow series, as presented in Table 2.10. Given the lack of records and the range of possible frequencies associated with different analysis techniques, the flood frequency estimates for Redearth Creek as derived above are considered to be appropriate for transfer to Forty Mile Creek at this time.

The estimated 2013 peak flow for Redearth Creek was about 76 m^3/s, which corresponds to a return period of about 200 years. These are considered as the most reasonable estimate for the peak 2013 flow and corresponding return period for Forty Mile Creek upstream of Bow River as presented in Table 2.9 as both basins have almost the same drainage area. No high water marks for the 2013 flood event on Forty Mile Creek near the Fenlands Recreation Center in Banff were available for this study to assess the peak flow. However, a review of the flood maps developed by nhc (2013) along Forty Mile Creek, the topography near the recreation center, and the water levels associated with the return period floods used in the nhc study suggests that a peak flow of 76 m^3/s at this location is not unreasonable.

Table 2.10: Instantaneous Flood Flows (m^3/s) on Forty Mile Creek and Redearth Creek

Return Period (Years)	Forty Mile Creek at Banff (Source: nhc, 2013, which does not include 2013 flood flow)	Forty Mile Creek upstream of Bow River Derived from Regional Relationships in Figure 2.3	Redearth Creek Derived from Recorded and Filled-in Annual Peak Flows at 05BB005	Forty Mile Creek upstream of Bow River Recommended
Drainage Area (km^2)	**139**	**148**	**147**	**148**
2	19.1	12.9	25.1	26
5	26.4	31.1	33.2	34
10	31.0	51.1	39.7	40
20	35.1	76.6	46.8	47
50	40.1	130	57.2	58
100	43.7	185	65.9	66
200	47.2	258	75.5	76
500	51.7	394	90.1	91
1,000	55.0	531	102	102

Summary

The results from the various studies conducted post-June 2013 flood suggest that using a flood return period of between 100 and 200 years for the June 2013 flood event in the upper tributaries of the Bow River is a reasonable approach to estimate the June 2013 peak flows on nearby streams.

2.9.5 Return Period of June 2013 Flood Peak

The June 2013 peak flow estimates were compared to the flood frequency estimates developed at the respective locations to estimate the return period of the June 2013 flood at each location of interest. Table 2.9 shows that the flood event experienced on several tributaries of the upper Bow River in June 2013 had a return period of between 100 and 200 years. Closer to Calgary, the flood event on the Bow River had a return period of about 100 years. In contrast, the upper Elbow River watershed likely experienced a 200-year to 400-year flood event primarily because the severe June 2013 storm event was centred around the upper portions of the Elbow and Highwood Rivers. Downstream of Calgary and the Highwood River, the flood event appears to have a return period of between 100 and 200 years depending on the location. This is likely due to the extreme flood event that was also experienced in the Highwood River, which contributed significantly to the flows in the Bow River in addition to the inflows from the upper Bow River watershed.

3.0 COMMENTS ON EFFECTS OF CLIMATE CHANGE ON FLOOD ESTIMATES

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

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

Using the predictions from the Canadian Regional Climate Model, Valeo et al. (2007) showed that May precipitation could increase by more than 35 percent under a $2xCO_2$ scenario. As a result, expected increases in precipitation during the month of May could nearly double spring flood peak flows.

The flood peaks in 2013 in the Bow River and Elbow River basins are the most significant large floods since 1932, as shown on the plots of annual maximum instantaneous flows in Figure 3.1. Based on recorded data over the past 103 years (1911 to 2013), the observed annual peaks in recent years do not appear to be increasing with time in either the Bow River or Elbow River. The trend in the Bow River in fact appears to be a decreasing one, likely due to flow regulation at TransAlta's hydropower reservoirs on the Bow River and its tributaries. There does not seem to be a trend in the Elbow River. In both cases, any apparent trend is not statistically significant.

About 80 percent of the recorded annual peaks in the Bow River and the Elbow River occurred at the end of May and in the month of June as shown in Table 3.1 and Figure 3.2. The frequency of peaks occurring outside this period (earlier or later) also does not appear to be changing with time. The recent patterns in the timing of these floods are similar to what were observed at the beginning the century. There is no clear evidence that the patterns in magnitude or timing of annual peaks have changed significantly over the past hundred years.

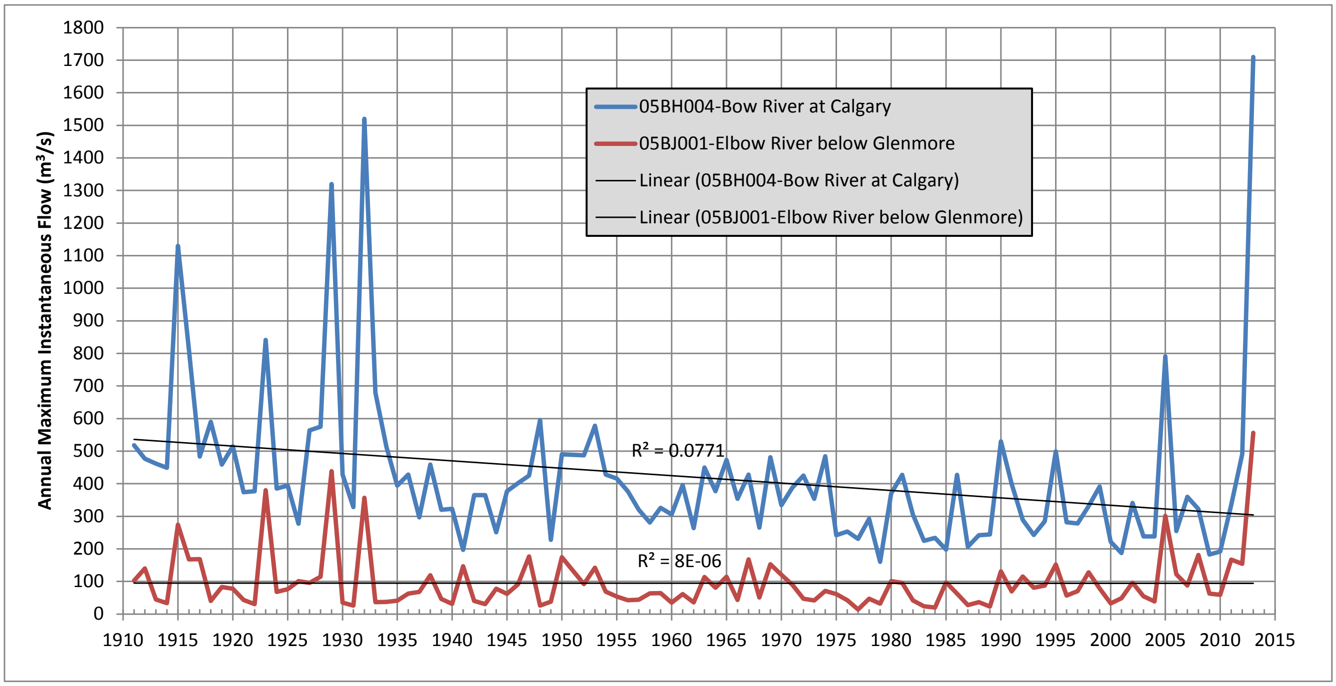
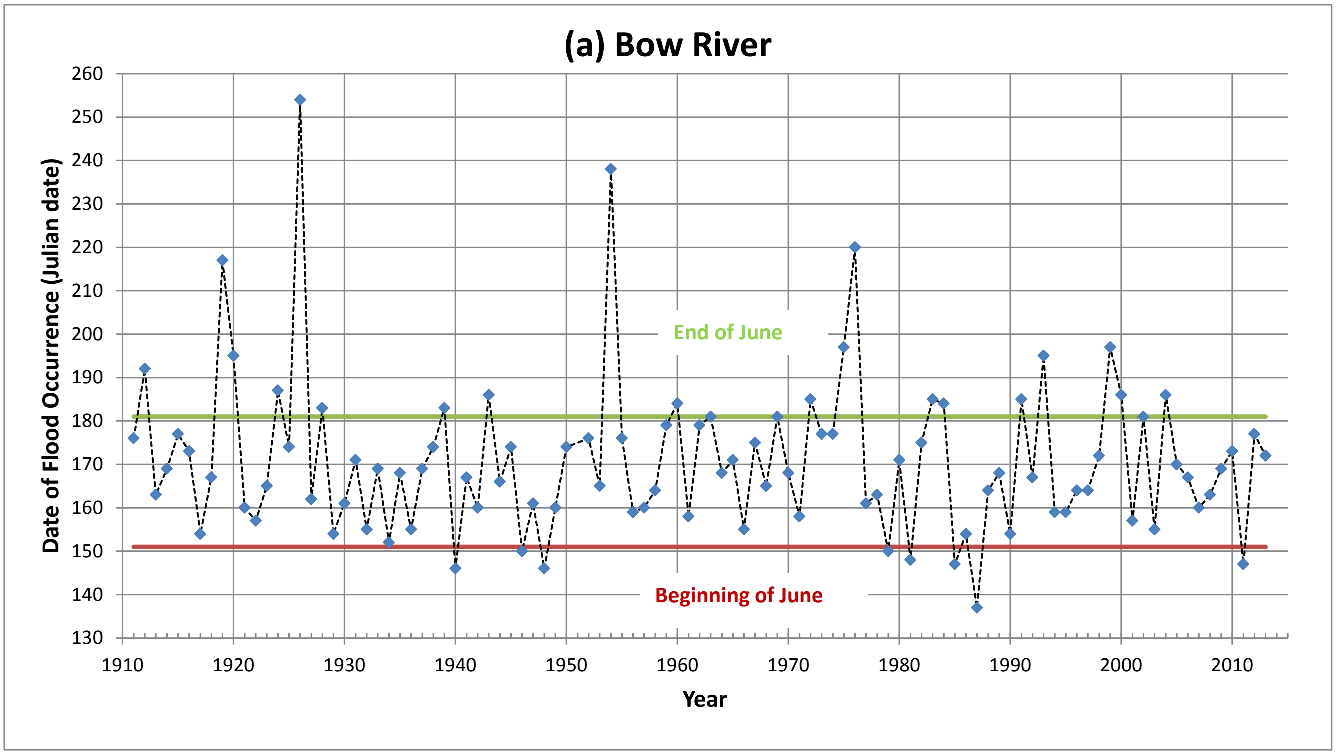


Figure 3.1: Annual Peak Series for the Bow River (WSC Station 05BH004) and the Elbow River (WSC Station 05BJ004)

Table 3.1: Time of Occurrences of Annual Maximum Daily Flood Events in the Bow and Elbow Rivers

Month	Bow River - Occurrences of Annual Maximum Daily Events since 1911		Elbow River - Occurrences of Annual Maximum Daily Events since 1911	
	Number	%	Number	%
April	-	-	4	4
May	8	8	24	23
June	74	73	58	55
July	16	16	7	7
August	3	3	8	8
September	1	1	4	4



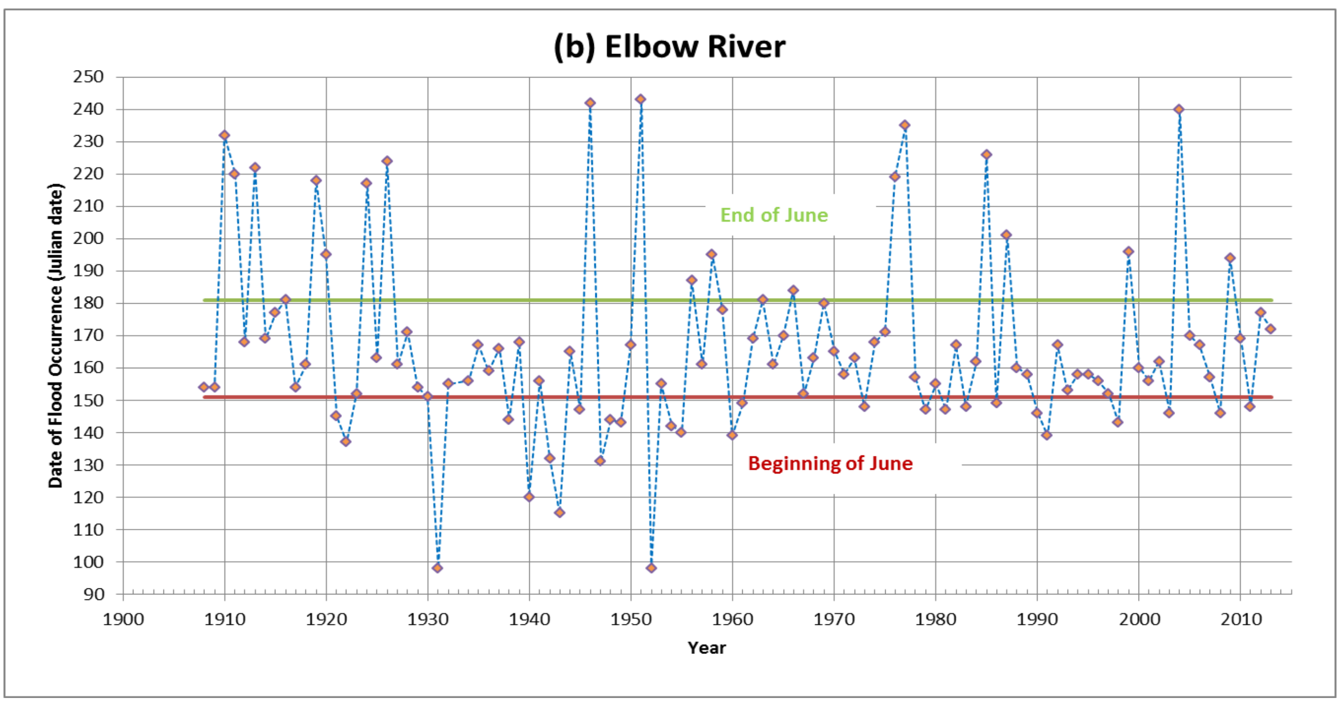


Figure 3.2: Time of Occurrences of Past Annual Floods in the Bow and Elbow River

4.0 COMMENTS ON SEASONALITY OF FLOOD PEAKS

The naturalized flow series for the Bow River below Bearspaw Dam and the Elbow River below Glenmore Dam were analyzed to identify whether one mechanism (snow melt or rainfall) dominates annual high flow generation. Based on recorded data over the past 100 years, about 80% of peak flows for the Bow River and the Elbow River occurred at the end of May and in the month of June as shown in Table 3.1, Section 3. This suggests that typical annual peaks generated from snowmelt/rain-on-snow dominate in the Bow River and Elbow River watersheds. However, major floods, including that of 2013 are clearly driven primarily by extreme rain events, with snowmelt not contributing significantly.

Frequency analyses were conducted as part of the 2010 study on the seasonal peak flow series that were generated from the naturalized (1930-2008) and recorded flows (1911 to 1930) to compare the flood estimates with those derived based on annual flow series. The spring flow series for each year were defined to occur from April to mid-June while the summer flow series were defined to occur from mid-June to September. The analyses were re-conducted with data up to 2013. Table 4.1 provides a comparison of the flood magnitudes generated for various return periods for the Bow River below Bearspaw Dam and the Elbow River below Glenmore Dam.

Table 4.1: Flood Magnitudes Derived using Seasonal Flood Series

Return Period (Years)	Bow River					Elbow River				
	Based on Spring Floods	Based on Summer Floods	Based on Annual Floods	Percentage compared to Annual Floods		Based on Spring Floods	Based on Summer Floods	Based on Annual Floods	Percentage compared to Annual Floods	
				Spring	Summer				Spring	Summer
2	342	325	374	-9%	-13%	48	38	57	-15%	-32%
5	474	450	520	-9%	-13%	90	72	104	-14%	-31%
10	568	547	640	-11%	-15%	130	105	151	-14%	-31%
20	664	650	777	-15%	-16%	181	148	213	-15%	-31%
50	796	802	991	-20%	-19%	274	229	327	-16%	-30%
100	902	932	1,184	-24%	-21%	371	315	448	-17%	-30%
200	1,015	1,075	1,411	-28%	-24%	497	431	611	-19%	-29%
500	1,173	1,291	1,772	-34%	-27%	728	650	915	-20%	-29%
1,000	1,300	1,475	2,100	-38%	-30%	968	883	1,239	-22%	-29%

For the Bow River, the flood peaks derived using spring flow series are less than the flood magnitudes derived using annual flow series by about 9 to 15 percent for return periods between 2 and 20 years, and by about 20 to 40 percent for higher return periods. The flood peaks derived using summer flow series are also significantly smaller than those derived using annual flow series. For the Elbow River, the flood peaks derived using spring flow series are less than the flood magnitudes derived using annual flow series by about 15 to 20 percent. The flood peaks derived using summer flow series are significantly smaller (by more than 30 percent) than those derived using the annual flow series. Therefore, the flood peak discharges for various return periods should be estimated based on the annual peak flow series.

