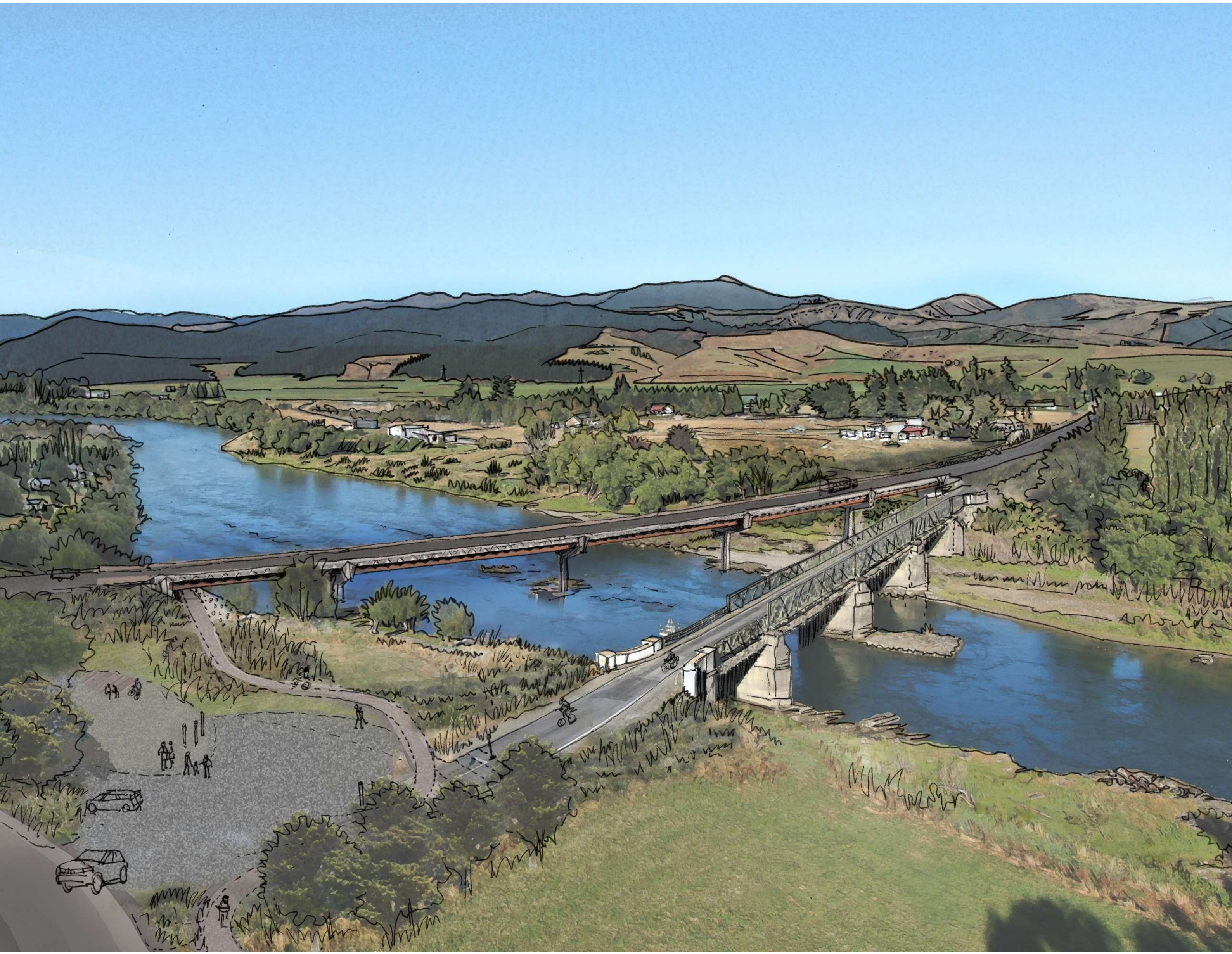
New Beaumont Bridge

Hydrological Assessment



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Contents

Document History and Status

Revision	Date	Author	Reviewed by	Approved by	Status
1	August 2018	Sheryl Paine	Jack McConchie	Mike Davies	First Issue
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Revision Details

Revision	Details
1	First issue of the document
2	Updated climate change adjustments based on MfE 2016 Climate Effects projections for Otago region
3	Updated flow design to include Q_{1000} based on Bridge Manual Amendment 3. Updated climate change based on MfE 2018 update.

1 Introduction

The SH8 Beaumont Bridge across the Clutha River is to be replaced by NZTA. To support the design and construction of the replacement bridge, the peak discharges and flood hydrographs for a range of design events, including the potential effects of climate change, were determined.

The Beaumont Bridge is located near the town of Beaumont, below the Roxburgh Dam in the Clutha catchment. The Roxburgh Dam is currently operated by Contact Energy Ltd. The Clutha River discharges into the Pacific Ocean, just downstream of the town of Balclutha (Figure 1.1).

The Teviot River is the only significant inflow to the Clutha River between Roxburgh Dam and the Beaumont Bridge. There is one other significant inflow between the Beaumont Bridge and the coast; the Pomahaka River.

