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Flood frequency analysis: combining a systematic record with historical, regional, model and analogue information

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Abstract

A systematic, or continuous, at-site record of annual maximum flood peaks can be readily combined with other information to predict flood quantiles and their standard errors using a Bayesian Markov Chain Monte Carlo inference approach. Sources of additional information include records of historic flood peaks, results of regional flood frequency analyses, output from rainfall-runoff models and prediction of flood peak magnitudes derived from analogue basins having similar flood hydrology.

The approach is illustrated by a case study using the Waimakariri River at Old Highway Bridge site, which has a long systematic and historic flood record and regional, model and analogue information. Various periods of the systematic record combined with some and all of the additional information show that as more information is included in the analyses, the standard errors of predicted values of both 100 and 300-year return period flood peaks reduces markedly.

While further work on sources of other information is desirable, including, in particular, paleohydrological investigations, the Bayesian inference approach should improve prediction of flood quantiles and their uncertainty for at-site, regional and national studies.

Keywords

flood frequency analysis; regional flood analysis; Bayesian MCMC flood analysis; flood estimation; statistical hydrology

Introduction

Estimation of flood peak magnitude and its frequency of occurrence is a primary issue in both research and operational hydrology. This information is essential, for example, for the design of engineering works such as bridges, dams and flood protection schemes; and in flood risk analysis, planning and regulation. Because of their importance, estimates should be as well-determined as possible and should be accompanied by a measure of their precision (Reis and Stedinger, 2005; Merz and Bloschl, 2008b).

The basic problem is to predict the relationship between flood peak discharge and return period at a gauged site where there is a systematic, or continuous, flow record. If, in addition to a systematic record, additional relevant and independent information is available, then it ought to be included in a frequency analysis to reduce the uncertainty of the estimates (Merz and Bloschl, 2008a; 2008b). Examples of additional information include data from paleohydrological investigations, historical flood records, regional flood frequency studies, rainfall-runoff modelling and analogue basins exhibiting similar flood generation behaviour. Acquisition of other information is a complex and wide-ranging subject not treated herein.

Combination of systematic annual maximum flood peak data with other data to predict flood quantiles may be readily achieved nowadays by using a Bayesian inference approach (Payastre *et al.*, 2011; Viglione *et al.*, 2013, Parkes and Demeritt, 2016). The purpose of this paper is to show by means of a New Zealand case study how this combination can be performed and to demonstrate the benefits of including additional information to reduce standard errors of flood quantile estimates. It extends earlier work by Pearson (1990) combining systematic and historical information in the Hutt River, New Zealand, using the maximum likelihood techniques of Stedinger and Cohn (1986). The aim is to encourage use of the Bayesian inference approach where appropriate for flood frequency analysis in New Zealand.

Theory

In flood frequency analysis, Bayesian inference is a method in which Bayes Theorem in used to combine systematic flood peak data with additional independent information. Bayes Theorem states that the posterior distribution of parameters, θ, having observed data, d, has the following probability density function (PDF), p:

$$p(\theta|d) = N[L_s(d|\theta)\ L_h(d|\theta)]\ \pi(\theta) \qquad (1)$$

where N is a normalisation constant, L is the likelihood function (or the PDF of the data conditional on the parameters) where L_s accounts for systematic data and L_h for historical data, and π is the prior PDF of the parameters. Herein the adopted distribution of the systematic data is the Generalized Extreme Value (GEV) distribution whose PDF, f, is given by:

$$f(Q|\theta) = (1/\theta_2)\ [1 - \theta_3(Q - \theta_1)/\theta_2]^{(1/\theta_3) - 1} \exp\{- [1 - \theta_3(Q - \theta_1)/\theta_2]^{(1/\theta_3)}\} \qquad (2)$$

where Q is the annual maximum flood peak discharge and θ_1, θ_2, and θ_3 are the location, scale and shape parameters, respectively (Stedinger *et al.*, 1993). The parameters are treated as random variables and the uncertainty associated with them can be modelled, which allows calculation of credible intervals (Bayesian analogue to confidence intervals in frequentist statistics) for estimated flood quantiles. The width of the credible intervals is a measure of the combined information content of the data and the prior.

The derivation and the mathematical expressions for the systematic and historical likelihood contributions L_s and L_h in Equation 1 can be found in Neppel *et al.* (2010). A noteworthy property of these expressions is that they allow consideration of uncertainty in the annual flood peak values, which will be useful in this paper as described subsequently.