4.1 Contribution of Storm Runoff to Flood Peak Flows

Within the City of Calgary, the Bow River and its tributaries (Elbow River, Nose Creek, Fish Creek and Pine Creek) receive significant stormwater runoff from urban and developed areas. Stormwater runoff contributing to the flood flows of the Bow River above its confluence with Elbow and to the tributary streams such as Elbow River, Nose Creek, Fish Creek and Pine Creek has already been accounted for in the recorded flow values. The analysis of the effect of the stormwater runoff was limited in the 2010 study to areas that are directly contributing runoff to the Bow River and were not included in the recorded data, such as the tributary sub-catchment contributing runoff in the reach of Bow River between its confluence with the Elbow River and Fish Creek.

As part of a Bow River loading study, a stormwater runoff simulation was completed for the entire City of Calgary using the QHM continuous simulation model (Golder, 2007). The simulation period for that study included the stormwater runoff during the June 2005 rainfall. The resulting simulated daily average peak storm runoff discharge from tributary sub-catchments contributing runoff to the Bow River between its confluence with the Elbow River and Fish Creek was estimated to be about 20.5 m^3/s and the peak runoff occurred on June 17, 2005. The instantaneous peak discharge (average runoff over a period of 1 hour) was about 50 m^3/s, and occurred at 23:00 hrs on June 17.

The instantaneous stormwater runoff from the tributary sub-catchments was about 6.4 percent of the peak discharge recorded on the Bow River on June 18, 2005. The lag-time between the flood runoff from the tributary sub-catchment and the peak flood on the main stem of the Bow River was about 19 hrs. The peak stormwater runoff occurred during the rising limb of the Bow River flood hydrograph and therefore the actual contribution of the storm runoff during the peak flow in the Bow River was less than 6.4 percent. The contribution of the receding stormwater runoff to the Bow River peak flow was estimated to be about 20.5 m^3/s, which was about 2.6 percent of the peak flood recorded on the Bow River in June 2005.

The analysis of the 2005 flood event showed that the contribution of the storm-runoff from the sub-catchment between the confluence of the Bow River and the Elbow River and Fish Creek to the peak flood flows in the Bow River was small. A similar conclusion is expected with reference to the storm runoff contribution to the June 2013 flood in the Bow River reach within the City of Calgary.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The 2014 hydrology assessment for the Elbow River and Bow River and its tributaries through The City was required to determine the flood magnitudes that would be used to prepared flood inundation mapping with the updated HEC-RAS hydraulic model of the Bow and Elbow River system through Calgary. As part of the 2014 hydrology assessment, naturalized flow series were generated at the major storage facilities on the Bow River and its tributaries upstream of Bearspaw Dam and on the Elbow River through Glenmore Reservoir.

A key consideration in the 2014 hydrology assessment was the effect of the extreme flood event that occurred in June 2013 in the Bow River, Elbow River, Highwood River and other river basins along the eastern slopes in southern Alberta. The peak flood flows documented or estimated in this study indicate floods of given return periods on the Bow River through Calgary are somewhat larger than those obtained during the 2010 study, however, flood flows near the mouth of Elbow River are significantly larger than those obtained during the 2010 study. For example, the estimated 100-year flood flows on the Bow River above and below the confluence with the Elbow River following the 2013 flood event are 2,020 and 2,820 m^3/s, respectively, compared to 1,710 and 2,450 m^3/s in the 2010 study and 1,970 and 2,670 m^3/s reported in the 1983 study. The differences between the flood estimates reported in the 2010 and current 2014 study are mainly due to inclusion of the significant flood that occurred in June 2013.

A comparison of the June 2013 peak flow estimates to the flood frequency estimates developed at the respective locations suggest that the flood event experienced on several tributaries of the upper Bow River in June 2013 had a return period of between 100-year and 200-year. Closer to Calgary, the flood event on the Bow River had a return period of about 100 years. In contrast, the upper Elbow River watershed likely experienced a 200-year to 400-year event primarily because the severe June 2013 storm event was centred around the upper portions of the Elbow River and Highwood River. Downstream of Calgary and the Highwood River, the flood event appears to have a return period of between 100-year and 200-year depending on the location. This is likely due to the extreme flood event that was also experienced in the Highwood River, which contributed significantly to the flows in the Bow River in addition to the inflows from the upper Bow River watershed.

5.2 Recommendations

Table 5.1 summarizes computed, naturalized instantaneous flood flows for the Bow River and its tributaries, including the Elbow River, for various return periods.

Table 5.1: Recommended Naturalized Instantaneous Flood Flows (m^3/s) for the Bow River and its Tributaries, Including the Elbow River, for Various Return Periods

Return Period (Years)	Bow River above Elbow River	Elbow River above Glenmore Dam	Elbow River below Glenmore Dam	Bow River below Elbow River	Nose Creek at Bow River	Bow River below Nose Creek	Fish Creek at Bow River	Bow River below Fish Creek	Pine Creek at Bow River	Bow River below Pine Creek	Highwood River at Bow River	Bow River below Highwood River
2	369	84.6	63.9	433	6.15	439	39.0	478	3.9	482	205	687
5	659	194	143	802	14.2	816	85.7	902	12.9	915	473	1,390
10	927	307	234	1,160	23.0	1,180	134	1,320	19.8	1,340	742	2,080
20	1,230	454	275	1,500	35.3	1,540	198	1,740	27.3	1,770	1,210	2,980
50	1,660	708	494	2,150	60.2	2,210	317	2,530	38.1	2,570	1,660	4,230
100	2,020	954	803	2,820	88.8	2,910	444	3,360	47.0	3,400	2,210	5,610
200	2,390	1,250	1,130	3,520	130	3,650	618	4,270	56.7	4,320	2,870	7,200
500	2,920	1,770	1,690	4,610	214	4,820	946	5,770	70.8	5,840	3,980	9,820
1,000	3,340	2,220	2,270	5,610	310	5,920	1,300	7,220	82.4	7,300	4,940	12,240

Report Signature Page

This report presents the methodology and results of the 2013 Bow River and Elbow River hydrology assessment and flood documentation study. Please direct any questions or clarification regarding the contents of this report to the following study team members who prepared this report.

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APPENDIX A

Naturalized Daily Flows and Flood Routing at Key Locations

A1 AVAILABILITY OF INPUT DATA

The process of developing natural flow estimates requires the use of historic records of reservoir levels and outflows from the date each structure started its operation. This appendix describes the methodology for calculating natural flows as well as how this methodology was implemented at each location of interest given the available data. It should be noted that the primary purpose of developing natural flows was to properly assess incoming annual peak flows into all major structures, and for as many years as possible. Naturalized annual peak flows constitute a principal input into the hydrologic frequency analyses, which is a key step in the development of design flood hydrographs with target return periods in the upper Bow River and its tributaries. Therefore, where seasonal flow data were available (i.e. data from April to October), they could still be used to help assess the annual maximum flows. Annual peak flows were assessed for as many years as possible, as further explained in subsequent sections that provide more information about each storage site where natural flow series were developed.

A2 PROJECT DEPLETION METHOD

Alberta Environment uses the Project Depletion Method to calculate natural flows on all major rivers in Alberta. The same methodology is employed by the Prairie Provinces Water Board (PPWB). The PPWB consists of representatives from Environment Canada (representing the Federal Government) and the representatives of the three Prairie Provinces. The short summary that explains the project depletion method in this section follows closely the documentation of the Natural Flow Computation Program (NFCP) program used in this study. Technical specifications for NFCP were approved by the PPWB in November of 2008.

Natural flows are river flows that would have been observed at selected locations in a river basin assuming there had been no human intervention by operation of large storage reservoirs or withdrawals. The most common approach to estimate natural flows is the Project Depletion Method, which is essentially aimed at “undoing” the impacts of human intervention in a systematic way, reach by reach, in a downstream progression.

The calculation procedure is explained below for a small example shown in Figure A1 that contains all elements found in complex river basins. There are two river reaches with a reservoir R_1 at their confluence. In this example, natural flow is calculated at the reservoir site. There is one diversion into the reservoir (D_1) and one return flow (RT_1) into the reservoir, one diversion channel out of the reservoir (D_2), and regulated outflow from the reservoir into natural channel reach C_3. The general approach to calculate natural flows at any location is to estimate local runoff which originates between the given location and the closest upstream locations at which natural flows had already been evaluated. Denote the natural flow at reservoir as Q_{R1} and the local runoff between natural flows Q_1, Q_2 and the reservoir as LR. The natural flow at the reservoir site can then be calculated as:

$$Q_{R1} = Q_1 + Q_2 + LR \quad (1)$$

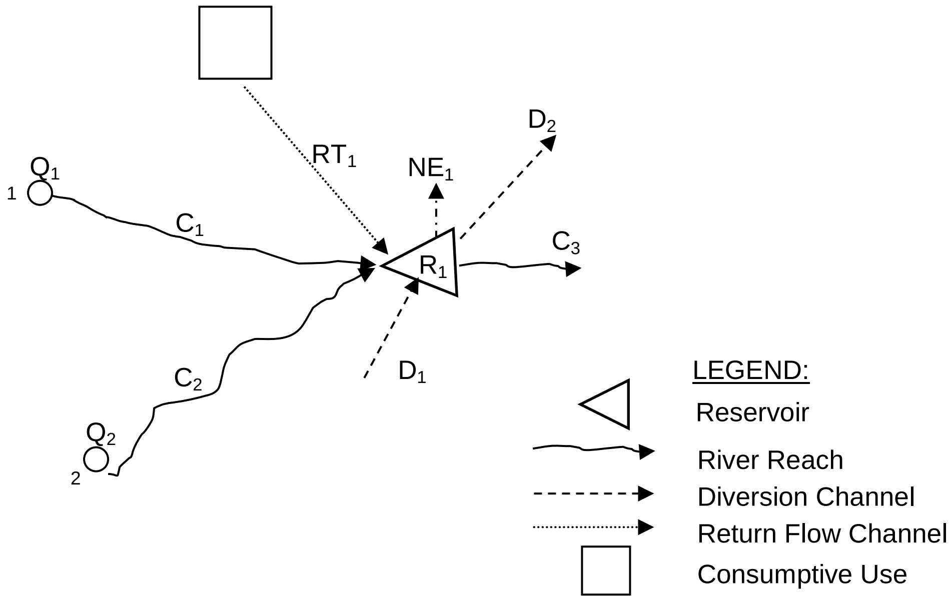


Figure A1: Sample Schematic for Calculation of Natural Flows

Consequently, the principal component of estimating natural flows is determination of the local runoff LR. Assuming Qr1 and Qr2 are the recorded flows at locations 1 and 2, LR for the reservoir in Figure A1 can be calculated using the following equation assuming average flow over time step t:

$$LR = Q_{C3} + Q_{D2} - Q_{RT1} - Q_{D1} + \Delta V/t - Q_{r1} - Q_{r2} \quad (2)$$

where:

Q_{C3}	the recorded flow in channel C_3
Q_{D1}	flow in diversion channel D_1
Q_{D2}	flow in diversion channel D_2
Q_{RT1}	flow in return flow channel RT_1
$\Delta V/t$	reservoir storage change over time step t

Reservoir storage change is further evaluated using the starting and ending storage (Vs and Ve) for a time step, along with adjustments for net evaporation (evaporation minus precipitation) for a given time interval *t*. Note that the sign for net evaporation is reversed since the consideration is to remove the effect of net evaporation (i.e. put the evaporation loss back in the river since this loss would not have happened if the reservoir had not been built):

$$\frac{\Delta V}{t} = \frac{Ve - Vs}{t} + \frac{(E - P)[A(Ve) + A(Vs)]}{2t} \qquad (3)$$

where:

V_e	volume at the end of time step *t* (m^3)
V_s	volume at the start of time step *t* (m^3)
P	total precipitation over time step *t* (m)
E	total evaporation from the reservoir surface over time step *t* (m)
$A(V_e)$	surface area (m^2) corresponding to the ending volume *Ve*
$A(V_s)$	surface area (m^2) corresponding to the starting volume *Vs*

To summarize, local runoff LR can in general be assessed by conducting a water balance calculation for a sub-catchment which is delineated by the downstream point for which LR is evaluated and the upstream control points where recorded flow series are available. The general expression is:

$$LR = \sum_{i=1}^{m} Q_i - \sum_{j=1}^{n} Q_j + \sum_{k=1}^{l} \frac{\Delta V_k}{t} \qquad (4)$$

where:

Q_i	average outflows (i=1,m) from a sub catchment within time step *t*
Q_j	average inflows (i=1,m) into a sub catchment within time step *t*

while the storage change term $\Delta V/t$ is summed up over all storage reservoirs in the sub-catchment area under consideration. Inflows and outflows into a sub-catchment include all diversions and return flows into it, as well as diversions out of it. Normally, natural flows should be calculated at all on-stream reservoir locations, especially when reservoirs have sizeable live storage.

Equation (1) suggests that natural flows be first determined at upstream locations (e.g. locations 1 and 2 in the example in Figure A1). The calculation then proceeds in the above manner for all requested locations in the river basin in a downstream progression. It should be noted that for short (e.g. daily) time steps, the length of river reaches along channels C_1 and C_2 may require the use of channel routing, such that the routed outflow from these channels takes part in the mass balance calculation at the reservoir node, both for calculating local runoff LR, which would require the routing of recorded flows along these channels, and for calculating the natural flow, which would require routing of the natural flow estimates previously made at nodes 1 and 2. Alberta Environment uses the Wilson's routing equation which was built into the SSARR model. A brief description of Wilson's equation is provided below.

As with the other river routing methods, the governing equation is related to channel storage change over a time step, which is a function of average inflow and outflow:

$$\frac{I_{t-1}+I_t}{2}-\frac{O_{t-1}+O_t}{2}=\frac{\Delta S}{t} \qquad (5)$$

By subtracting both sides of the above equation with O_{t-1} , multiplying by $t/(O_t\text{-}O_{t-1})$ and by letting $\Delta S/(O_t\text{-}O_{t-1}) = TS$, the above equation becomes:

$$Ot=\frac{\left[\frac{I_{t-1}+I_t}{2}-O_{t-1}\right]\cdot t}{TS+\frac{t}{2}}+O_{t-1} \qquad (6)$$

where the term *TS* represents the average travel time along a river reach for given flow conditions, evaluated either by reading from the *TS* vs *Q* table or by using a functional form of the travel time vs flow curve as:

$$TS=\frac{Kts}{\left(\frac{O_{t-1}+O_t}{2}\right)^n} \qquad (7)$$

The routing coefficients *Kts* and *n* must previously be determined by finding the best fit curve for a given set of the available *(Ts,Q)* coordinates. Usually, *Ts* can be determined for any given flow rate by linear interpolation from a table of *(Ts,Q)* points (these tables were provided by Alberta Environment and used in this project). In the above definition of *Ts*, the base of the denominator shown below represents the average channel flow over a time step as the arithmetic average of the outflows at the beginning and the end of the time step:

$$\frac{O_{t-1}+O_t}{2}$$

Various implementations of the SSARR method may rely on different estimates of the average channel flow during a given time step (which may also include inflows into the channel in some form). The method relies on the established empirical relationship between the travel time and flow for a given channel. Once this relationship is available, the calibration consists of deciding how many sequential phases a given river reach should be divided into, which is conducted using repeated simulation trials until the observed downstream hydrograph closely matches the simulated channel outflow. All work on calibration of the SSARR method in the South Saskatchewan River basin had already been done by Alberta Environment. The upper Bow River Basin schematic that was obtained from Alberta Environment already has the channels broken into lengths that work as single phase channels (i.e. no further subdivision is required).

