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Envelope curves for extreme floods in New Zealand

George A. Griffiths, Shailesh Kumar Singh* and Alistair I. McKerchar
New Zealand Institute for Earth Science, Christchurch, New Zealand
**Corresponding author: shailesh.singh@niwa.co.nz*

Abstract

The construction of envelope curves bounding values of non-dimensional annual maximum flood peak magnitude is illustrated for regional, regional extreme value and at-a-site flood frequency relationships expressed in terms of return period. The curves are modelled by power laws and examples are given showing their derivation. They may be used to provide a reliable and rapid check on extreme flood peak estimates and in determining improved estimates of the return period of outliers in flood peak records.

An updated formula is given for predicting at-a-site non-dimensional flood peak magnitude as a function of both return period and the average annual number of floods. The formula applies to any site independent of hydrological region and may be employed to extrapolate flood frequency relationships and treat outliers.

Allowance for the effects of shifts in flood peak time series and human-induced climate change should be made when using the envelope curves and the predictive formulae developed in this study. Further work is needed to develop envelope curves for other hydrological regions and to apply the approach developed herein to annual maximum daily rainfalls.

Keywords

envelope curves; flood frequency estimation; extreme floods; design floods

Introduction

An envelope curve in flood hydrology is a smooth curve commonly bounding extreme measured or estimated values of annual maximum flood peak discharge, Q_p, on a plot of Q_p versus catchment area, A, or versus return period, T. Envelope curves are very useful in planning and design for checking that estimates of Q_p are of the correct order of magnitude (Maidment, 1992) or for prescribing, for example, a likely limit (based on experience) to the value of T for an outlier in a site record of values of Q_p, or indeed, a partial duration series of flood peak values. Their use has a long history in hydrology beginning, perhaps, with Jarvis (1926) and they have been employed most commonly for the relationship between Q_p and A.

Within New Zealand, Schnackenberg (1949) gives an envelope defined by:

$$Q_p = 352A^{0.5} \quad (1)$$

where Q_p is in m^3/s and A in km^2. Griffiths *et al.* (2019) updated this formula using data from 1950 to 2018 to yield the envelope curves:

$$Q_p = 400A^{0.43} \qquad A \geq 90 \text{ km}^2 \quad (2)$$
$$Q_p = 18A^{1.12} \qquad A < 90 \text{ km}^2 \quad (3)$$

In this study we construct envelope curves for non-dimensional flood peak discharge, Q_r, versus T. Q_r is equal to Q_p/Q_m where Q_m is the index flood (Hosking and Wallis, 1997) computed as the mean of annual maxima, that is, the mean annual flood recorded at a site. Q_m is a scaling factor and in New Zealand is proportional to catchment area to the power of 0.81 (McKerchar and Pearson, 1989). The use of Q_r allows site-specific calculation of T for given values of Q_p and Q_m. An envelope curve predicts, for given T, the Q_r values for the largest flood expected and, for given Q_r, the smallest values of T expected.

Three types of envelope curves are considered herein. In all three the envelope curve is determined by simply drawing a straight line on a logarithmic plot of Q_r versus T, which forms an upper bound to all values of Q_r. The first type applies to a regional curve fitted to all values of Q_r recorded at sites within an assumed hydrological region in the manner of Beable and McKerchar (1982). The second type, again for a hydrological region, applies to the most extreme values of Q_r generated by large cyclones and storms recorded during a known period (here, from the late 1860s) plotted as in the regional curve approach above. The third type applies at any individual site. For all types the value T for a given value of Q_r is estimated using the well-known (and most commonly used in flood frequency analysis in New Zealand) Gringorton plotting position (Gringorten, 1963):

$$T = \frac{n + 0.12}{i - 0.44} \qquad (4)$$

where n is the length of record in years and i is the flood rank value from 1 to N. Where site records are short and/or outliers are present, envelope construction can be supported by an empirical formula of the form $Q_r(m, T)$ based on relations given in Griffiths *et al.* (2019) in which m is the annual average number of a floods at site exceeding $0.5Q_m$. The parameter m largely eliminates the need to define homogeneous hydrological regions, so the formula is applicable at any site in New Zealand.

The purpose of this study is to determine easy-to-use methods of constructing envelope curves applicable in New Zealand. The aim is to provide designers and planners with a tool for readily checking estimates of a flood peak magnitude or return period, particularly for large values.