The posterior distribution in Equation 1 is multi-dimensional (3 GEV parameters) and, moreover, it depends on a normalization constant, N, that can be written as a complicated integral not soluble in closed form. To circumvent these difficulties, we employ the computationally attractive and straightforward Markov Chain Monte Carlo (MCMC) approach to simulate many GEV parameters from the posterior distribution in Equation 1. The details of the MCMC algorithm used in this paper can be found in Renard *et al.* (2006). In turn, these many GEV parameter values can be transformed into many quantiles of given return period, from which credibility intervals or any other statistics (for example, mean or standard deviation) can be derived.

Where additional information is in the form of values of Q of given return period, T, the empirical Bayesian method of Kuczera (1983) is used to combine these values with an estimate, Q_a, from a systematic record or a combination of systematic, historical and prior information (on EV2 parameters) (Equation 1). For a single value, Q_1, the combined estimate, Q_{c1}, is given by:

$$Q_{c1} = s\, Q_1 + (1\text{-}s)\, Q_a \qquad (3)$$

in which s is the shrinkage factor and is

$$s = \text{var}(Q_a) \ / \ [\text{var}(Q_a) + \text{var}(Q_1)] \qquad (4)$$

where var is the variance. Finally, the prediction variance for Q_{c1} is:

$$\text{var}(Q_{c1}) = s\ \text{var}(Q_1) \qquad (5)$$

and the standard error of Q_{c1} is the square root of Equation 5. Equations 3, 4 and 5 may be used sequentially when more than one value of Q is supplied.

Application

The Bayesian inference method for combining a systematic site record of annual maximum flood peaks with additional records and data of various types is now demonstrated using a New Zealand case study. To provide focus in the case study, the selected objective is to estimate the magnitude of the 100 and 300-year return period flood peaks Q_{100} (annual exceedance probability of 0.01) and Q_{300} (annual exceedance probability of 0.0033), respectively, and their approximate standard errors.

The Waimakariri River at Old Highway Bridge (site number 66401; Walter, 2000) near Christchurch is the selected site. This wide, braided river poses the greatest flood hazard in New Zealand because of its size, potential to overflow and proximity to Christchurch. Moreover, there is a long systematic record at the site together with a wealth of additional information suitable for combination with this record.

Information sources

Systematic record

A continuous record of water level or stage for the Waimakariri River at Old Highway Bridge site is available for 49 years (1967-2015) and the stage-discharge rating curves are stable at the upper end. Nine floods exceeding 2,000 m^3/s occurred in the 49 years of record and six of these, including the three largest, were gauged. The series of annual maxima (Fig. 1) displays no trend, periodicity, persistence or shifts and the peaks are assumed to be independently and identically distributed (Griffiths *et al.*, 2011). The mean annual flood (MAF) is 1,460 m^3/s and the coefficient of variation (Cv) is 0.368 (Table 1). To allow for inaccuracies in the measurement of stage and in the rating in a simple way, an error of ±5% is associated with each flood peak.

Historic record

Stage records for the Gorge Bridge, some 53 km upstream of the Old Highway Bridge

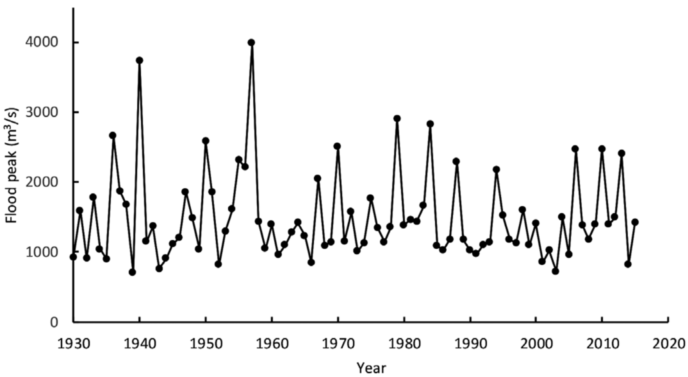

Figure 1 – Time series of annual maximum flood peak discharges for Waimakariri River at Old Highway Bridge (1930-2015)

Table 1 – Mean annual flood statistics for Waimakariri River at Old Highway Bridge.

