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Towards prediction of extreme floods in New Zealand

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Abstract

Prediction equations for non-dimensional flood frequency as a function of average annual number of floods at a site are derived for return periods of 10 to 500 years. These equations may be used to provide a reasonably reliable and rapid check on extreme flood peak estimates derived using other methods. Separate equations apply to the North Island and South Island, each treated as a single region, and require knowledge of the mean annual flood value at a site.

Envelope curves for recorded extreme flood peaks as a function of catchment area are presented based on five significant flood peaks. World maxima are about 1.25 times greater than New Zealand values for areas exceeding 90 km^2 and from 1.25 to 12 times greater for smaller basins. It is likely that New Zealand maxima will be exceeded in the future.

Problems with employing estimates of probable maximum flood are reviewed. Probable maximum flood use in design is not recommended as the estimates are subjective and not free from risk of exceedance. A probable maximum flood estimate for the Waimakariri River near Christchurch is likely to have a return period of the order of 10^4 years.

Allowance for the effects of human-induced climate change should be made when using the prediction equations and envelope curves derived in this study. Further work is needed employing a much larger sample of catchments to provide more accurate prediction equations for non-dimensional flood frequency for return periods exceeding 500 years.

Keywords

flood peak; flood frequency estimation; extreme flood; design floods; statistical hydrology.

Introduction

Predicting flood peak magnitude for a specific return period at a given hydrological recording station or other site, together with an estimate of its standard error, is an essential task in many engineering problems – for example, in floodplain management schemes and in the design of reservoir spillways, bridges and culverts, sewerage systems and urban drainage. Analysis of extreme floods and their potential impacts is also of the first importance to planners, consent and civil defence authorities and people likely to be affected by these events.

Flood frequency analysis may be undertaken using site and regional data or by employing a rainfall-runoff model to route a design rainfall event. An issue with the latter approach is that the return period of a design rainfall may be significantly different from that of the flood it generates.

On a national scale flood frequency analysis in New Zealand has been carried out by Beable and McKerchar (1982) and

McKerchar and Pearson (1989) using the Index Flood method (Kinnison and Colby, 1945; Dalrymple, 1960; Hosking and Wallis, 1997; Dawdy *et al.*, 2012). The principal steps in this approach are: (1) estimation of flood quantiles at gauged sites within a region by fitting a statistical distribution to the series of assumed independently and identically distributed annual maximum flood peak discharges, Q, at each site; (2) delineation of homogeneous hydrological subregions within the region; (3) development of a non-dimensional flood frequency relationship Qr(T), where Qr is non-dimensional flood frequency and T is return period for each subregion using pooled site data scaled by the index flood – usually the mean annual flood, Qa, where Qr = Q/Qa and (4) estimation of the required quantiles at an ungauged site or site with little data using the subregion relationship and relevant value of Qa, which may be calculated from site data or other means (for New Zealand practice see, for instance, Griffiths and McKerchar, 2012).

Here, interest lies in estimating Q_r for values of T from 10 to 500 years assuming Q_a is known at a given site. Beable and McKerchar (1982) partitioned New Zealand into eight regions and developed regional growth curves of $Q_r(T)$ with T ranging up to 200 years. McKerchar and Pearson (1989) produced contours of $Q_r(T=100)$ covering the country; these enable calculation of Q_r at a site for values of T up to 200 years. In both studies the dependence of Q_r on meteorological or hydrological variables or catchment characteristics, as in the quantile method of Benson (1964), was not explored.

Our approach herein is to consider the whole of the North Island of New Zealand as one region and the South Island as another and seek to develop prediction equations for $Q_r(T)$ in terms of meteorological or hydrological variables, basin characteristics or a combination of these.

We also update the envelope of maximum recorded flood peak discharges as a function of catchment area in New Zealand and provide commentary on the relationship between the probable maximum flood approach to estimating extreme floods and the frequency approach. The purpose of this paper, which is a companion paper to Griffiths *et al.* (2014), is to examine the limits of reasonable prediction of extreme floods in New Zealand. The aim is to provide designers and planners with indicative values and an easy-to-use tool for checking estimates of flood peak magnitude for large return periods. The analysis is based on flood data measured during the period 1950–2018.