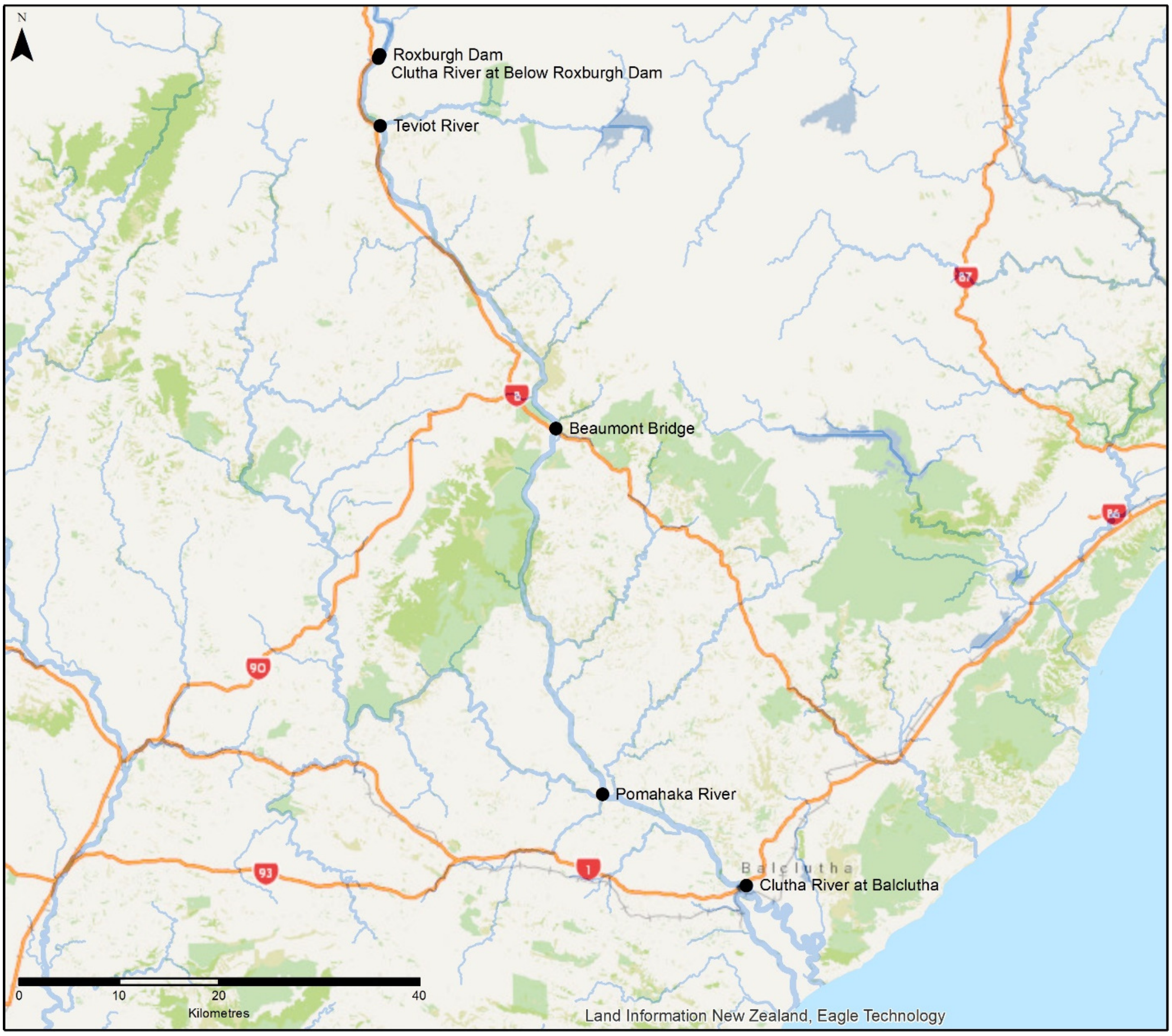

Figure 1.1 Location of the Beaumont Bridge, Roxburgh Dam, and flow sites of relevance.

2 Hydrological Analysis

2.1 Flow data

To complete this analysis, several flow monitoring sites were investigated (Table 2.1). Otago Regional Council (ORC) maintain flow sites at several locations within the Clutha catchment; including at Balclutha, and on the Teviot and Pomahaka Rivers. Contact Energy Ltd hold data for the Total Discharge from Roxburgh Dam, and flow in the Clutha River approximately 2km downstream of the dam. Contact Energy have given permission to use these data.

Therefore, while there is no flow data for the Clutha River at the Beaumont Bridge, there are records on the Clutha River near the Roxburgh Dam and at Balclutha towards the coast (Figure 2.1).

Table 2.1 Flow sites on the Clutha River.

Name	Start date	End Date	Gaps (days)	Time-step
Clutha at Balclutha	6 Jul 1954	31 May 2018	138	15-min
Pomahaka at Burkes Ford	4 Aug 1961	24 May 2018	723	15-min
Teviot at Bridge Hut Road	16 Mar 1994	27 Oct 2004	181	15-min
Clutha at Below Roxburgh Dam	28 Mar 2001	26-Apr-2018	2.5	15-min
Roxburgh PS at Total Discharge	1 Aug 1965	1-Jun-2018	0	3-hourly

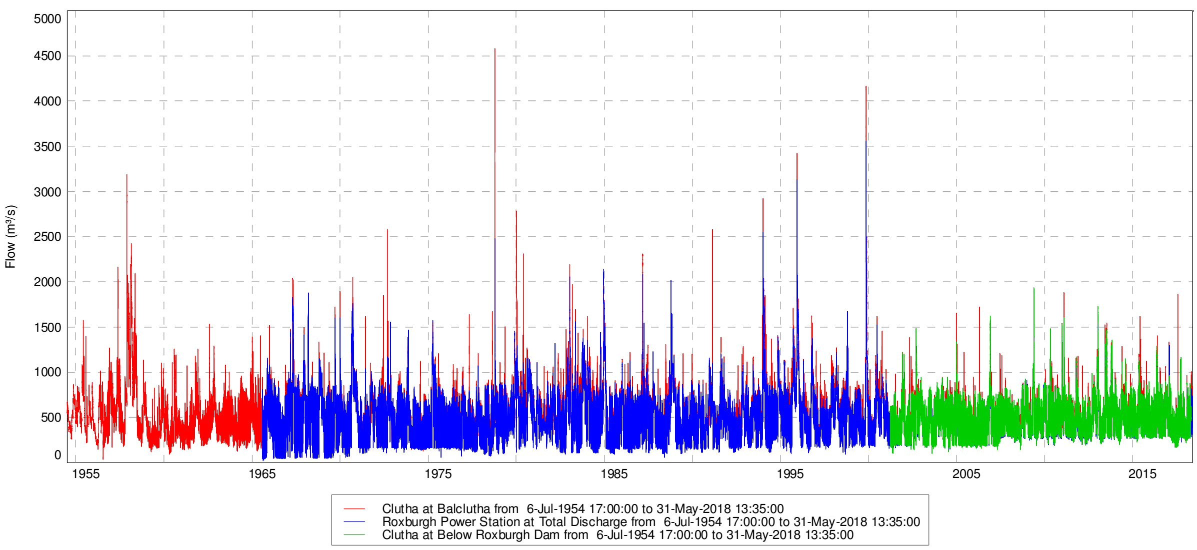

Figure 2.1 Comparison of the three flow records for the Clutha River.

Flows in the Clutha River have been modified by the Roxburgh Dam since it was commissioned in 1956, and the Clyde Dam since 1992. While the dams have a significant effect on the overall flow regime and flow duration curve of the Clutha River downstream, they have less effect on the frequency and magnitude of large flood events. The flood signature of the Clutha River appears to be largely unaffected by dam construction (Figure 2.1).

Since it is the furthest downstream, the Roxburgh Dam is likely to have the greater influence on the frequency and magnitude of floods experienced in the lower river i.e. near Beaumont. However, since any effects of the Roxburgh Dam have apparent since at least 1956, those effects are inherent in the instrumental flow records further downstream. Any effects of the dam are therefore included in any analysis of the annual flood maxima. This is appropriate since these effects are likely to also persist into the future.

2.2 Flow analysis

Since there is no flow gauge near the Beaumont Bridge, the flows at both Roxburgh Dam and Balclutha were investigated to determine their suitability for estimating the flows at Beaumont Bridge. Several flood events, when all three records could be compared, were analysed; 2013, 2009 and 2006 (Figure 2.2, Figure 2.3 & Figure 2.4).