Period	Record type	Record length	Mean annual flood (m^3/s)	Standard deviation (m^3/s)	Coefficient of variation (Cv)
1989-2003	Systematic	15	1208	355	0.294
1996-2015	Systematic	20	1395	514	0.369
1967-2015	Systematic	49	1460	537	0.368
1930-1966	Historical	37	1516	755	0.498
1930-2015	Systematic and historical	86	1484	636	0.429

(OHB), are available for 86 years (1930-2015). There are no significant inflows to the river channel between the two sites. A correlation between stage at Gorge and flow at OHB for all significant floods in the systematic record (1967-2015) allows estimation of the 37 annual maxima at OHB for 1930-1966 (Fig. 1). Flood waves propagate kinematically between the two sites and the wave velocity varies with rate of rise, formation of kinematic shocks (Goring, 1988) and initial flow conditions in the river channel. These effects produce scatter in the correlation, which is greater for smaller peaks. To allow for this scatter in a simple way, it is assumed from the correlation that flood peaks exceeding 1,500 m^3/s have an associated error of ±15% and those less an error of ±25%. The MAF for the historical record is 1,516 m^3/s and the Cv is 0.498 (Table 1) which is greater than the value for the systematic record because more larger floods occurred during the 1930-1966 interval (Fig. 1). For the combined record of 1930-2015, the MAF is 1,484 m^3/s and the Cv is 0.429 (Table 1).

A final point is that no paleohydrological evidence deducible from tree rings, slack water deposits, and the like (Stedinger *et al.*, 1993) is available for the Waimakariri River.

Regional analysis

Griffiths *et al.* (2011) extended earlier work by McKerchar and Pearson (1989) on flood frequency in the Canterbury region. Estimates of Q_{100} and Q_{300} and associated errors are readily obtained from their analysis; the values are Q_{100} = 4,150 ±1,080 m^3/s and Q_{300} = 5,120 ±1,490 m^3/s. Also, Griffiths and McKerchar (2016) developed flood frequency prediction relations for New Zealand in terms of mean basin elevation and average number of floods exceeding half the mean annual flood. From this analysis predicted values of Q_{100} and Q_{300} at the OHB site are 3,600 ±1,100 m^3/s and 4,350 ±1,520 m^3/s, respectively.

Rainfall-runoff model

Griffiths *et al.* (1989) calibrated a nonlinear rainfall-runoff routing model named RORB (Laurenson and Mein, 1985) for the Waimakariri River. This model predicts values of Q_{100} = 3,990 ±1,200 m^3/s and Q_{300} = 4,400 ±1,540 m^3/s at the OHB site.

For some basins, historical rainfall records are available and these may be used to generate flood peak values at a site by employing a rainfall-runoff model. Such records predating historical flood records are not available for the Waimakariri Basin.

Analogue basins

Analogue basins are defined as basins that have a similar hydrological response in regard to flood generation as a basin for which flood peak predictions are sought. To find analogue basins for the Waimakariri Catchment, we used Euclidean distance in characteristic space as a similarity measure (Robson and Reed, 1999) where the eight characteristic parameters chosen were catchment area, mean annual runoff, mean rainfall, mean elevation, main channel slope, drainage density, shape parameter (θ_3), and seven-day mean annual low flow per unit area (as a measure of basin storage). From this analysis eight basins were selected as analogues, with the following flow monitoring sites: Acheron at Clarence (62103), Waiau at Marble Point (64602), Hurunui at Mandamus (65104), Rakaia at Fighting Hill (68526), South Ashburton at Mt Somers (68806), Rangitata at Klondyke (69302), Ahuriri at South Diadem (71116) and Jollie at Mt Cook Station (71135).

The distribution of the values of θ_1, θ_2, and θ_3 for the analogue basins was found to be approximately normal and the three distributions were adopted as prior distributions in the application of Equation 1 to the OHB site.

Combination of information

Information from the various sources can be combined in various ways. Here, we select three versions of the systematic record each with eight combinations typical of what often occurs in practice where each combination involves a coupling of the systematic record with other information from one or more of the sources. Our objective is to show how the values of Q_{100} and Q_{300} and their standard errors and credible intervals vary from record to record and combination to combination and what this may imply.

The three systematic records chosen were the full record of 49 years (1967-2015), a 20-year record from 1996 to 2015 to illustrate the effect of shorter record length, and a 15-year record from 1989 to 2003 to show the effect on predictions of a period where no large floods occur (Fig. 1; Table 2). The eight combinations examined for each of the three systematic records are listed in Table 2.