Analysis

In place of using growth curves or contours for the computation of Q_r, as mentioned above, we seek to express Q_r as a function of the meteorological and hydrological variables and basin characteristics (or their surrogates) mainly responsible for flood generation within a region as a whole. Thus, the value of $Q_r(T)$ at any site in the region may be predicted using one equation for a given T.

To characterise meteorological variability within a region we initially sought to use rainfall intensity for a duration equal to catchment time of concentration. However, the only formula available to compute time of concentration for New Zealand (Griffiths and McKerchar, 2012) requires estimation of the Manning channel roughness coefficient for each catchment. This is difficult to do and results are only available for a relatively small number of basins. Additionally, although rainfall intensity for a given duration may be determined nationally using the High Intensity Rainfall Design System (HIRDS) (Carey-Smith *et al.*, 2018) its accuracy varies considerably among catchments depending upon the availability of relevant rainfall data. For these reasons we selected basin mean annual rainfall, P, and the 24-hour rainfall intensity of 2.33-year return period, I_{24}, as employed by Beable and McKerchar (1982), to describe catchment meteorology.

To characterise basin properties the selected variables included area (A), mean elevation (E), main channel slope (S_b), stream frequency (S_f), soil drainage (D), depth-weighted macroporosity (D_p) and 7-day mean annual low flow (Q_7/A) (to reflect catchment storage).

As to hydrological variables, we observed that McKerchar and Pearson (1989) obtained an average value of $Q_r(T{=}100)$ of about 2 for Westland, whereas for the South Canterbury and North Otago areas it was about 5. One reason for this difference is that in Westland there is a high frequency of storms and resultant flooding leading to a relatively high value of Q_a. In South Canterbury and Otago the opposite is the case and in some years there are only a few very minor floods. As a surrogate for storm frequency we selected average annual number of floods, m, where $Q{>}0.5\,Q_a$ as described in Figure 1. No previous use of m was found in a literature search that included the extensive list of catchment attributes given in Razavi *et al.* (2013). Accordingly, our relation for $Q_r(T)$ can be expressed as:

$$Q_r(T) = f(I_{24}, P, A, E, S_b, S_f, D, D_p, Q_7/A, m) \quad (1)$$

where f is some function.

Data selection

A sample of 40 basins of widely differing size and hydrologic, geologic and topographic characteristics was chosen from the North and South Islands. Details of recording sites, record length and basin area and Q_a, m and $Q_r(T)$ values are given in Table 1. The latter values were calculated by fitting an Extreme Value Type 1 or Type 2 distribution (Hosking *et al.*, 1985) to the annual maxima at a site using L-moments as described in detail by McKerchar and Pearson (1989). In fitting the distributions we limited the $Q_r(T)$ values to T = 500 years as results for larger values of T were tenuous given the relatively short record lengths (Table 1). Finally, the assumption made in fitting these extreme value distributions is that the annual maxima at a site are independent and identically distributed random variables. To check this assumption, the maxima were examined statistically and pictorially for evidence of trend, persistence, periodicity and shifts. In particular, we applied the Mann-Kendall test for trend, Spearman rank order correlation test for persistence, Mann-Whitney split sample test for location difference and the Wald-Wolfowitz split sample test for any difference. The two split sample tests were conducted as 50-50 splits. In all cases the null hypothesis was accepted at the 0.05 significance level. Similar or related results

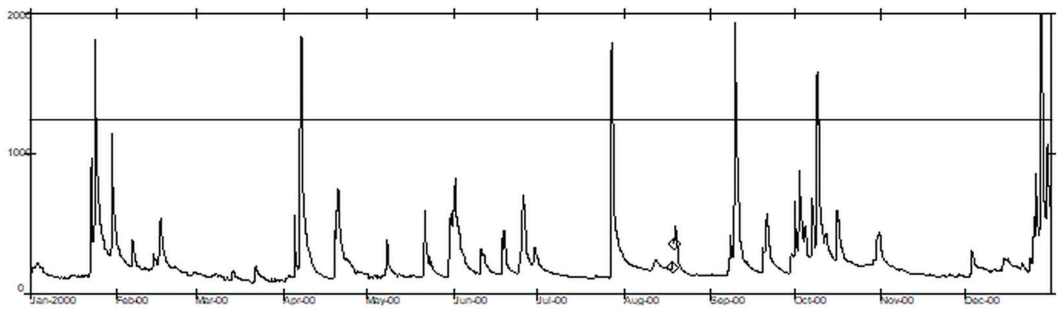

Figure 1 – Calculation of number of floods greater than or equal to $0.5\,Q_a$. Flow time series is for Rakaia River at Fighting Hill for 2000. Horizontal line is drawn at $0.5\,Q_a$. Number of peaks for 2000 is m = 6.