These figures show that the Total Discharge from Roxburgh Dam and the Clutha River Below Roxburgh Dam records are very similar, as expected. The Total Discharge record is 'smoothed' as it is a 3-hour average, whereas the Below Roxburgh Dam gauge records instantaneous flows at 15-min intervals. The Balclutha record, also 15-min data, shows a similar pattern to those sites upstream, but is lagged by ~12-hours.

While the Balclutha recorder is much further downstream, with a 25% larger catchment area, the flows are similar to those upstream at Roxburgh Dam. Both the 1995 and 1999 floods show that the flows at Balclutha were ~10-15% larger than at Roxburgh Dam. This pattern is observed in many of the flood flows, but not all.

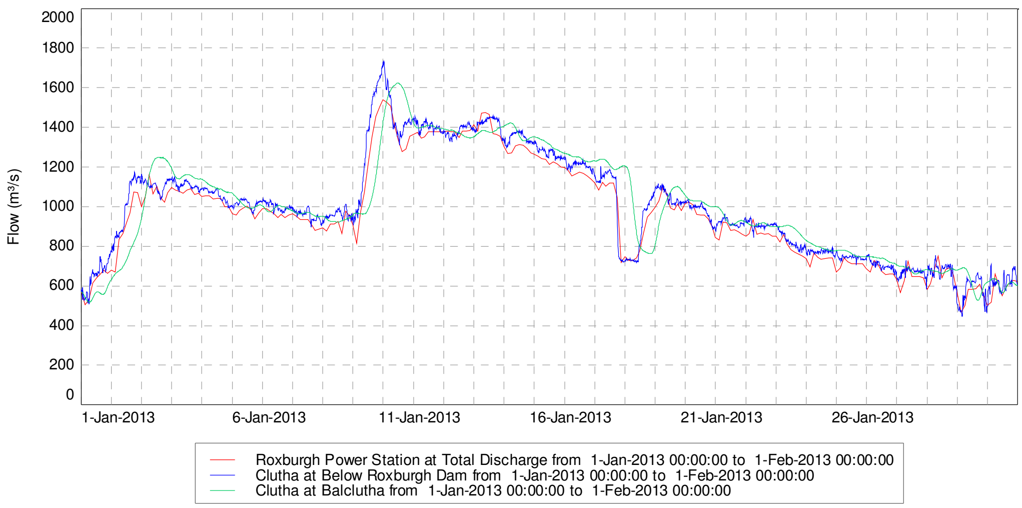

Figure 2.2 January 2013 flood. Comparison of the dam outflow, Clutha River below Roxburgh Dam, and the Clutha River at Balclutha.

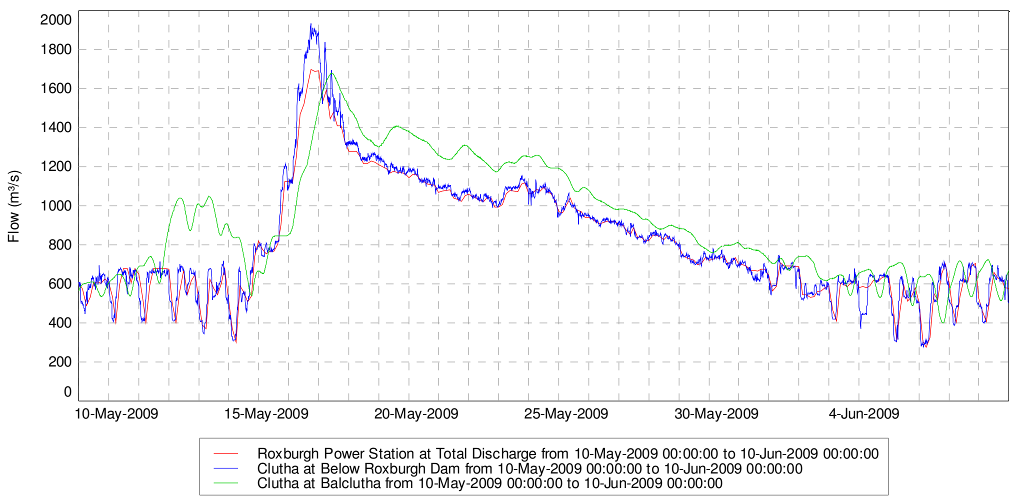

Figure 2.3 May 2009 flood.

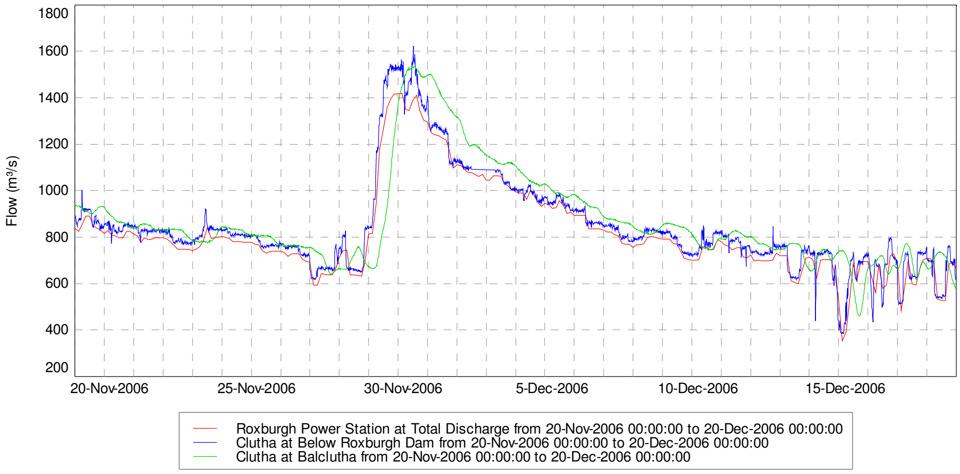

Figure 2.4 November 2006 flood.

It is therefore suggested that the Clutha River at Balclutha flow record be used to estimate flows at Beaumont Bridge, with no scale factor applied to account for the difference in catchment area. While this may over-estimate some flood peaks, because of the difference in catchment area, any difference in flow between the two locations is likely to be within the uncertainty of the flow measurement; especially during large flood events.

The current Beaumont Bridge is 134 years old and has therefore passed flows larger than 4000m³/s safely.

2.3 Frequency analysis

An analysis of the annual flood maxima series was undertaken to determine the magnitude and frequency of the various design events. The frequency analysis was undertaken on the annual flood maxima series derived from the entire length of record. Three types of statistical distribution were assessed for how well they modelled the actual annual flow maxima series (i.e. Gumbel, Pearson 3 (PE3) and GEV). The distribution which provided the best fit to the annual maxima series was then used to estimate flows of design floods with specific annual exceedance probabilities (i.e. AEPs) or average recurrence intervals (i.e. ARIs).