The use of the SSARR channel routing method is optional (i.e., natural flows can be calculated with or without channel routing), since calculating natural flows using sufficiently long (monthly, seasonal or annual) time steps does not require channel routing. In this study, the time step was daily, while the travel time between the most upstream point of interest (Banff) and the most downstream point at Bearspaw Reservoir is well above one day, indicating that channel routing is required. The use of the SSARR routing method in the calculation of natural flows does not change the methodology. Instead, it merely introduces a more realistic account of flow changes in large river systems where the total travel time is greater than the calculation time step. It should also be noted that the SSARR river routing is as accurate as the available input data. As any other differential equation, a coarse time step and a large variation between the flows in two subsequent time steps may jeopardize the accuracy of the results.

It should be noted that the Wilson's equation deals with the transformation of surface water movement aimed to account for the channel storage change from day to day. However, large channel storage changes may happen in the Bow River during the formation of ice cover in November, and its subsequent melting in April. These transformations of water into ice and back into liquid can also be understood movements of flow into and out of storage, but such channel storage changes are not modelled by the Wilson's equation.

A3 GENERATION OF DAILY NATURAL FLOWS AT SPRAY LAKE

Figure A2 shows the Spray Lake and diversion to the three downstream power plants that eventually discharge into the Bow River at Canmore. The Spray River drains in the northerly direction and joins the Bow River at Banff. Flow monitoring station 05BC001 is located just upstream of the confluence. The Spray Lake is a naturally occurring lake, which was dyked off to divert water through three hydro power plants over a shorter distance and a large drop in elevation. The diversion route is indicated in orange color in Figure A2. The total catchment area of Spray Lake at the mouth is approximately 751 km^2, of which about 520 km^2 drain into Spray Lake. Although the remaining catchment area downstream of the Lake is roughly one third of the total, the upstream runoff into Spray Lake is considerably higher due to higher specific yield, such that roughly 85% of the total annual natural flow of Spray Lake at the mouth (station 05BC001) originates upstream of the dam.

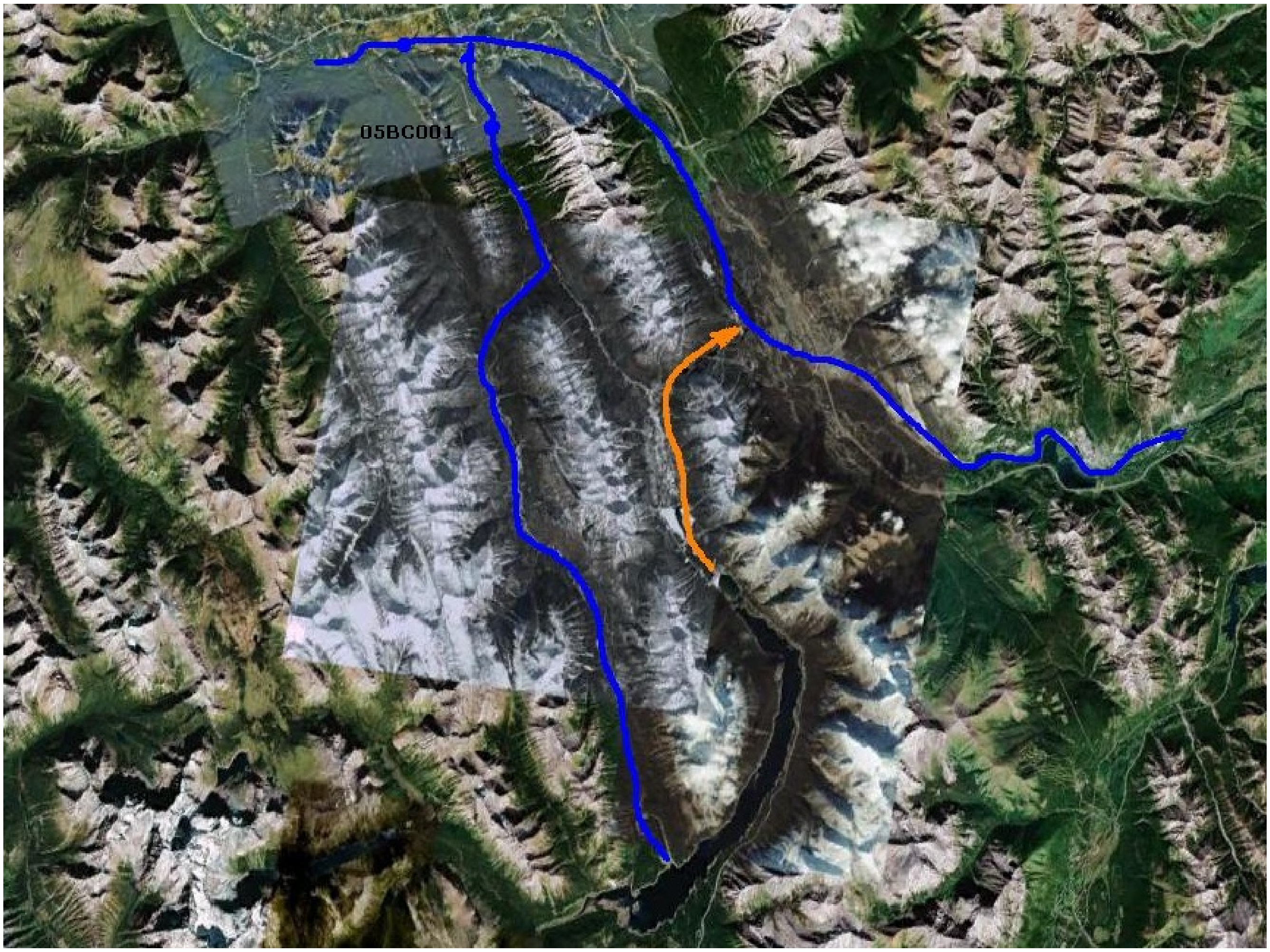


Figure A2: Spray Lake and Hydro Power Diversion

Proper calculation of natural flows at Spray Lake requires the historic daily lake levels as well as all daily outflows from the lake. The old Spray river channel still collects the runoff downstream of the lake, but after construction of the dam in 1949 it also serves as a potential spillway conduit to evacuate large floods that exceed the capacity of the diversion route. The spillway into the Spray River has historically been used only once in 1974. There are several issues associated with assessing daily natural flows at the dam site:

- Daily diversion flows for power generation from Spray Lake were only available after 1975, which makes it impossible to properly assess natural flows at the dam site between 1949 and 1975;
- Between 1918 and 1939 peak flows at the dam site were based on recorded flows at station 05BC002. This station is now submerged by the lake. Its original drainage area was 360 km^2, which was increased by a factor of 1.3 to account for additional catchment area into the lake that was created by the dam (520 km^2) less the adjustment for the considerable increase in the lake surface area which is handled by net evaporation directly in the water balance equation. Regression equation Y=0.77X+10.543, assessed on the basis of the available data for both series, has a good fit (R^2 = 0.86);

- For periods from 1912 to 1917 and 1940 to 1948, peak flows were generated based on the relationship established between the natural Spray River flows at the mouth 05BC001 (drainage area 750.6 km^2) and the peak flows at the dam site from 1918 to 1939 from records available at station 05BC002, which is expressed by the regression equation mentioned under b) above; and
- For the 1949 to 1975 period, both peak flows and continuous daily flows were estimated based on inferential relationship developed between the recorded flows of Spray River at the mouth and the calculated natural flows at the dam after 1975. Different models were used for assessing annual peak flows and continuous time series, due to the difficulties of relating the reduced flows at the mouth to the flows at the dam for the available period after 1975. These models are further discussed below.

Infill of daily continuous natural flow estimates for Spray Lake at the mouth is required to enable proper flood routing from Banff all the way to Ghost Reservoir, as well as to allow more accurate calculation of natural flows at Ghost reservoir. The model used for the development of continuous daily natural flows at the mouth for the 1949 – 1975 period was calibrated to meet the two following objectives:

a) Fit the regression between the recorded Spray River at the mouth after 1975 (with reduced catchment area) and the sum of natural flows at the dam and flows at the mouth for the same period (R^2 = 0.923) ; and

b) Make sure that the resulting flow estimates also follow the same statistical distribution and have similar mean and standard deviation as the available estimates of natural flow at 05BC001 for the periods with available data.

The above two objectives were met. However, the resulting annual peak flows from this model were not distributed according to the same frequency that was found in the years of available data. It was felt that if the peak flows from this series were used as input into the frequency analyses, they may reduce the anticipated design peak flows at the dam, which would unnecessarily bias the estimates towards lower values. This concern was also driven by comparison of the flows at 05BC001 for the 1949 – 1975 period with the flows at the same site for 1975 – 2008 period. Recorded peak flows at 05BC001 between 1949 and 1975 are higher on average than the flows encountered in the post 1975 period, as shown in Table A1. Also, daily flows at the mouth and at the dam may differ in the range of 2 to 10 times with a high variance. Although the in-filling of daily flow series at 05BC001 was completed for the 1949 – 1975 period, it is suggested that future updates to the database of natural flows provided in this study include retrieval of the recorded outflows from the dam from TransAlta, in order to allow proper evaluation of daily natural inflows into the Spray Lake.

Annual peak flow estimates at the Spray Lake were based on the regression established for the post-1975 period between the recorded flows at the mouth (station 05BC001) and the sum of these flows with the naturalized flows at the dam site, which represent the equivalent of the natural flows at the mouth. This regression equation is $Y = 2.942X + 26.415$, however, the regression fit is not as consistent (R^2 = 0.59), and the regression line slope is subject to significant changes if selected outliers are removed. Table A1 provides a listing of all peak flows for the three distinct periods (prior to 1949, 1949 – 1975, and post 1975).

Station 05BC001 shows the Spray River flows that were measured after the dam was constructed. As mentioned earlier, the peak flows at this station were considerably higher in the 1949 to 1975 period than in the post 1975 period. This justifies higher annual peak flows at the dam estimated for the same period. It should also be noted that Mud Lake diversion, which transfers some of the runoff that would naturally occur into the Lower Kananaskis Lake, was included in the estimates of natural flows at the dam since it is functions as a permanent modification to the watershed. The Mud Lake diversion would continue to operate during floods.

Table A1: Summary of Daily Naturalized Peak Flow Estimates for Spray River at Dam and at the Mouth (05BC001)

Year	Peak Flow at the Dam (m^3/s)	Year	Peak Flow at the Dam (m^3/s)	Peak Flows at 05BC001	Year	Peak Flow at the Dam (m^3/s)	Peak Flows at 05BC001
1912	65.7	1949	144	39.9	1976	62.3	9.17
1913	75.1	1950	85.0	19.9	1977	47.6	8.50
1914	76.9	1951	191	55.8	1978	72.1	11.2
1915	60.7	1952	68.5	14.3	1979	43.3	8.09
1916	108	1953	88.2	21.0	1980	59.4	11.4
1917	62.7	1954	83.8	19.5	1981	83.0	15.7
1918	96.9	1955	73.5	16.0	1982	70.5	11.0
1919	74.7	1956	70.0	14.8	1983	58.2	7.03
1920	76.9	1957	52.2	8.75	1984	65.8	9.01
1921	63.1	1958	49.8	7.96	1985	150	8.72
1922	57.7	1959	56.7	10.3	1986	102	17.4
1923	112	1960	56.1	10.1	1987	43.5	7.64
1924	52.8	1961	89.4	21.4	1988	63.6	10.3
1925	65.1	1962	48.3	7.45	1989	64.8	7.79
1926	43.7	1963	49.8	7.96	1990	75.2	17.5
1927	78.6	1964	85.3	20.0	1991	71.8	12.3
1928	73.8	1965	83.5	19.4	1992	52.4	10.1
1929	64.3	1966	76.4	17.0	1993	52.9	9.09
1930	57.2	1967	72.9	15.8	1994	44.8	6.40
1931	52.7	1968	48.7	7.56	1995	109	18.8
1932	121	1969	65.2	13.2	1996	84.0	14.9
1933	131	1970	70.2	14.9	1997	72.5	9.35
1934	73.2	1971	68.2	14.2	1998	58.8	9.99
1935	57.9	1972	156	43.9	1999	71.9	10.4
1936	62.7	1973	67.0	13.8	2000	47.2	6.95
1937	48.9	1974	115	30.0	2001	39.8	8.36
1938	70.4	1975	48.8	7.62	2002	93.8	19.4
1939	51.4				2003	53.1	12.1
1940	48.1				2004	57.6	10.3
1941	45.2				2005	70.3	23.5
1942	56.8				2006	73.1	11.5
1943	61.8				2007	95.2	17.7
1944	35.2				2008	58.1	11.6
1945	55.9				2009	50.1	10.5
1946	71.0				2010	49.8	9.1
1947	53.8				2011	67.9	42.0
1948	101				2012	96.8	21.2
					2013	238.9	42.9

A4 GENERATION OF DAILY NATURAL FLOWS AT LAKE MINNEWANKA

Lake Minnewanka is a naturally occurring lake that was raised to increase its storage. In addition to this, about 15% of the total runoff into Lake Minnewanka comes from the Ghost river catchment via the Ghost River diversion. This diversion was built in 1941 and a flow monitoring station has operated until 1994. Although the station has been discontinued, this diversion continues to operate, and it would also operate during floods. Consequently, in this study Ghost diversion was considered as integral part of runoff into Lake Minnewanka for calculation of natural flows into the lake.

Natural flows into Lake Minnewanka were estimated based on its recorded outflows available from Water Survey of Canada stations 05BD002 until 1941 and from station 05BD004 from 1942. The Lake elevations (WSC station 05BD003) are available from 1917. There are many days with missing data prior to 1943, when the continuous daily records began. However, the records between 1917 and 1943 are usually available at least once or twice a week, which allowed the use of linear interpolation as the first approximation for infilling the missing data, particularly since this lake is large and the levels do not vary substantially from day to day. Until 1941, the dam was operated in the range between 1450 and 1455 m, with flow regulation having a relatively small impact on the downstream Bow River flows at Ghost and Bearspaw Dams The mean annual flow of Cascade River at the mouth is 8.4 m^3/s, compared to about 90 m^3/s for the Bow River at Bearspaw dam. Effects of flow regulation are more pronounced after 1942, when the lake levels were raised to operate in the range between 1465 and 1475 m and the Ghost diversion started to operate. Table A2 shows a comparison of daily peak natural flows at Lake Minnewanka for three periods (prior to 1943, 1943 – 1975, and after 1975).

Table A2 shows that expected peak natural flows were higher during the 1943-1975 period than during the post-1975 period. There is presently no plausible explanation for this statistical discrepancy, but it can be noted that the diversions from the Ghost River were higher in the period prior to 1980s, and that the more recent modification of the diversion weir restricts the diverted flows to a maximum of 400 cfs (11.33 m^3/s), which did not exist in the earlier period between 1943 and 1975.