Data selection

Flood peak discharges for the period 1867 to 2023 for the North Island and 1877 to 2023 for the South Island were obtained from the New Zealand historical weather event catalogue (New Zealand Historical Weather Events Catalogue, 2025), Soil Conservation and Rivers Control Council (1957) (for 1920–1953) and from archives of Earth Sciences New Zealand and regional councils (Tables 1 and 2). These records are incomplete because the peak discharges resulting from large cyclones and storms have not all been measured owing to the limited number of sites, particularly in the early days, and recording instrument failures for various reasons. Calculation of Q_m values was also not possible at many sites because record length was too short (<10 years) to obtain an accurate result. Moreover, many Q_p values have large errors, some of the order of ± 30% (Griffiths and McKerchar, 2015) because they have been estimated by using methods such as slope area, surface velocity and hydrological and hydraulic modelling, as opposed to generally more accurately derived values determined from rating curves derived from standard open channel flow measurement at established recording sites on rivers and streams.

In assembling the data, a question that naturally arose was: what cyclone or storm generated a Q_r value with the largest return period since the 1860s? The answer, in our view, is the “Great Storm” of February 1868, which produced a massive flood in the Pahau River near Culverden in North Canterbury.

Table 1 – Extreme floods in the Hawke's Bay hydrological region (1867–2023).

River	Site	Site No	Year of Q_p	Flood peak, Q_p (m^3/s)	Mean annual flood, Q_m (m^3/s)	Dimensionless flood peak, Q_r
Tutaekuri	Puketapu	23032	2023	4800	618	7.77
Esk	Waipunga Bridge	22802	1938	1832	285	6.43
Wairoa	Railway Bridge	21415	1948	11443	2100	5.45
Tukituki	Red Bridge	23201	1897	5235	1490	3.51
Tukituki	Red Bridge	23201	1919	5663	1490	3.80
Waiau	Otoi	21409	2006	1565	371	4.22
Esk	Waipunga Bridge	22802	2018	1108	285	3.89
Tukipo	SH50	23220	2013	384	101	3.80
Tukituki	Red Bridge	23201	1893	4895	1490	3.29
Taurekaitai Str	Wallingford	24325	2004	563	179	3.15
Tukipo	SH50	23220	2022	319	101	3.16
Taurekaitai	Wallingford	24325	1988	553	179	3.09
Tukituki	Red Bridge	23201	1917	3964	1490	2.66

Table 2 – Extreme floods in the West Coast hydrological region (1877–2023).

River	Site	Site No	Year of Q_p	Flood peak, Q_p (m^3/s)	Mean annual flood, Q_m (m^3/s)	Dimensionless flood peak, Q_r
Ahaura	Gorge		2020	4047	1530	2.65
Ahaura	SH Bridge	91407	1957	2832	1320	2.15
Ahaura	SH Bridge	91407	1940	2517	1320	1.90
Haast	Roaring Billy	86802	1950	7277	3900	1.87
Buller	Te Kuha	93203	2021	8860	4870	1.82
Inangahua	Landing	93206	1975	2704	1540	1.76
Karamea	Gorge	95102	1914	3143	1960	1.60
Grey	Dobson	91401	1997	5950	3800	1.57
Buller	Te Kuha	93203	1993	7560	4870	1.55
Grey	Dobson	91401	2011	5890	3800	1.55
Grey	Dobson	91401	1988	5840	3800	1.54
Glenroy	Blicks	93217	1977	262	180	1.46
Grey	Dobson	91401	1940	5287	3800	1.39
Maruia	Falls	93209	1968	995	748	1.33
Grey	Dobson	91401	1970	4825	3800	1.27

Neither Q_r nor T is known for this event as no measurements of flood peak discharge were made. However, a remarkable account of the flood is given by Travers (1881) who journeyed through the area within a fortnight of the event. He noted that the Pahau, in ordinary floods, is rarely more than two or three hundred yards broad on the Culverden Plain but in the 1868 flood must have been upwards of two miles wide. This observation was mainly based on the location and size of siltation and timber deposits. Another massive flood occurred in 1923 but flooded Culverden to a much lesser degree. The daily rainfall for this event measured at nearby Emscote was 500 mm, some seven times the mean daily value for this rain gauge and having a return period of at least 300 years.

Analysis

Construction of envelope curves for a regional curve, regional extreme values and at a site is first described. Then, six examples of applications are presented, three each for the North Island and South Island within assumed homogenous hydrological regions.

Regional curve envelope

A regional curve is derived by compiling annual maximum values of Q_r and their corresponding T values for all sites in a region. The (Q_r, T) pairs will not be independent because a large cyclone or storm event will produce flooding in several rivers at the same time. The relationship between Q_r and T is then fitted by a flood frequency distribution – commonly in New Zealand an Extreme Value Type 1 or 2 (EV1, EV2) distribution (Hosking and Wallis, 1997) or a Kappa distribution (Kjeldsen *et al.*, 2017). The problem with this approach is that the data are often rather scattered with several values of Q_r for similar values of T and it may not be possible to draw a realistic envelope curve as some of the largest values of Q_r, even for small values of T, are outliers (as in Figure 1). One approach to solving this problem is to estimate more realistic values of T for the outliers using the empirical formula given as Equation 5 below.