As is standard practice, the frequency analyses were performed on a 12-month partition. That is, only the largest flood in each year was plotted, and the most appropriate statistical distribution fitted to those annual values. It is sometimes difficult to find a single statistical distribution that provides a robust model of the annual maxima series. In these situations, some subjectivity is required in selecting the most appropriate model. The criteria adopted in this study were:

- The distribution that provided the best-fit through all the flood maxima;
- The distribution with the most realistic shape; and
- The distribution that provides the closest approximation to the extreme floods.

While this process may appear subjective, in most cases the choice of a specific statistical distribution for the annual maxima series results in relatively minor differences in the estimated flow-frequency table.

Using this approach, the 50%, 20%, 10%, 2% and 1% AEP design flows were estimated from the Clutha at Balclutha flow record; assuming a PE3 distribution (Table 2.2). The corresponding frequency distribution is contained in Appendix A.

Table 2.2 Flood estimates for various design storm events.

ARI (yr.)	AEP (%)	Flow (m^3/s)
2.33	50	1,580
5	20	2,130
10	10	2,630
20	5	3,140
50	2	3,810
100	1	4,320

The reliability of design flood estimates is a function of the length of flow record used in the analysis, and the appropriateness of the flow record to a particular flood model. As a rule of thumb, AEPs should not be extrapolated beyond twice the length of the annual flood maxima series (Davie, 2008). NIWA, however, use a general rule of thumb of five times the length of the maxima series. Uncertainty of the design flood estimates increases rapidly with more extreme events i.e. <1% AEP; therefore, the estimation of the extreme flows has large inherent uncertainties.

2.4 Estimation of the Q_{1000}

A recent amendment of the NZTA Bridge Manual (NZTA, 2018) lowered the design criteria for the replacement Beaumont Bridge, from an estimate of the likely magnitude of the 0.04% AEP event; i.e. the 2500-year design flood (Q_{2500}), to that of a 0.1% AEP event (the 1000-year design flood – Q_{1000}). As the Q_{2500} event had already been calculated, this report is updated to provide the Q_{1000} flood.

The Q_{1000} flood is the 'Ultimate Limit State' event defined in the NZTA Bridge Manual (3rd Edition, 2018) for permanent bridges on the State Highway Network that are classified as Arterial (such as the Beaumont SH8 Bridge). A lesser ULS standard is applied to bridges of lower importance. The ULS is the magnitude of the flood event under which bridge '*collapse shall be avoided*' (Section 2.3.2e); however, the bridge can be overtopped.

It is worth remembering that an extreme rainfall event (i.e. R_{1000}) does not necessarily generate a Q_{1000} flood event. Therefore, Q_{1000} flood events should be estimated from an instrumental flow record; rather than an extrapolated rainfall record, and an assumed rainfall-runoff relationship.

Extrapolating the results from the Clutha at Balclutha annual flood maxima series allows an estimate of the possible magnitude of the Q_{1000} event i.e. 5,850 (Figure 2.5), based on the GEV distribution. The Q_{2500} flow event previous determined was 6,500 m^3/s.

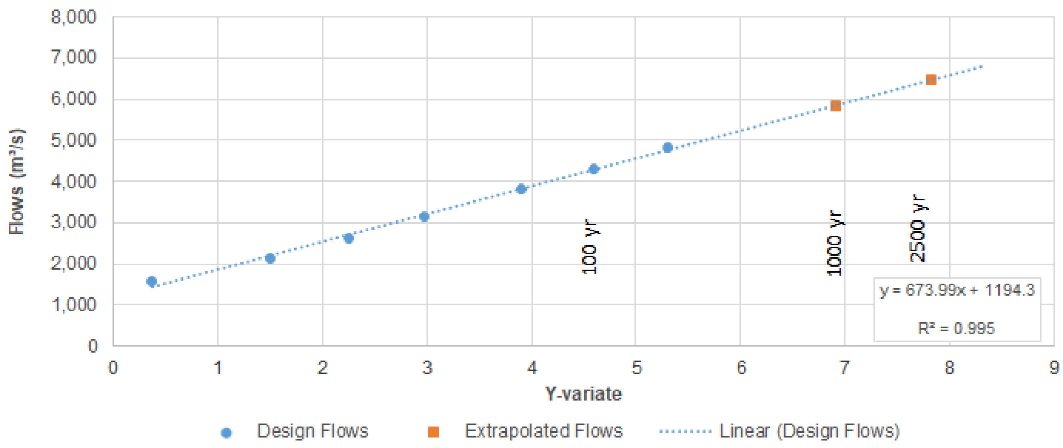

Figure 2.5 Estimation of the Q_{1000} flood event.

Although the NZTA Bridge Manual requires the magnitude of the Q_{1000} flow as an 'Ultimate Limit State' event to be estimated, the actual relevance of a flood of this magnitude in the Clutha River at the Beaumont Bridge, needs to be considered carefully. For example:

- Whether the design flood remains within the channel. In most situations, a Q_{1000} flow will include a significant overbank component. It is critical that the relevance and significance of both the 'in-channel' and 'out of channel' components of flow are considered from design and bridge safety perspectives;

- The size of the channel to be bridged. If the river is incised, then once the river banks have been overtopped the flood water will spread across the floodplain. If the extreme design flow does not remain in the channel, any scour estimates based on the total flow are likely to be misleading; and

- The nature of the topography upstream of the bridge.

Understanding the 'hydrological' context of the proposed bridge crossing, as well as the uncertainty inherent in any design flood estimation, are therefore critical considerations.

This is particularly the situation with the Clutha River. Since the river is incised only a relatively short depth below the adjacent floodplain, water will start 'leaving the channel' during extreme flood events. It is likely that during a 1% AEP flood, a significant portion of the flood will be 'out of the channel', and inundating the adjacent floodplain rather than affecting the bridge.

Rather than estimating the total design flow from the catchment, and assuming this will all pass through/under the proposed bridge, it would be better to determine the actual capacity of the channel, and the nature of the passage of flood-waters past the site. Scour protection can then be designed to mitigate the energy of these flows, rather than the total runoff from the entire upstream catchment.

2.5 Hydrographs

The expected design flood hydrograph is also required to support the design and construction of the Beaumont Bridge. For this study, the five largest floods from each of the three flow records were 'normalised', and then compared (Appendix B). The 'normalisation' process scales the hydrographs as a function of both time and peak discharge. This allows the direct comparison of the hydrograph shapes (Figure 2.6).