Table 1 – Hydrological and physiographic characteristics of selected New Zealand basins and calculation of Q_r

River	Location	Site No. (from Walter, 2000)	Years of record	Basin area (km^2)	Mean annual flood (m^3/s)
North Island				A	Q_a
Maungaparerua	Tyrees Ford	3506	45	11.1	51.3
Whakatane	Whakatane	15514	56	1557	958
Motu	Houpoto	16501	55	1393	1650
Ngahere	Ngahere Weir	23005	45	0.521	1.276
Ngaruroro	Kuripapango	23104	49	370	296
Omakere	Fordale	23210	48	54.4	56.7
Whareama	Waiteko	25902	42	398	351
Whangaehu	Waihi	29244	45	36.3	27.9
Hutt	Kaitoke	29808	48	88.8	270
Mill Ck	Papanui	30516	43	9.35	7.62
Makohine	Viaduct	32754	35	99.5	73.0
Whanganui	Paetawa	33301	56	6643	2286
Kai iwi	Handley Rd	33502	35	192	31.7
Punehu	Pihama	36001	43	29.5	39.4
Awakino	Gorge	40810	34	226	209
Waipa	Otewa	43481	30	317	173
Tahunaatara	Ohakuri Rd	1043428	47	210	38.1
Mangahanene	SH1	1443462	40	8.75	5.66
Waitangi	SHBr	43602	46	17.6	14.1
Mangakahia	Gorge	46618	52	246	510
South Island				A	Q_a
Hunters Gully	Weir	57022	40	5.02	2.77
Cobb	Trilobite	52916	40	46.8	93.8
Wairoa	Irvines	57521	51	462	694
Wairau	Dip Flat	60114	61	505	355
Acheron	Clarence	62103	52	973	330
Camp Stm	Craigieburn	66405	48	0.9	0.540
Rakaia	Fighting Hill	68526	53	2560	2523
Avon	Gloucester St Br.	66602	29	38	17.7
Rocky Gully	Rockburn	69621	43	23	14.5
Hakataramea	Above MHBr.	71103	47	899	165
Maerewhenua	Kellys Gully	71106	46	187	138
Jollie	Mt Cook Station	71135	53	139	66.5
Sutton Stm	SH87	74338	26	151	66.2
Pomahaka	Burkes Ford	75232	51	1924	397
Mataura	Gore Highway Br.	77504	50	3465	634
Makarewa	Counsell Rd/FW Br	78634	42	998	228
Arawata	County Br.	86301	23	971	2942
Haast	Roaring Billy	86802	43	1020	3717
Grey	Dobson	91401	44	3830	3799
Buller	Te Kuha	93203	47	6350	4797