Table A2: Summary of Daily Naturalized Peak Flow Estimates for Cascade River at Lake Minnewanka

Year	Peak Flow at the Dam (m^3/s)	Year	Peak Flow at the Dam (m^3/s)	Year	Peak Flow at the Dam (m^3/s)
1917	89.0	1943	53.1	1976	40.6
1918	72.6	1944	37.9	1977	38.1
1919	155	1945	51.0	1978	51.2
1920	106	1946	47.8	1979	29.8
1921	53.6	1947	47.4	1980	58.8
1922	39.7	1948	130	1981	89.0
1923	124	1949	29.2	1982	48.1
1924	53.6	1950	87.1	1983	38.1
1925	36.6	1951	78.0	1984	36.9
1926	39.0	1952	71.5	1985	29.6
1927	50.0	1953	130	1986	75.5
1928	65.2	1954	72.1	1987	27.8
1929	69.1	1955	59.4	1988	48.4
1930	60.1	1956	63.8	1989	38.3
1931	34.4	1957	46.5	1990	94.4
1932	116	1958	44.4	1991	61.3
1933	84.9	1959	47.8	1992	40.9
1934	39.7	1960	40.9	1993	38.6
1935	50.1	1961	61.5	1994	32.5
1936	38.1	1962	51.5	1995	102
1937	30.6	1963	52.9	1996	60.3
1938	47.3	1964	70.6	1997	43.6
1939	46.8	1965	122	1998	49.6
1940	30.6	1966	62.5	1999	45.0
1941	18.1	1967	73.5	2000	24.4
1942	53.3	1968	38.0	2001	41.3
		1969	83.0	2002	58.8
		1970	88.8	2003	49.2
		1971	77.4	2004	53.8
		1972	77.4	2005	80.1
		1973	87.9	2006	32.8
		1974	105	2007	85.2
		1975	36.7	2008	43.6
				2009	27.1
				2010	32.5
				2011	57.1
				2012	111
				2013	307

A5 GENERATION OF DAILY NATURAL FLOWS AT THE UPPER AND LOWER KANANASKIS LAKES

Upper and Lower Kananaskis Lakes are also naturally occurring lakes that were raised to higher elevations to provide more balancing storage and head for hydro power generation. The upper Kananaskis Lake receives runoff from the catchment area of about 150 km^2 and it drains into the lower Kananaskis Lake, which, in addition to receiving outflow from the Upper Kananaskis Lake, also receives inflow from a local catchment area of roughly the same size (151 km^2), although some of the runoff originating from this area is diverted into the Spray Lake via the Mud Lake diversion. The Lower Kananaskis Lake eventually drains into the Barrier Lake, located some 50 km downstream of it.

The Upper Kananaskis Dam had its normal full supply level raised in 1942 by about 14 m. The Lower Kananaskis Dam was built in 1955 with an increase in full supply elevation by 11 m and allowed annual fluctuation of water levels by 14 m. Prior to 1942, both lakes have been operated as natural water bodies. The hydro power plants associated with these lakes are known as Interlakes and Pocaterra. The following procedure is needed to calculate natural inflows into both lakes:

a) Use the Upper Kananaskis storage levels and outflow records to remove the effect the storage and calculate natural flows at the Upper Kananaskis Lake; and

b) Use the Lower Kananaskis storage levels, outflows and the outflow from the Upper Kananaskis as a part of the total inflow to assess the net runoff from the local contributing catchment into the Lower Kananaskis Lake.

The data available for full implementation of the above procedure are only available for the 1985 to 2013 for both reservoirs. Water levels at both lakes and the outflows from the Lower Kananaskis Lake are also available for 1975-1985 period, but the turbine flows out of the Upper Kananaskis Lake are missing. It was decided to naturalize flows from 1975 to 1985 for the combined Upper and Lower Kananaskis sub-catchments by using the storage change at both reservoirs and outflows from the Lower Kananaskis Lake. Daily peak flows for the years with missing data were developed based on the regression established between total natural flow for both catchments and each individual catchment for the 1985 – 2007 data. This approach provided 10 more years of data (1975-1984) that can provide input into statistical frequency analyses. The resulting regression fit and equations are shown in Figure A3 and A4. Table A3 shows the annual maximum daily natural flow estimates for the Upper and Lower Kananaskis Lakes (indicated as Interlakes and Pocaterra in Figures A3 and A4).

Flows from Interlakes to Pocaterra are readily available from TransAlta in electronic format only for the 1985 – 2013 period, while data for years prior to 1985 are only available on microfiche.

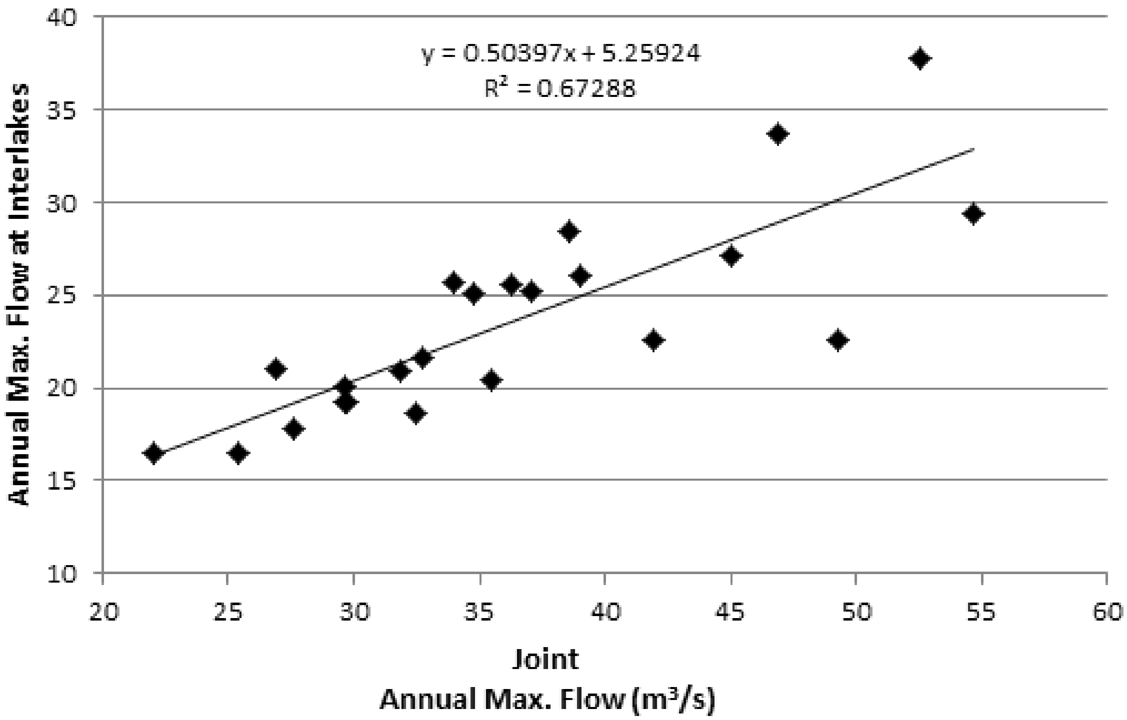


Figure A3: Interlakes Peak Flow vs Total (Interlakes and Pocaterra) Peak Flow

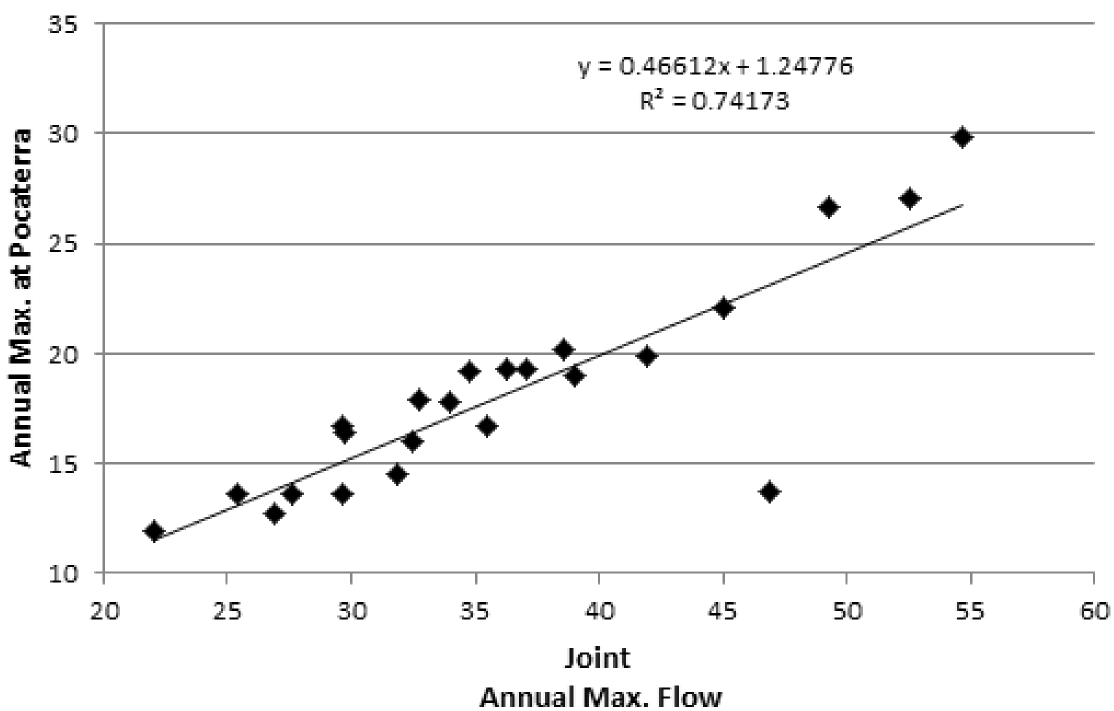


Figure A4: Pocaterra Local Inflow vs Total (Interlakes and Pocaterra) Natural Flow

Table A3: Summary of Daily Naturalized Peak Flow Estimates for Kananaskis River at Interlakes and Pocaterra

Year	Joint Annual Maximum Flow below Pocaterra (includes total catchment)	Estimated Annual Maximum Flow above Interlakes	Estimated Annual Maximum Local Inflow into Pocaterra
1975	35.5	23.2	17.8
1976	26.7	18.7	13.7
1977	30.3	20.5	15.4
1978	37.6	24.2	18.8
1979	38.9	24.8	19.4
1980	34.4	22.6	17.3
1981	41.3	26.1	20.5
1982	37.9	24.4	18.9
1983	31.5	21.1	15.9
1984	33.3	22.0	16.8
1985	27.6	17.8	13.6
1986	52.6	37.8	27.0
1987	46.9	33.6	13.7
1988	37.1	25.2	19.3
1989	31.9	20.9	14.5
1990	39.0	26.1	19.0
1991	38.6	28.5	20.2
1992	34.0	25.7	17.8
1993	29.8	19.2	16.4
1994	26.9	21.0	12.7
1995	49.3	22.6	26.6
1996	45.0	27.2	22.0
1997	35.5	20.5	16.7
1998	34.8	25.0	19.2
1999	32.8	21.6	17.9
2000	25.4	16.5	13.6
2001	22.0	16.5	11.9
2002	54.7	29.4	29.8
2003	29.7	20.1	13.6
2004	29.6	19.2	16.7
2005	32.5	18.6	16.0
2006	36.3	25.6	19.3
2007	41.9	22.6	19.9
2008	14.6	–	14.6
2009		16.4	10.3
2010		14.7	10.4
2011		22.1	23.8
2012		26.5	32.0
2013		64.7	24.0

A6 GENERATION OF DAILY NATURAL FLOWS AT BARRIER LAKE

Proper evaluation of daily natural flows at the Barrier Dam requires the following information:

a) Estimated daily natural flows at both the Upper and Lower Kananaskis Lake. This was only available for the 1985 – 2013 period.

b) Continuous daily recorded outflows from the Lower Kananaskis Lake (Pocaterra). Some data are available prior to 1955 but mainly as seasonal records, and there is a large section of data completely missing from 1955 to 1975, when the continuous records begin.

c) Calibrated travel time vs flow relationship for the 50 km Kananaskis River reach between Pocaterra and Barrier to allow proper channel routing. This information is not currently available. Calculation of actual flows conducted by Alberta Environment's model does not use any channel routing on this reach.

d) Historic daily elevations of Barrier Reservoir. These have been made available by Alberta Environment from 1948 to 1988, and they are also available from Water Survey of Canada as a continuous record from 1970 to 2013 (station 05BF024). These two datasets do not always agree well in the overlapping period from 1970 to 1988.

Historic daily outflows from the Barrier Reservoir

For periods prior to 1985, there were two Water Survey of Canada stations in operation. Station 05BF025 is located immediately downstream of the dam, with a total catchment area of 899 km^2 and a continuous flow record from 1975 to 2008 (which eliminates the need to use TransAlta's data), while station 05BF001 is located further downstream and includes a slightly larger catchment of 933 km^2 due to a small tributary upstream of it. The data record at this station is available from 1911 to 1962, but there were many missing data gaps that required in-filling, including the complete blackout period from 1963 to 1974 inclusive. Alberta Environment maintains a weekly natural flow database, which contains mean weekly outflows from the Barrier dam from 1948 to 2001. The mean weekly recorded flow data were used as a basis for infilling the missing Barrier outflows, using the linear interpolation model the middle of one week to the middle of the subsequent week, as shown in Figure A5.

The model shown in Figure A5 is considered acceptable for providing continuous estimates of daily flows from the Kananaskis River in the 1963 – 1974 period, and for in-filling occasional missing data prior to 1963, since the continuous stream records are required for estimation of natural inflow hydrographs at Ghost and Bearspaw reservoirs. Although daily flow estimates obtained in this way were used to remove the effect of the Barrier Reservoir storage, the resulting flows were not considered appropriate for estimation of peak daily flows at the Barrier Reservoir site, because this model obviously underestimates annual daily peak flows which are never higher than the annual weekly peak flows. Therefore, the 1963 – 1974 (inclusive) period was not used in the assessment of peak annual flows.

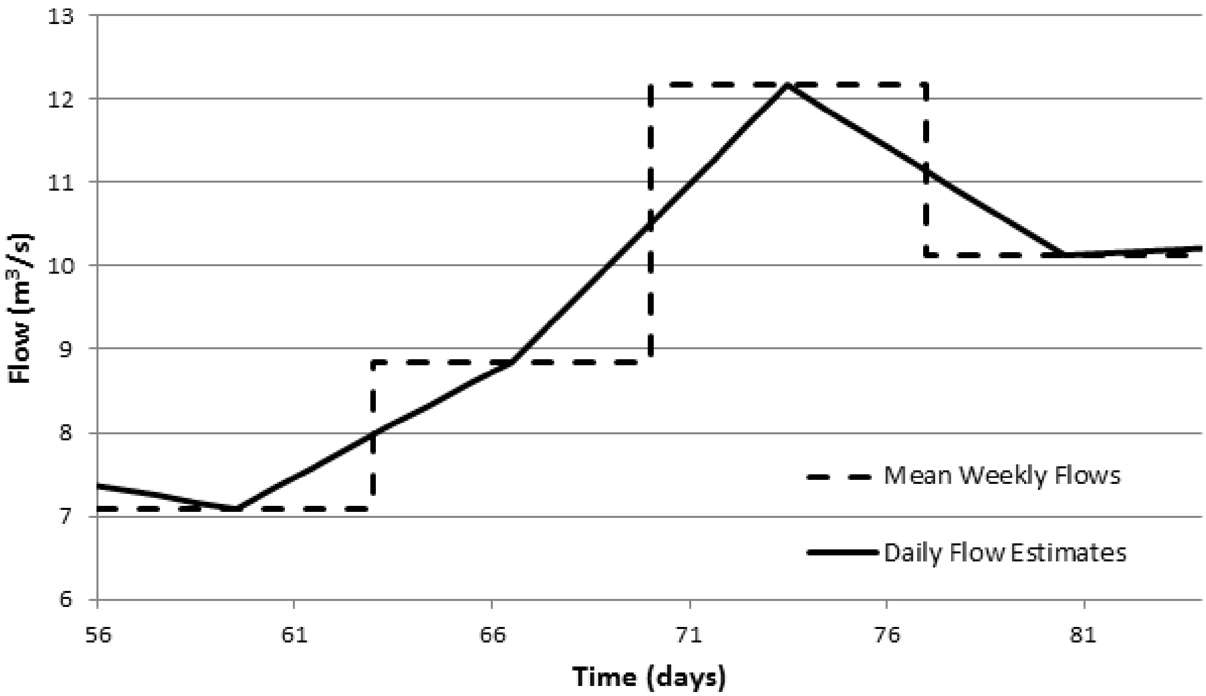


Figure A5: Approximate Conversion of Mean Weekly Flows to Mean Daily Flows

The Barrier Dam was built in 1948, before raising the Pocaterra levels in 1955. Prior to 1948, the additional raising of the Upper Kananaskis Lake level starting in August of 1942. Hence, there was a reason to suspect that the annual peak flows at the Barrier dam site exhibited statistical difference before and after 1943, and especially after 1955 due to additional inclusion of the balancing effect of the Lower Kananaskis Lake. To investigate this assumption, the annul peak flows at the Barrier Reservoir site were separated into two series (pre and post 1943) and plotted using the probability plot with the standard Weibull plotting position formula [r/(n+1), where r is the sequential number of data point in the sorted order, while n is the total number of data points]. The resulting plot is in Figure A6.