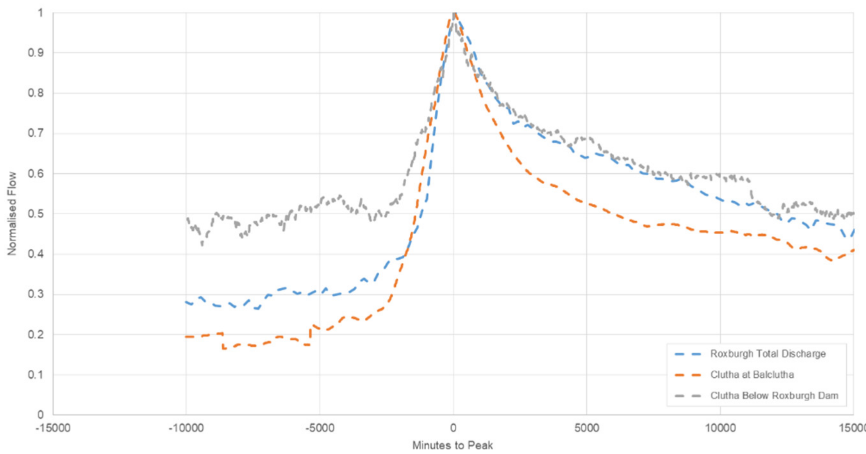

Figure 2.6 Comparison of the average normalised hydrographs for the three sites on the Clutha River.

Figure 2.6 shows that, while the average hydrographs for each site are different, they all approximate the same general shape. It is therefore suggested that the 'normalised' Clutha at Balclutha hydrograph be used to represent design floods at Beaumont Bridge.

3 Climate change

If predicted global warming eventuates, it may cause more than just a rise in the world's temperature. Warmer temperatures mean that more water vapour will enter the atmosphere, while also increasing the air's ability to hold moisture. Furthermore, sensitivity analysis has indicated that changes in rainfall are often amplified in runoff.

The Ministry for the Environment (MfE) have released climate change predictions for New Zealand (NZ) based on the IPCC 5th Assessment (MfE, 2016). For the IPCC 5th Assessment, a new set of four forcing scenarios was developed, known as representative concentration pathways (RCPs). These pathways are identified by their approximate total (accumulated) radiative forcing by 2100, relative to 1750.

These RCPs include; one mitigation pathway (RCP2.6) which requires removal of some of the CO_2 presently in the atmosphere, two stabilisation pathways (RCP4.5 and RCP6.0), and one pathway (essentially 'business as usual') with very high greenhouse gas concentrations by 2100 and beyond.

The ensembled average temperature increase for each of these scenarios is 0.7 °C, 1.4 °C, 1.8 °C and 3.0 °C by 2090 for NZ, but the results vary slightly for individual regions.

In 2018, MfE released a revision of the 2016 prediction report (MfE 2018). This revision is the same as the original report, except for the incorporation of results relating to very extreme rainfall – the "HIRDS" report (Carey-Smith *et al.*, 2018). That report updated "augmentation factors" for deriving extreme rainfall depths from future increases in temperature. These augmentation factors differ to those presented in earlier reports.

The HIRDs study used 6 of the Global Climate Models (GCMs) used for the IPCC future predictions of the 4 RCPs, for further downscaling to higher resolution Regional Climate Models (RCMs) for NZ. Results from these RCMs were used to the determine the rainfall augmentation factors which vary based on storm duration and ARI (*Table* 3-1), and future NZ temperatures increases (Table 3-2). It is important that the two tables are used in conjunction to each other.

Table 3-1: Percent increase in rainfall expected from 1°C increase in temperature. Most likely change shown on top line and the range provided in brackets. Values derived based on RCM results across NZ. Source: Table 13, MfE 2018.

Duration	ARI 50-year	ARI 100-year
24-hour	8.4 (5.1 - 12.5)	8.6 (5.2 - 12.8)
48-hour	7.4 (3.4 – 11.4)	7.5 (3.5 – 11.5)
72-hour	6.8 (2.9 – 11.1)	6.9 (2.9 - 11.2)
96-hour	6.4 (2.6 – 11.0)	6.5 (2.7 - 11.2)

Table 3-2: Projected increases in mean annual temperature by 2040, 2090, and 2110 for NZ (Source: Table 14, MfE, 2018). Extrapolated values for 2070 and 2120 are shaded.

Scenario	2040 (°C)	2090 (°C)	2110 (°C)	2070 (°C)	2120 (°C)
RCP2.6	0.59	0.59	0.59	0.6	0.6
RCP4.5	0.74	1.21	1.44	1.0	1.6
RCP6.0	0.68	1.63	2.31	1.2	2.6
RCP8.5	0.85	2.58	3.13	1.9	3.4

Note: The data in the first 3 columns are from Tables 14 in Ministry for the Environment (2018). The shaded values are extrapolated from the MfE tabulated data. The MfE table cover the projected mean temperature change between 1986-2005 and the periods 2031-2050 (2040), 2081-2100 (2090) and 2101-2120 (2110). They are the average of the 6 RCM model simulations (driven by different GCM).

The direct effect of global warming on runoff, and particularly flooding, has not been quantified. Since interest is generally in extreme events, when catchment storage is approaching saturation, it is assumed that an increase in rainfall will produce a similar increase in runoff.

The percentage increases in temperature (Table 3-2) are relative to the base period being 1986-2005 (1995). To provide the necessary level of service incorporating 50-year and 100-year adjustments for climate change, the required timeframes are now 2070 and 2120 respectively.

The rainfall augmentation factors vary based on storm duration and return. There has been no direct analysis of (rainfall) storm duration. However, from the analysis of observed flood events on the Clutha River (Figure 2-6 and Section 2.2), the time to peak ranges from 24 to 72 hours. Accounting for attenuation of the flood due to the size and storage available in the catchment, we can assume a storm duration ranges between 24 and 96 hours duration. Therefore, a rainfall augmentation factor of 8% (*Table* 3-1) was adopted.

Assuming the higher mitigation pathway of RCP6.0, with a New Zealand RCM predicted increase in temperature of 1.2°C by 2070 and 2.6°C by 2120 (Table 3-2), the 50-year and 100-year Clutha flow adjustment is 10% and 21% respectively (Table 3-3). The corresponding adjustment based on RCP8.5 is 15% and 27%.

Table 3-3: Climate change percent adjustments to rainfall (and flow) based on RCP6.0 and using an 10% increase in rainfall per degree of projected temperature increase.

Scenario	2070 (%)	2120 (%)
RCP2.6	5	5
RCP4.5	8	13
RCP6.0	10	21
RCP8.5	15	27

Table 3.4 illustrates the 50-year and 100-year RCP6.5 climate change adjustments. However, adjustments of the 2018 peak flow to allow for other climate change scenarios can be easily assessed. This can be done by: Identifying the desired scenario climate change adjustment from Table 3-3; and then using this new value to scale the 2018 design flood estimate.

