

Report on Six Case Studies

of

Flood Frequency Analyses

**Alberta Transportation
Transportation and Civil Engineering Division
Civil Projects Branch**

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of

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prepared for

**Alberta Transportation
Transportation and Civil Engineering Division
Civil Projects Branch**

by

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INTRODUCTION

Alberta Transportation, Civil Projects Branch (formerly part of Alberta Public Works, Supply and Services) has identified a problem of consistency regarding flood frequency analyses prepared for water management projects. With a view to better defining the problem, this document briefly assesses six cases where inconsistent flood frequency estimates have arisen. The assessments of each case are based on selected documents that were readily available, and do not necessarily include a review of all past studies.

The cases considered are as follows:

1. Willow Creek near Claresholm, related to the Pine Coulee Dam project.
2. Highwood River at High River, related to the Little Bow River Dam project and to floodplain delineation.
3. Red Deer River at Drumheller, related to a hospital project at Drumheller and to floodplain delineation.
4. Sawridge Creek at Slave Lake, related to urban flood damages.
5. Bow River at Calgary, related to floodplain delineation.
6. Oldman River near Brocket, related to Oldman River Dam project.

CASE 1- WILLOW CREEK NEAR CLARESHOLM

1.1 Flood Record

The Claresholm gauging station (1160 km²) has an annual flood record from 1944 to present. In project hydrology studies, the Claresholm record was extended by correlation using a downstream station at Nolan (2290 km²) which has additional records for the period 1910-23. An intermediate station at Granum (2000 km²) replaced Nolan during the period 1924 through 1941 with a gap 1932/33/34, but this station was not used because there was no period of overlap with other stations that could be used to check correlations. However, given the small drainage area difference between Nolan and Granum, it could be argued that flows at Granum should be similar to those at Nolan and that the Granum data could have been used to further extend the Claresholm series.

Figure 1.1 shows a sequential plot of a partly-synthetic 1910-97 instantaneous series for Claresholm, further extended by using Granum daily maxima as a rough indicator for the period 1924-41. None of the Willow Creek stations provides data for 1932, a year of high floods in other streams draining the eastern slopes. An estimate for 1932 was derived for present purposes by correlation with the Highwood River, as indicated below.

Figure 1.2 shows a correlation of flood peak data for Willow Creek at Claresholm versus Highwood River at Aldersyde for years of common records. Although Environment Canada records do not provide a value for the 1932 flood in the Highwood River, it is believed to have been the highest of record until 1995, and estimates in the order of 800 m³/s have been quoted - see Case 2. On the basis of the correlation, the 1932 peak on Willow Creek may have ranged from about 300 to 500 m³/s with a most likely value of about 400 m³/s. This value has been added to the Willow Creek series in Figure 1.1. With inclusion of this estimate for 1932, the 1995 flood peak of nearly 500 m³/s (see below) does not appear so extreme.

1.2 Studies Reviewed

Two project flood-frequency studies have been reviewed. The first, by Acres International Ltd (1993), used a partly-synthetic 63-year record for the period 1910-23 + 1944-92, developed as indicated above. Missing instantaneous maxima were filled in by correlation with daily maxima, but observed instantaneous values were available for all the highest floods.

A second study by Alberta Environmental Protection (1997) used the same flood series, but extended to 1997. Flood-frequency estimates increased greatly, mainly because the 1995 flood exceeded the previous 1953 maximum by over 75%. The 100-year instantaneous estimate rose by 45% and the 500-year estimate by nearly 80%.

Neither report includes any estimate for 1932 nor mentions statistical checks of the data for stationarity, homogeneity etc. Both studies seem to have assumed the flood series to be stationary, despite the existence of Chain Lakes Reservoir in the headwaters since the middle 1960's.

1.3 Acres Results (1993)

The Acres study tabulates 2-year to 1000-year flood-frequency estimates derived using various probability distributions. Adopted estimates were based on the Pearson-III distribution fitted by moments. 100-year and 500-year instantaneous estimates were 272 and 452 m³/s. If consideration is given to the unrecorded 1932 event, Acres' 100-year estimate of 272 m³/s was probably exceeded twice in the 83-year period 1910-92.

The Acres report includes a linear-probability plot of daily maxima with Pearson-III fitting line and confidence band. The four highest points all lie well above the line. Even accepting the validity of the data series, predictions based on the fitting line could be regarded as non-conservative.

A confidence or reliability band shown on the Acres plot indicates a range for the 100-year (daily) maximum of about 100 to 350 m³/s. For the 500-year (daily) maximum, the range is from about 100 to 550 m³/s. The basis for the band and the intended level of confidence are not stated.

1.4 AEP Results (1997)

The flood of 1995 peaked at 498 m³/s, exceeding the previous record of 1953 by 76%. AEP analyzed an extended flood series (1910-23 + 1944-97) using a range of probability distributions - again omitting consideration of the unrecorded 1932 event. The adopted fit, based on a check of the most probable fit to the seven highest events, was a 3-parameter log-Normal distribution, apparently fitted by the method of Maximum Likelihood. This yielded 100-year and 500-year instantaneous estimates of 395 and 707 m³/s, compared with 272 and 452 m³/s in the 1993 Acres study. If consideration is given to the unrecorded 1932 event, AEP's 100-year estimate may have been exceeded twice in the 88-year period 1910-97.

Although the difference between the AEP and Acres results is mainly due to inclusion of the 1995 flood, it is also partly due to different fitting methods. If the AEP 1997 fitting methodology is applied to the 1993 data series, 100-year and 500-year estimates are 15% and 20% higher than Acres' values.

1.5 Discussion

Both the Acres (1993) and AEP (1997) studies for Willow Creek near Clareholm neglect an additional 13 years of data for the Granum station. It may have been reasonable to assume that these are compatible with the Nolan data utilized in both studies.

Both studies omit estimates for the 1932 event, which on the basis of Highwood River data is likely to have been the highest on Willow Creek until 1995. Omission of this event skews the results of both analyses.

The sequential plot of **Figure 1.1** seems to show indications of a dual-population situation: very few values lie between 100 and 250 m³/s.

Neither of the studies reviewed mentions possible non-stationarity in the data series - at least for the lower events - due to the existence of Chain Lakes Reservoir since the middle 1960's. Nor do they mention possible non-homogeneity resulting from a mix of rainfall and snowmelt events.

Figure 1.3 shows a flood-frequency plot for the extended, partly-synthetic 88-year instantaneous series 1910-97 that is shown sequentially in **Figure 1.1**. The difference between 2-parameter and 3-parameter log-Normal fitting lines is very slight. On a

2-parameter log-Normal basis, the 100-year estimate is approximately 415 m³/s, slightly higher than the AEP estimate of 395 m³/s. Inclusion of an estimate for 1932 does not much change the results, partly because 13 years of rather low events based on the Nolan record were also added. Only the 1995 event exceeds the new 100-year estimate.

The 1995 event, being so much larger than the previous recorded maximum in 1953, resulted in a major increase in predicted maximum discharges for long return periods. On the basis of Acres' results in 1993, a flood of 1995 magnitude would have been allocated a return period of more than 1000 years. If an estimate for 1932 had been included in Acres' data series, occurrence of the 1995 flood would not have made such a large difference to predictions.

In this case, the pre-1995 data series was comparatively long. If the earlier record had been only 20 to 30 years long, the occurrence of the 1995 event could have completely overturned previous estimates. In such cases, debates about distributions and fitting methods become largely irrelevant.

1.6 References

Acres International Ltd. 1993. Pine Coulee Project, Project Memorandum - Hydrology (draft).

Alberta Environmental Protection 1997. Flood frequency estimates, Willow Creek at the diversion to Pine Coulee, by A. DeBoer, Hydrology Section.

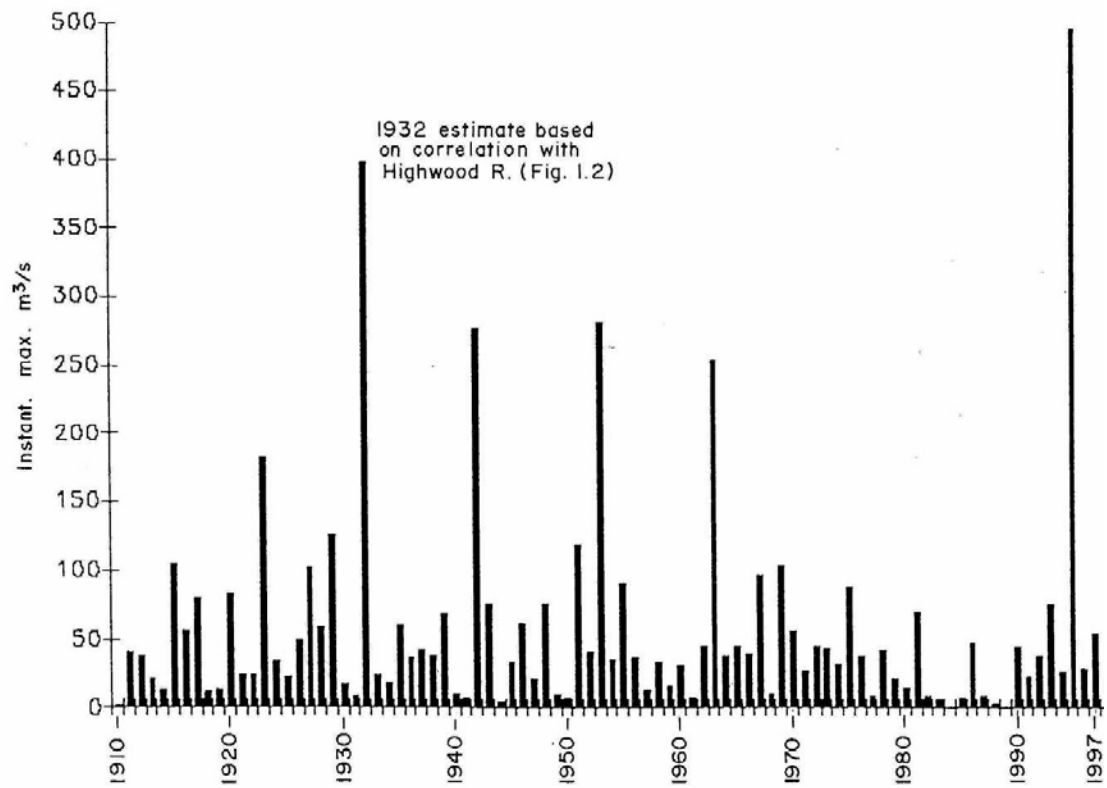


Figure 1.1 Partly-synthetic instantaneous series for Willow Creek near Claresholm, 1910 - 1997