Regional extremes envelope

For a given time period, the largest values of Q_r generated within a hydrological region by a large cyclone or storm event are compiled, one for each event recorded to ensure statistical independence of values. A plot of Q_r versus T is then made where T values for the period are estimated using the Gringorten plotting formula. This data can normally be fitted by a simple power law, which will differ from one region to another. An envelope curve can be readily drawn as an upper bound to the values of Q_r. The curve position is based upon a sample of Q_r values as the number of cyclones and storms not measured is unknown. The regional extremes relationship provides an overview and perspective of the maximum Q_r values that have occurred, and can be expected to occur again, and their relative frequency since the start of records (from the late 1860s). Moreover, as the record lengthens the maximum values of Q_r to date will almost certainly be exceeded.

Site envelope

For any New Zealand site, irrespective of hydrological region, Griffiths *et al.* (2019) present graphical relations of Q_r versus m with T as a parameter. We have updated these relations and they can be expressed by the simple empirical formula:

$$Q_r = E_f a m^{-b} \tag{5}$$

in which

$$a = 0.72T^{0.45} \tag{6}$$

and

$$b = 0.18 lnT - 0.22 \tag{7}$$

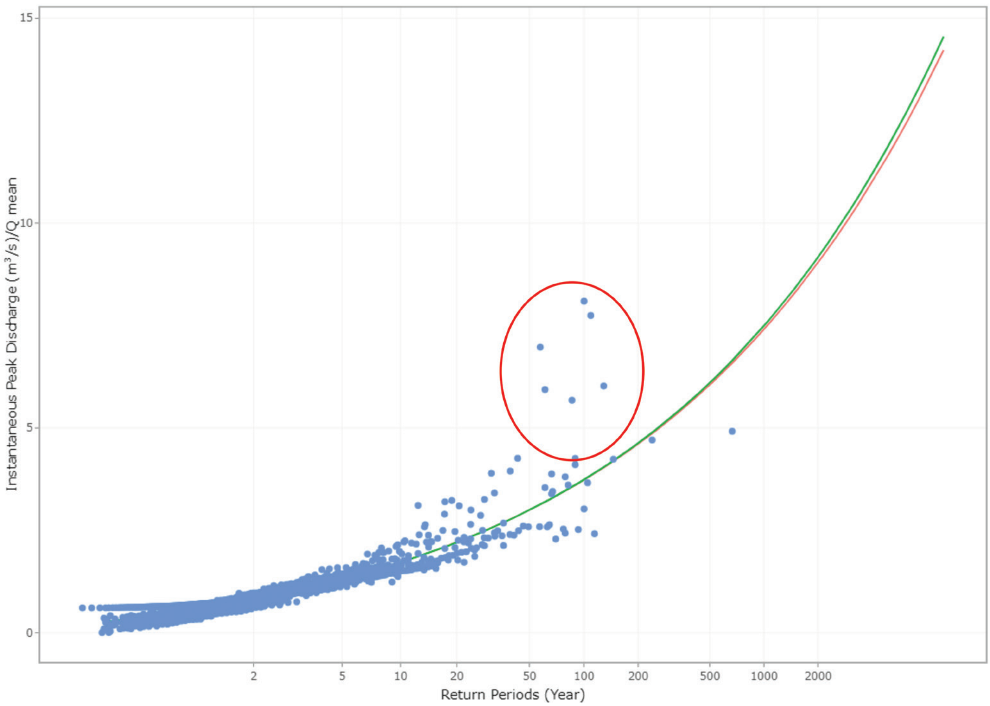

Figure 1 – Regional flood frequency curve for HBHR. Non-dimensional flood peak discharge (Q_r) versus return period (T) fitted by a Kappa (green) and GEV (red) distribution using L moments. Note the outliers where $Q_r > 5.70$ (red circle).

E_f is a coefficient to be chosen by the user solely or in a combination as an adjustment factor (see Example 3), safety factor (say 10–15% increase for freeboard in stopbank design) or an allowance for likely climate change effects (say 5–10% increase for 1-in-100-year flood peak by 2050). Equations 5 to 7 may, for given m (calculated from site data) and T, be solved directly for Q_r or, for given Q_r and m, iteratively for T. Equation 5 may be employed to extend Q_r versus T fits of site data and to estimate T values for outliers in this data. Again, an envelope curve can be readily drawn as an upper bound to the values of Q_r.

Example 1: Regional envelope (North Island)

The Hawkes Bay Hydrological Region (HBHR), as defined by the regional council boundary, was chosen as an example largely because of the comparative wealth of flood peak data available for the period 1867–2023 and previous analysis by Singh *et al.* (2024).