Table 2 – Combinations of systematic and additional information examined for Waimakariri River at Old Highway Bridge. Q_{100} and Q_{300} estimates and their standard errors are calculated for each combination for systematic records: 1967-2015, 1996-2015 and 1989-2003.

Combination number	Description
1	Systematic record with a ±5% error in each peak value. Error allowance applies in all other combinations.
2	Systematic record plus historical (1930-1966) with ±25% error for peaks <1500 m^3/s and ±15% for peaks >1500 m^3/s. Error allowance applies in all other combinations.
3	Systematic record plus the 2 largest peaks in the historic record (1930-1966).
4	Systematic record plus the 3 peaks >2600 m^3/s in the historical record (1930-1966).
5	Systematic record plus prior distributions for θ_1, θ_2 and θ_3 from analogue basins.
6	Systematic record plus historical record (1930-1966) plus prior distributions for θ_1, θ_2 and θ3.
7	Systematic record plus three estimates each of Q_{100} and Q_{300} and their standard errors from regional analyses and rainfall-runoff modelling.
8	Systematic record plus historical (1930-1966) plus prior distributions plus regional and model estimates; i.e., all information.

Equations 1 and 2 were used to calculate Q_{100} and Q_{300} and their standard errors for Combinations 1 to 6 (Table 2) and Equations 3, 4 and 5 for Combinations 7 and 8. In Combination 7, Q_a was supplied from Combination 1 and in Combination 8, Q_a was supplied from Combination 6.

Results

Predicted values of Q_{100} and Q_{300} and their standard errors for the combinations in Table 2 and the three systematic records (1967-2015, 1996-2015 and 1989-2003) are listed in Table 3. We take the most informed estimates of Q_{100} and Q_{300} to be those of Combination 8 for the full systematic record (1967-2015) (Table 3). The values are 4,010 ±510 m^3/s and 4,860 ±750 m^3/s, respectively, and these are adopted as the standards for comparisons.

Looking at Q_{100} estimates first, for Combination 1 (Table 3 and Fig. 2) the three estimates range from 2520 to 3710 m^3/s and the standard errors increase substantially from the full systematic record in the 1989-2003 and 1996-2015 records. Addition of the historical flood record in Combination 2, which contains two larger peaks, increases the standard error slightly for the full record and markedly for the 1989-2003 record, which contains no very large floods. The increase in the latter standard error here is expected statistically but may be concerning to the hydrologist; on the other hand it provides valuable knowledge about the extreme flood magnitudes in the basin.

Combinations 3 and 4 demonstrate that if only the largest peaks in the historical record are included then reasonable estimates of Q_{100} are obtainable, albeit with much larger errors in the cases of the 1996-2015 and 1989-2003 records. In combination 5, the addition of regional values of EV2 parameters has the effect of reducing Q_{100} estimates and standard errors for all three systematic records.

Combination 6, which is Combinations 2 and 5 together, is more variable than just Combination 5 because of the introduction of the full historical record and this has a significant influence on the estimates from the 1989-2003 systematic record in particular (Fig. 3).

With the addition of information from modelling and regional analyses in Combination 7, all estimates of Q_{100} and the associated standard errors are similar and lead to nearly the same result in Combination 8 (Fig. 4).

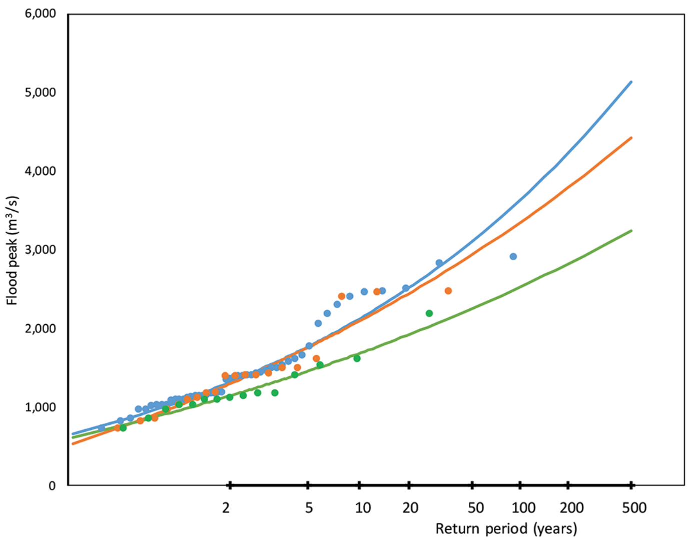

Figure 2 – Systematic records of annual maxima at Waimakariri River at Old Highway Bridge fitted by GEV distributions (Combination 1, Table 2) (blue: 1967-2015; orange: 1996-2015; green: 1989-2003).