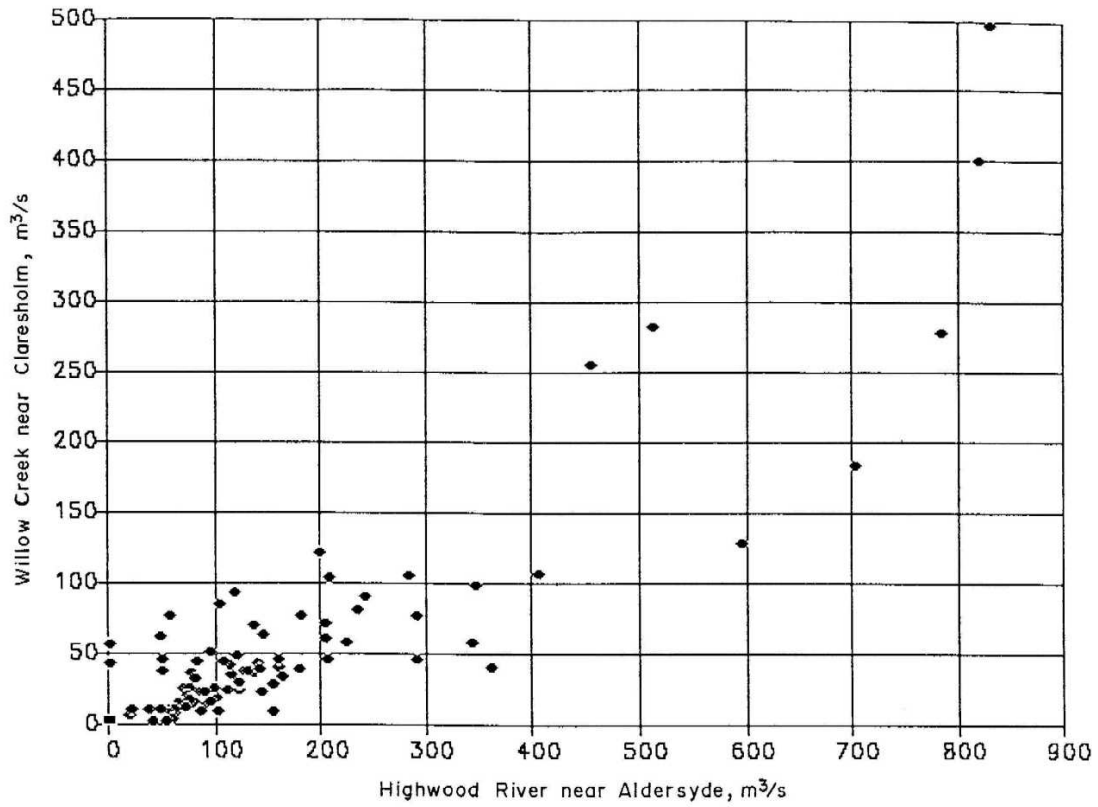


Figure 1.2 Correlation of instantaneous peaks, Willow Creek vs. Highwood River

Flood Frequency – Three Parameters Lognormal Distribution

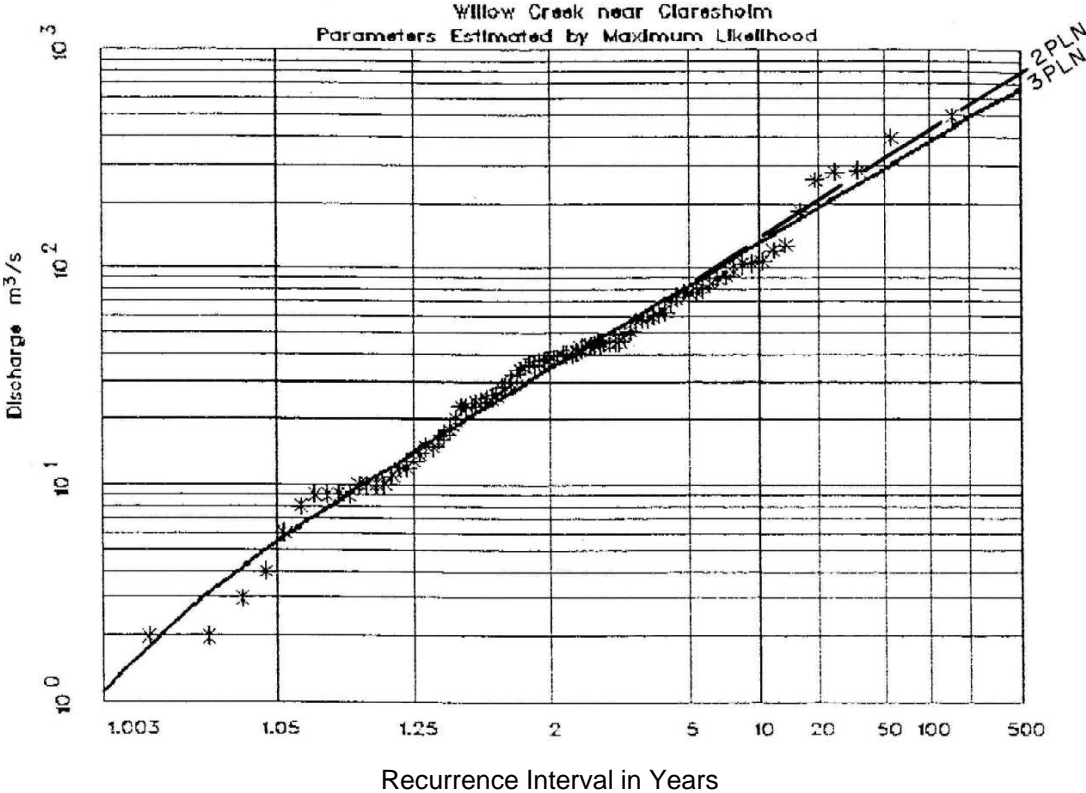


Figure 1.3 Flood frequency plot for Willow Creek series of Figure 1.1

CASE 2 - HIGHWOOD RIVER ABOVE HIGH RIVER

2.1 Flood Record

Flood frequencies above High River town were required in connection with the Little Bow River Dam project. The main source of data is the downstream gauging station near Aldersyde. By including a station below the Little Bow Canal that began in 1986, a nearly continuous record of annual maximum discharges can be constructed from 1912 to 1996. Instantaneous maximum values are reported for most years since 1957, and for all but one (1932) of the higher floods before then. The drainage basin is basically unregulated with respect to floods.

Alberta Environment (1991) adjusted recorded values for occasional spills to the Little Bow River (in 5 years only) and for generally trivial canal withdrawals, to provide a "naturalized" instantaneous series upstream of High River town. If the subsequent record flood of 1995 is added, the seven highest events in the series rank as follows:

Rank	Year	Peak flow m ³ /s
1	1995	830 (estimate)
2	1932	818 (estimate)
3	1952	782
4	1923	702
5	1929	593
6	1953	510
7	1963	453

The 1995 estimate used here was arrived at by adding an arbitrary allowance of 27 m³/s to the recorded peak for overflow below Little Bow Canal. The origin of the 1932 estimate is explained in Section 2.3 below. A plot of the entire 1912-96 sequence is shown in **Figure 2.1**.

2.2 Studies Reviewed

The following three studies were reviewed:

- Northwest Hydraulic Consultants (1974), prepared in connection with flood damage studies for the Town of High River.
- Alberta Environment (1991), prepared in connection with floodplain mapping.

- Northwest Hydraulic Consultants (1992), prepared in connection with PMF/design flood studies for the Little Bow project. (Because occasional large floods in the Highwood River can spill to the Little Bow River - which occupies an abandoned glacial route of the Highwood River - estimation of potential extreme floods upstream of High River town formed an important element of the Little Bow project studies.)

The NHC (1974) frequency analysis was based on a 61-year Aldersyde flood series 1912-72. A reduction factor was applied to transfer flood frequency estimates upstream of High River. Only the Aldersyde estimates are used herein, to allow for better comparisons with the later studies.

AE (1991) and NHC (1992) transferred the 78-year Aldersyde record for 1912-89 to upstream of High River town without adjustment for the relatively small drainage area difference. As noted in Section 2.1 above, AE adjusted some items by adding irrigation withdrawals (trivial) and unrecorded spills, to form a 78-year series of "naturalized" instantaneous peaks upstream of High River. Drafts of the NHC study used a slightly different series, but the AE naturalized series was adopted in the final NHC report of 1992.

2.3 NHC Results (1974)

The 1912-72 Aldersyde data series used by NHC contains an estimated value for 1932, although the Environment Canada gauge record does not contain values for that year. The instantaneous peak is shown as the highest of record at 26,000 cfs (736 m³/s). It appears that the basis for this figure was local opinion that the 1932 event was the highest experienced; an arbitrary 1000 cfs (28.3 m³/s) was therefore added to the recorded value for 1942, the next highest event.

The data were fitted graphically with a log-Normal line that provided a reasonable visual fit to the upper end of the series. The recommended 100-year instantaneous estimate was 1360 m³/s. Extrapolated, the fitting line yields a 1000-year estimate of about 2800 m³/s. These estimates are considerably higher than those derived in later studies. The main reasons appear to be that (1) the data base did not include the 1973-89 period of relatively low events, and (2) the fitting line was not determined statistically, but was drawn empirically with a bias towards the higher points.

2.4 AE Results (1991)

AE's data series also contains an estimate for the 1932 event. The previous Aldersyde instantaneous estimate of 736 m³/s was adjusted for spill, to produce a value of 818 m³/s upstream of High River.

The data were initially trial-fitted with 6 curves representing various probability distributions and fitting methods. A (non-log) Pearson-III distribution fitted by moments was adopted, as giving the "consistently most probable" fit to the higher points using AEP's own test method. For final estimates, the naturalized data series was "historically adjusted" to the 100-year period 1890-1989, on the argument that from 1890 to 1912 no flood had reached the level of the four highest floods in the subsequent period of record. (A very severe flood of unknown magnitude had, however, occurred in the 1880's.)

Final estimates for 100-year and 1000-year instantaneous peaks were 750 and 1120 m³/s - 55% and 40% respectively of the earlier NHC estimates as quoted above. The 100-year estimate seems too low: even in 1991, two recorded floods had exceeded that value, and by 1996 three floods had exceeded it. The 1000-year estimate also seems low, being only 35% greater than the actual maximum recorded.

2.5 NHC Results (1992)

This study fitted the data with three probability distributions, from which the log-Pearson III was adopted. NHC's preliminary estimates (1990) led to a debate with AE and some reduction. Final 100-year and 1000-year estimates (after consideration of AE's objections to higher draft values) were 960 and 2100 m³/s respectively. These values are substantially lower than the NHC 1974 estimates based on empirical log-Normal fitting, but also considerably higher than the 1991 AEP estimates based on (non-log) Pearson-III fitting. Visually, NHC's LP3 fit appears debatable, since most of the higher floods plot somewhat above the curve (**Figure 2.2**).

2.6 Discussion

The following table compares 100-year and 1000-year estimates from the three studies reviewed above:

Study	Record period	Fitting method	100-year m³/s	1000-year m³/s
NHC 1974	1912-72	Empirical	1360	2800 (by extr.)
AEP 1991	1912-89	P3 (M/M)	750	1120
NHC 1992	1912-89	LP3 (M/M)	960	2100

Neither of the later studies mentions statistical tests on the 1912-89 data series, which is implicitly treated as stationary and homogeneous. The sequential plot of **Figure 2.1** may reveal some indication of a dual-population situation.

Despite the 85-year length of the Highwood River record, analysis at different times and by different agencies has produced estimates for the 100-year flood that vary over nearly a twofold range. If the data record had started in 1950 instead of 1912 and if there had been no information on historical floods, frequency estimates prepared in 1991 would have been considerably lower and the subsequent 1995 event would have been assigned an extremely long return period. On the basis of the available record since 1912, however, the 1995 flood is comparable with several other events before 1950, and appears to have a return period of less than 100 years.

2.7 References

Alberta Environment 1991. Flood frequency analysis of the Highwood River at High River. Prepared by S.J. Figliuzzi, Hydrology Branch.

Northwest Hydraulic Consultants 1974. Flood regime study of the Highwood River at High River. Prepared by E.K Yaremko for Alberta Environment and Town of High River.

Northwest Hydraulic Consultants 1992. Flood frequency analyses, Highwood and Little Bow Rivers. Ancillary Report 2 by M. Leytham and C.R. Neill, in Volume II of Studies for Probable Maximum Flood, Little Bow River Dam. Prepared for Alberta Public Works, Supply and Services.

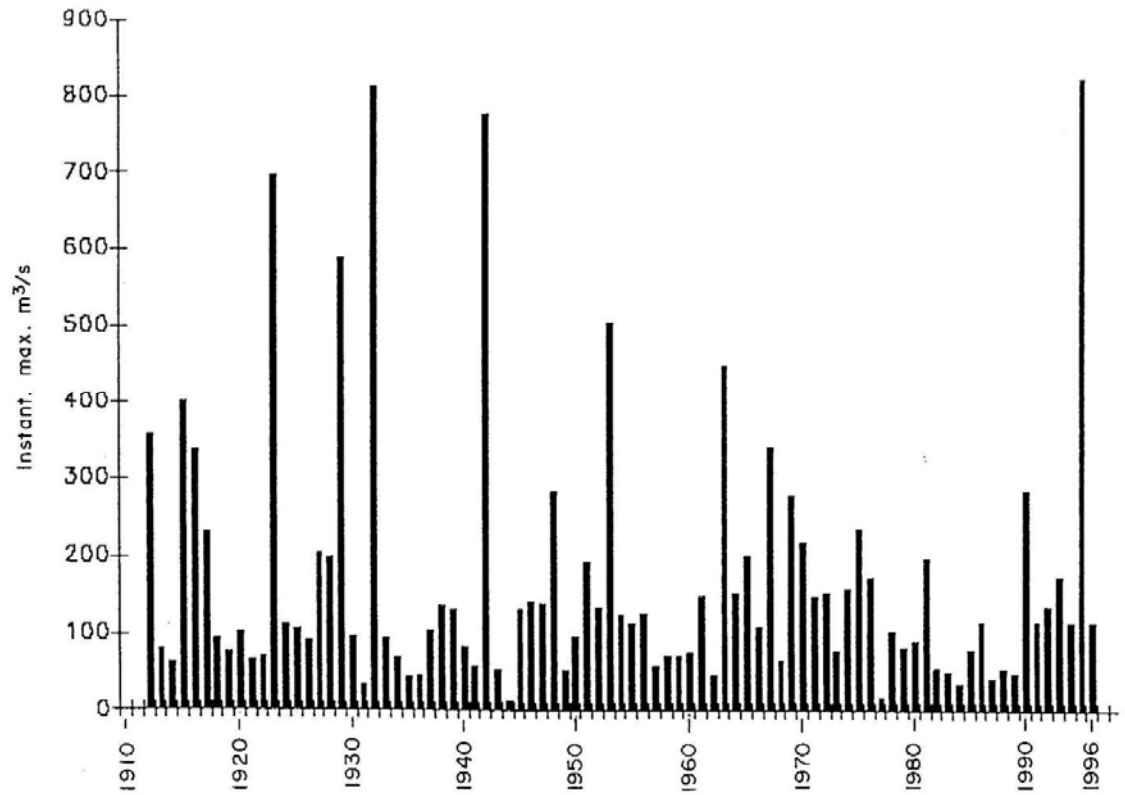


Figure 2.1 Naturalized instantaneous series for Highwood River above High River, 1912 - 1996