Figure 1 displays the regional flood frequency curve for this region with the flood peak data fitted by a four-parameter Kappa distribution using L moments. It is evident that a realistic envelope curve cannot be drawn bounding the large values because of the presence of outliers with values of $Q_r \geq 5.70$. These outliers occur mainly due to problematic estimates of corresponding T values from limited lengths of site record, sometimes less than 20 years. We used site data fitted generally by General Extreme Value curves using L moments (Hosking and Wallis, 1997) supported by predictions using Equations 5 to 7 to estimate more plausible values of T for the six outliers in Figure 1. With these adjusted values, and a logarithmic scale for Q_r values, a power law fit of the HBHR data is defined by:

$$Q_r = 0.74T^{0.37} \quad (8)$$

with $r^2 = 0.88$ and SE = 0.13 as shown in Figure 2, where r^2 is the coefficient of determination and SE is the standard error of the logarithms. A drawn envelope curve has the equation:

$$Q_r = 0.89T^{0.44} \quad (9)$$

Example 2: Regional extremes envelope (North Island)

Figure 3 is a plot of regional extreme values recorded over 157 years (Table 1). A power law fit of the data yields the equation:

$$Q_r = 1.37T^{0.32} \quad (10)$$

with $r^2 = 0.97$ and SE = 0.05. The drawn envelope curve is given by:

$$Q_r = 1.52T^{0.32} \quad (11)$$

The largest value of Q_r (7.77) has a corresponding value of $T = 281$ years as determined from the Gringorten formula. The occurrence of a flood peak with this return period at least once during the 157 years of record is not surprising and according to the binomial model is given by:

$$p = 1 - (1 - \frac{1}{T})^{nw} \quad (12)$$

where p is probability of occurrence and w the number of independent sites in a hydrological region. We find for $w = 1$ that $p = 0.43$ and for, say, $w = 10$ then $p = 0.99$, that is, an occurrence is extremely likely at a least one site.

Example 3: Site envelope (North Island)

The site Ngaruroro at Fernhill (site number 23102) in the HBHR was chosen as an example because it has a long record (94 years) which enables illustration of the fit of Equation 5 to site data. Also, the record contains a significant outlier generated by Cyclone Gabrielle in 2023 for which an improved probable estimate of its associated return period is desirable.

Figure 4 displays the site data with a predicted flood frequency relationship for the site according to Equation 5 with Q_m = 896 m^3/s and $m = 1.25$ (calculated from site data). A value of $E_f = 0.878$ was employed to better fit the data as to location. The equation of this line is:

$$Q_r = 0.72T^{0.37} \quad (13)$$

with r^2 =0.94 and SE = 0.08. For the outlier plotted at $Q_r = 6.02$, Equation 13 yields $T = 234$ years. The EV2 relation predicts that $T > 1{,}000$ years, which is excessive. Equation 8 predicts that $T = 296$ years. If the outlier is the largest value recorded at the site since 1867 (this is unknown although likely) then from the Gringorten formula $T = 281$ years. From the above a value of $T = 230$ years seems reasonable for the outlier, as Equation 5 is likely to be the most accurate. The envelope curve has the equation:

$$Q_r = 0.79\,T^{0.41} \quad (14)$$

Finally, for the Ngaruroro at Fernhill site, A = 1,930 km^2 and with Q_m = 896 m^3/s Equation 2 predicts that Q_p = 10,348 m^3/s with $Q_r = 11.5$ as the envelope value for the largest flood peak which appears to be very high. Our envelope curve predicts that for $Q_r = 11.5$ then $T = 687$ years.

Example 4: Regional envelope (South Island)

The West Coast Hydrological Region (WCHR), as defined by the regional council boundary, was chosen as an example in contrast to the HBHR because it experiences a much higher frequency of storms. For instance, Griffiths and McSaveney (1983) reported more than 100 storms in 850 days in the Cropp Basin near Hokitika. The ratio of runoff to rainfall for storms was also found