Average no. of floods per year ≥$0.5Q_a$	Non-dimensional flood frequency, Q_r, for specified return periods, T (years)				
m	***T*=10**	**50**	**100**	**200**	**500**
2.73	1.64	2.27	2.53	2.80	3.15
2.18	1.45	2.22	2.54	2.86	3.29
3.42	1.51	2.01	2.23	2.44	2.72
2.42	1.55	2.09	2.32	2.55	2.85
2.10	1.53	2.05	2.27	2.49	2.78
2.00	1.73	2.45	2.75	3.05	3.45
1.88	1.81	2.62	2.96	3.29	3.74
2.44	1.70	2.39	2.68	2.97	3.35
4.02	1.35	1.70	1.84	1.99	2.19
2.00	1.75	2.50	2.81	3.12	3.54
2.57	1.64	2.27	2.53	2.80	3.15
3.78	1.44	1.88	2.06	2.24	2.48
2.09	1.39	2.05	2.33	2.60	2.97
4.93	1.47	1.94	2.14	2.33	2.59
2.59	1.52	2.04	2.26	2.43	2.77
2.10	1.62	2.24	2.50	2.76	3.10
4.28	1.49	1.96	2.16	2.36	2.62
1.58	2.01	3.00	3.42	3.84	4.39
2.24	1.93	2.85	3.24	3.63	4.14
2.23	1.66	2.30	2.57	2.83	3.19
m	***T*=10**	**50**	**100**	**200**	**500**
2.11	1.48	2.70	3.51	4.56	6.48
6.64	1.33	1.65	1.78	1.92	2.10
3.27	1.56	2.23	2.54	2.87	3.34
3.12	1.46	1.92	2.12	2.31	2.56
2.44	1.61	2.50	2.96	3.49	4.30
1.83	1.80	3.30	4.19	5.28	7.11
3.52	1.53	2.21	2.55	2.91	3.45
5.04	1.47	1.93	2.12	2.32	2.57
1.00	1.97	5.01	7.31	10.59	17.18
0.85	1.94	5.06	7.46	10.93	18.00
1.32	1.91	2.80	3.17	3.55	4.06
2.55	1.56	2.63	3.26	4.03	5.32
1.27	2.01	3.49	4.27	5.14	6.48
2.10	1.75	2.94	3.58	4.33	5.50
2.45	1.72	3.29	4.30	5.60	7.90
3.79	1.48	2.32	2.80	3.37	4.31
6.80	1.36	1.70	1.85	1.99	2.18
4.70	1.48	1.93	2.12	2.31	2.56
6.02	1.35	1.69	1.83	1.98	2.17
5.57	1.42	1.81	1.98	2.15	2.37

regarding independence and identical distributions were obtained by McKerchar and Pearson (1989) and Henderson and Collins (2016) for floods and by Griffiths *et al.* (2014) for annual maximum rainfalls.

Calibration of prediction formula

Data for the independent variables in Equation 1 were abstracted from Hutchinson (1990), Beable and McKerchar (1982) and McKerchar (1991). Stepwise multiple regression was then carried out on the logarithms. The only significant variables in terms of explanation of variance of $Q_r(T)$ were m for the North Island and m and P for the South Island. However, because m and P are significantly correlated only m was retained. Ordinary least squares regression with logarithms of the data was then employed to determine prediction equations of the form:

$$Q_r(T) = am^b \quad (2)$$

where a and b are constants and T ranges from 10 to 500 years. The results are listed in Table 2 (along with fit statistics) and illustrated in Figures 2 and 3.

Example

Flood peak data for 1930–2018 from Waimakariri River at Old Highway Bridge, one of the longest river flow records available in New Zealand, are used to illustrate the fit of the prediction equations (Table 2, South Island). Figure 4 shows this fit together with that of an Extreme Value Type 2 (EV2) distribution.

Performance assessment

A jack-knife resampling procedure was employed to provide some assessment of the performance of the prediction equations (Table 2; Figs. 2 and 3). This consisted of firstly considering each site in a set of N sites as an unknown site and then removing it temporarily from the set. The remaining N-1 sites (here N=20 for each island) were then used to calibrate a prediction equation (Table 2), which was then employed to calculate a value of $Q_r(T)$ for the unknown site. The process was repeated for all N=20 sites for each island, then the relative error or bias and root mean square error were computed. Table 3 gives the results.

Table 2 – Prediction equations and statistics of fit for non-dimensional flood frequency, Q_r, as a function of average annual number of floods, m, for various return periods.

Region	Return period, T (yrs)	Prediction equation	Pearson correlation coefficient	Standard error of logarithms
North Island	10	$Q_r = 1.97m^{-0.223}$	0.642	0.061
	50	$Q_r = 3.09m^{-0.351}$	0.762	0.069
	100	$Q_r = 3.56m^{-0.387}$	0.776	0.073
	200	$Q_r = 4.04m^{-0.415}$	0.782	0.077
	500	$Q_r = 4.68m^{-0.446}$	0.794	0.079
South Island	10	$Q_r = 1.96m^{-0.197}$	0.938	0.021
	50	$Q_r = 4.21m^{-0.502}$	0.944	0.050
	100	$Q_r = 5.70m^{-0.626}$	0.927	0.071
	200	$Q_r = 7.66m^{-0.749}$	0.912	0.095
	500	$Q_r = 11.2m^{-0.911}$	0.894	0.129