The results for the Q_{300} estimates (Table 3, Fig. 5) exhibit similar behaviour to those of the Q_{100} but with larger differences between the three systematic records and larger standard errors, which is to be expected with the larger extrapolations involved.

The overall conclusion to be drawn from the results is that the effect of combining additional information with all three versions of the systematic record is to narrow the range of the Q_{100} and Q_{300} estimates and their standard errors; that is, the uncertainty of the predictions reduces. This result conforms to statistical expectations and is consistent with previous studies (see, for example, Payastre *et al.*, 2011; Viglione *et al.*, 2013).

Finally, the results in Table 3 are based on stationary records. If they are to be employed for prediction then potential changes that may introduce a trend or trends in the annual maxima need to be considered. Changes in flood regime can arise in many ways and result from, for instance, changes in climate, land use and in a river system itself (Griffiths *et al.*, 2009; Viglione *et al.*, 2016; Parkes and Demeritt, 2016). Trends can be treated using, for example, Bayesian methods (Renard *et al.*, 2006).

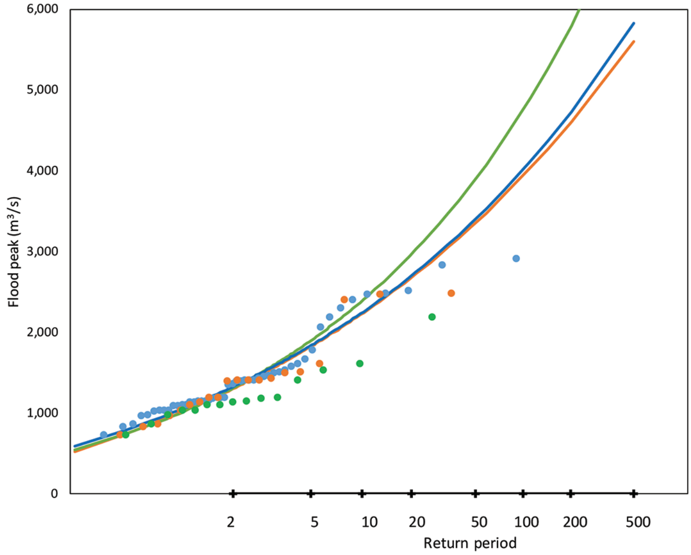

Figure 3 – GEV distributions for Waimakariri River at Old Highway Bridge combining systematic records, historical data (1930-1966) and prior distributions for GEV parameters (Combination 6, Table 2) (blue: 1967-2015; orange: 1996-2015; green: 1989-2003).

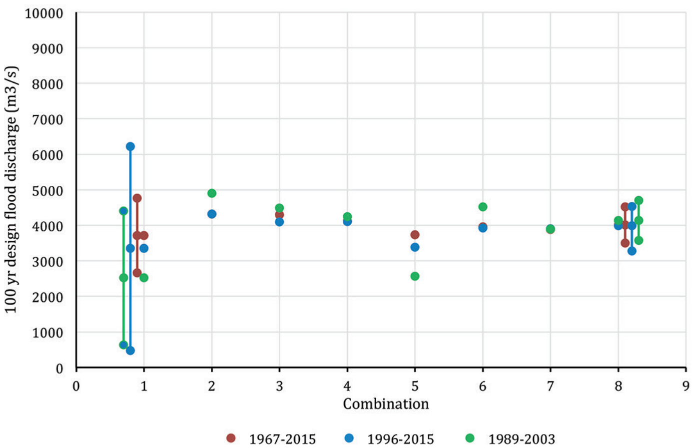

Figure 4 – Predicted values of 100-year return period peak discharge for different combinations (Table 2) of systematic and other information for Waimakariri River at Old Highway Bridge. Vertical lines for Combinations 1 and 8 are estimates of standard errors.