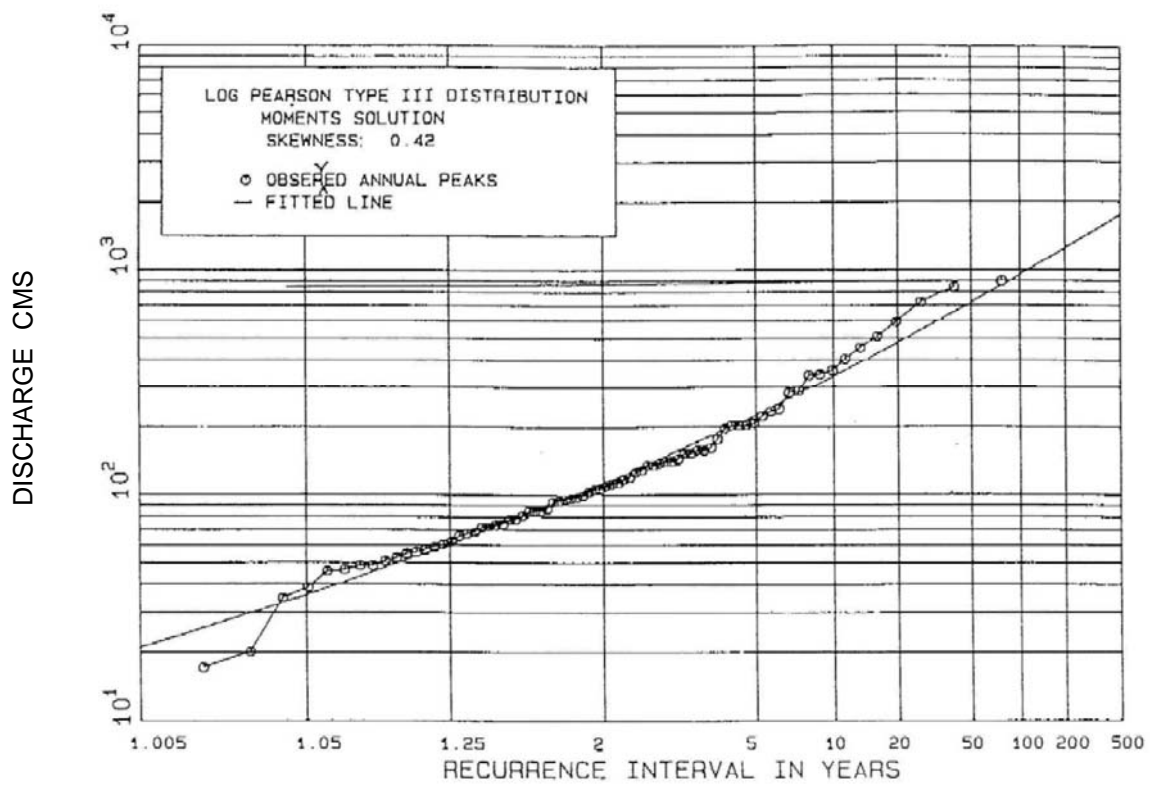


Figure 2.2 Flood frequency plot by NHC (1992) for naturalized instantaneous series 1912 - 1989 Highwood River above High River

CASE 3 - RED DEER RIVER AT DRUMHELLER

3.1 Flood Record

The Red Deer River at Drumheller (24 800 km²) has a broken flood record covering the periods 1916-30 and 1959-present. The missing years include several of the highest floods measured upstream at the city of Red Deer, including the record one of 1915.

For the Red Deer station (11 600 km²) there is a continuous record of annual maximum discharges from 1913 to present, excepting only 1933 and 1934 which are believed to have been comparatively low years. The seven highest events rank as follows:

Rank	Year	Instant.peak flow m ³ /s
1	1915	1930
2	1954	1480
3	1929	1210
4	1932	1200*
5	1952	1170
6	1923	1130
7	1928	1030

* estimated from daily

All of these events occurred in the first half of the record period. Since 1983, there has been some degree of flood regulation from the upstream Dickson Dam.

Figure 3.1 shows a sequential record of the reported daily maxima at Red Deer. Before 1967, instantaneous peaks are available only for the larger events, for which the average instantaneous/daily ratio is about 1.15. (The daily maxima of **Figure 3.1** form a slightly different ranking from the above table.)

3.2 Studies Conducted

Project-related flood frequency studies include the following:

- Alberta Environmental Protection (1996), in connection with floodplain mapping at Drumheller.
- Northwest Hydraulic Consultants (1997), in connection with floodproofing of a proposed hospital at Drumheller.

Acres International Ltd. (1998) reviewed differences between AEP and NHC estimates for the 1000-year flood, but did not present additional analyses.

To develop flood frequency estimates for Drumheller, AEP and NHC used slightly different methods for constructing a continuous Drumheller data series. They also adopted different statistical distributions for fitting the data.

3.3 AEP Methodology (1996)

The following steps were followed:

1. Missing instantaneous data were estimated from daily maxima using a regression equation.
2. Values post-dating the commissioning of Dickson Dam in 1983 were de-regulated, using recorded damsite flows and reservoir levels as input to a SSARR-based routing model. The results provided "naturalized" instantaneous series for both Red Deer and Drumheller.
3. The 81-year naturalized instantaneous 1913-95 series for Red Deer was fitted by a (non-log) Pearson-III distribution to derive estimates for various return periods.
4. Similar estimates for Red Deer were also derived for a reduced 51-year (broken) record period corresponding to the actual Drumheller record period.
5. The 51-year naturalized instantaneous series for Drumheller was fitted by a Pearson-III distribution to derive estimates for various return periods. These were then adjusted to the 81-year period by applying ratios indicated by the two analyses for Red Deer (steps 3 and 4 above).
6. Using a reservoir regulation model, predicted natural flows at various return periods were reduced by regulation, assuming the availability of 24-hour flow forecasting updated every 12 hours. The reduced 100-year estimate assuming flow forecasting was recommended for delineating floodplain boundaries.

3.4 NHC Methodology (1997)

The following steps were followed:

1. Gaps in the Drumheller daily series were filled in by applying an average multiplier of 1.2 to the Red Deer daily series, to produce a 70-year, partly-synthetic Drumheller daily record. The period after completion of Dickson Dam in 1983 was not represented.
2. This extended Drumheller daily series was fitted by a 2-parameter log-Normal distribution to give natural-flow daily estimates for various return periods.
3. A multiplier of 1.15 was applied to the daily estimates to obtain instantaneous estimates.
4. For return periods up to 200 years, instantaneous values were reduced to allow for regulation with flood forecasting, using the reduction amounts derived by AEP (step 6 in Section 3.3 above).

3.5 Comparison of AEP and NHC Results

NHC and AEP estimates for Drumheller at long return periods are listed below:

Return Period Years	<u>Instantaneous maximum discharges, m³/s</u>	
	NHC	AEP
100	2080	1640
200	2460	1840
1000	3140	2610

All estimates for 100 and 200 years are based on Dickson Dam regulation with flood forecasting. The NHC 1000-year estimate was derived by extrapolation from the regulated values at lower return periods, and therefore also implies regulation with flow forecasting. The AEP 1000-year value, on the other hand, is a natural-flow estimate not adjusted for regulation.

Present review of NHC analyses indicates that errors crept into tabulated instantaneous values for 20-year and 500-year return periods. The tabulated 500-year value was too

low by about 200 m³/s, causing the extrapolated 1000-year value to be low by about 400 m³/s. With correction of these errors, the NHC 1000-year estimate (implying regulation) increases to about 3500 m³/s.

3.6 Reviews of NHC-AEP Differences

A memo by AEP transmitted to NHC on 7/Nov/97 presented a summary comparison of the NHC and AEP procedures. It was concluded that differences in data treatment had only minor effects, and that the major difference could be attributed to the different statistical distributions used for fitting: Pearson-III (AEP) versus 2-parameter log-Normal (NHC).

In a response memo dated 10/Nov/97, NHC indicated that considering the more than ten-fold extrapolation of the record period, a 20% difference in 1000-year estimates was essentially trivial. It was concluded that the higher NHC prediction should be preferred for project purposes.

Acres international Ltd. of Calgary were asked by Alberta Public Works, Supply and Services to review the situation. In a letter report of 5/Feb/99, Acres noted that the two estimates of the 1000-year flood differed by only 20% and were well within the likely confidence bands of each analysis. Their final paragraph includes the following statements:

"In our judgment, the Log Normal distribution should be used if it appears adequate, as was done by NHC.....By extrapolating the regulated flood peaks, the NHC analysis implicitly assumes a significant degree of regulation..... In our opinion, the degree of flood peak reduction will be very small and, therefore, we conclude that the 1:1000 flood may be higher than the NHC estimate of 3140 m³/s."

3.7 Discussion

The NHC (1997) analysis used a partly-synthetic Drumheller series for the period 1916-82 only. A re-analysis has been conducted for present purposes using an extended series 1913-95, with the 1983-95 data de-regulated as per AEP (1996). The following comparison results:

Return Period Years	<u>Instantaneous maximum discharges, m³/s</u>	
	1912-82 series	1913-95 series
100	2280	2210
200	2700	2640
1000	3850	3790

The tabulated values are based on log-Normal fitting of a "naturalized" series, without allowance for future regulation with flood forecasting, and the previous 1000-year estimate has been corrected. The comparison shows that differences arising from the different record periods are essentially negligible. A plot based on the extended series (last column above) is shown in **Figure 3.2**. The fit to a log-Normal distribution is remarkably good.

Figure 3.1 clearly demonstrates a clustering of larger floods in the first half of the record (1913-54) and especially in the period 1915-32. There seems to be no way of knowing whether this was due to special circumstances or whether another cluster of comparably high floods can be expected in decades to come. If a record had been available for 1913-55 only, considerably larger flood frequency estimates would have been derived. Such irregularities in data sequences put into question the effort often expended on obtaining a "best fit" for the particular record period at hand.

Acres' review of the AEP and NHC analyses questions whether it was proper to rely on reservoir regulation controlled by flood forecasting. Their conclusion appears reasonable: that NHC's project estimate for the 1000-year flood, rather than being too high, was probably on the low side.

None of the studies reviewed discusses the stationarity and homogeneity of the data series.

3.8 References

Alberta Environmental Protection 1996. Flood frequency report for Red Deer River at Drumheller, by A. De Boer, Hydrology Branch.

Northwest Hydraulic Consultants 1997. Letter report by E.K Yaremko to Drumheller Regional Health Authority dated 16 April, and letter from E.K. Yaremko to Alberta Public Works, Supply and Services dated 22 October.

Acres International Ltd. 1998. Letter from M.J. Nozdryn-Plotnicki to Alberta Public Works, Supply and Services dated 5 February.

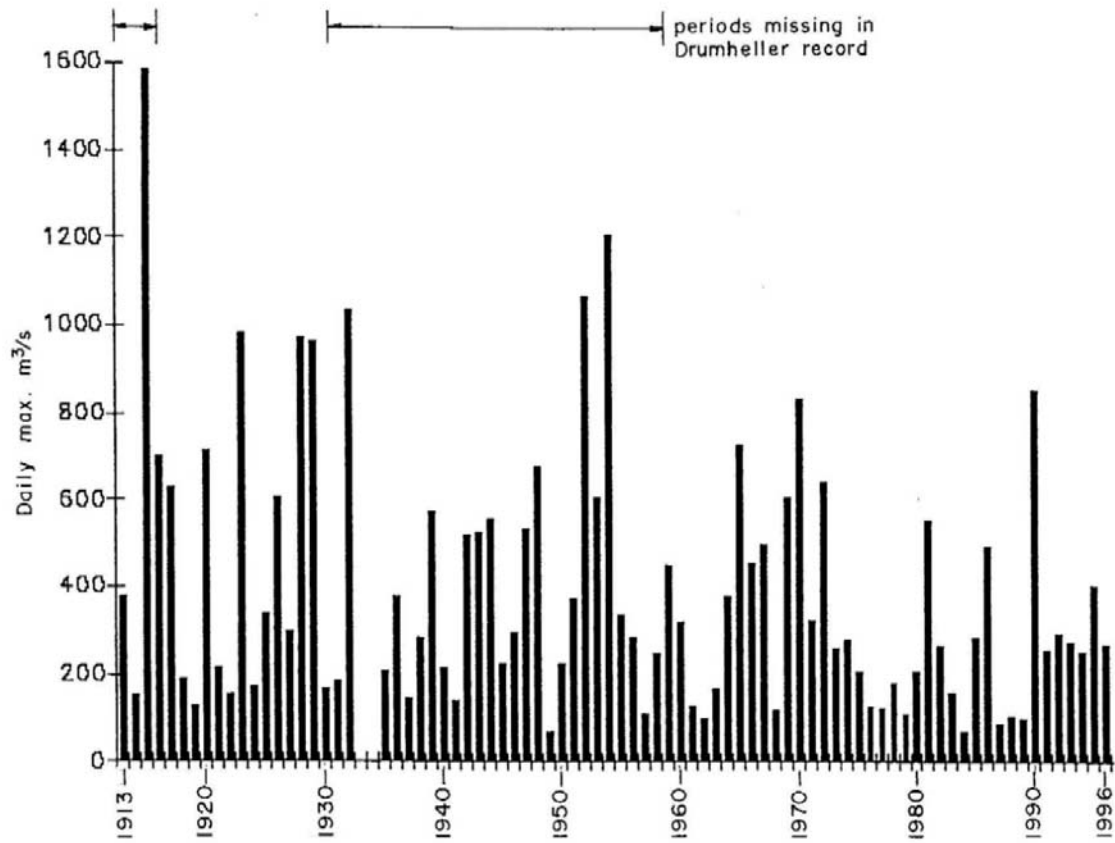


Figure 3.1 Daily series for Red Deer River at Red Deer 1913 - 1996

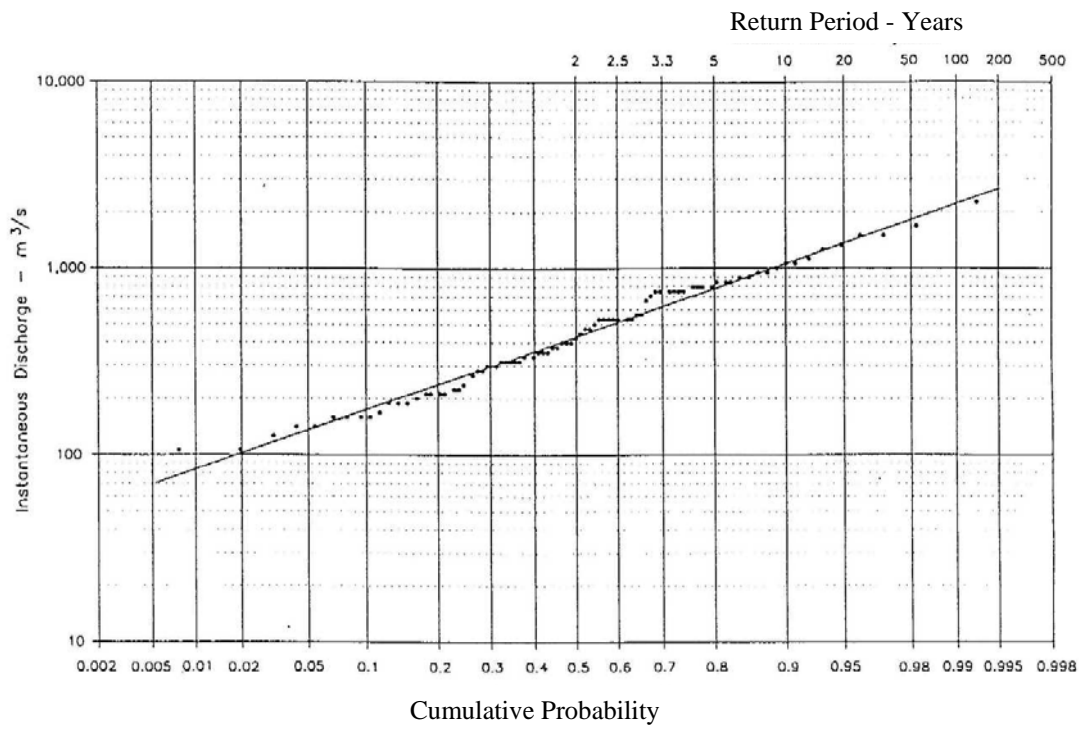


Figure 3.2 Flood frequency plot for partly – synthetic instantaneous series at Drumheller, 1913 – 1995 (with log – Normal fitting)

CASE 4 - SAWRIDGE CREEK AT TOWN OF SLAVE LAKE

4.1 Background

The magnitude and frequency of floods in Sawridge Creek became issues in litigation against the Province of Alberta arising from flooding in the Town of Slave Lake in July 1988. Northwest Hydraulic Consultants were engaged by Alberta Justice to provide technical analyses and advice to defence counsel.