Table 3.4 Design flood estimates adjusted for climate change (m³/s) based on RCP6.0 and a 8% increase in rainfall per 1 degree increase in projected temperature. Values are rounded to the nearest 50 m³/s

ARI (yr.)	AEP (%)	2018	2070	2120
50	2	3,810	4200	4600
100	1	4,320	4750	5250
1000	0.1	5,850	6,450	7,100
2500	0.04	6,500	7150	7850

4 Low flow analysis

It is possible that some construction activities would be facilitated by low flows in the Clutha River. Therefore, an analysis of the low flows at Beaumont Bridge was undertaken. This was to determine the seasonality of the flow series i.e. the times throughout the year when the lowest flows would be expected, and the diurnal pattern of river flow caused by management of Roxburgh Dam.

As for the previous analysis, the Clutha at Balclutha flow site was used for the low flow analysis. The summary statistics for Clutha at Balclutha are displayed in Table 4.1. Flows have been as low as 37m³/s, but the mean and median flows are 572m³/s and 532m³/s respectively.

Table 4.1 Summary statistics of Clutha at Balclutha (1954-2018). Flows in m³/s.

Name	Min.	Mean	Median	Max.	L.Q.	U.Q.
Clutha at Balclutha	37.1	572.1	531.7	4581.3	398.8	690.8

To determine the seasonality of flows, the average monthly statistics were derived; along with the absolute minimum and maximum monthly values. This established the overall range of flows that could be experienced at the site (Table 4.2).

Table 4.2 Monthly summary statistics for Clutha at Balclutha flow dataset. In m³/s.

Month	Average Minimum	Average Mean	Average Maximum	Absolute Range (Min-Max)
January	329	628	1024	139-2921
February	272	526	871	133-2578
March	239	491	838	102-2309
April	245	490	826	99-2044
May	270	568	973	95-2163
June	297	595	1001	117-2314
July	258	522	908	37-1864
August	265	517	853	108-1679
September	282	543	895	113-2583
October	332	629	1023	109-4581
November	372	680	1043	122-4167
December	362	670	1045	159-3420

On average, the lowest flows occur in March and April i.e. autumn. The largest flows occur during spring and early summer; when flows are augmented by snow-melt from the upper catchment. Autumn tends to have lower flows, as temperatures and snowmelt decrease and rainfall is low.

On a daily scale, during these months i.e. March and April, the lowest flows at Balclutha occur in the early evening i.e. 19:00 (Figure 4.1). Flows begin to decrease quite rapidly from about 11:00, reach a minimum at about 18:00, and start to increase again from about 20:00.

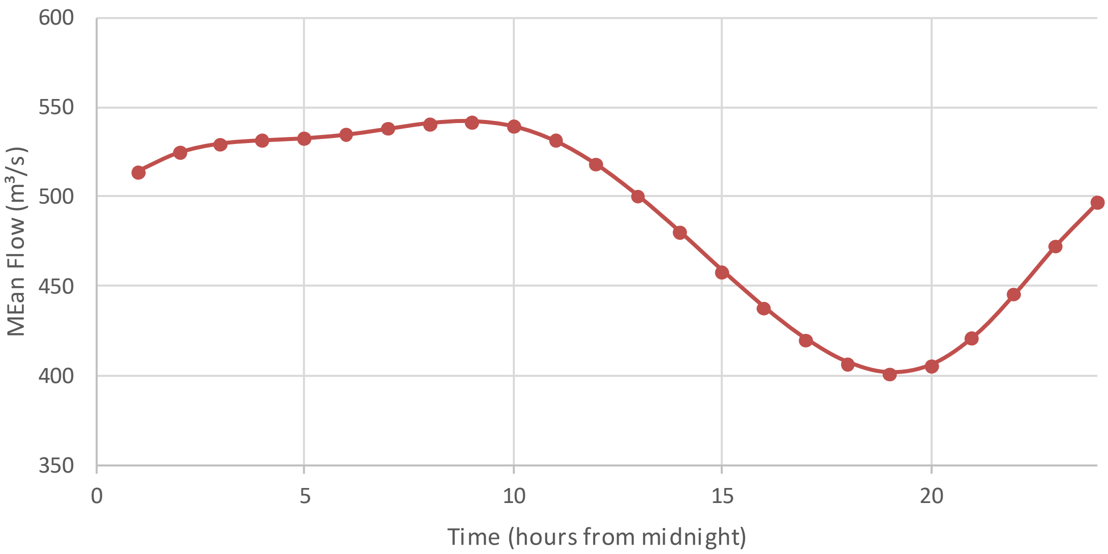

Figure 4.1 *Mean flows in March and April for Clutha at Balclutha based on flow record from 1954-2018.*

This pattern is a function of releases from Roxburgh Dam. While releases are greatest in the morning, there is an approximate 12-hour lag caused by travel time down the Clutha River to Balclutha.

The Beaumont Bridge is approximately 47km downstream of the Roxburgh Dam, and 60km upstream of Balclutha. This equates to a lag time of approximately 5.3 hours between Roxburgh Dam and the Beaumont Bridge; assuming an average flow velocity between the dam and Balclutha.

There is very limited data available currently relating to the diurnal pattern of flow, and therefore water level, variation near the Beaumont Bridge. Some limited data was collected over 3rd July 2018 by Elliot Sinclair. It is not known how representative these data are of the more general pattern of flow variability.

These data are compared with the total discharge from Roxburgh Power Station in Figure 4.2. The discharge from Roxburgh was lagged initially by 5.3 hours; however, this lag appears too long. A lag of 4.2 hours provides a better fit between the outflow from Roxburgh and changes in water level at Beaumont (Figure 4.2). This would be consistent with an expectation of a faster average velocity in the upper catchment.

Based on the limited data available, the lowest flows at Beaumont Bridge are likely to occur between 7am and 11am.