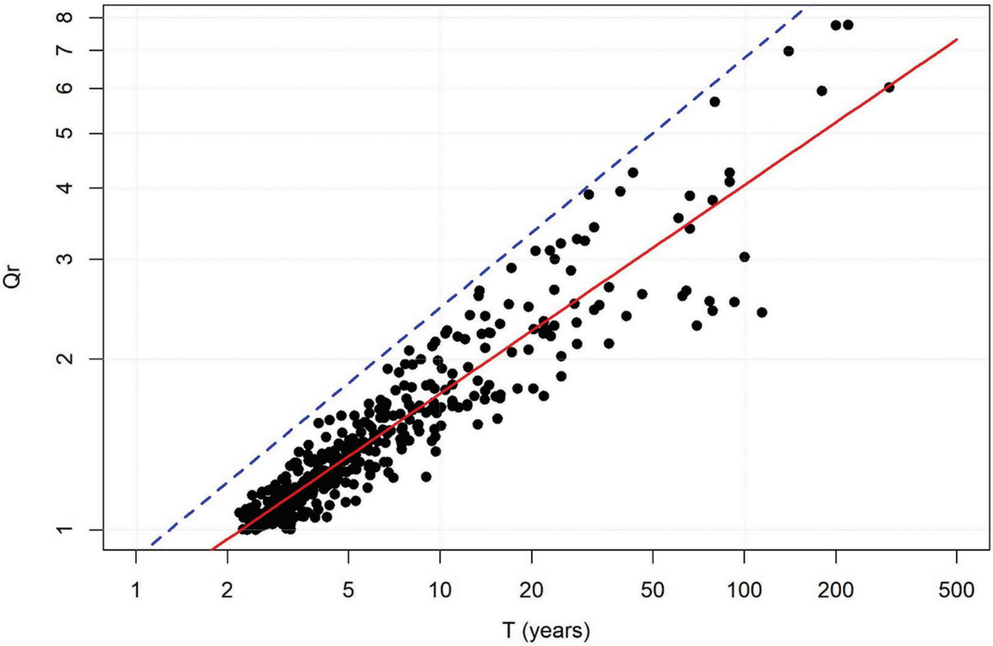

Figure 2 – Regional flood frequency curve for HBHR. Non-dimensional flood peak discharge (Qr) versus return period (T) with adjusted values of T for the six outliers in Figure 1. Solid line is fitted power law (Eq. 8). Dotted line is an envelope curve (Eq. 9).

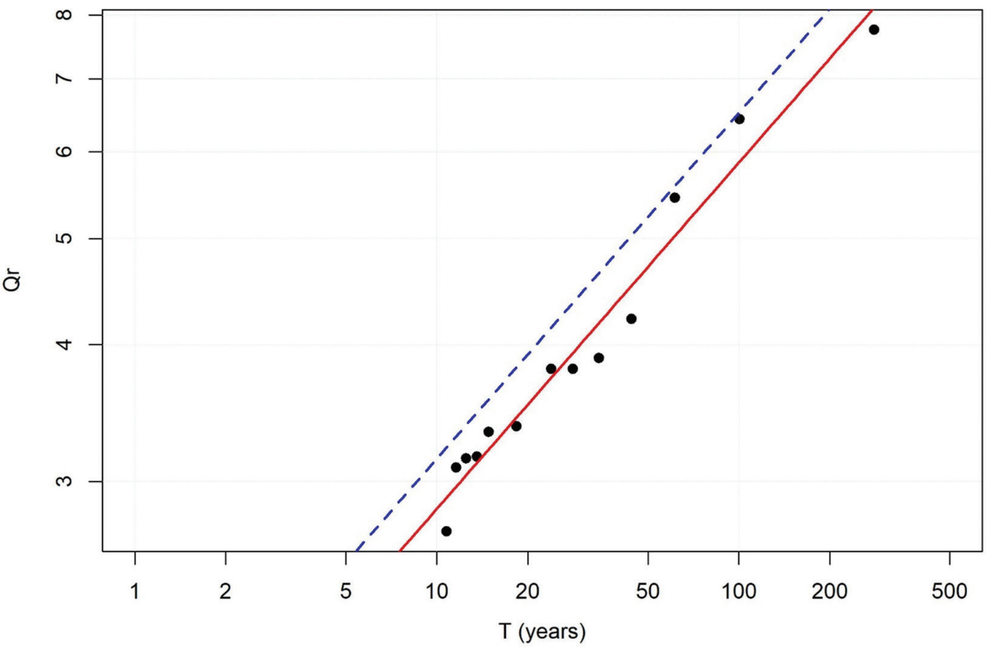

Figure 3 – Regional extreme flood frequency curve for HBHR. Non-dimensional flood peak discharge (Qr) versus return period (T). Solid line is fitted power law (Eq. 10). Dotted line is an envelope curve (Eq. 11).