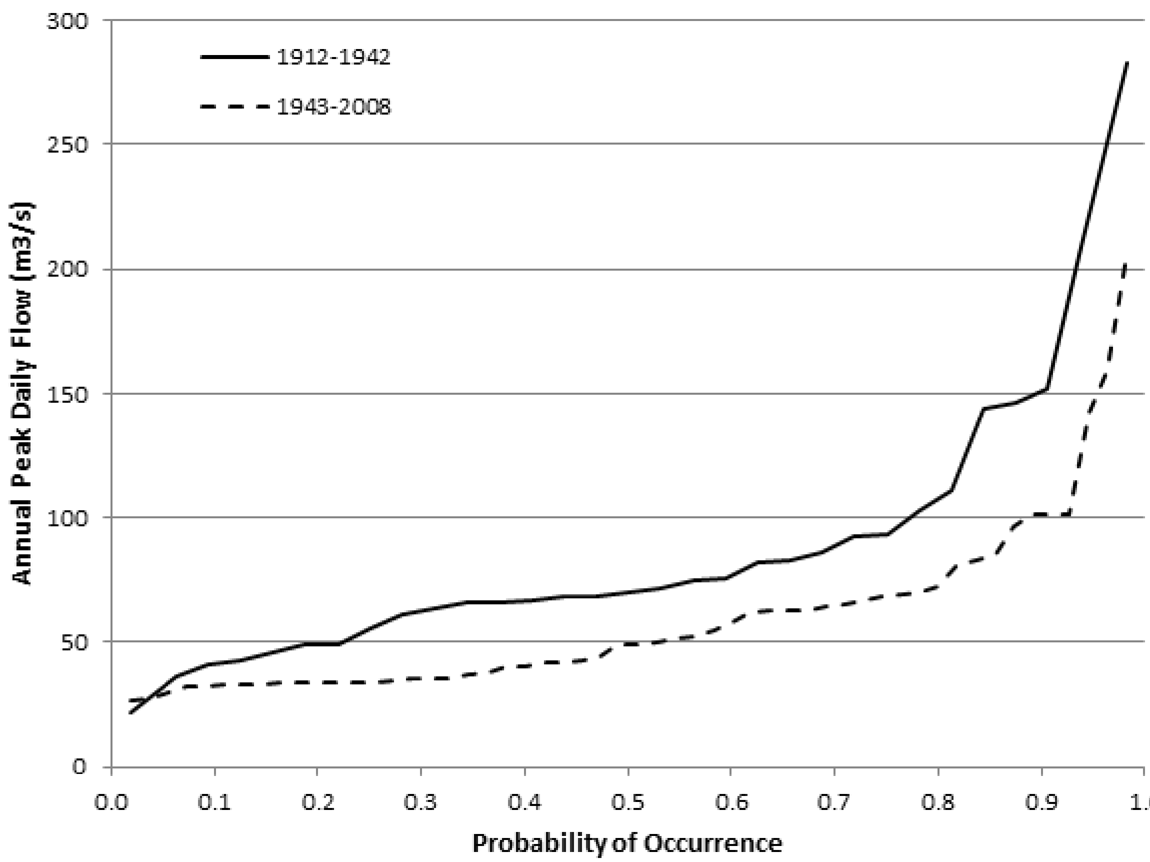


Figure A6: Annual Peak Flows at Barrier Lake Pre- and Post-1943

It is obvious that the peak flows encountered after 1942 are smaller. For example, the median peak flow in the post 1943 period of 50 m^3/s corresponds to the median peak flow of about 70 m^3/s in the pre-1943 period. This model was further refined by using the moving average for both of the above plots, which were then fitted with higher order polynomials to define a functional relationship for each curve. The post 1943 natural peak flows obtained by removing the effect of the Barrier Lake were then adjusted to include increases that correspond to the difference between the two probability curves shown above. The actual differences that were added were depended on the magnitude of the post 1943 flood. For very small peak flows, the added adjustments were also small and in a few cases of very small peak flows they were left unchanged. Table A4 shows the resulting annual peak flow estimates for pre and post 1943 period, excluding the 1963-1974 period for reasons outlined above.

Table A4: Summary of Daily Naturalized Peak Flow Estimates for Barrier Lake

Year	Peak Flow at the Dam - Natural Conditions (m^3/s)	Year	Initial Estimates of Peak Flows at the Dam (m^3/s)	Adjusted Estimates of Peak Flows at the Dam (m^3/s)
1912	92.3	1943	49.3	71.4
1913	60.9	1944	26.6	32.7
1914	67.1	1945	62.9	85.4
1915	152	1946	66.5	93.3
1916	209	1947	50.1	70.6
1917	85.8	1948	148	229
1918	93.4	1949	104	182
1919	75.0	1950	95.5	159
1920	71.4	1951	97.8	167
1921	68.0	1952	57.2	77.4
1922	65.7	1953	106.2	188
1923	144	1954	90.9	144
1924	75.9	1955	61.7	82.8
1925	68.0	1956	44.6	71.3
1926	48.7	1957	32.1	52.3
1927	103	1958	44.7	71.2
1928	82.1	1959	46.1	71.5
1929	146	1960	47.8	71.7
1930	69.7	1961	65.4	89.8
1931	45.9	1962	103	177
1932	283	1975	44.6	71.4
1933	111	1976	35.8	60.8
1934	55.8	1977	31.4	46.8
1935	49.3	1978	38.0	64.4
1936	63.4	1979	31.8	50.5
1937	43.0	1980	50.0	71.2
1938	82.7	1981	76.0	118
1939	41.3	1982	37.12	62.9
1940	36.5	1983	30.2	43.9
1941	21.7	1984	24.9	28.7
1942	66.3	1985	31.6	48.7
		1986	68.9	98.7
		1987	28.0	38.1
		1988	32.9	56.9
		1989	91.6	150
		1990	72.0	110
		1991	45.9	72.0
		1992	40.4	67.2
		1993	38.6	65.2
		1994	24.0	25.3
		1995	106	187
		1996	46.3	70.9
		1997	32.3	53.9
		1998	52.8	72.9
		1999	26.9	35.0
		2000	17.9	17.9
		2001	21.0	21.0
		2002	69.3	102.7
		2003	32.6	55.4
		2004	29.5	41.4
		2005	88.1	135
		2006	48.4	71.3
		2007	54.2	74.0
		2008	56.0	75.8
		2009		27.3
		2010		33.8
		2011		47.2
		2012		71.6
		2013		301

A7 GENERATION OF DAILY NATURAL FLOWS AT GHOST RESERVOIR

The impoundment of Ghost Reservoir started in August of 1929. Prior to 1929, the only possible change to natural flows upstream of Ghost Reservoir would be due to the operation of Lake Minnewanka on Cascade River, which at that time was operating in the lower range between 1450 and 1455 m. Although the Cascade River flows have been adjusted for the effects of Lake Minnewanka storage, the missing link required for estimating natural flows at the Ghost Reservoir site prior to 1929 are the recorded flows in the vicinity of the Ghost reservoir site.

Station 05BE006 (Bow River below Ghost dam) started operation in 1933. The upstream flow monitoring station at Seebe (05BE004) started operation in 1923. The Ghost River tributary (station 05BG001) that also contributes significant flows to the Ghost Reservoir storage has missing data between November 1920 and December 1928. The recorded flow data series that represents recorded outflows (or inflows) into the Ghost Reservoir do not exist prior to 1930.

Hence, it was only possible to assess natural flows into Ghost reservoir between 1930 and 2008, following required in-filling of the missing data. When the outflows were missing, the storage change and both inflows (Station 05BE004 at Seebe and the Ghost River tributary station 05BG001) were used to generate the outflow estimates. When the storage levels were missing and both outflows and inflows were available, storage levels were estimated by balancing inflows and outflows and by solving for the end of day storage as the only unknown. A regression was also developed between the Bow River below Ghost Reservoir (05BE006) and the Bow River at Calgary (05BH04), and it was used occasionally for in-filing the missing data when there was no other option.

The following information was necessary to estimate daily natural flows at the Ghost Reservoir for the 1930 – 2008 period:

a) Recorded and natural flows of the Bow River downstream of confluence with the Spray River;

b) Recorded and natural flows of the Cascade River at Lake Minnewanka;

c) Recorded and natural flows of the Kananaskis River at Barrier Reservoir;

d) Time of travel vs flow for all routing reaches of the Bow river between Banff and the Ghost Reservoir as well as on the Kananaskis river below the Barrier dam;

e) End of day Ghost Reservoir elevations;

f) Recorded Ghost Reservoir outflows; and
g) Precipitation and evaporation on Ghost reservoir.

The NFCP model was run on a daily basis from 1930 to 2008 to obtain estimates of natural flows at the Ghost Reservoir. The model schematic is shown in Figure A7. The calculation procedure starts at the most upstream nodes, and evaluates natural flows at each node in a downstream progression. This procedure requires separate routing of recorded flows from the three upstream control points, which are the confluence of the Bow and Spray Rivers, Lake Minnewanka and the Barrier Reservoir downstream to the Ghost reservoir. These routed flows were used to calculate the local inflow into the Ghost Reservoir by subtracting them from the Ghost Reservoir outflow adjusted for storage change. Once the local inflow is calculated in this manner, it is added to the sum of routed natural flows starting from the same three control points and ending at the Ghost Reservoir. This is a complex procedure that is significantly aided by the existing computer model designed for this purpose.

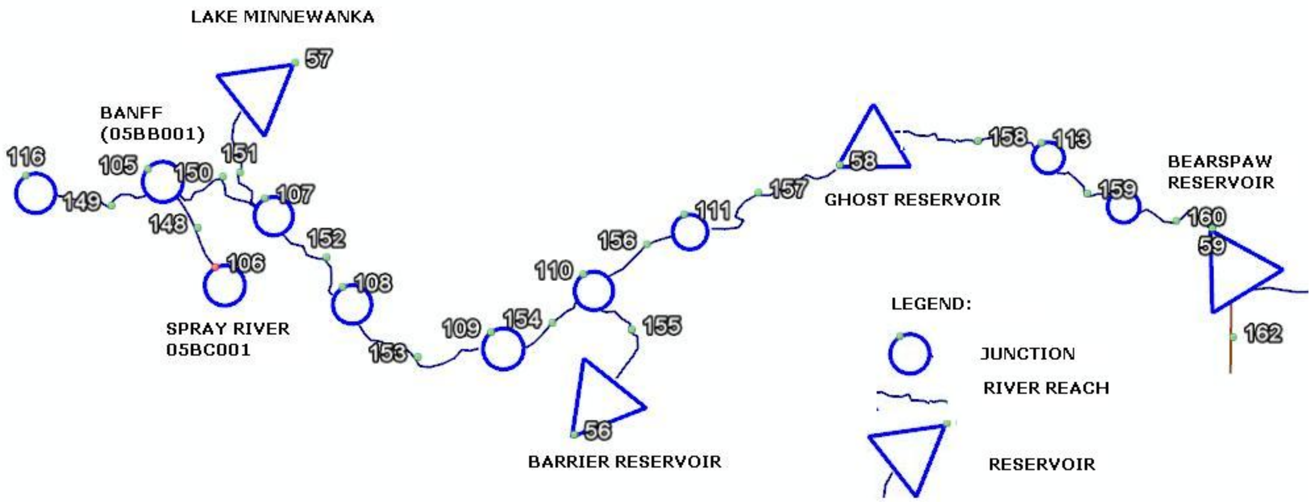


Figure A7: NFCP Modelling Schematic

Denote with R recorded flows, N natural flows, F( ) the channel routing function, LI local inflow, $\Delta V / \Delta t$ storage change and NE net evaporation on the Ghost Reservoir. The calculation of local inflow into the Ghost Reservoir process can then be mathematically expressed as:

$$LI_{58} = \Delta V / \Delta t + NE + R_{158} - F(R_{150} + R_{151} + R_{155})$$

It should be understood that the actual routing of flows happens channel by channel, and that two channels that meet at a node provide the sum of routed flows at their downstream ends which is further routed through the downstream channel. In that sense, the term $F(R_{150} + R_{151} + R_{155})$ schematically represents the result of combined routing of all three control flows through all sequential channels in the schematic, resulting with the routed outflow from channel 157. The natural flow is then the sum off the three upstream natural flows routed to the Ghost Reservoir site, and adjusted by the evaluated amount of local inflow LI_{58}, hence:

$$N_{58} = LI_{58} + F(N_{150} + N_{151} + N_{155})$$

The same considerations are valid regarding the routing of natural flows as for the routing of recorded flows (i.e. channel routing must follow the sequence of channels shown in the schematic). There are inaccuracies in this procedure that can be related to many missing values that had to be filled using various regression models, as well as ice formation which resulted in erroneous flow or elevation measurements. In some days in the winter the calculated natural flows have negative values, which implies that more work is required to modify the data and rectify these situations. However, the high flow events show reasonable hydrographs which provide insight into the duration and timing of flood events, in addition to the peak flows. Table A5 shows the resulting summary of peak flows obtained from the daily 1930 – 2008 series. It is noted that the first half of the natural flow series (1930 – 1969) has the three benchmark statistics (25 percentile, median and 75 percentile) of flows which are on average 50m^3/s higher than the peak flows in the second half of the series from 1970 to 2008.

Table A5: Summary of Daily Natural Peak Flow Estimates for Ghost Reservoir

Year	Peak Flow at the Dam - Natural Conditions (m^3/s)	Year	Peak Flow at the Dam - Natural Conditions (m^3/s)
1930	454	1970	342
1931	313	1971	382
1932	816	1972	445
1933	575	1973	328
1934	430	1974	518
1935	408	1975	246
1936	432	1976	268
1937	282	1977	227
1938	402	1978	298
1939	294	1979	205
1940	302	1980	326
1941	179	1981	475
1942	314	1982	298
1943	346	1983	241
1944	234	1984	270
1945	319	1985	228
1946	385	1986	390
1947	375	1987	222
1948	676	1988	308
1949	204	1989	312
1950	461	1990	528
1951	432	1991	425
1952	378	1992	279
1953	537	1993	243
1954	408	1994	239
1955	386	1995	594
1956	399	1996	382
1957	281	1997	334
1958	282	1998	318
1959	314	1999	346
1960	255	2000	214
1961	400	2001	222
1962	270	2002	400
1963	346	2003	261
1964	403	2004	281
1965	582	2005	562
1966	370	2006	307
1967	454	2007	509
1968	261	2008	382
1969	356	2009	287
		2010	308
		2011	453
		2012	607
		2013	1539

A8 GENERATION OF DAILY NATURAL FLOWS AT BEARSPAW RESERVOIR

Natural flows at Bearspaw Reservoir were also generated as part of the NFCP run, as shown in Figure A8 which also includes the Bearspaw Reservoir. Daily reservoir elevations were received from Alberta Environment, and they were also available from TransAlta from 1985 to 2007. There are occasionally large differences between the reservoir levels available from those two sources, requiring judgement in the final data selection. Outflows from the Bearspaw Reservoir are available from TransAlta only after 1985.

There are two Water Survey of Canada stations on the Bow River below the Bearspaw dam. Station 06BH008 is close to the dam, but its record begins in 1983 and it is incomplete. The only other long term flow monitoring station in the relative vicinity of the Bearspaw dam is the Bow River at Calgary (05BH004). This station also needed some in-filling of missing data between 1930 and 2008, which was accomplished by developing a relationship with the Bow River below Ghost Dam (05BE006). The use of the Bow River at Calgary data is not a perfect solution, since there is a time lag of 6 to 8 hours between the Bearspaw dam and the flow monitoring station, but it was the only choice at this point. Bearspaw Reservoir outflows should be obtained from Transalta for the period since the dam started operation. Water Survey of Canada does not monitor Bearspaw reservoir levels.