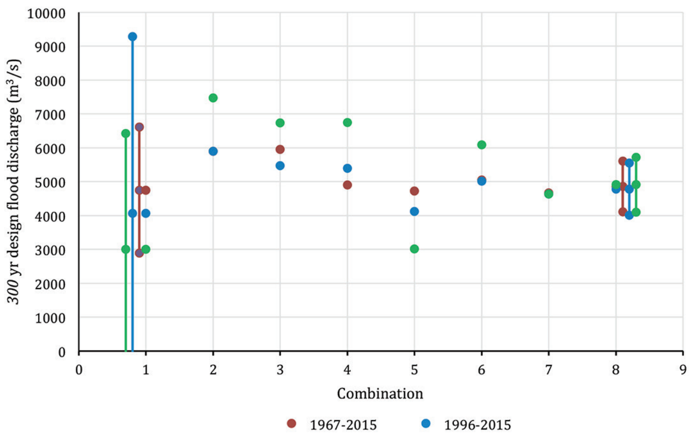

Figure 5 – Predicted values of 300-year return period peak discharge for different combinations (Table 2) of systematic and other information for Waimakariri River at Old Highway Bridge. Vertical lines for Combinations 1 and 8 are estimates of standard errors.

Table 3 – Prediction of Q_{100} and Q_{300} values and standard errors from combinations of systematic and other information for the Waimakariri River at Old Highway Bridge (see Table 2 for combination descriptions).

Systematic record	Combination	Return period (yrs)	Flood peak (m^3/s)	Standard error (m^3/s)	Standard error (%)
1967-2015	1	100	3710	1050	28
(Full record)		300	4750	1860	39
	2	100	4320	1220	28
		300	5900	2260	38
	3	100	4300	1050	24
		300	5950	1860	31
	4	100	4120	1050	24
		300	4900	1860	31
	5	100	3730	740	20
		300	4720	1270	27
	6	100	3960	830	21
		300	5050	1430	28
	7	100	3880	550	14
		300	4670	790	17
	8	100	4010	510	13
		300	4860	750	16
1996-2015	1	100	3350	2870	86
(Short record)		300	4060	5220	129

Table 3 continued

Systematic record	Combination	Return period (yrs)	Flood peak (m^3/s)	Standard error (m^3/s)	Standard error (%)
1996-2015	2	100	4320	1970	45
(Short record)		300	5900	3910	66
	3	100	4100	2600	58
		300	5470	5890	108
	4	100	4110	1840	45
		300	5400	3500	65
	5	100	3390	950	28
		300	4120	1550	38
	6	100	3930	950	24
		300	5020	1660	33
	7	100	3910	630	16
		300	4640	860	19
	8	100	3990	540	14
		300	4780	770	16
1989-2003	1	100	2520	1880	74
(No large floods)		300	3000	3420	110
	2	100	4900	3410	70
		300	7470	7730	103
	3	100	4490	2770	62
		300	6740	5970	88
	4	100	4240	2110	50
		300	6750	4250	70
	5	100	2570	730	28
		300	3010	1220	41
	6	100	4520	1110	25
		300	6090	2100	34
	7	100	3890	610	16
		300	4630	850	19
	8	100	4140	560	14
		300	4910	810	17

Future work

Refinement of the Bayesian inference approach is desirable in at least three areas. First, the handling of uncertainty in the peak discharge data (Neppel *et al.*, 2010; Le Coz *et al.*, 2014), selection of probability density functions and estimation of PDF parameters. A generalisation of the Bayesian method using, for instance, Dempster-Shafer theory is a possible approach (Qi *et al.*, 2016) in treating PDF uncertainties. Second, investigation of sources of additional information in New Zealand ought to be undertaken, notably paleohydrological estimates of flood peak and time of occurrence, and historical statements about floods that might be able to be included in analyses using a fuzzy Bayesian approach (Salinas *et al.*, 2016). Third, application of the Bayesian approach to other appropriate sites should lead to improved flood frequency estimates for at-site, regional and national analyses.

Conclusions

Combination of a systematic record of annual maxima with other information to predict flood quantiles may be readily achieved using a Bayesian MCMC inference approach.

In the Waimakariri River case study, the annual maxima of 49 years of systematic record are stationary and identically distributed. Combination of this record with other independent information yields predictions of Q_{100} and Q_{300} with reducing standard errors as more information is included. This result applies even with a short systematic record of 15 years having no large floods.

Application of the Bayesian inference approach should generally provide improved estimation of flood quantiles with less uncertainty for at-site, regional and national studies. Further work on other possible sources of information is desirable, notably paleohydrological investigations.

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