The flood control system at Slave Lake includes an artificial channel that enables part of a high flood discharge to bypass the Town. There are also low dikes along Sawridge Creek. The system was constructed in 1971-72 and upgraded in 1983-84. Flooding in 1988 was due mainly to escape of water from the bypass channel. The escape of water was ascribed in part to construction or maintenance deficiencies in the bypass channel dikes and to debris blockage of a bridge over the channel.

4.2 Flood Record

The Environment Canada record for Sawridge Creek near Slave Lake (233 km²) began in 1976 and reports flows immediately upstream of the Town. From 1962 to 1975, flood peak discharges only were determined by Alberta Environment with the aid of a crest stage gauge. The two sets of data were combined into a single record by NHC, as they appeared to be reasonably compatible statistically.

Subsequent re-evaluation of the initially reported value for the 1988 flood (see Section 4.5 below) raised the question of whether certain earlier values might have been under-reported. Except in one case, however, possible discrepancies were not judged important enough to warrant tampering with the data.

4.3 Original Design Flood Determination

A design flood value was first determined by PFRA in 1970. In the absence of sufficient data for Sawridge Creek, a runoff/precipitation analysis for the adjacent Swan River basin was transferred to Sawridge Creek with some rudimentary calibration against high water marks. The derived design flood was 133 m³/s, apparently intended to represent a 100-year instantaneous peak.

4.4 Frequency Analyses Preceding 1988

The growing Sawridge Creek record was frequency-analyzed by AE at various times between 1974 and 1988. Estimates for the 100-year instantaneous peak ranged from 113 to 142 m³/s. The last estimate, based on data up to 1987, was 124 m³/s.

NHC made an independent analysis of the pre-1988 record using a 26-year combined AE/EC peak record 1962-87, and obtained a 100-year estimate of 165 m³/s. The difference from AE estimates was mainly due to a different fitting distribution.

4.5 Magnitude of 1988 Flood

In order to analyze the 1988 flooding, it was necessary to know the magnitude of the 1988 flood peak as it entered the Town of Slave Lake upstream of the bypass channel entrance. At that time the Environment Canada gauging site on Sawridge Creek was located downstream of the Town and did not directly measure excess flows that entered the bypass channel upstream of the Town. To arrive at a total inflow for reporting purposes when the bypass channel operated, the bypass flows were computed using the hydraulic characteristics of the ungated channel entrance and of the channel itself.

The magnitude of the 1988 flood peak upstream of the Town was first estimated by Environment Canada as 165 m³/s. Alberta Environment then produced an independent estimate of 156 m³/s - not much different. On the basis of NHC's frequency analysis, these estimates seemed to place the return period at about 100 years. However, the project as upgraded in 1983-84 was supposed to take a 100-year flood with freeboard of 0.6 to 0.9 m. With these flow estimates and given the extensive flooding that developed, there appeared to be a strong case against the authorities on the grounds of deficiencies in design, construction or maintenance.

The Environment Canada and Alberta Environment computations were reviewed in detail by NHC in 1994, and deficiencies were found in both methods of analysis. NHC's best estimate was 270 m³/s. After mutual consultation, Environment Canada revised their figure to 250 m³/s, the value which now appears in the data archives.

4.6 Analysis of Extended Data Series

Using a 31-year data series extending from 1962 to 1992, NHC obtained a revised 100-year estimate of 205 m³/s. On the basis of a 2-parameter log-Normal fit, the return period of the 1988 event was estimated as about 300 years. Given the shortness of the record, however, the confidence level of these estimates is low.

Figures 4.1 and 4.2 show a sequential record and the frequency plot. The 1988 value, being so much larger than the rest, exercises a strong influence on the analysis.

On the basis of a peak flow of 250 m³/s and a return period in the order of 300 years, it appeared that the 1988 event far exceeded project design criteria. It was possible to show that the flood would have spilled to some extent into the Town even if all elements of the flood control system had been up to design standards. This re-assessment somewhat weakened the case for the plaintiffs, and the case was eventually settled out of court.

4.7 Discussion

Detailed re-evaluation of the reported 1988 flood peak revealed deficiencies in computations conducted by two different agencies. Although the two-channel gauging situation at Slave Lake may be somewhat unusual, this experience shows that reported figures for extreme floods cannot always be taken on trust.

In the light of information available even up to 1987, PFRA's original design flood estimate does not appear unreasonable.

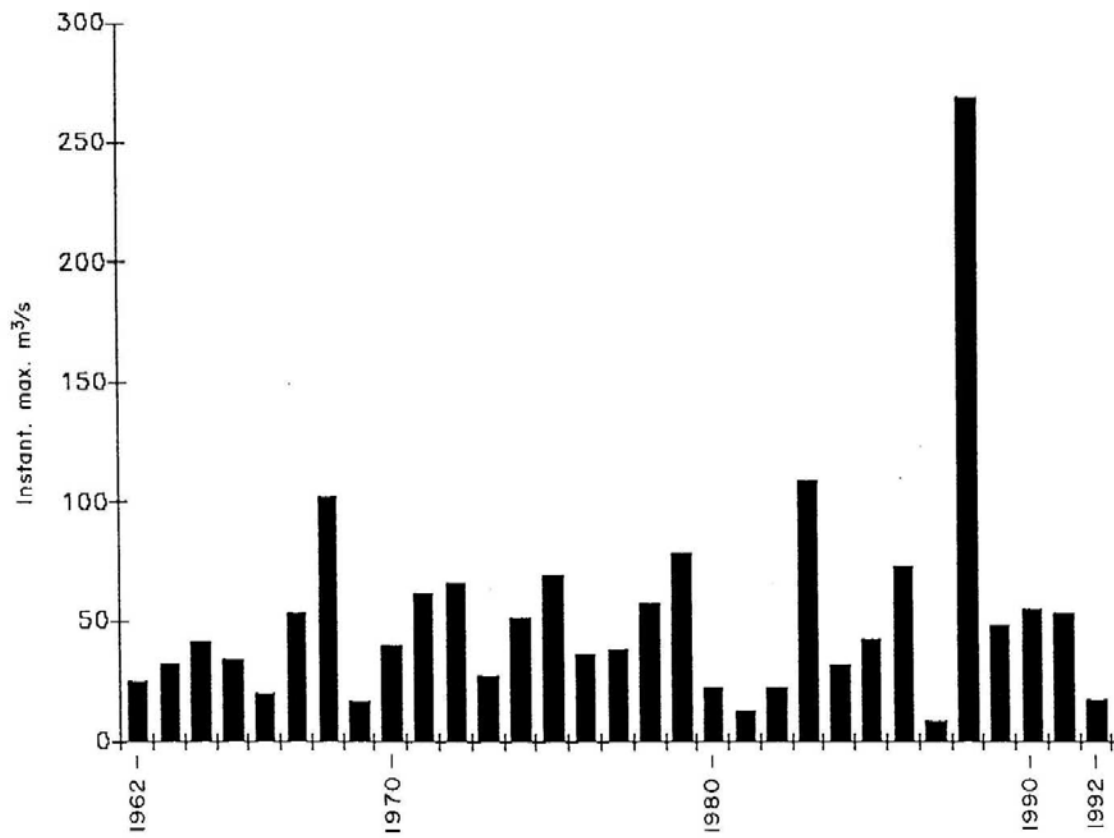


Figure 4.1 Combined instantaneous series for Sawridge Creek above Slave Lake town, 1962 - 1992

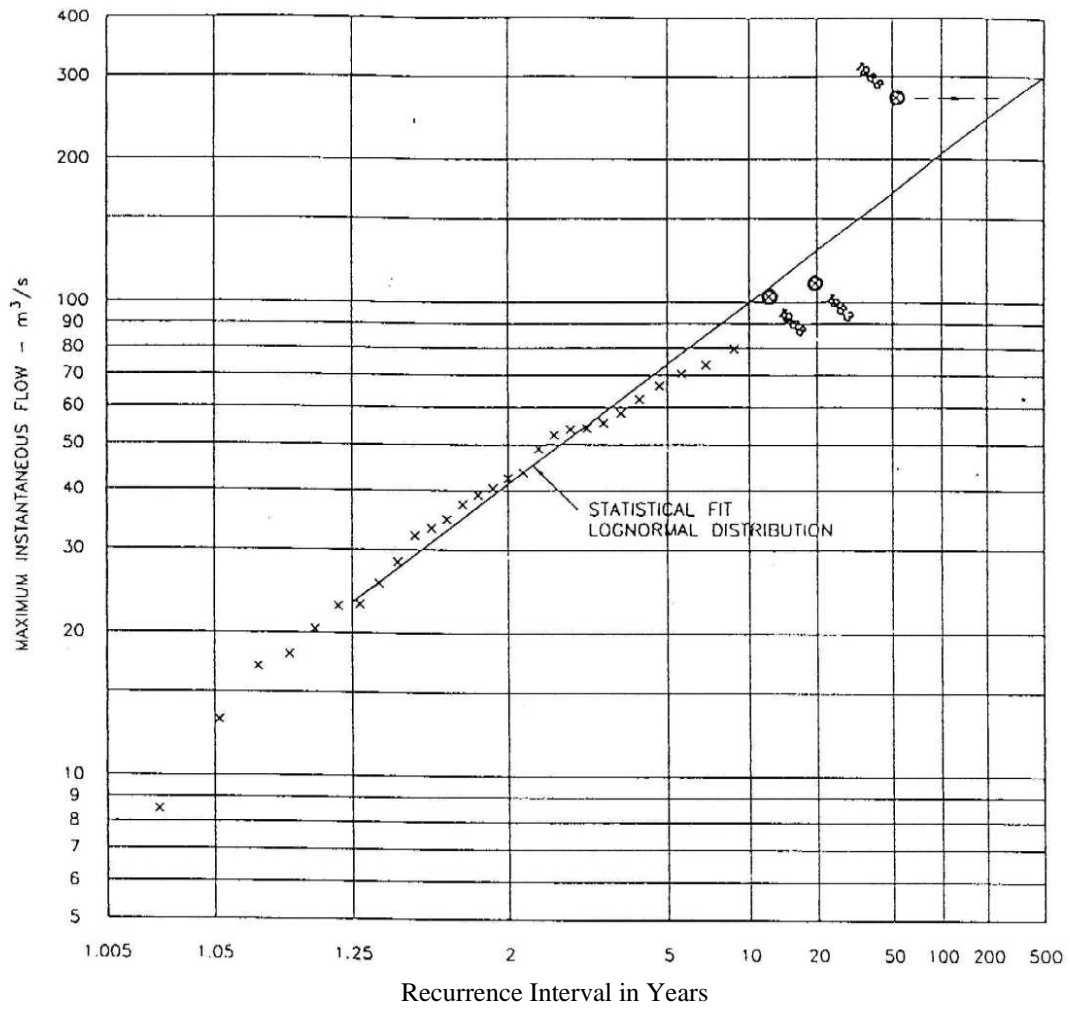


Figure 4.2 Flood frequency plot for series of Figure 4.1 Sawridge Creek above Slave Lake town

CASE 5 - BOW RIVER AT CALGARY

5.1 Background

The flood record of the Bow River at Calgary exhibits a peculiar time series. Various studies connected with floodplain delineation have arrived at substantially different conclusions regarding flood frequencies.

This case assessment refers only to the Bow River above the Elbow River. The record for the Elbow River at Calgary is somewhat similar to the Bow River record, but is not discussed herein.

5.2 Flood Record

The Bow River at Calgary (7860 km²) has a continuous record from 1911. The three largest known floods all occurred before 1911 - in 1879, 1897 and 1902. Reasonably reliable estimates are available for the floods of 1897 and 1902. The 1879 flood may have been even greater, but in recent studies it has been assigned the same peak discharge as the 1897 event.

Figure 5.1 shows a sequential plot of instantaneous flood peaks at Calgary covering the 118-year period 1879-1996. Missing values before 1911 are plotted as zero. A few missing instantaneous peaks after 1910 have been estimated from reported daily maxima.