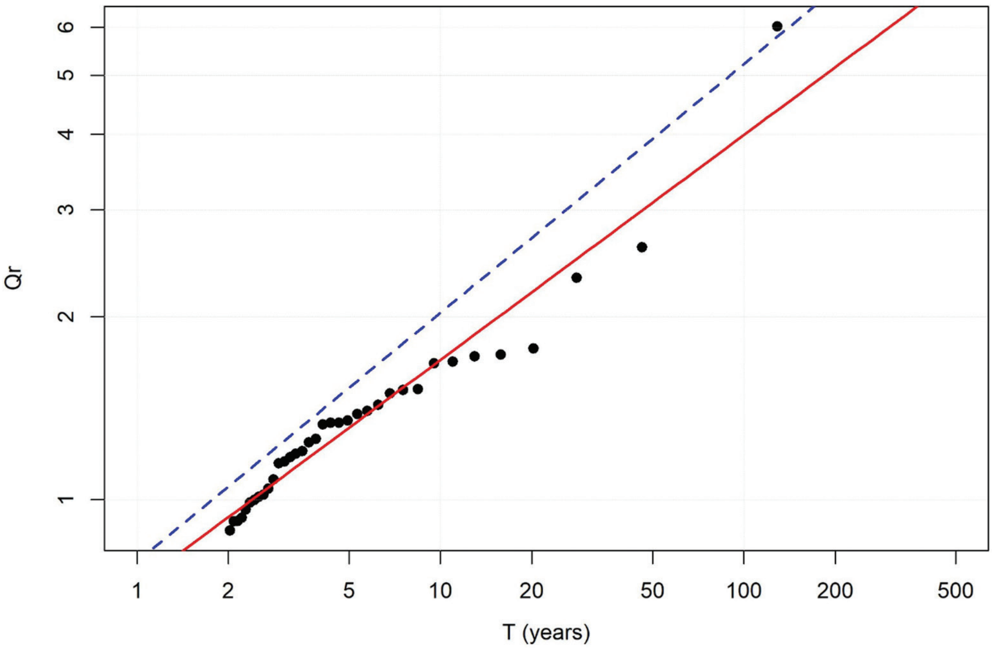

Figure 4 – Flood frequency curve for Ngaruroro at Fernhill in the HBHR. Non-dimensional flood peak discharge (Qr) versus return period (T). Solid line is a predicted distribution using Eq. 5 (Eq. 13). Dotted line is an envelope curve (Eq. 14).

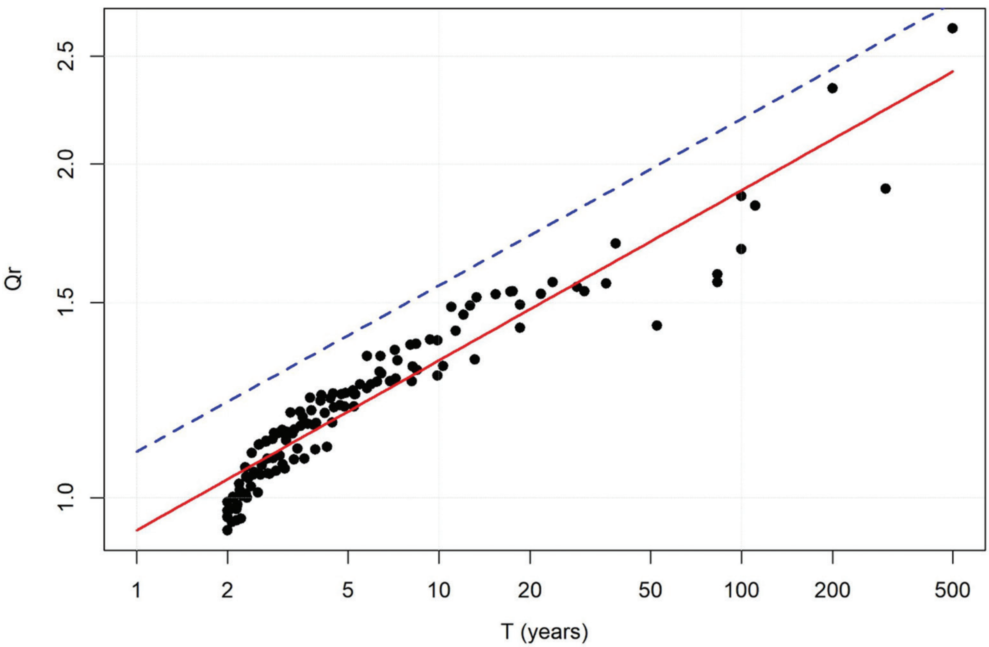

Figure 5 – Regional flood frequency curve for WCHR. Non-dimensional flood peak discharge (Qr) versus return period (T). Solid line is fitted power law (Eq. 15). Dotted line is an envelope curve (Eq. 16).

to be high. Record length here is from 1877 to 2023, similar to that for the HBHR.

Figure 5 displays the regional flood frequency curve for the region on logarithmic scales and fitted by the power law:

$$Q_r = 0.93T^{0.15} \quad (15)$$

with r^2 =0.90 and SE = 0.06.

There are no significant outliers present owing mainly to the high frequency of storms, generally high antecedent wetness, and relatively large values of Q_m, and an easily drawn envelope curve has the equation:

$$Q_r = 1.1T^{0.15} \quad (16)$$

Note the smaller exponents (both 0.15) compared to the HBHR values of 0.37 and 0.44, respectively.