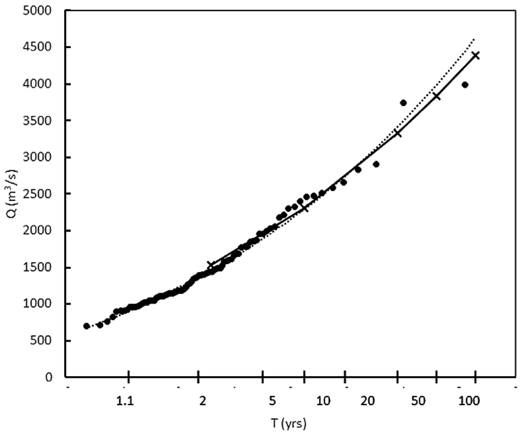

Figure 2 – Flood peak discharge (Q) versus return period (T) for Waimakariri River at Old Highway Bridge (Site No. 66401), 1930–2018. Solid line is predicted distribution using South Island prediction relations (Table 2 and Fig. 3). Dotted line is an EV2 distribution fitted using L-moments.

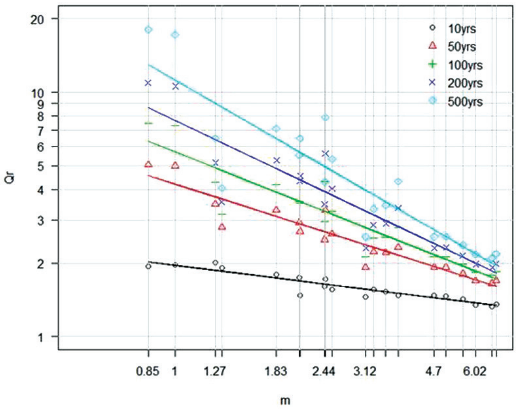

Figure 3 – North Island prediction equations (as in Table 2) for Q_r as a function of average annual number of flood peaks, m, and return period, T.

Better performance occurs in the North Island where m and $Q_r(T)$ are not as variable as in the South Island. Overall, the correlation coefficients and standard errors in Table 2 and the relative and root mean square errors in Table 3 demonstrate that our new approach has the potential to provide

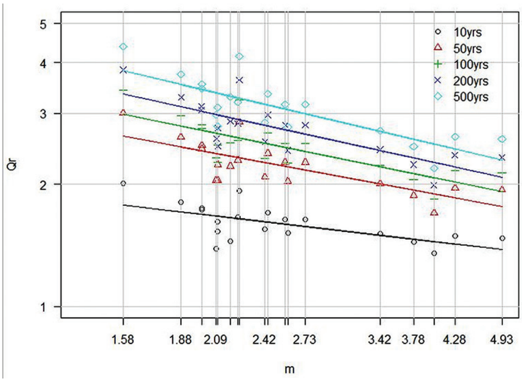

Figure 4 – South Island prediction equations (as in Table 2) for Q_r as a function of average annual number of flood peaks, m, and return period, T.

reasonably accurate prediction of $Q_r(T)$, at least for use as a tool for quickly checking estimates obtained by other methods, although further development is desirable as noted below.

Envelope curves

The first attempt at determining the classic relationship between maximum recorded flood peak discharge and catchment area for New Zealand was made by J. Wood in 1918, reported in Schnackenberg (1949). His formula is:

$$Q = 36.5A^{0.75} \quad (3)$$

where Q is in m^3/s and A in km^2.

Later, Schnackenberg (1949) presented an envelope line for world and New Zealand data drawn above the data and defined by the curve:

$$Q = 352A^{0.5}$$

Current world maxima are enveloped by the curves determined by regression (Herschy, 2003):

$$Q = 500A^{0.43} \qquad A \geq 90 \text{ km}^2 \quad (4)$$

and

$$Q = 100A^{0.8} \qquad A \leq 90 \text{ km}^2 \quad (5)$$

Table 3 – Prediction equation (in Table 2) performance assessment.