Time series of the Bearspaw Reservoir levels provided by Alberta Environment begins in 1955, but this series does not contain the data related to the initial impoundment. Hence, for the period prior to 1955, the levels were kept constant with the evaporation and precipitation set to zero. Calculation of natural flows at Bearspaw reservoir was conducted within the NFCP using the following steps:

a) Calculate local inflow between the Ghost and Bearspaw reservoirs as:

$$LI_{59} = \Delta V / \Delta t + NE_{59} + R_{162} + D_{163} - F(R_{158})$$

where R162 is the outflow from the Bearspaw dam into the Bow River, D163 is the diversion by the City of Calgary, and F (R_{158}) is the routed recorded outflow from the Ghost Dam.

b) Calculate the natural flows by adding the local inflow LI59 to the routed natural flow at Ghost Reservoir:

$$N_{58} = LI_{59} + F(N_{58})$$

The resulting natural flows show that the local runoff that originates between the Ghost and Bearspaw reservoirs does not significantly increase the natural flows at the Ghost dam. In fact, during large floods, the peak flows are often lower at Bearspaw than at the Ghost dam, since the channel attenuation overcomes the additional flow increases due to local runoff. This is likely caused by the lower channel slope and larger width compared to the river sections upstream of the Ghost dam. Table A6 provides the annual flood inflow series to Bearspaw Reservoir.

Table A6: Summary of Daily Naturalized Peak Flow Estimates for Bearspaw Reservoir

Year	Peak Flow at the Dam Natural Conditions (m^3/s)	Year	Peak Flow at the Dam Natural Conditions (m^3/s)
1930	425	1970	414
1931	311	1971	419
1932	1223	1972	448
1933	619	1973	347
1934	454	1974	527
1935	405	1975	249
1936	420	1976	282
1937	273	1977	245
1938	404	1978	304
1939	301	1979	198
1940	280	1980	321
1941	185	1981	498
1942	336	1982	308
1943	359	1983	246
1944	238	1984	271
1945	348	1985	215
1946	403	1986	486
1947	414	1987	212
1948	688	1988	318
1949	208	1989	302
1950	488	1990	539
1951	432	1991	408
1952	447	1992	332
1953	599	1993	251
1954	447	1994	290
1955	398	1995	563
1956	398	1996	357
1957	299	1997	329
1958	312	1998	318
1959	327	1999	375
1960	312	2000	211
1961	428	2001	205
1962	287	2002	372
1963	350	2003	265
1964	404	2004	269
1965	521	2005	676
1966	372	2006	315
1967	424	2007	486
1968	281	2008	355
1969	439	2009	219
		2010	228
		2011	403
		2012	507
		2013	1712

A9 GENERATION OF DAILY NATURAL FLOWS AT GLENMORE RESERVOIR

Glenmore reservoir level data are available form Water Survey of Canada (station 05BJ008), with data records from 1976 to 2008. Additional water level data were obtained from 1933 to 1988 from Alberta Environment. There are two Water Survey of Canada stations downstream of the dam (05BJ005 and 05BJ001). Together, they provide continuous data coverage for the 1912 – 2008 period. There is also one more flow monitoring station upstream of the dam (05BJ010), with data available after 1979.

The reservoir level data begin with the reservoir being close to full in 1933, so the actual impoundment of the dam could not be included in the calculation of natural flows. Consequently, the reservoir was modelled with fixed elevation (i.e., zero storage change) and zero net evaporation for all years prior to 1933, implying that the recorded flows downstream of the dam was equal to natural. Natural flows after 1933 were assessed by using the outflows from the dam adjusted for Glenmore reservoir storage change. The results of the updated bathymetric survey were used in this study to incorporate the latest estimate of the storage capacity curves. Table A7 provides the resulting summary of flood series derived from the daily flow series.

Table A7: Summary of Daily Naturalized* Peak Flow Estimates for Glenmore Reservoir

Year	Peak Flow at the Dam Site (m^3/s)	Year	Peak Flow at the Dam (m^3/s)	Year	Peak Flow at the Dam (m^3/s)
1908	159	1933	55.3	1971	83.2
1909	94.0	1934	23.5	1972	42.0
1910	18.6	1935	29.2	1973	44.0
1911	89.5	1936	30.0	1974	62.3
1912	122	1937	53.6	1975	45.6
1913	38.8	1938	60.0	1976	38.1
1914	28.9	1939	91.4	1977	15.8
1915	239	1940	36.5	1978	45.6
1916	146	1941	34.3	1979	33.5
1917	147	1942	123	1980	52.8
1918	35.4	1943	30.9	1981	87.3
1919	72.5	1944	24.3	1982	36.1
1920	67.7	1945	73.8	1983	30.8
1921	37.4	1946	50.6	1984	21.0
1922	26.5	1947	69.1	1985	54.8
1923	331	1948	128	1986	53.2
1924	59.5	1949	37.0	1987	29.1
1925	66.5	1950	34.9	1988	32.9
1926	88.1	1951	136	1989	21.5
1927	83.3	1952	81.9	1990	121.8
1928	100	1953	129	1991	49.4
1929	382	1954	45.6	1992	108
1930	30.6	1955	45.9	1993	81.5
1931	22.9	1956	37.2	1994	60.4
1932	311	1957	30.6	1995	218
		1958	55.2	1996	41.8
		1959	47.7	1997	51.9
		1960	30.0	1998	96.0
		1961	50.4	1999	53.4
		1962	30.2	2000	18.1
		1963	122	2001	42.6
		1964	64.0	2002	79.4
		1965	103	2003	31.2
		1966	37.0	2004	36.2
		1967	192	2005	374
		1968	50.5	2006	110
		1969	128	2007	78.1
		1970	94.7	2008	173
				2009	46.9
				2010	60.9
				2011	180
				2012	146
				2013	484

** Naturalized daily peak flow estimates may be slight different from published values of daily peak flows*

Floods recorded prior to 1933 have greater median and 75 percentile values, than the other two periods that were compared (1933 – 1969) and (1970 – 2008) are statistically similar.

A10 ROUTING OF DESIGN HYDROGRAPHS

Following development of inflow hydrographs for the various return periods, the next step was to route the hydrographs through the storage structures to account for the effects of storage and evaporation on the flood flows. Routing was conducted using the existing guidelines for operating these structures during floods. In some cases there is allowance for variability to provide flexibility to the operation such as “keep the outflow between 100 and 160 m^3/s if inflow is above 100 m^3/s”. Setting up a computer model to mimic the behaviour of an operator may therefore involve strengthening of the rules by the modeller, in order to ensure repeatability of simulation runs. The new version of the WRMM model from Alberta Environment was used in this study. This model includes both channel routing using the SSARR routing method, as well as reservoir routing. The routing equations are formulated as constraints to a linear program. The benefit of this model is that it has flexibility to represent various reservoir operating policies, including a mix of rule curves and multiple water use zones and priority factors that drive the simulation as cost parameters in the objective function.

A11 FLOOD ROUTING AT GLENMORE RESERVOIR

Glenmore reservoir was built in 1933 on the Elbow River to provide water supply for the City. Its original design did not include an allowance for flood storage. However, flood operational guidelines exist, and they provide instructions on the reservoir drawdown and release policies for the bottom outlet and spillway. Considerable judgement is required on the part of the operators in terms of the draw down of the reservoir during a flood event, ranging from 2 m to 4 m.

Low level outlet releases are linked to the incoming flows and the achieved drawdown. The maximum low level outlet flows is 165 m^3/s. This limit is achieved during the condition where it is necessary to evacuate the incoming flood and simultaneously lower the reservoir level to a desired target drawdown. Once the target drawdown is reached, the outflows will be equal to inflows, and if inflows exceed 165 m^3/s the reservoir will begin to fill since the outflow remains set at 165 m^3/s. Once the reservoir levels has reached the invert of the spillway, the flood will be evacuated through both the low level outlet and the spillway for the first 1.0 m of flow depth over the dam crest and with a gradual shut down of the bottom outlet. At a water level of 1.0 m above the dam crest, the low level outlet is closed and the spillway continues to discharge the flood as it has reached sufficient head to provide adequate outflow capacity.

As part of the model setup, the results of the most recent bathymetric surveys from the City of Calgary were used in this study. Table A8 provides a summary of the initial assumptions, along with the key elevations and outflows obtained from applying the existing rules for routing design hydrographs through the Glenmore Reservoir.

Table A8: Summary of Flood Routing Results for the Glenmore Reservoir

Return Period (years)	Initial Conditions		Reservoir Elevation (m)		Flows (m^3/s)		Spillway Required
	Starting Reservoir Elevation (m)	Starting Outflow (m^3/s)	Minimum	Maximum	Maximum Inflow	Maximum Outflow	
2	1,074.83	100	1,072.33	1,074.83	56	100	NO
5	1,074.83	100	1,072.33	1,074.83	107	100	NO
10	1,074.83	150	1,072.33	1,074.83	154	165	NO
20	1,074.33	165	1,072.33	1,074.33	211	165	NO
50	1,074.33	165	1,071.33	1,076.58	302	245	YES
100	1,074.33	165	1,071.33	1,076.83	385	366	YES
200	1,074.33	165	1,071.33	1,077.08	481	477	YES
500	1,073.66	165	1,071.33	1,077.36	632	624	YES
1,000	1,073.66	165	1,071.33	1,077.61	766	757	YES

Table A8 shows that the low level outlet has sufficient capacity for floods that have magnitude which is less or equal to the 50 year return period, assuming the current operating rules are implemented in a timely manner. The analysis also shows that the use of the spillway will be required for floods with return flow period above 50 years.

A12 FLOOD ROUTING THROUGH THE UPPER BOW SYSTEM

Synthetic inflow hydrographs for the selected return flow periods were developed for all key storage structures in the Upper Bow River basin. Their routing through the storage structures and interconnecting river reaches was conducted based on the existing flood operating guidelines obtained from TransAlta Utilities. In their definition of the operating rules, TransAlta distinguishes the Key Elevations for each reservoir as a guideline for triggering the use of the spillway. When the storage is below the Key Elevations, incoming flows are only released through the turbines, subject to the maximum capacity of each plant. Most hydro power plants in the system are designed to operate turbines during flows up to flows above the long term historic averages, and most are designed to also operate during floods together with spillway structures, thus allowing hydro power plants to act as low level outlets and add to the total outflow capacity, while simultaneously generating power. Table A9 provides a listing of maximum flow capacity for each hydro power plant in the Upper Bow River Basin.

Table A9: Maximum Flows through Hydro Power Plants

Name of Hydro Power Plant	Maximum Outflow (m^3/s)
Three Sisters	24.6
Spray	45.3
Rundle	62.3
Interlakes	19.8
Pocatera	31.2
Barrier	36.8
Cascade	39.6
Kananaskis	120.7
Horseshoe	104.8
Ghost	243.5
Bearspaw	155.7

The Key Elevations at which the spillway operation begins have been established as part of earlier PMF studies, and they are adhered to every year to meet the existing safety requirements. These elevations typically involve a mandatory drawdown of reservoir levels in May of each year, with a gradual return to the full supply levels in June and early July. In addition to the Key Elevations, Transalta has also established target elevations for each storage reservoir as a function of time, as part of earlier operational studies. These target elevations were based on the overall integrated system modelling, with the existing downstream maintenance flow requirements in the Bow River. It was decided that the second week of June (Julian day 161) is the most likely timing for floods of high magnitude. Consequently, the target elevations provided a reasonable estimate of the starting reservoir levels for this week. These levels are somewhat below the Key elevations, but they are normally very close to them (usually lower but within 1 to 2 meters). A typical sketch of the key and target elevations is shown in Figure A8.

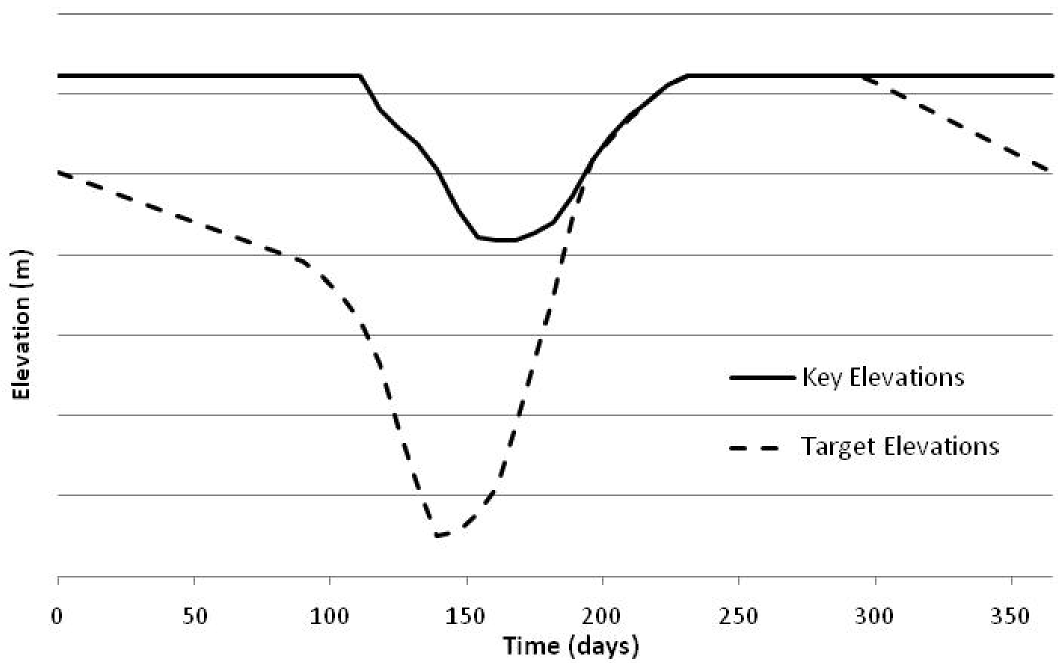


Figure A8: Key and Target Elevations for a Typical Upper Bow Storage Reservoir

TransAlta's flood operating guidelines that were used in this study are summarized as follows:

- Start from the target elevation for the starting date of the flood, and attempt to bring the reservoir to the target elevation at the end of the current time step. This may be possible if there is sufficient inflow. If not, set the outflow to zero and attempt to bring the reservoir level as close as possible to the target elevation at the end of the time step.
- If Inflow is above the hydro power plant outflow capacity (as may be anticipated during floods), set the outflow equal to the plant capacity and keep the surplus water in storage, thus ending at a reservoir level higher than the target elevation at the end of a time step.
- Once the reservoir level reaches the Key Elevation, keep the plant operation at full capacity and open the spillways to evacuate the excess water and maintain the key elevations as close as possible.

Some reservoirs have alternate outlet structures with a prescribed sequence of start-up and shut-down (examples are Spray Lake and Lower Kananaskis Lake). These rules were taken into consideration in the model setup.

The highest retention capacity is available at Upper and Lower Kananaskis Lake, Lake Minnewanka and Spray Lake. Except for Spray Lake, these are also the locations that have the lowest peak inflows, such that their attenuation does not add much to the reduction of the incoming floods into the Ghost and Bearspaw reservoirs. The principal control points that determine runoff into Ghost Lake are the Bow River at Banff, Spray River at the mouth, and the Kananaskis River at Barrier Dam. The first two control points function as natural flow gauges, while the Barrier Dam has negligible flood retention capacity. Therefore, all three control points can be assumed to essentially function without any flood retention capability, and subsequent routing of their runoff through Ghost Lake and Bearspaw reservoir also has little capacity to reduce the incoming flood peaks.

The Upper Bow River Basin modelling schematic is illustrated in Figure A9. Included in the model are smaller structures, such as the Kananaskis hydro power plant, in order to include their outflow capacity tables. Channel routing is applied in all channels between Banff and Bearspaw, and on the channel between the Barrier reservoir and the confluence of the Bow and Kananaskis rivers, based on the information provided by Alberta Environment. The model was run using 6-hourly time steps, over an event base of 16 days, which translates to 64 consecutive time steps of 6 hour length. To achieve this, the WRMM was modified to increase its current limit to 52 time steps per year.