Example 5: Regional extreme envelope (South Island)

Figure 6 is a plot of regional extreme values recorded over 147 years (Table 2). A power law fit yields:

$$Q_r = 0.85T^{0.21} \quad (17)$$

with r^2 = 0.97 and SE = 0.04. The envelope curve is given by:

$$Q_r = 0.89T^{0.21} \quad (18)$$

Again, note the lower exponent values (both 0.21) compared to HBHR values of 0.32 in both cases.

Example 6: Site envelope (South Island)

The site Buller at Te Kuha (site number 93203) in the WCHR was chosen because it has a long record (61 years) with a significant outlier whose presence enables illustration of the use of Equation 5. Figure 7 displays the site flood peak data for 1964 to 2024. A power law fit yields:

$$Q_r = 0.98T^{0.15} \quad (19)$$

with r^2 = 0.94 and SE = 0.04. The envelope curve is given by:

$$Q_r = 1.1T^{0.15} \quad (20)$$

Not plotted on Figure 7 is the largest recorded flood in the Buller River, which occurred in 1926. At the time, the flood flow was estimated to be 7,645 m^3/s (Q_r =1.58, Q_m = 4,832), but in the 1950s the estimate was revised to be near to 12,742 m^3/s (Q_r = 2.64) although no reason for the increased estimate was given (Soil Conservation and Rivers Control Council, 1957, p159). The estimate of Q_r = 1.58 is too low as the regional curve (Eq. 15) and the site curve (Eq. 19) predict that T = 34 and T = 24 years, respectively. On the other hand, the upper estimate of Q_r = 2.64 seems too high as the curves predict that T = 1,049 and 740 years, respectively. The matter cannot be resolved definitively. However, a value of, say, 10,500 m^3/s (Q_r = 2.17) for the outlier is a reasonable guess as the regional and site curves predict T = 286 and T = 200 years, respectively, and Equation 5 predicts T = 240 years. The Gringorten estimate for the largest value in the 147 years of record is T = 263 years.

Climate change

The site records of annual maxima used in this study were examined for climate change effects by undertaking statistical checks for trend, persistence, periodicity and shifts. Of these only shifts were found to be significant at some West Coast sites, as observed previously by McKerchar and Henderson (2003). Four shifts in time were detected in flood records. These correlate with two or more changes in phase of the Interdecadal Pacific Oscillation of which there have been four, ranging in length from 20 to 30 years, since 1913. The shifts alternately cause an increase then a decrease in the value of Q_m of about 10% in size. For our regional analysis (Figure 1) they were not found to have any significant effect on results.

As to the future behaviour of flood peaks, the most recent report from the Intergovernmental Panel on Climate Change

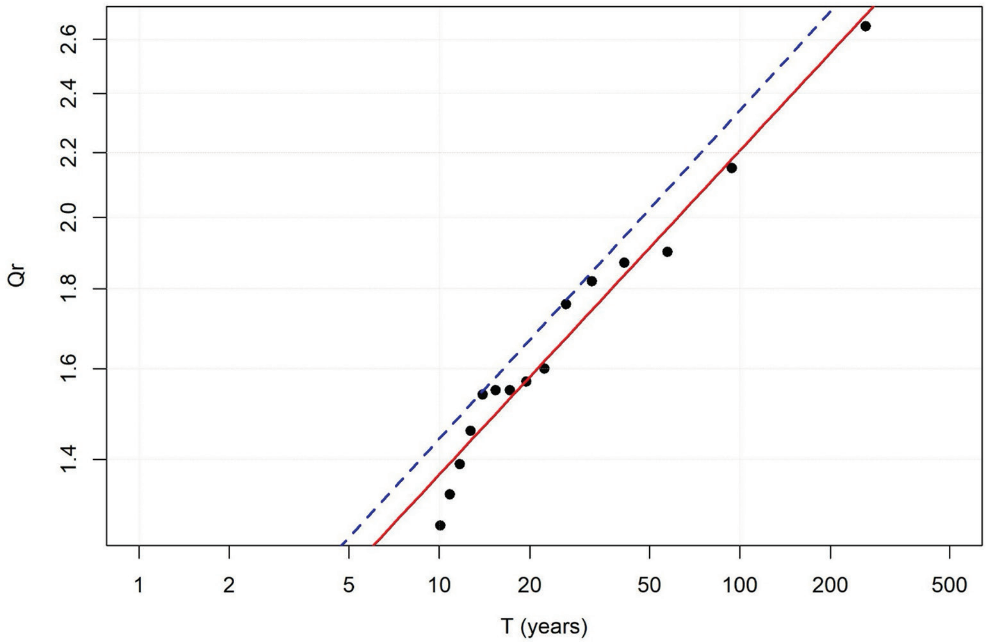

Figure 6 – Regional extreme flood frequency curve for WCHR. Non-dimensional flood peak discharge (Qr) versus return period (T). Solid line is fitted power law (Eq. 17). Dotted line is an envelope curve (Eq. 18).