The fourth-highest known flood at Calgary occurred in 1932. Since then, there have been no floods of much significance. The nine highest events all occurred before 1934.

Other Bow River flood records of interest include:

- Banff (2210 km²), continuous 1909-96;
- near Seebe (5170 km²), 1923-62 and 1979-96;
- below Ghost Dam (6550 km²), 1933-62 and 1968-89.

The Banff record (**Figure 5.2**) does not resemble the Calgary record, the larger events being reasonably distributed through the record. Near Seebe, however, the six highest

floods occurred in the first 11 years of record 1923-33, another time series peculiarity. The record below Ghost Dam seems to show a gradually declining trend. Four sources of information on Calgary flood frequencies are reviewed below. Others exist, but these appear sufficient to define the problem.

5.3 Monenco's Calgary Floodplain Study (1968)

A hydrologic analysis of floods on the Bow River is contained in a report by Montreal Engineering Co. (1968). The analysis considers historical flood patterns, meteorological factors and the effects of storage and forest fires. Points of interest include the following:

- The 1902 event (third-highest known) occurred in the middle of a very wet summer, with the countryside around Calgary saturated.
- The 1929 and 1932 events, the fifth- and fourth-highest known, both occurred on June 3. Both resulted mainly from heavy rain in the foothills west of the city. When there is heavy rain in the foothills, the headwaters are usually receiving snow. The largest rainfall events are associated with cyclonic storms drawing moisture from the Gulf of Mexico. Snowmelt floods do not occur at Calgary.
- The last major flood stage at Banff occurred in 1884, before streamflow records began.
- For the 1932 event, a hydrograph and routing analysis indicated that the amount of reservoir storage present in the drainage basin in 1968 would have reduced the natural flood peak at Calgary by about 13%. (There has been no significant increase in storage since then.) Although determinations were not made for other events, it is clear that storage alone cannot explain the large difference in flood magnitudes before and after 1933. The main factor seems to be an absence of large cyclonic storms over the Bow basin.
- Monenco concluded that it was difficult to draw firm conclusions about flood frequencies. A maximum discharge of 100,000 cfs (2830 m³/s) was selected arbitrarily for floodplain mapping. Its return period was estimated as probably in the range of 100 to 150 years.

5.4 Monenco's Bowness Flood Study (1971)

A hydrologic summary in the main report (Montreal Engineering Co. 1971) mentions a study of 43 of the largest storms in southern Alberta. The conclusion seems to have been that before 1933 large storms frequently followed paths critical to the Bow River, but

since then none had done so. Quoted flood-frequency estimates imply (by interpolation) a 100-year instantaneous value of about 2500 m³/s.

5.5 Monenco's Calgary Flood Study (1973)

In article by Owen and Nancarrow (1977) summarizes hydrologic conclusions from another Calgary flood study (Montreal Engineering Co. 1973). A number of hypotheses are advanced for the peculiarities of the Calgary record, but all are discounted except persistence of an absence of flood-producing rainstorms over the lower part of the Bow basin since 1932. It is indicated that no major changes in forest cover were identified. (For the period of large historical floods before 1910, however, this conclusion seems to be at variance with statements in AE's 1983 study - see Section 5.6 below).

The article indicates that the designated flood for floodplain delineation was selected as 80,000 cfs (2265 m³/s) to represent the historical floods of 1879 and 1897. The estimated return period was 70 years.

Another document examined (Montreal Engineering Co. 1979) gives more background to the above-quoted article, and details the method used to construct a dual-slope or "dog-leg" flood frequency curve based on adoption of two marginal probability distributions. It is shown that the Calgary flood series can be broken into two sub-series with quite different probability distributions, with a discontinuity in the range of 600 to 700 m³/s. It is suggested that the lower set represents ordinary within-bank annual maxima, associated with strato-nimbus cloud conditions over the eastern slopes, and the upper series represents major floods associated with cumulo-nimbus cloud conditions.

5.6 Alberta Environment's Calgary Flood Plain Study (1983)

The hydrology appendix first considers the statistics of the continuous streamflow record 1908-80. A split-sample test confirmed that the 1908-43 and 1944-80 periods were highly incompatible. It was concluded that the two samples did not belong to the same flood population.

Reference is made to extensive forest fires that are said to have burned 60% to 80% of the Eastern Slopes in the late 1800's and early 1900's, and that might partly account for the extreme floods before 1910. The conclusion is drawn, however, that because forest influences on runoff come and go, the early and late records should be combined for purposes of frequency analysis.

The previous Monenco analysis of storage effects is extended by considering the Ghost reservoir. Similar conclusions are arrived at: that storage effects on major floods are minor and there have been no major rainfall runoffs downstream of Banff since 1932. Supporting rainfall data are not presented.

Notwithstanding the demonstrated non-stationarity of the recorded flood series and the admitted effects of increasing storage in the basin, a frequency analysis was conducted on the whole recorded series. A (non-log) Pearson III distribution was fitted and adjusted for the historical floods of 1879, 1897 and 1902 using U.S. Water Resources Council methods (**Figure 5.3**). The 100-year adjusted estimate is 1980 m³/s - exceeded only by the floods of 1879 and 1897. This is 87% of Monenco's designated flood of 1973.

5.7 Discussion

Various difficulties arise over conducting a flood frequency analysis for the Bow River at Calgary. Some relevant points are as follows:

1. The amount of live storage in the basin was increased at intervals over the period 1912 to 1955, to a total of about 9000 cms-days. Logically, all recorded flood peaks should be naturalized before attempting a frequency analysis.
2. More important than the storage effect is a large statistical discrepancy between the earlier and later records, apparently caused by a major shift in rainstorm patterns after 1932. The cause of this shift and its possible periodicity are unknown. It is generally considered unjustified in statistical practice to lump together two series from clearly different source populations and fit a single probability distribution. One study used a method of combining two component distributions into a single dual-slope frequency curve.

In such cases, the most rational method of selecting a project flood may be to adopt an arbitrary value or a specific historical flood. Both these approaches have been used at different times. Construction of a composite frequency curve from identified marginal distributions also appears to be a legitimate approach.

5.8 References

Alberta Environment 1983. Calgary floodplain study, volume II, Appendix B, Hydrologic Analysis by A. DeBoer.

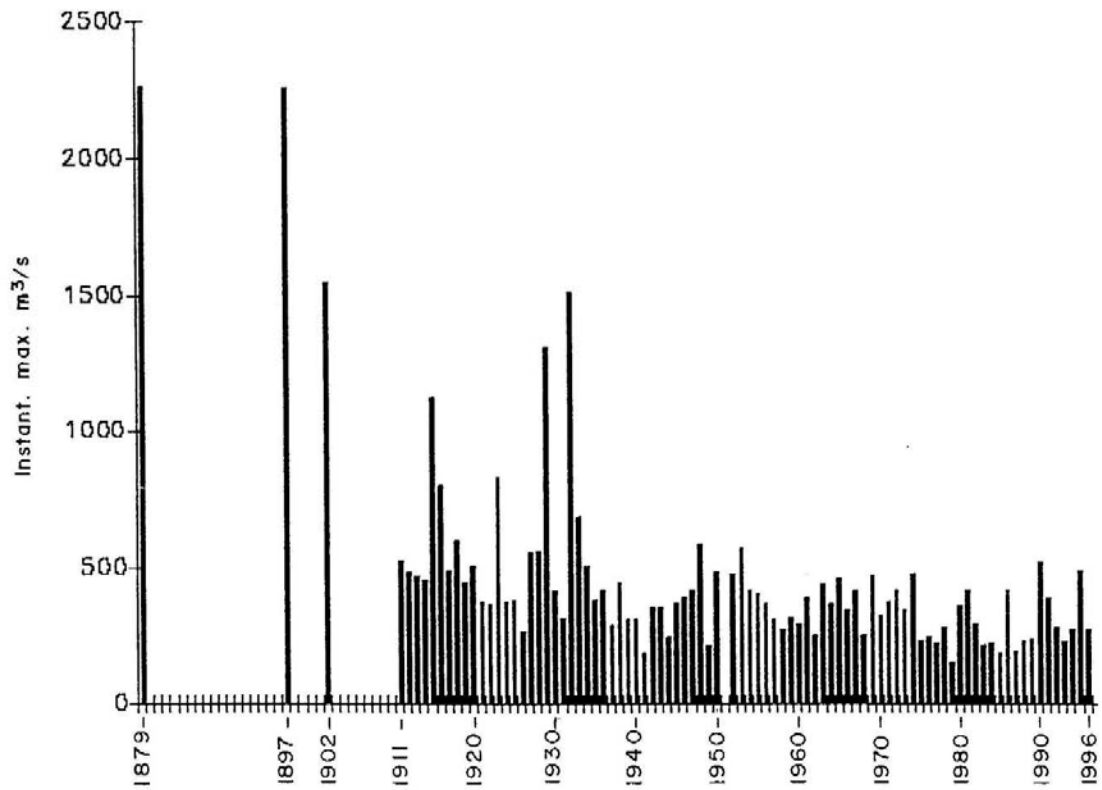
Montreal Engineering Co. 1968. Flood plain of Bow River in the City of Calgary. Report to Water Resources Division, Alberta Department of Agriculture.

Montreal Engineering Co. 1971. Report on Bowness flood study. Report to Water Resources Division, Alberta Department of Agriculture.

Montreal Engineering Co. 1973. City of Calgary flood study, Volume 1, Bow River report.

Montreal Engineering Co. 1979. Hydrologic study of floods in Calgary. Attachment 1 to Appendix B of Interim Report, Elbow River Flood Study.

Owen, J.A. and Nancarrow, D.R. 1977. Flooding in the City of Calgary. In Proceedings of Canadian Hydrology Symposium 77, National Research Council.



**Figure 5.1 Instantaneous series for Bow River at Calgary,
1911 - 1996 plus 3 historical floods**

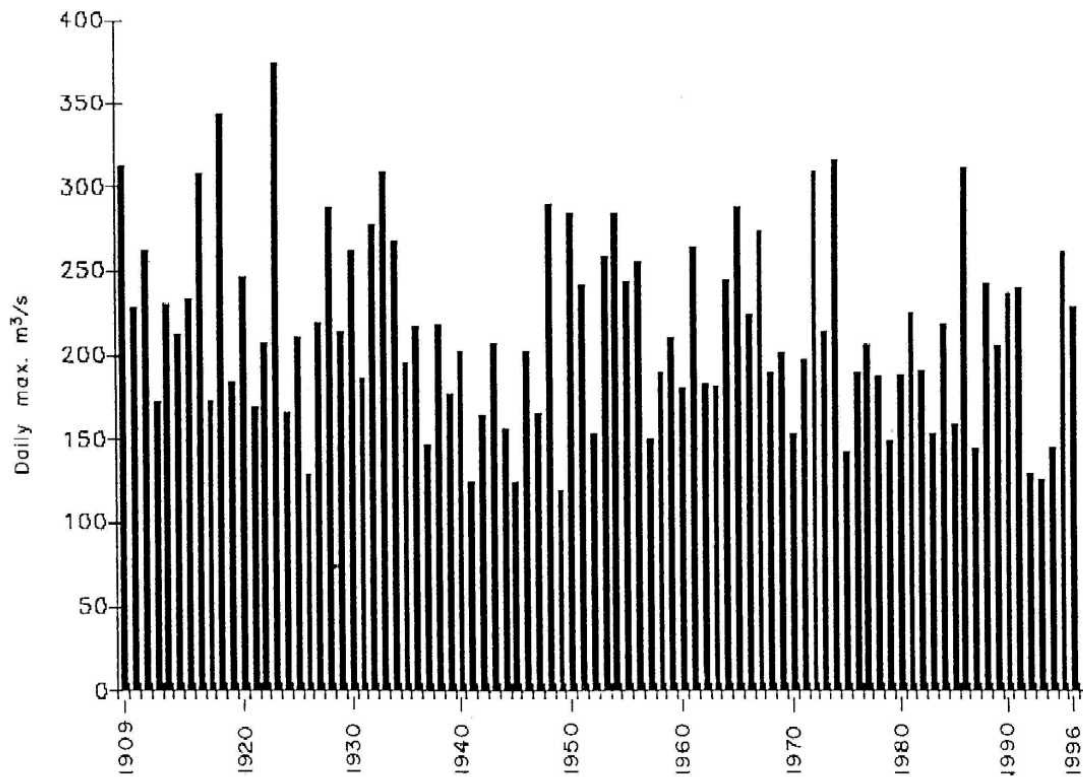


Figure 5.2 Daily Series for Bow River at Banff, 1909 - 1996

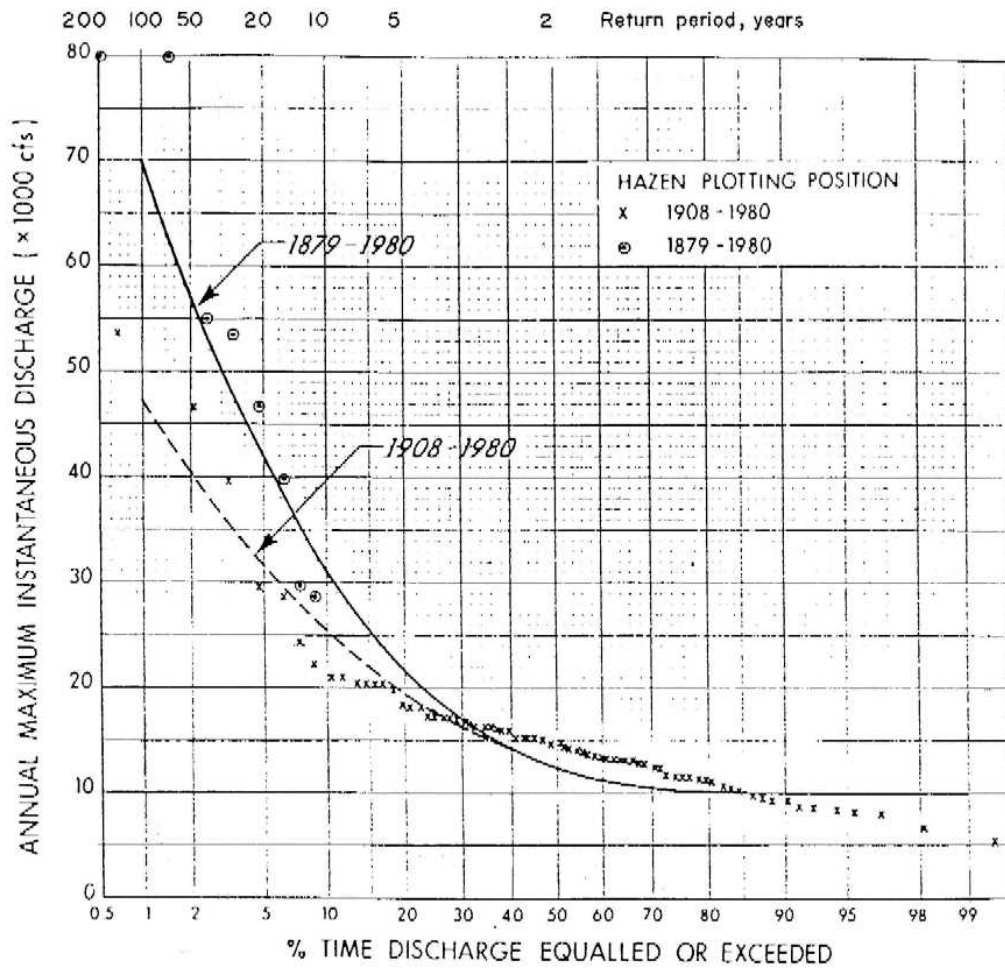


Figure 5.3 Flood frequency plot by AE(1983) for Calgary instantaneous series 1908 - 1980, with and without adjustment for historical floods