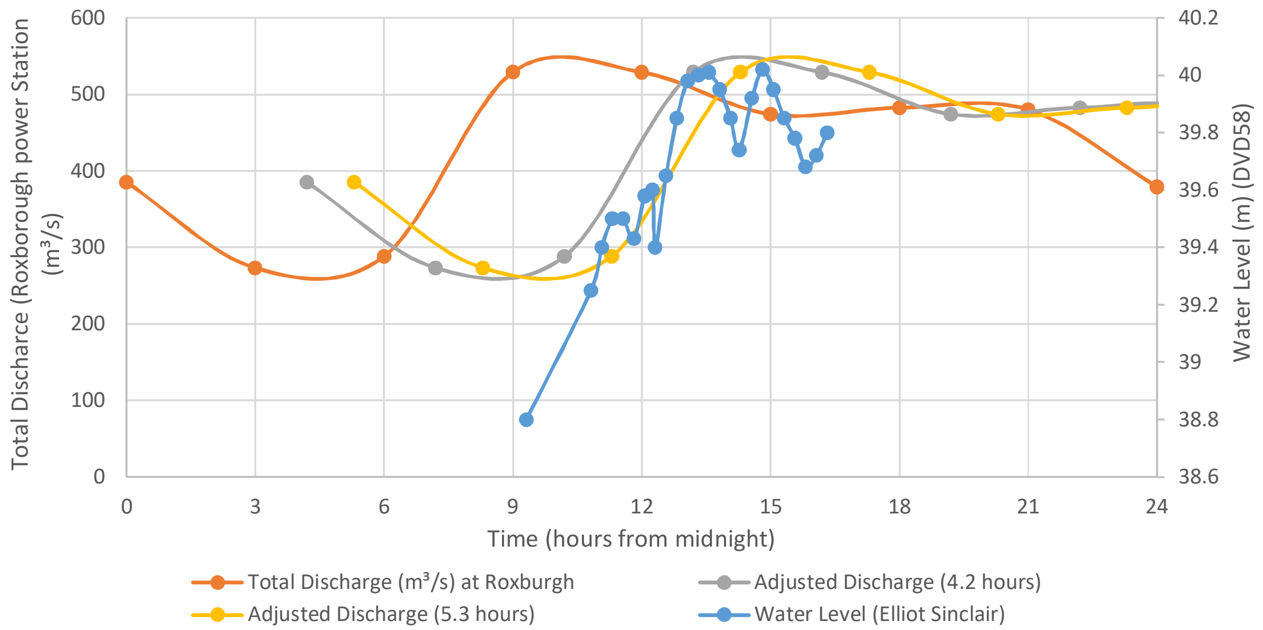

Figure 4.2: *Comparison of water levels at Beaumont and discharges from Roxburgh Power Station, lagged to allow for different travel times.*

5 Summary

The peak flows for a range of design events at Beaumont Bridge have been determined. A comparison of flows at Roxburgh Dam and Balclutha shows that the Clutha at Balclutha record is the best representation of those flows likely to be experienced at Beaumont Bridge.

A 1% AEP design event would be just over 4,300m³/s. This is likely to be slightly conservative i.e. high, because of inflows between Beaumont Bridge and Balclutha. The Q_{1000} design flow is expected to be 5,850m³/s.

Flows can be increased from current estimates by 10% and 21% respectively, to account for the potential effects of climate change out to 2070 (50-year) and 2120 (100-year).

Flows at Beaumont Bridge are likely to be lowest from 7am to 11am; although they start to decrease earlier. The optimum window from the perspective of 'expected low flows' is therefore likely to be in the early morning. This estimate, however, is based on very limited empirical data from Beaumont.

6 References

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Appendix A
Frequency analysis

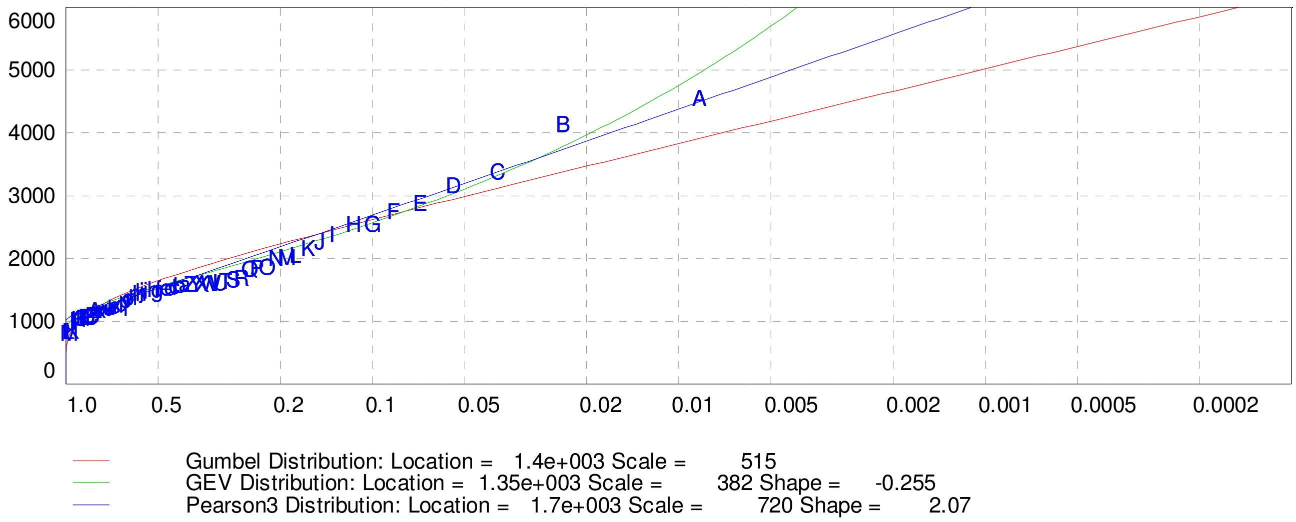

Figure 6.1 Frequency analysis of the Clutha at Balclutha flow record (1954-2018).