Table A10 provides a summary of the routed peak flows for two simulations. The first simulation was based on the synthetic hydrographs which were derived for all key locations in the Upper Bow Basin. The other simulation was based on constructing flood hydrographs with added historic information available from high water marks. This simulation included only Ghost Lake and Bearspaw reservoir, since there was no historic information in the upper parts of the catchment that could be used to extend this analysis further upstream. It should be noted that in the base case simulation (based on the 79 years of daily natural flows estimated for the Upper Bow Basin), the floods with the same return period were assumed to occur simultaneously at all key locations in the basin. This may not be a realistic assumption for more frequent flood events, and as a result the routed peak flows appear to be slightly higher than the ones that would have been obtained by conducting frequency analyses of the recorded flows downstream of Bearspaw reservoir.

Table A10: Peak Flows of Routed Flood Hydrographs

Return Period (Years)	Naturalized Flood Flows of Systematically Recorded Data and Historic Data (m^3/s)	Naturalized Flows of Systematically Recorded Data (m^3/s)
2	378	445
5	536	551
10	682	671
20	863	751
50	1,178	862
100	1,492	950
200	1,893	1,068
500	2,584	1,338
1,000	3,301	1,564

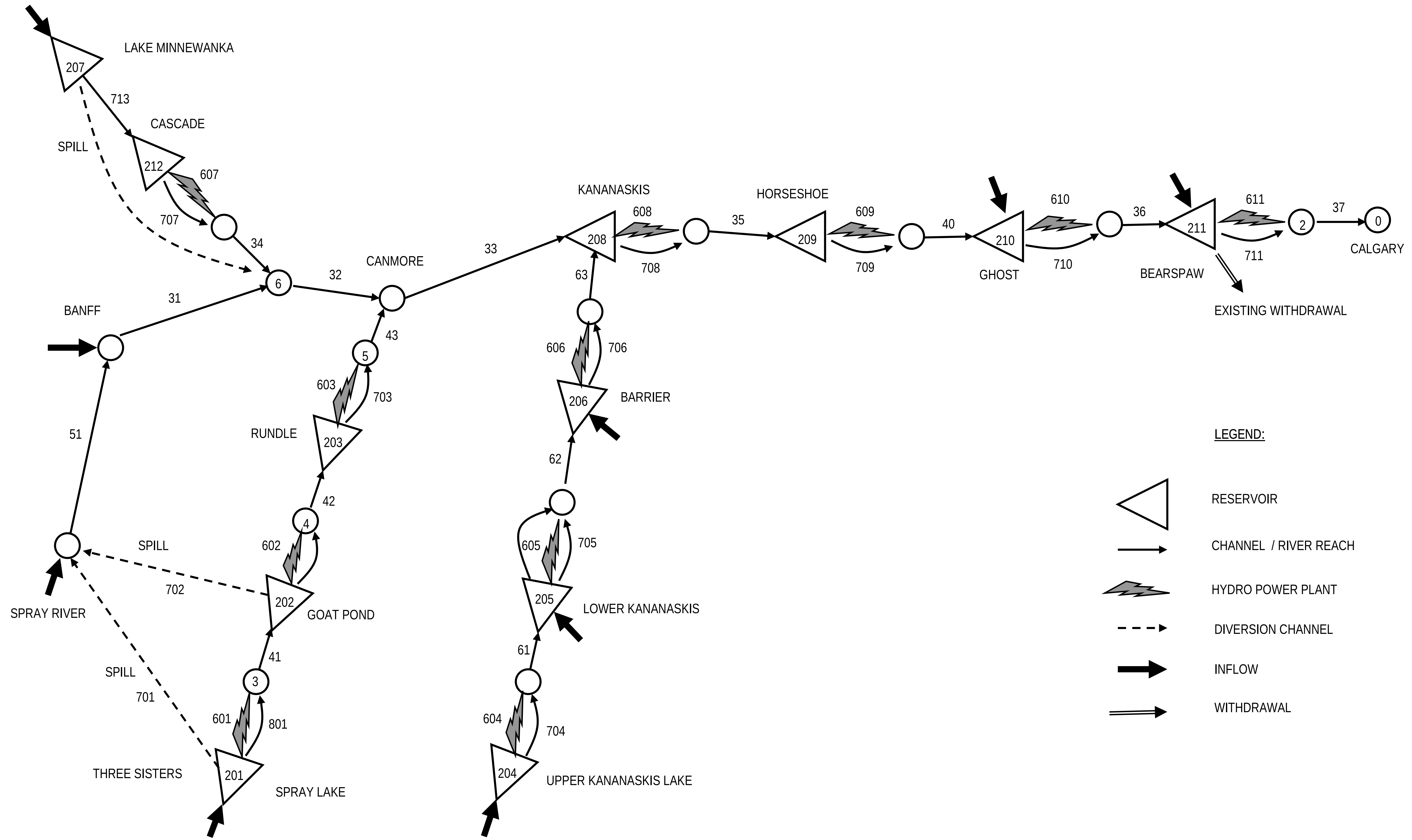
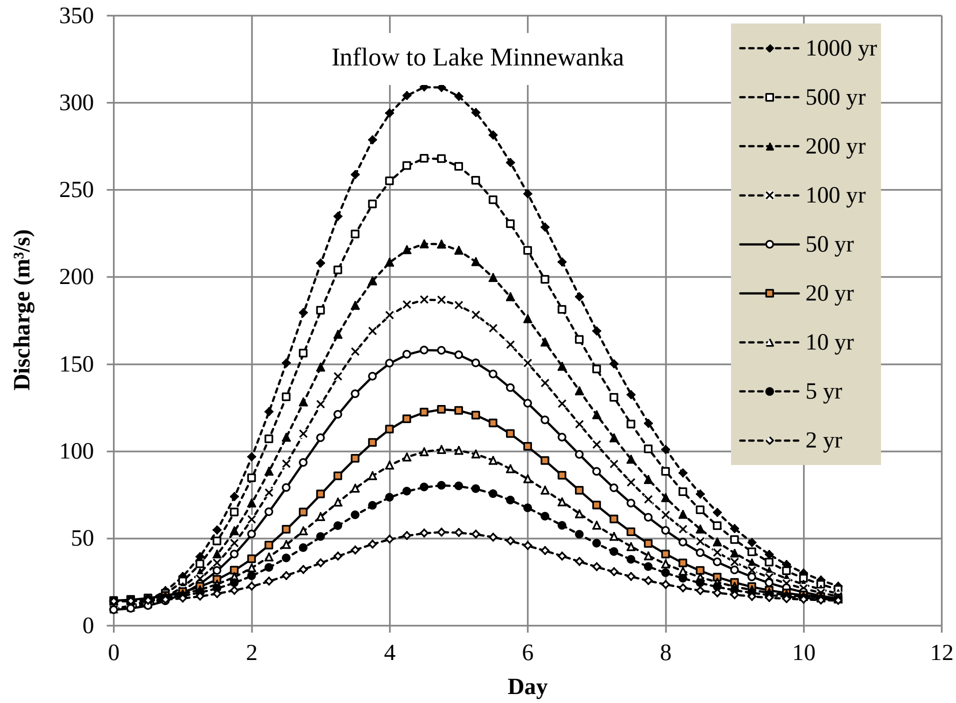
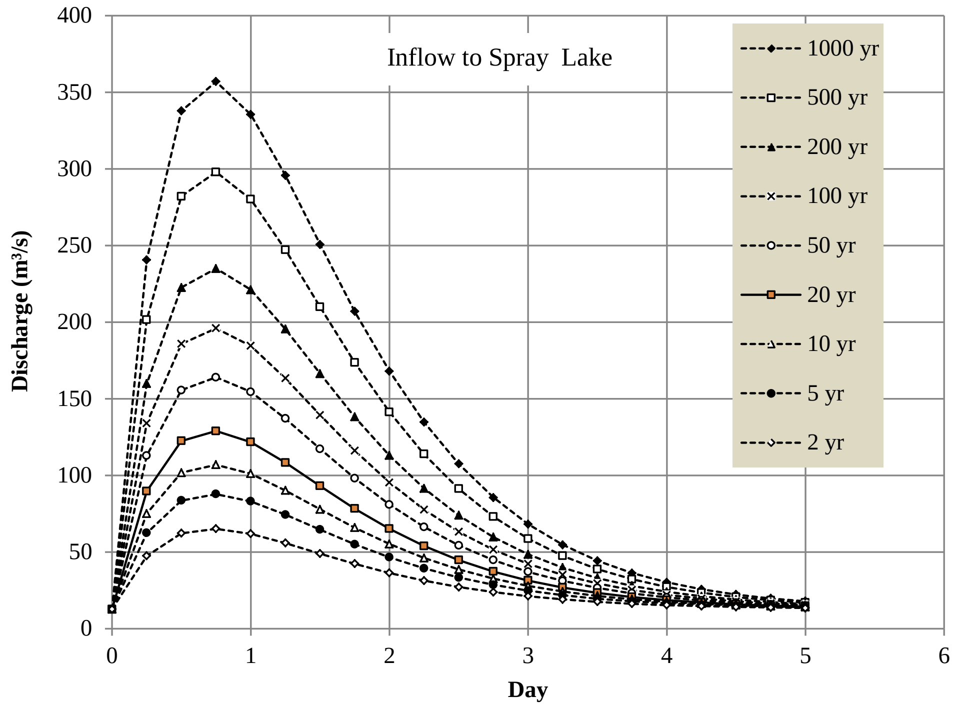


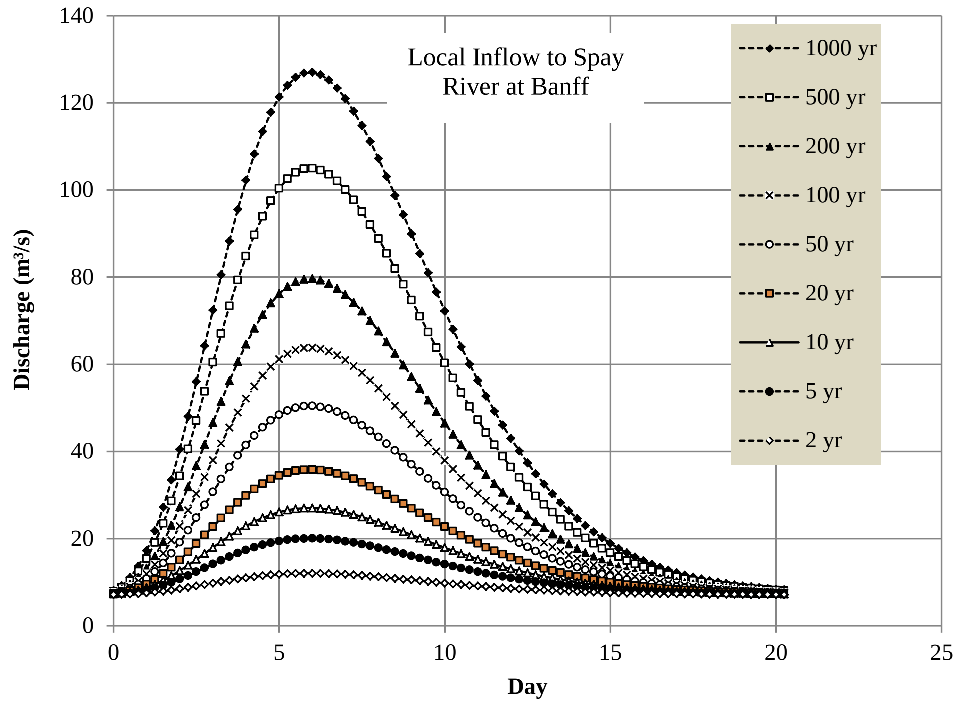
Figure A9: Upper Bow River Basin Modelling Schematic

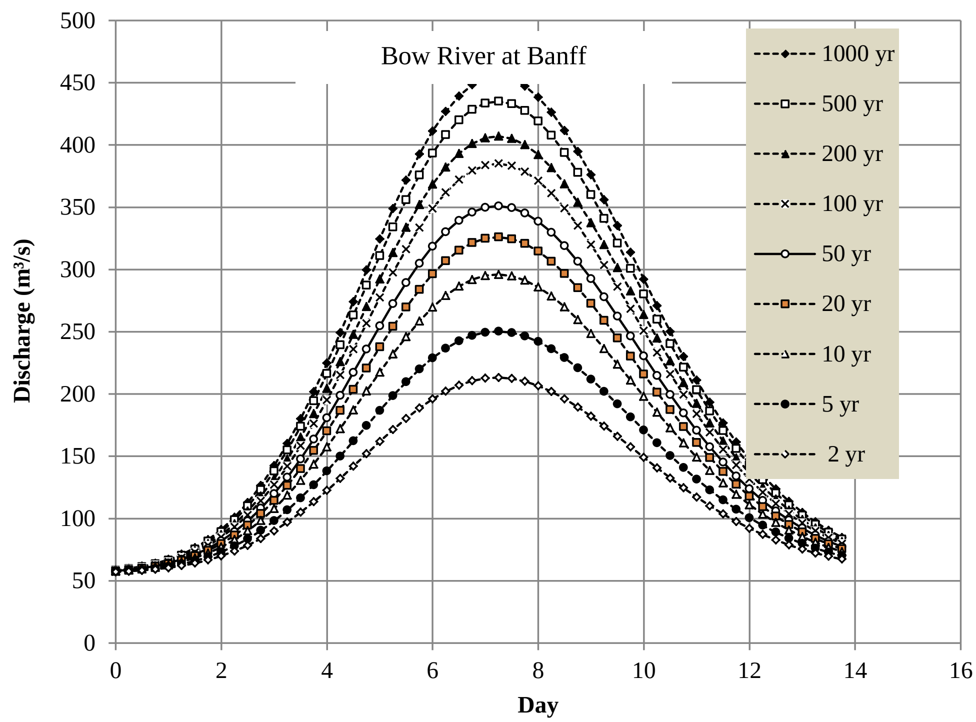
APPENDIX B

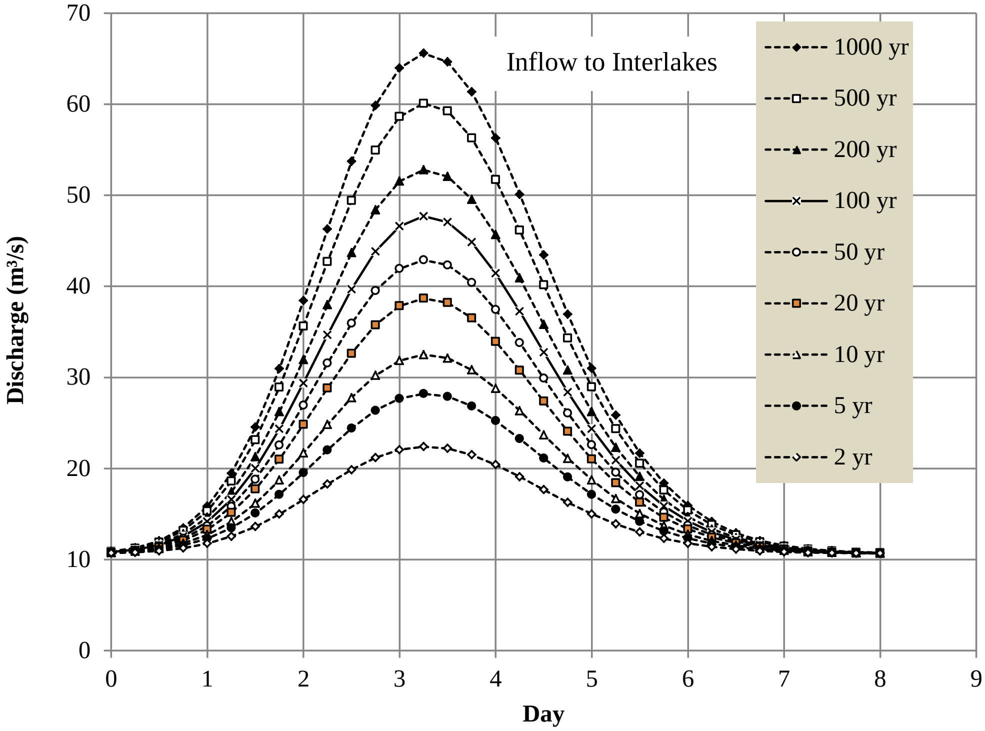
Naturalized Daily Flood "Hydrographs"