CASE 6 - OLDMAN RIVER NEAR BROCKET

6.1 Background and Flood Record

Flood frequencies near Brocket were investigated in connection with the Oldman River Dam project in the mid-1980s. The primary source of data was the Environment Canada gauging station a short distance downstream, designated as Oldman River near Brocket (# 05AA024, drainage area = 4400 km²). This has an annual maximum discharge record extending from 1966 to present - except that the "Extremes Report" has no entries for 1995, when the largest flood since 1966 occurred. Since around 1990, flows at the station have been affected by the Oldman River Dam.

In flood frequency studies conducted for the project (**Hydrocon 1985**), the short 19-year record then available for Brocket (1966-84) was extended by correlating and interpolating earlier records for upstream and downstream stations, to create a 73-year table of maximum daily discharges covering the period 1910-84 except for a 2-year gap in 1932-33. (The events of 1932 and 1933 seem to have been unremarkable at Lethbridge, so their omission is probably of little significance.)

Within Hydrocon's extended 1910-84 series, the three highest daily maxima are as follows:

1923: 1865 m ³ /s	(synthesized)
1975: 1220	(recorded)
1948: 1045	(synthesized)

A historical flood of 1908 is thought to have been higher at Lethbridge than the flood of 1923. Because of a lack of information from other locations, no 1908 estimate was developed for Brocket.

As noted above, data for the 1995 flood are missing in the Brocket station record. However, estimates of hourly inflows to the Oldman River Reservoir a short distance upstream were synthesized by Alberta Environment on the basis of reservoir levels and outflows (**Magowan and Ruttan 1997, Magowan 2001**). Estimated daily and instantaneous maxima are approximately 2050 and 3490 m³/s. Assuming the synthesis to be reasonably reliable, the peak/daily ratio is then 1.70. The peak inflow appears to have occurred at midnight on 6/7 June, a timing that tends to maximize the ratio.

Figure 6.1 shows a time-series plot of Hydrocon's extended daily record for 1910-84, updated with data to 1998 including the 1995 event. Except for 1995, the data from about 1990 on are affected by the new upstream reservoir. On the basis of this series, the 1995 event is the highest known at Brocket in about 90 years - with the possible exception of 1908.

Environment Canada's post-1965 record for Brocket provides instantaneous as well as daily maxima. **Figure 6.2** shows a time-series plot of instantaneous maxima for 1966-98; again, the data from 1990 on are affected by the upstream reservoir, except for the 1995 estimate of reservoir inflow.

6.2 Hydrocon's Flood Frequency Results (1985)

Analysis of daily maxima

Hydrocon's flood frequency analyses were based on an extended 73-year daily record for Brocket, as referred to above and plotted in **Figure 6.1**. Five different probability distributions were fitted to the data (EV1, LN, 3PLN, P3, LP3). The P3 (Pearson Type III) was adopted for estimation purposes because it gave the most conservative results for the longer return periods of interest.

Plotted fitting curves with data points were shown for all trial distributions except the adopted one. For the adopted distribution, a curve was provided with +/- 95% confidence limits added but without data points.

Figure 6.3 shows Hydrocon's plot for the LP3 distribution. On a logarithmic scale, the adopted P3 fitting curve is only marginally higher and has not been shown. The 5 highest points remain above both curves. The fit seems to be governed principally by the central mass of points, and influenced to some degree by the 4 lowest points which depart notably from the general trend.

The notable gap between the 5 highest points and the rest evident in **Figures 6.1 and 6.3** suggests the possibility of dual populations. For example, whereas Hydrocon's P3 curve produced 100- and 500-year (daily) estimates of 1500 and 2100 m³/s, a graphical fit leaning towards the highest points suggests 100- and 500-year values in the order of 1800 and 3000 m³/s.

Quantification of uncertainty

The Hydrocon report provided an indication of uncertainty by showing a 90% confidence band around the adopted frequency curve (**Figure 6.3**). The method of computation was not indicated. The plotted 90% confidence band seems remarkably narrow - for example, at the 1000-year return period the range between limits amounts to less than 25% of the adopted estimate. The narrow range is probably related to the fact that the P3 distribution, unlike most others used for flood series, is not based on logarithmic data transformations.

An independent check on the basis of the LN (lognormal) distribution - which provided a fitting curve not drastically different from the adopted P3 - indicates a 90% confidence band range of about 60% on the 1000-year estimate. This magnitude of range seems more credible.

(Confidence limits as discussed above account only for statistical sampling uncertainty and do not take into account additional distribution uncertainty - that is, uncertainty as to which distribution might best represent the unknown long-term population. Nor do they account for data uncertainty: in this connection it may be recalled that of the 5 highest events in Hydrocon's series, only one was actually gauged at Brocket. The real range of uncertainty in the 1000-year estimate is therefore likely to be much greater than 60%.)

Derivation of instantaneous quantile estimates

Given that the greater part of the extended 73-year record had been synthesized using daily data, and that the main use of the results was for estimating n-year inflows to a storage reservoir, it would be unreasonable to criticize Hydrocon's use of the daily series for frequency analysis. For purposes of developing continuous hydrographs, they estimated instantaneous quantiles by applying a constant multiplying factor of 1.25 to all estimated daily quantiles.

The multiplying factor of 1.25 was based on observed ratios over the 19-year gauged period 1966-84, which produced a mean of 1.11 and a maximum of 1.28 (in 1975). The higher 1923 flood does not seem to have been investigated in this respect. But although the adopted multiplier was near the upper end of the observed range, it did not allow for the likelihood that higher ratios would have been observed in a longer data period; a frequency analysis of observed ratios might have been useful in this connection. Also, the time of day at which the observed peaks occurred - a factor that usually has an

important bearing on observed ratios - does not seem to have been investigated. (This effect can be examined by synthesizing continuous hydrographs using reported daily flows and instantaneous peaks.)

Hydrocon's daily and instantaneous estimates for selected return periods were as follows:

Return period, years	Daily, m³/s	Instant., m³/s
100	1500	1880
500	2110	2640
1000	2375	2970
10000	3270	4090

The Hydrocon report noted that the adopted flood frequency curve would assign a return period of about 250 years to the 1923 flood, while a historical flood of 1908 (estimated only at Lethbridge) would probably have had an even longer return period. This means that according to the analysis, two floods with return periods exceeding 240 years had occurred in the space of about 80 years. No comment was made about the very low probability of such an outcome.

Flood hydrographs

The method used by Hydrocon to develop hypothetical hydrographs corresponding to return periods ranging from 5 to 10,000 years can be summarized as follows:

1. Initial hydrograph shapes were patterned after the flood of June 1975, it being the only large flood for which hourly flow data were available. The rise time from baseflow to peak was set at 36 hours, and at 7 days after start of rise, discharges had receded to about 15% of peak value.
2. The initial hydrograph shapes were adjusted to some degree so that their runoff volumes would match the results of frequency analysis of annual maximum volumes. These volume analyses were conducted for durations of 3, 5 and 7 days.

6.3 Relationship of PMF to Flood Frequency Estimates

A separate project study by **Alberta Environment (1985)** estimated the Probable Maximum Flood using standard hydrometeorological methods. Their PMF had an instantaneous peak of approximately 9500 m³/s, approximately 5 times Hydrocon's 100-

year value. This ratio, although very high, is not incompatible with some other recent studies.

The PMF hydrograph was of markedly shorter duration than the flood frequency equivalents. The rise time was only 24 hours instead of 36, the duration up to the 15% recession point was less than 3 days instead of 7, and runoff was virtually complete at 5 days. The PMF and 10,000-year hydrographs are compared in **Figure 6.4**.

6.4 Flood Experience after 1984

As can be seen from **Figures 6.1 and 6.2**, annual maxima at Brocket in the post-study period 1985-98 (affected by reservoir operations from 1990 or so) were generally low, except for the record flood of 1995. As reconstructed from operational data, this event was clearly the highest since 1910 in terms of both daily and instantaneous maximum discharges. Compared with the previous high of 1923 as synthesized by Hydrocon, the daily maximum was higher by 10%.

As the highest in a record period of about 90 years, the return period of the 1995 event might be estimated empirically as around 140 years. In contrast, the flood frequency analysis of 1985 assigns a return period of around 400 years to the daily estimate, and in the order of 2500 years to the instantaneous estimate.

6.5 Hydrograph Shapes

AE's reconstruction of 1995 hourly reservoir inflows will be assumed generally reliable, except for minor irregularities probably due to factors such as wind set-up. As shown in **Figure 6.4**, the actual hydrograph shape differs greatly from Hydrocon's flood-frequency equivalents, but is more compatible with AE's PMF hydrograph.

Figure 6.5 shows a more detailed comparison of the 1995 hydrograph against a hydrograph scaled down from the PMF to match the 1995 peak. The rate of rise for 1995 is somewhat steeper, and the time to peak is shorter.

Figure 6.6 compares (1) a reconstructed continuous hydrograph developed graphically from recorded daily flows for the 1923 event as recorded near Fort Macleod (station # 05AB007, drainage area 5700 km²), and (2) the reconstructed 1995 hydrograph at Brocket (drainage area 4400 km²). The 1923 event at Fort Macleod appears to have had a time of rise from baseflow to peak of approximately 12 hours, and a peak/daily ratio of approximately 1.6. These results are very similar to those for the 1995 event at Brocket.

Similar results for 1923 can be derived by superimposing recorded daily hydrographs from the main stem and tributaries upstream of Brocket.

6.6 Discussion

The 1985 flood frequency studies for the Oldman River Dam project have not stood the test of post-project experience. Some comments on this result are offered below.

1. The extension of the short Brocket record using data from other gauges, and the use of the extended daily series for frequency analysis, seem to have been appropriate in the light of the available data.
2. It was also appropriate to test several probability distributions to fit the data, but adoption of the apparently most conservative (P3) did not necessarily provide realistic estimates of flood magnitudes for long return periods. Insufficient attention was given to the fact that for all tested distributions, the 5 highest data points remained above the fitting curve - so that derived quantiles for return periods exceeding 10 years were low compared to empirical evidence. Given the difficulty of fitting the highest points with a single probability distribution, consideration could have been given to treating the series as representing two flood populations, or to graphical fitting.
3. The quantification of sampling uncertainty using confidence limits was appropriate up to a point, but the numerical limits seem unreasonably narrow. The reason for such narrow limits cannot easily be determined, since no explanation or source for the methodology was provided in the report. Consideration was given to sampling uncertainty only - the data were assumed to be free from error, and the selected distribution was assumed to best represent the flood population.
4. The transformation of estimated daily flood frequency quantiles to instantaneous equivalents was non-conservative, since it used a constant peaking factor of 1.25 based on only a 19-year period of common records and did not consider the effect of clock times on peaking factors. The 1995 flood, and probably the 1923 flood, apparently produced much higher values. The likely result of using the 1.25 factor was that the magnitude of instantaneous flood frequency quantiles was considerably under-estimated.

5. Although this is not really a problem of frequency analysis, there are large discrepancies between hydrograph durations and shapes as derived in Hydrocon's flood frequency study on the one hand, and in Alberta Environment's PMF study on the other hand. The PMF hydrograph is of relatively shorter duration, with a much steeper rise. The shapes of reconstructed 1995 and 1923 flood hydrographs are more compatible with the PMF, although they seem to have even shorter times to peak. The main reason for the flood-frequency hydrographs being so long appears to be that they were modelled on the 1975 flood, which was only the third-highest in the period 1910-98.

6.7 References

Hydrocon 1985. Preliminary Engineering Report, Oldman River Dam, Appendix A, Flood Frequency Analysis. prepared by Hydrocon Engineering (Continental) Ltd. for UMA/Acres and Alberta Environment.