Region	Prediction equation for $Q_r(T)$	Relative error	Root mean square error (%)
North Island	$Q_r(10)$	0.21	8.79
	$Q_r(50)$	0.26	10.0
	$Q_r(100)$	0.30	10.6
	$Q_r(200)$	0.35	11.1
	$Q_r(500)$	0.39	11.5
South Island	$Q_r(10)$	0.10	4.90
	$Q_r(50)$	0.54	12.1
	$Q_r(100)$	1.33	17.5
	$Q_r(200)$	2.61	23.6
	$Q_r(500)$	5.20	31.8

Using data from 1950 to 2018 we identified the maximum recorded New Zealand flood peak discharges and catchment areas (Table 4). Only five values were found of sufficient magnitude to define a pattern similar to world maxima (Fig. 5). The envelope curves for these New Zealand values are given by:

$$Q = 400A^{0.43} \qquad A \geq 90 \text{ km}^2 \qquad (6)$$

and

$$Q = 18A^{1.12} \qquad A \leq 90 \text{ km}^2 \qquad (7)$$

These curves should be regarded as rather approximate, are certain to be exceeded in the future and should only be used with considerable caution in design. For $A \geq 90$ km^2 world maxima are some 1.25 times greater than New Zealand maxima (based on data from one New Zealand flood event) and for $A \leq 90$ km^2 the difference ranges from about 1.25 to 12 times greater (based on data from four New Zealand flood events).

The publication *Floods in New Zealand 1920-1953* (Soil Conservation and Rivers Control Council, 1957) lists extreme flood peaks recorded in New Zealand in 1920–1953. None of the values listed exceeds those of Table 4, except the erroneous value listed for Sheepskin Creek at Lake Wanaka.

Probable maximum flood

Probable maximum flood (PMF) is defined by the Federal Energy Regulatory Commission (2001) as the flood that may be expected from the most severe combination of critical meteorological and hydrological conditions that are reasonably possible in the drainage basin under study. Calculation of PMF values requires estimates of probable maximum precipitation (PMP) and detailed rainfall-runoff modelling for the catchment of interest. PMP is defined by the World Meteorological Organization (2009) as theoretically the greatest depth of rain for a given duration that is physically possible over a given storm size area at a particular geographic location at a certain time of year under modern climate conditions. Since its introduction in the 1940s the concept of PMP, and by implication PMF, has been severely criticised (Benson, 1973; Koutsoyiannis, 1999; Papalexiou and Koutsoyiannis, 2006) on a number of grounds. Technically, estimates are subjective and there is little or no justification for selecting one estimate from another. Ethically, there is the implication that PMP and PMF design values are free from risk, as the probability of exceedance is zero.

Table 4 – Maximum recorded New Zealand flood peak discharges and their catchment areas.

River	Site	Site number (from Walter, 2000)	Catchment area (km^2)	Flood peak (m^3/s)	Date
Haast	Roaring Billy	86802	1020	7690	3-Dec-79
Cropp	Gorge	90607	12.2	350	19-May-88
Maungaparerua	Tyrees Ford	3506	11.1	225	20-Mar-81
Pukewaenga	Conservation	46662	0.389	4.26	13-Jun-79
Moutere	Catchment 5	57405	0.07	1.31	21-Aug-73

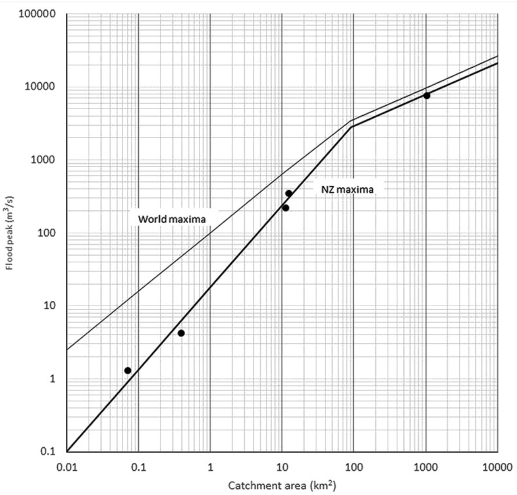

Figure 5 – Maximum recorded flood peak discharges as a function of catchment area. The world maxima and the New Zealand maxima lines are given by Equations 5 & 6 and 7 & 8, respectively.