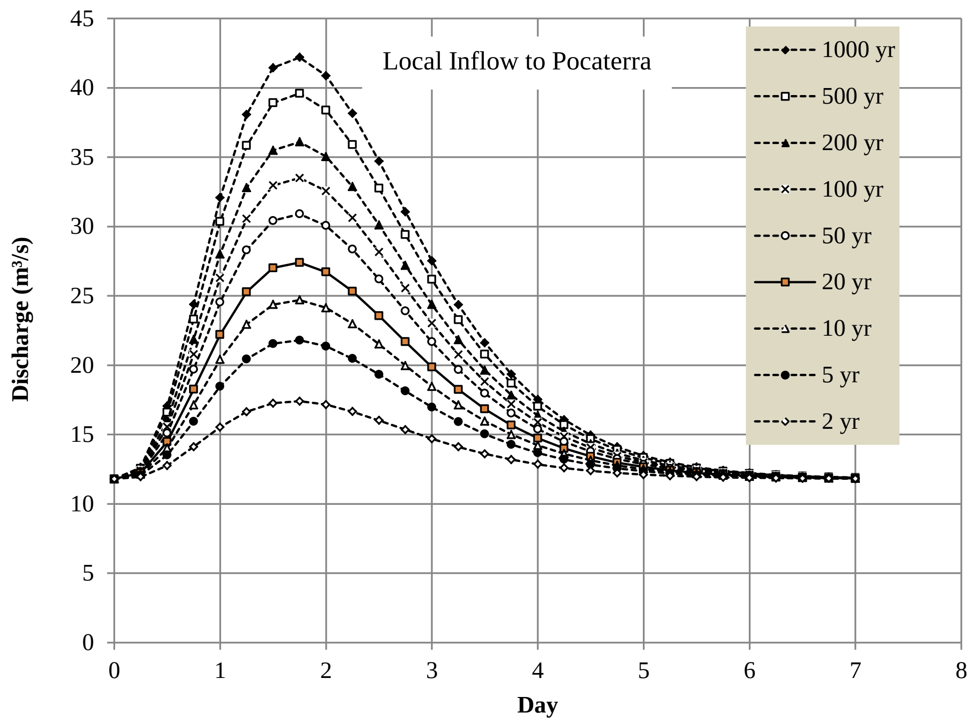

Inflow to Lake Minnewanka
Discharge (m³/s)
Day
0
50
100
150
200
250
300
350
0
2
4
6
8
10
12
1000 yr
500 yr
200 yr
100 yr
50 yr
20 yr
10 yr
5 yr
2 yr

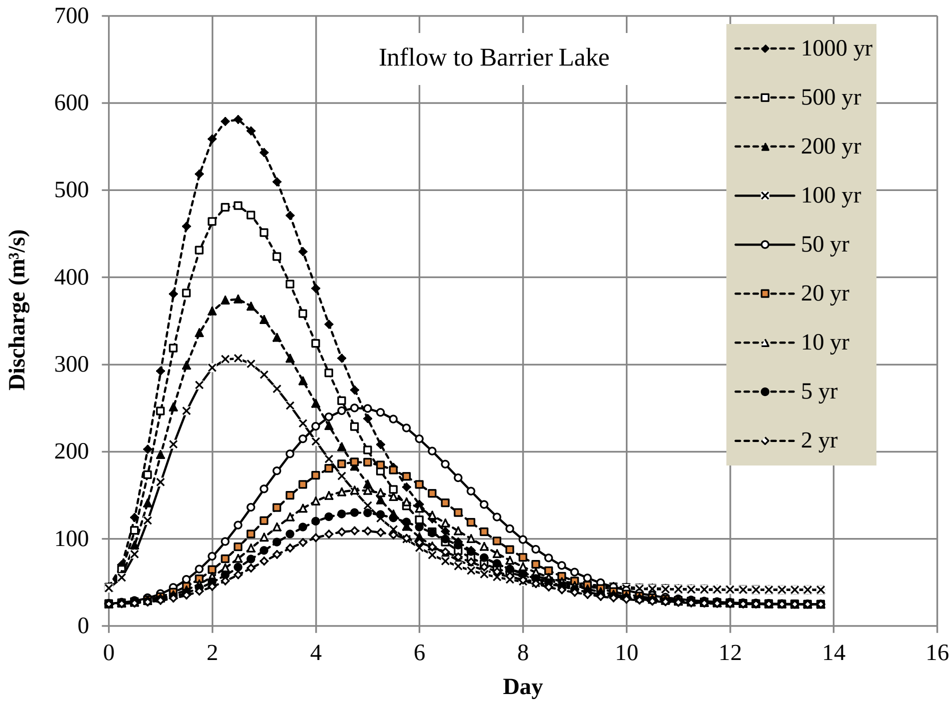

Inflow to Spray Lake
Discharge (m³/s)
Day
0
50
100
150
200
250
300
350
400
0
1
2
3
4
5
6
1000 yr
500 yr
200 yr
100 yr
50 yr
20 yr
10 yr
5 yr
2 yr

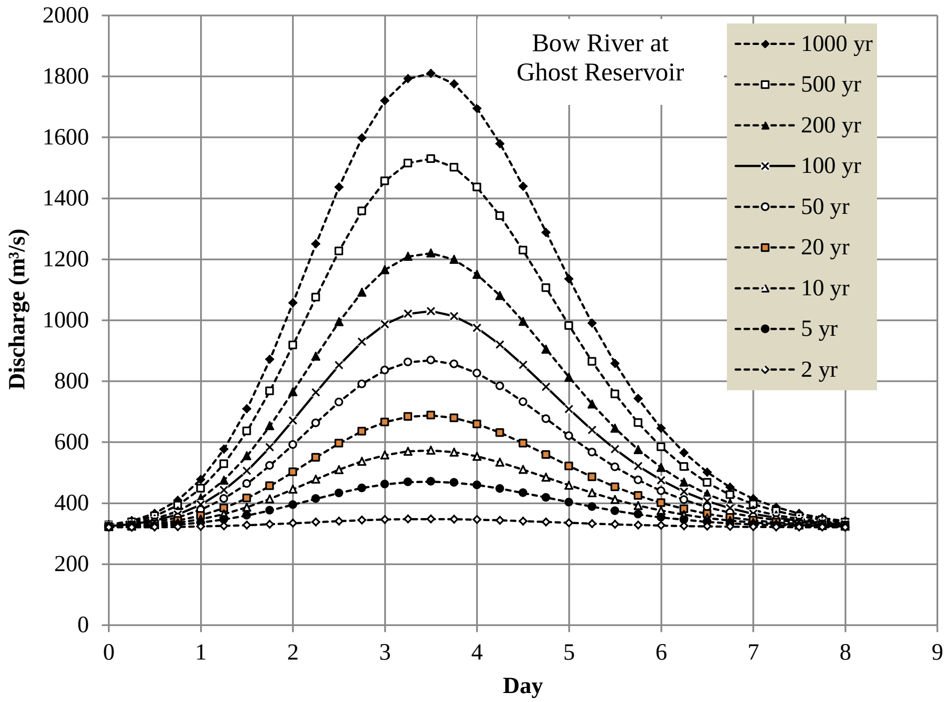

Local Inflow to Spay
River at Banff
Discharge (m³/s)
Day
140
120
100
80
60
40
20
0
0
5
10
15
20
25
1000 yr
500 yr
200 yr
100 yr
50 yr
20 yr
10 yr
5 yr
2 yr

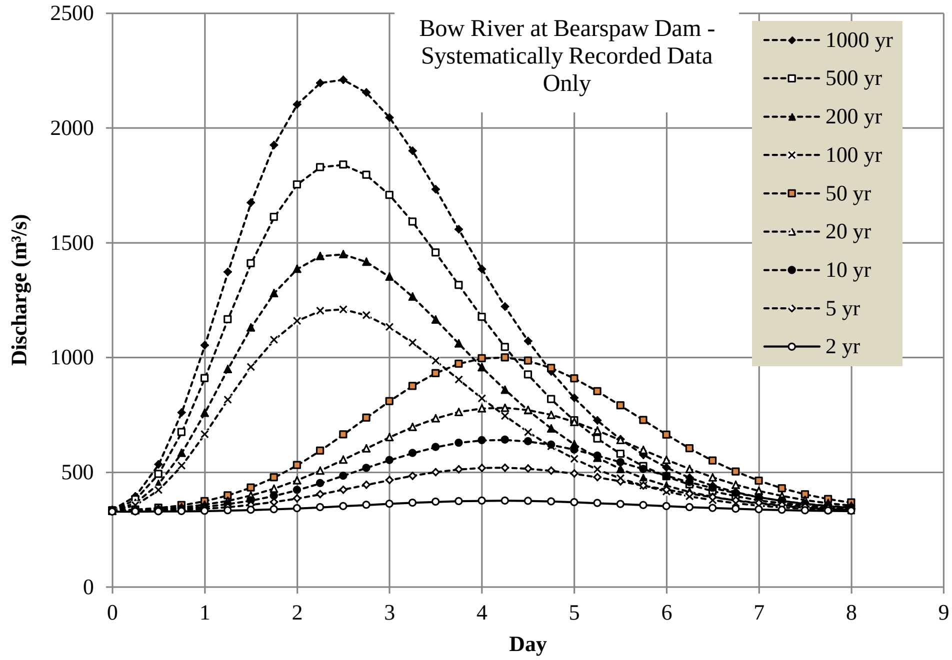

Bow River at Banff
Discharge (m³/s)
Day
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
1000 yr
500 yr
200 yr
100 yr
50 yr
20 yr
10 yr
5 yr
2 yr

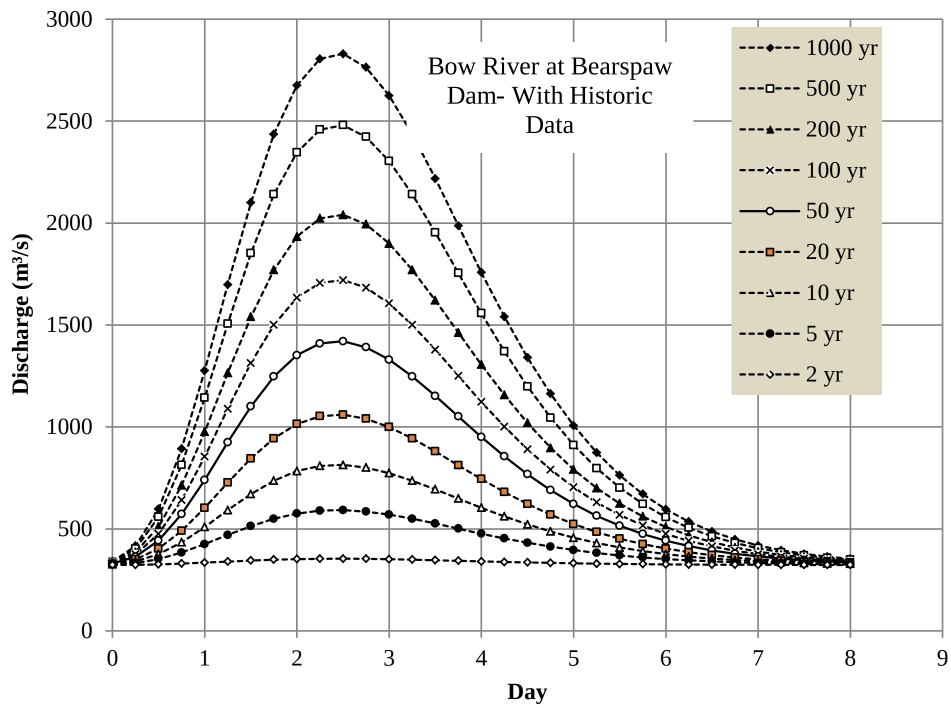

Inflow to Interlakes
Discharge (m³/s)
Day
0
10
20
30
40
50
60
70
0
1
2
3
4
5
6
7
8
9
1000 yr
500 yr
200 yr
100 yr
50 yr
20 yr
10 yr
5 yr
2 yr

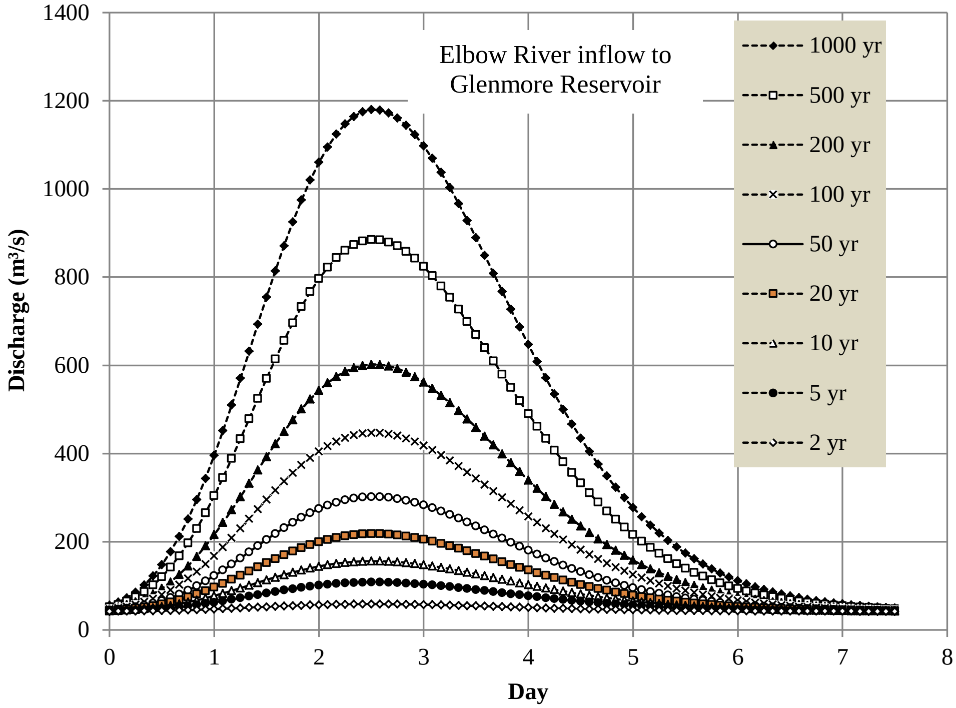

Local Inflow to Pocaterra
Discharge (m³/s)
Day
0
5
10
15
20
25
30
35
40
45
0
1
2
3
4
5
6
7
8
1000 yr
500 yr
200 yr
100 yr
50 yr
20 yr
10 yr
5 yr
2 yr


Inflow to Barrier Lake
Discharge (m³/s)
Day
0
100
200
300
400
500
600
700
0
2
4
6
8
10
12
14
16
1000 yr
500 yr
200 yr
100 yr
50 yr
20 yr
10 yr
5 yr
2 yr


Bow River at
Ghost Reservoir
Discharge (m³/s)
Day
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
1
2
3
4
5
6
7
8
9
1000 yr
500 yr
200 yr
100 yr
50 yr
20 yr
10 yr
5 yr
2 yr


Bow River at Bearspaw Dam - Systematically Recorded Data Only
Discharge (m³/s)
Day
1000 yr
500 yr
200 yr
100 yr
50 yr
20 yr
10 yr
5 yr
2 yr
0
500
1000
1500
2000
2500
0
1
2
3
4
5
6
7
8
9


Bow River at Bearspaw Dam- With Historic Data
Discharge (m³/s)
Day
1000 yr
500 yr
200 yr
100 yr
50 yr
20 yr
10 yr
5 yr
2 yr
0
500
1000
1500
2000
2500
3000
0
1
2
3
4
5
6
7
8
9


Elbow River inflow to
Glenmore Reservoir
1000 yr
500 yr
200 yr
100 yr
50 yr
20 yr
10 yr
5 yr
2 yr
Discharge (m³/s)
Day
0
200
400
600
800
1000
1200
1400
0
1
2
3
4
5
6
7
8

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