Magowan, D. and Ruttan, J.A. 1997. Operation of the Oldman River Dam during the June 1995 flood. Paper prepared for 19th ICOLD Congress, Florence, Italy.

Magowan, D. 2001. Private communication, Alberta Environment, Lethbridge. (Informal set of operational data and computed flows for Oldman River Dam during 1995 flood.)

Alberta Environment 1985. Probable Maximum Flood for the Oldman River Dam. By R.A. Bothe, S.J. Figliuzzi and J.H. Taggart, Hydrology Branch.

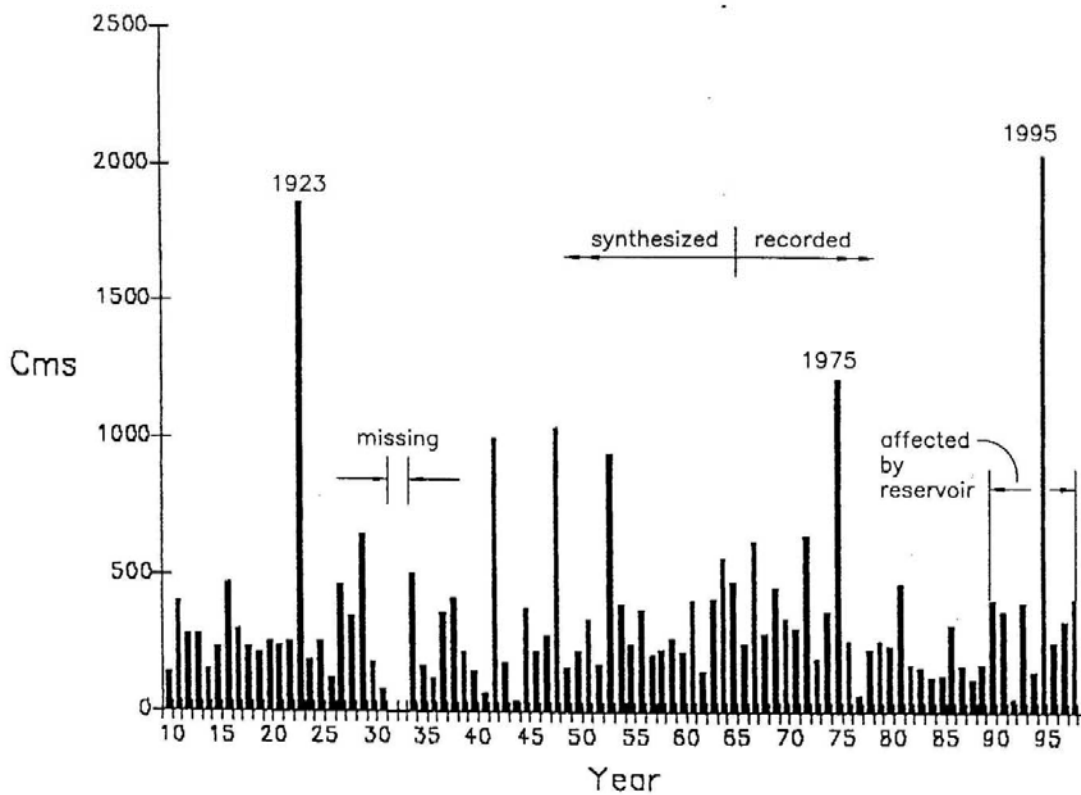


Figure 6.1 Daily series for Oldman River near Brocket, 1910 - 1998

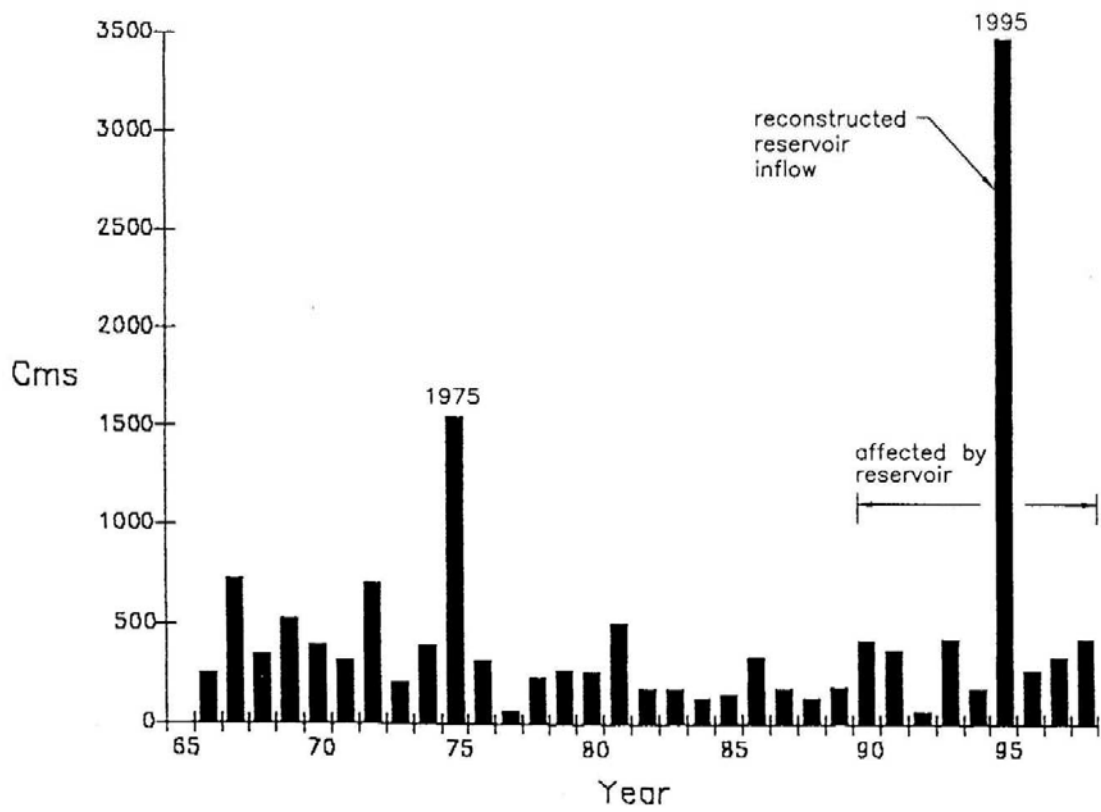


Figure 6.2 Instantaneous series for Oldman River near Brocket, 1966 - 1998

PARAMETERS ESTIMATED BY MOMENTS

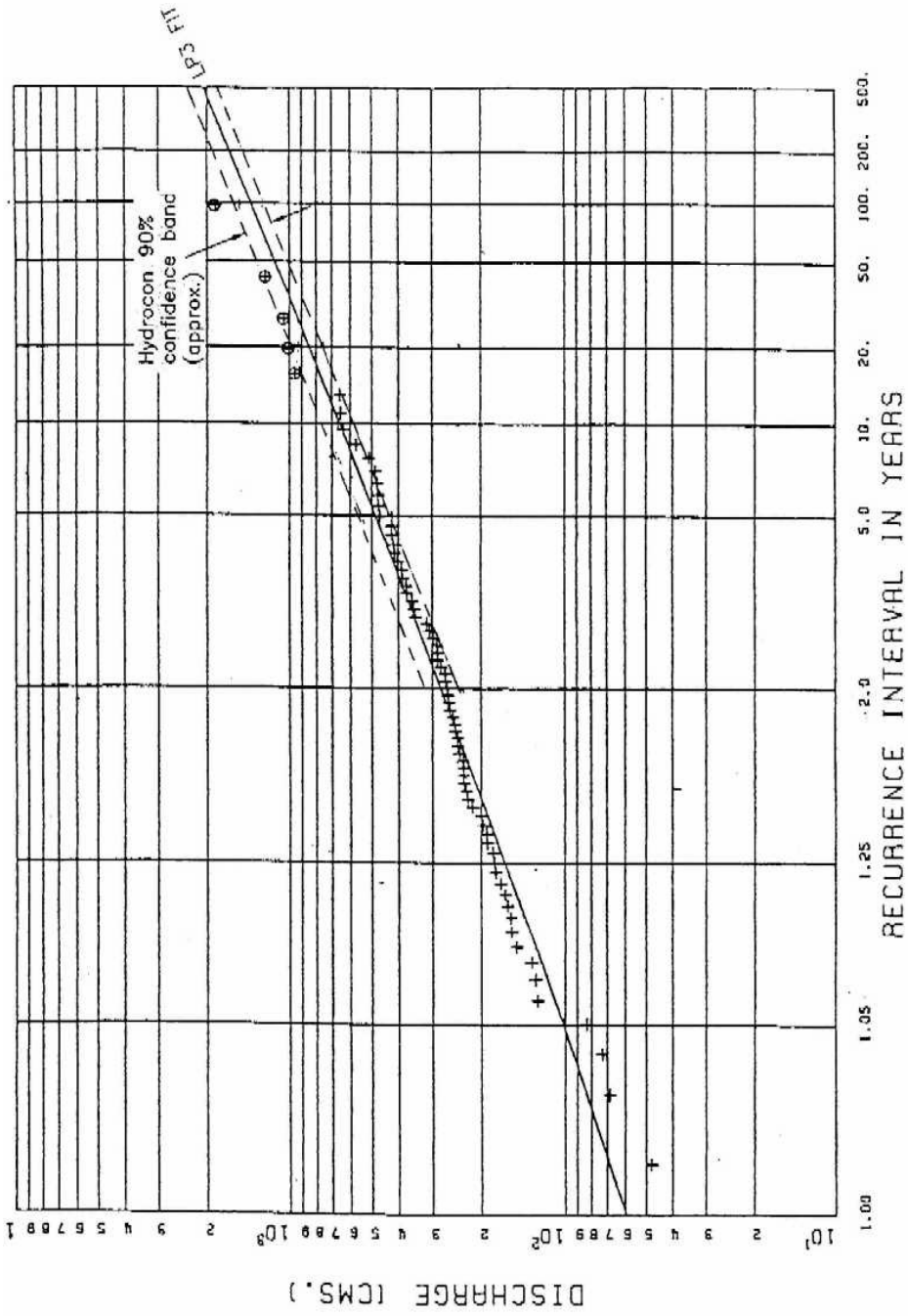


Figure 6.3 Hydrocon's flood frequency curve for Brocket extended daily series 1910 - 1984, with approx. confidence band. (Adopted P3 fit is only marginally different from LP3 as shown.)

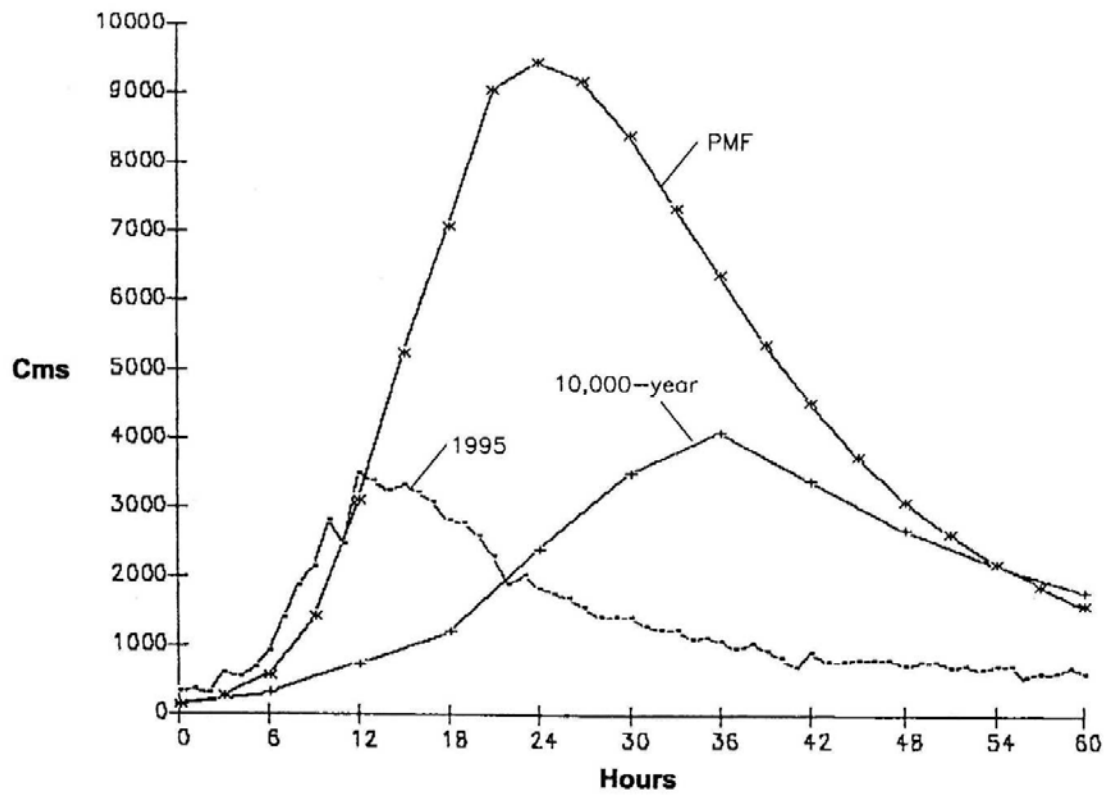


Figure 6.4 Reconstructed 1995 inflow hydrograph compared with pre-project 10,000-year and PMF