In practice these estimates have been exceeded (Willike, 1980). Despite these substantial and convincing criticisms, PMF estimates have been used for more than 40 years in New Zealand for assessment of the flood hazard posed by hydroelectric dams (Jowett and McKerchar, 1983) and for urban flood protection schemes. (Estimation methods for PMF are detailed in McKerchar, 2010.) However, for modern economic and hazard analyses this approach is unsuitable for design as there is a need to associate probabilities with estimates of flood extremes. A more consistent and intrinsically more logical approach is to design for specified very low probability events (Pilgrim and Corderey, 1993).

An example of PMF estimation in New Zealand is provided by Griffiths *et al.* (1989) as part of a study of the potential flood hazard in Christchurch posed by the Waimakariri River. Based on PMP values predicted by Tomlinson (1980) a PMF value of 8000 ± 1000 m^3/s was determined using a non-linear rainfall-runoff model. The return period for this value, calculated using considerable extrapolation, is probably of the order of 10^4 years (Griffiths *et al.*, 2017). This result is consistent with the general frequency analysis of PMP values by Koutsoyiannis (1999) assuming the frequency of the PMP and PMF estimates for the Waimakariri River are of the same order of magnitude. Finally, it is of interest to note that the envelope curve for New Zealand data (Eq. 6) predicts a maximum flood peak for the Waimakariri River of some 11,500 m^3/s. This is, however, based on one flood estimate from Westland, which has a much more intense rainfall regime than the Waimakariri catchment.

Climate variability and change

Based on the results of the statistical tests on annual maximum flood peak series for numerous sites we infer that although the New Zealand flood regime has been markedly variable since at least 1950, its behaviour has not, as yet, changed significantly. Mention should be made that McKerchar and Henderson (2003) found that the Interdecadal Pacific Oscillation (IPO) had some influence in parts of New Zealand and noted that short flood records in these areas recorded mainly within the 1947–1977 or 1978–1999 periods may not be representative of long-term flood risk (for further detail see Ministry for the Environment, 2010). The influence of the IPO on the maximum flood peak discharges in Table 4 is unclear. In the wetter IPO phases the frequency of extreme floods is higher than in drier phases but what effect, if any, the IPO has on magnitude is unknown.

Any effects of climate change induced by humans will be superimposed on this natural variability. To provide guidance on assessing the impacts of human-induced climate change on flood magnitude we recommend use of the tools discussed in Ministry for the Environment (2010) with reference to Ministry for the Environment (2018) for updated information. Accommodation in hydraulic design of stationary shifts in flood regime is treated in Griffiths *et al.* (2009). Finally, in Table 4 all extreme floods occurred in the 1970s and 1980s; this suggests effects of climate change on flood magnitude in New Zealand are not apparent as yet.

Future work

Further investigation is needed into the dependence of Q_r on meteorological and hydrological variables and basin characteristics. Analysis of a much larger sample of flow sites is desirable to better define and assess the performance of the prediction relations of Table 2 with a view to extending their application to higher return periods. Additionally, results may be improved by deriving prediction equations applicable within subregions of the North and South Islands. The results of the suggested further analysis should be compared with those of the regional frequency approach of McKerchar and Pearson (1989) and Henderson and Collins (2016).

Measurement of extreme flood discharges is usually very difficult and often indirect means, such as the slope-area method, are required. To aid analysis and improve reliability of slope-area calculations, hydrologists are encouraged to record as much relevant hydrologic and hydraulic information as practicable together with the magnitude of any associated errors.

Conclusions

Prediction equations for non-dimensional flood frequency as a function of the average annual number of floods per year may be used to provide a quick check on other estimates of extreme flood peaks at a site, for return periods of 10 to 500 years. One set of equations applies to the North Island as a whole region and another set to the South Island. Application of the equations requires knowledge of the mean annual flood magnitude at a site.

World maximum recorded flood peak discharges for a given basin area are from 1.25 to 12 times greater than New Zealand recorded maxima for areas from 0.01 to 1,000 km^2.

Employment of estimates of probable maximum flood in design is not recommended as they are subjective and not free from risk of exceedance. An estimate of PMF for the Waimakariri River is likely to have a return period of the order of 10^4 years.

Results obtained herein are based on flood peak measurements obtained in the period 1950–2018. When using results of this study, allowance should be made for the effects of human-induced climate change and it is recommended that Ministry for the Environment guidelines be followed.

Further work is needed employing a much larger sample of sites with the aim of providing more accurate prediction of non-dimensional flood frequency for return periods greater than 500 years.

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