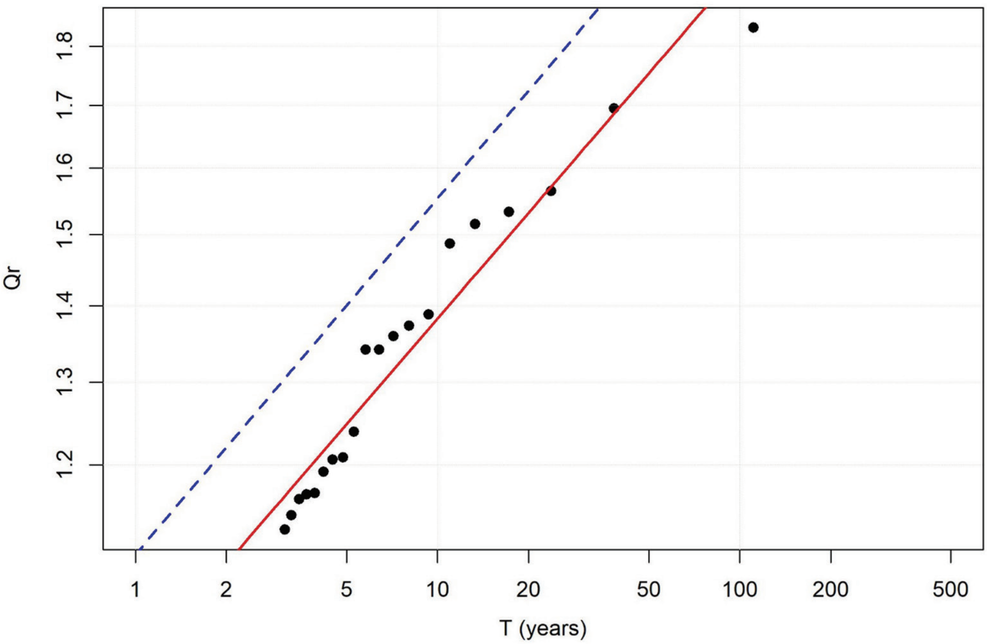

Figure 7 – Flood frequency curve for Buller at Te Kuha in the WCHR. Solid line is fitted power law (Eq. 19). Dotted line is an envelope curve (Eq. 20).

(Bodeker *et al.*, 2022) has two key findings relevant to this study concerning the likely effects of anthropogenic activity on climate change. The first key finding is that future effects of the El Niño Southern Oscillation are hard to predict but are not expected to change significantly this century. Conclusions about the future behaviour of the Interdecadal Pacific Oscillation (IPO) are rather uncertain. However, there is medium confidence that a weaker and high frequency IPO is expected under global warming which in future will affect the frequencies of El Niño and La Niña events. The second key finding is that annual rainfall and streamflow patterns are expected to change, with increases in the west and south of the country and decreases in the east and north.

The greatest impact of anthropogenic influences is likely to be expected first in changes in extremes (Collins, 2021). Overall, there is medium confidence that river flooding will increase. Projections indicate that the 1-in-50-year and 1-in-100-year flood peaks for rivers in many parts of the country may increase by 5 to 10% by 2050 and more by 2100 (with large variation between models and emission scenarios) with a corresponding decrease in return periods for specific peaks (Bodeker *et al.*, 2022).

Conclusions

Envelope curves can be readily constructed by drawing a curve on a plot of non-dimensional flood peak magnitude versus return period, which provides an upper bound to extreme measured or estimated values of peak size. Construction can be made simpler by using, for instance, logarithmic scales so that flood peak data lies on and around a straight line. An envelope curve is then easily modelled by a power law. This approach applies at both the hydrological region and site level.

Employment of a predictive equation at a site for non-dimensional flood peak magnitude for a nominated return period requires knowledge of mean annual flood and the average annual number of floods at a site. The predicted flood frequency curve may be used to extend or modify the curve fitted through site data and to estimate more realistic values of the return periods of outliers.

Allowance should be made in estimating flood peak magnitudes for the probable effect of human-induced climate change. An increase of 5 to 10% in peak size for 1-in-50 and 1-in-100-year flood peaks is predicted in many rivers by 2050.

Further investigation is needed into regional and regional extreme value flood frequency curves and their associated envelopes in all hydrological regions in New Zealand. Additional testing is desirable for the performance of the prediction equation for at-site flood frequency relations.

Finally, the methodology used herein could be usefully employed to analyse annual maximum daily rainfalls, as some records are available from the 1860s onwards.

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