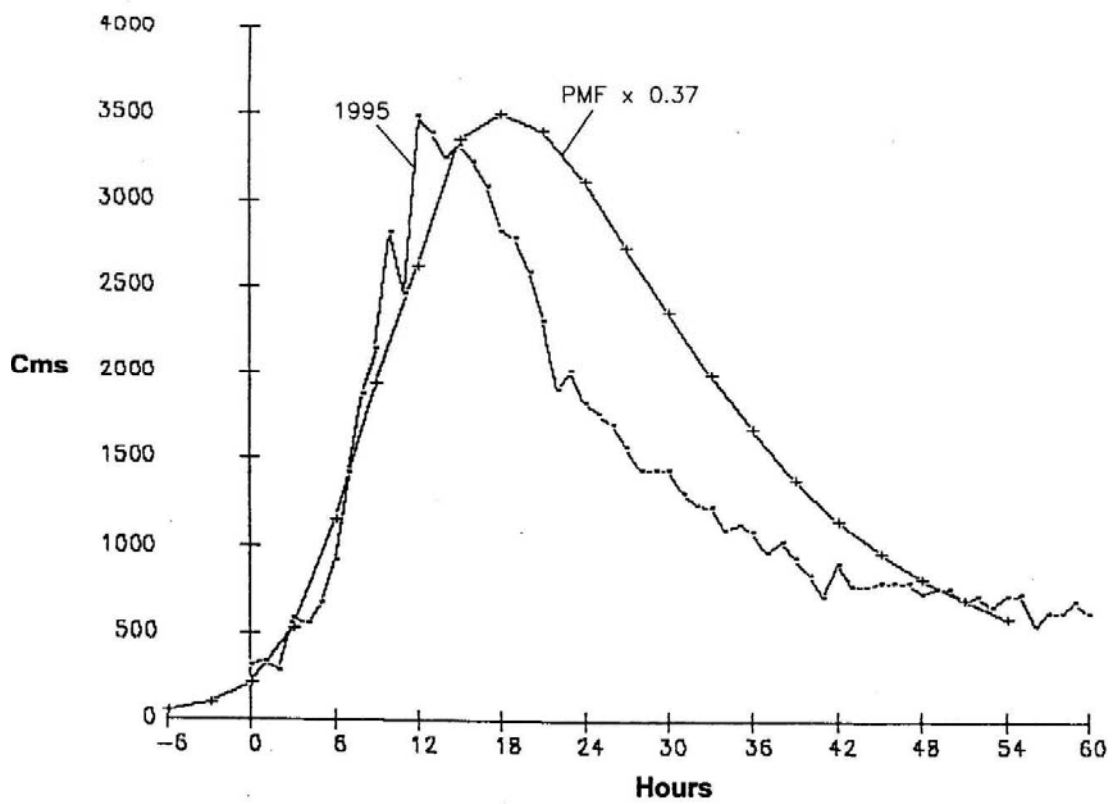


Figure 6.5 1995 hydrograph vs. scaled-down PMF

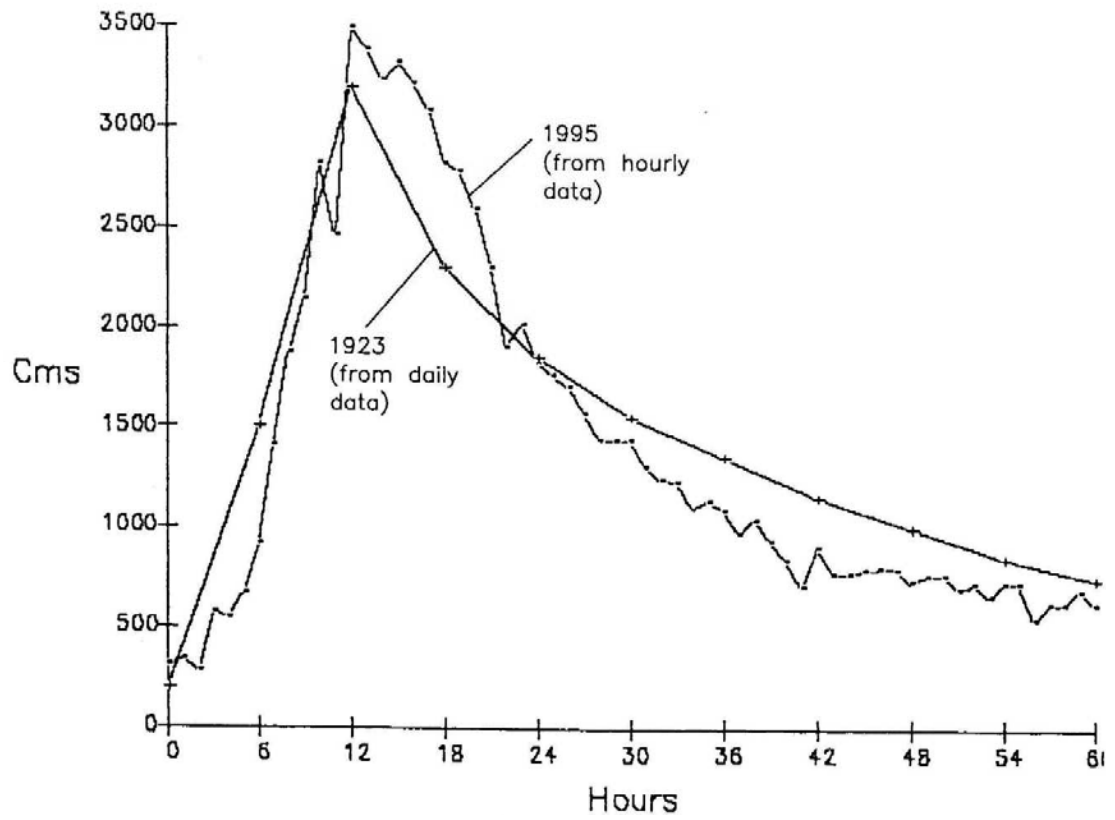


Figure 6.6 Reconstructed 1995 reservoir inflow vs. estimated 1923 at Fort Macleod

KEY POINTS AND OVERALL COMMENTS

Some key points about each of the cases reviewed are summarized below:

Case 1 - Willow Creek near Claresholm

1. Records from several gauging stations in the lower part of the basin can be combined with reasonable confidence to provide a nearly continuous flood record from 1910 to present. The larger events are reasonably distributed through the record period.
2. Despite the relatively long data series, a post-1995 estimate of the 100-year flood exceeded a pre-1995 estimate by about 45%. The discrepancy would not have been so large if the pre-1995 study had taken account of an unrecorded flood in 1932 that was probably the highest of record before 1995. A previous study of the nearby and similarly situated Highwood River had shown that its highest known flood - again not present in the gauge record - occurred in 1932.
3. Except for a few low events that may reflect regulation by headwaters storage, a partly-synthetic instantaneous peak series extending from 1910 to 1997 is well fitted by a 2-parameter log-Normal distribution (**Figure 1.3**).

Case 2 - Highwood River near High River

1. Records from two gauging stations near High River can be combined to provide a virtually continuous flood record from 1912 to present. The two highest floods in 1995 and 1932 are partly estimated. Except for the record 1995 event, most of the larger floods are in the first half of the record period.
2. Two flood-frequency studies by different groups in 1991 and 1992 led to significantly different estimates for long return periods.
3. There are indications that the Highwood River flood data may derive from two distinct populations.

Case 3 - Red Deer River at Drumheller

1. The gauge record at Drumheller has a 30-year gap, but a continuous upstream record at Red Deer can be used to provide a partly-synthetic flood series at Drumheller extending from 1913 to present. The seven highest floods are all in the first half of the record.
2. Two flood-frequency studies by different groups in 1996-97 led to controversy over estimates for long return periods. A review by a third group concluded that both estimates for the 1000-year flood were probably low.
3. Re-analysis of a partly-synthetic 1913-95 series produces a remarkably good fit to a 2-parameter log-Normal distribution (**Figure 3.2**).

Case 4 - Sawridge Creek near Slave Lake

1. The Environment Canada gauge record began in 1976 only, but for flood analysis purposes can be extended back to 1962 using crest-stage gauge data recorded by Alberta Environment. Rating curve measurements at the 1988 EC gauge location required separate computation and addition of bypass channel flows.
2. A design 100-year flood magnitude was first estimated in 1970, largely on the basis of data transfer from another basin. Flood-frequency analyses conducted in subsequent years using local data derived various estimates reasonably close to the original figure. Nevertheless, a record flood in 1988 overtopped flood control works that were supposed to accommodate the 100-year flood with substantial freeboard. Initial reported values for the peak discharge put it only 25% over the original 100-year estimate and made the overtopping of the works somewhat difficult to explain - although there were complications over debris blockage and freeboard deficiencies.
3. Detailed reviews of methods used to determine the 1988 flood magnitude revealed computational deficiencies and led to an increase of more than 50% in its accepted value, which seemed to place it well outside project criteria. Such findings indicate that reported values for extreme floods may not always be reliable, especially when the method of determination is somewhat indirect.
4. The record is too short and erratic for meaningful comment on fitting distributions.

Case 5 - Bow River at Calgary (above Elbow River)

1. The gauge record at Calgary extends from 1911 to present, and estimates are available for three previous historical floods going back to 1879 - all three being higher than any events after 1910. The nine highest known floods all occurred before 1934. The highest discharge recorded since 1933 is less than 25% of the highest historical peaks.
2. Considerable effort has been expended by a number of organizations to discover reasons for the peculiar Calgary record. Although storage volumes in the basin have gradually increased over the years, it has been shown that the effect on large peaks at Calgary is relatively small, since the latter result mainly from rainfall on areas below the reservoirs. The main factor put forward is the absence since 1933 of severe multi-day rainfalls on the Eastern Slopes within the Bow basin. One study suggests that the highest historical peaks may to some extent reflect widespread forest destruction by fire in the late 19th and early 20th centuries, but others do not support this viewpoint.
3. Although the non-stationarity of the Calgary record is visually evident and easily demonstrated statistically, some studies have fitted a single distribution to the whole record as if it met statistical criteria - a procedure that is generally regarded as contrary to good practice. One study constructed a composite frequency curve based on identifying two separate marginal distributions.
4. Determining a project flood for Calgary on the basis of frequency criteria poses severe difficulties because of the nature of the record. It may be more reasonable to specify an arbitrary value or a particular historical event. If frequency criteria are used, the non-homogeneity of the record should be recognized.

Case 6 - Oldman River near Brocket

1. Project flood frequency estimates were developed in 1985 using a 73-year series of daily maxima, the majority of which were synthesized for the Brocket station on the basis of upstream and downstream stations with longer records. In this 73-year series, the highest two daily values were 1865 m³/s in 1923, and 1220 m³/s in 1975. Estimates were developed for return periods of up to 10,000 years on the basis of an extrapolated Pearson Type III distribution (not logarithmic) as fitted to the data. Instantaneous peaks were estimated as 1.25 x daily maxima for all return periods. To indicate uncertainty, 90% confidence limits were quoted, but their derivation was not explained and their range seems remarkably narrow.

2. Flood hydrographs for return periods up to 10,000 years were modelled basically on the flood of 1975 (the only large event for which hourly flow data could be developed), with some adjustment to match volumes as given by frequency analyses of the latter. Time to peak from start of rise was approximately 36 hours. A PMF hydrograph developed by a different organization showed a time to peak of approximately 24 hours only.

3. A new record flood occurred in 1995, after completion of the Oldman River Dam upstream of the Brocket station. As reconstructed from reservoir operational data, this flood was the highest since 1910 or earlier. The estimated maximum daily value was about 10% higher than in 1923, and the estimated peak instantaneous value would have been assigned a return period of over 2000 years using the pre-project frequency analysis of 1985. The time to peak was only about 12 hours.

Overall comments

1. Many flood records in Alberta exhibit a high degree of statistical variability and/or a high degree of irregularity in their time series. The results of a flood frequency analysis may depend greatly on the particular period of years that is available for analysis. An extreme example is the Bow River at Calgary; in this case, separate analyses using the pre-1934 and post-1933 periods would produce huge differences.
2. In conducting flood frequency analyses for a particular station, it may be advisable to expend considerable effort on scrutinizing the data and possibly extending the series by reasonable means - such as use of other stations on the stream or in nearby basins subject to the same meteorological events.
3. Broken records pose particular problems, especially where the unrecorded period may have included one or more notable floods or even the highest flood of record. It may be misleading to combine the separate parts into a consolidated series without considering the likely magnitude of the missing events.
4. In some cases, the question of which fitting distribution to adopt may make a considerable difference to flood-frequency estimates. In such cases, it seems advisable to adopt the simplest distribution that will give a reasonable fit - that is, a 2-parameter distribution, often log-Normal - and to lean towards higher rather than lower estimates for long return periods. The use of 3-parameter distributions should be approached with caution, since the reliability of skew coefficients derived from short records is generally low. Fitting curves that are strongly concave-down on a log-probability grid, implying a strong negative skew in the log-transformed data, should be viewed with suspicion.
5. In other cases, the question of fitting distributions pales into insignificance compared to other issues like data reliability, period of record, and time series irregularity. Where the series exhibits severe irregularities - the Bow at Calgary being an extreme case - the associated meteorological and basin conditions should be investigated.
6. There may be strong indications for caution and review when estimates for long return periods have in fact been exceeded or approached in the data record. It may be good practice in some cases to use the flood of record for design, if it exceeds the estimate for the designated return period.

7. When developing hydrographs to be associated with flood frequency estimates for project purposes, consideration should be given to the variability of time to peak and hydrograph shape. Where insufficient station data are available to indicate worst-case conditions, it may be advisable to examine data from other stations with similar hydrologic characteristics, as well as PMF or other hydrographs developed by runoff modelling. In some basins, it may be necessary to consider snowmelt and rainfall hydrographs separately.

8. Reports on flood frequency studies should include (1) complete data tables, (2) consideration of statistical tests on the data, (3) comparisons of predictions based on different distributions and fitting methods, (4) plots showing both data and fitting curves, preferably on log-probability grids, and (5) consideration of confidence/reliability issues. Many of the studies reviewed fell short of these requirements, making independent review of recommendations difficult without additional analysis.