Appendix B
Normalised hydrographs

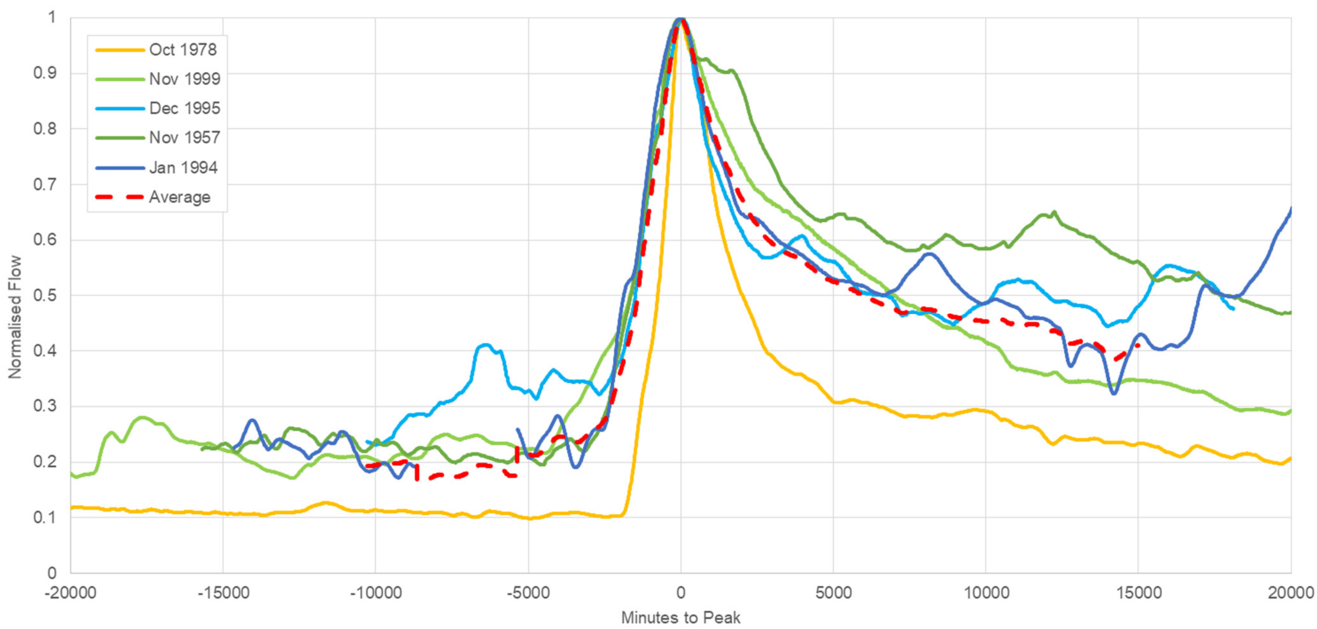

Figure 6.2 *Normalised hydrographs for the five largest events in the Clutha River at Balclutha.*

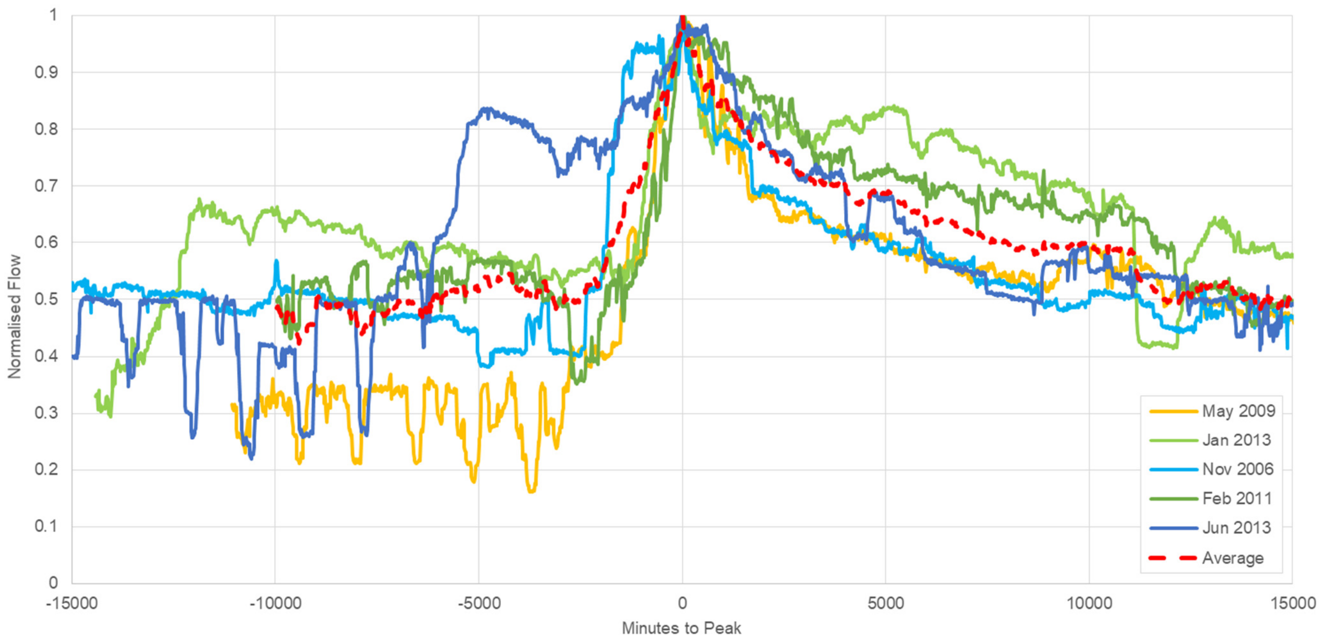

Figure 6.3 *Normalised hydrographs for the five the largest events in the Clutha River Below Roxburgh Dam.*

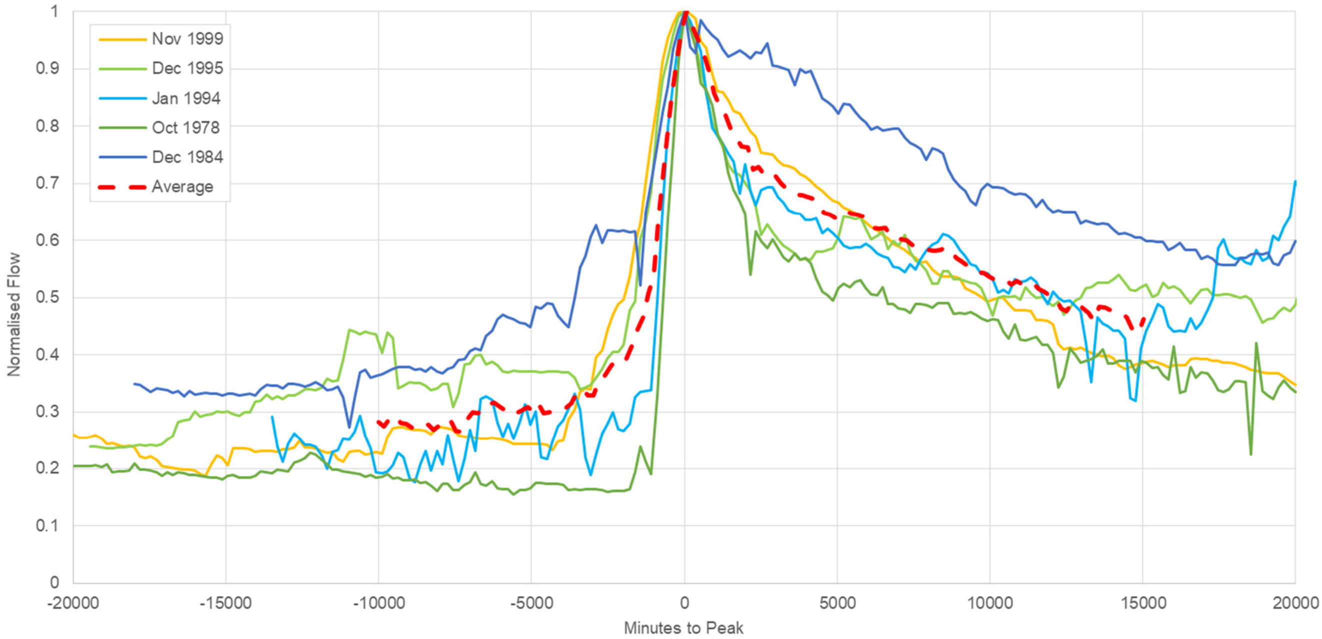

Figure 6.4 *Normalised hydrographs for the five the largest Total Discharge events at Roxburgh Power Station.*