FLOOD ESTIMATION — A REVISED DESIGN PROCEDURE

Charles P Pearson*, BSc(Hons) MSc(Hons)
Alistair I McKerchar*, BE(Hons) PhD

Contour maps of a specific discharge factor and a flood frequency factor are presented. The maps are based directly on measured discharge series from a large sample of river recording stations. The two parameter EV1 distribution was found to be sufficient for New Zealand's flood frequency purposes. Thus when basins are ungauged, an estimate of a design flood with specified return period can be obtained by using the two maps. These maps provide the basis for a design procedure that improves on the Beable and McKerchar (1982) regional method. Where there is a short record, a procedure for pooling the map estimate with the data is given, and is illustrated with an example.

Keywords: *flood frequency — regional estimation — extreme value distributions — contour maps*

1. INTRODUCTION

The Beable and McKerchar (1982) regional flood estimation (RFE) procedure was based on annual flood peak data up until 1978 (160 sites, 2662 station years). With the additional 10 years of data available since that study, a revised flood estimation method for New Zealand using contours on maps has been developed. It is the result of a comprehensive study of both flood peak data for gauged catchments (343 sites, 6324 station years) and criticisms of RFE procedures. The revised method uses data up to the end of 1987, though in some cases the series is complete to 1986 or 1988, and its development is described in the report by McKerchar and Pearson (1989). This paper explains its application and is a brief presentation of the procedure. The paper parallels the McKerchar and Beable (1983) paper on the RFE method.

From flood frequency analyses of 275 annual maxima flood series of length 10 or more years, the two parameter extreme value type 1 (EV1 or Gumbel) distribution was found to be sufficient for most records for New Zealand. This is an attractive finding, because it means that once two statistics are specified for any catchment in the country, the EV1 distribution can be used with confidence for design flood estimation. The two statistics used are a specific discharge factor which is used to dimensionalise a Gumbel plot, and a flood frequency factor which relates to the slope of a Gumbel plot. Values of these two factors for any catchment in the country are obtained from contour maps. Seismic design loadings for earthquake engineering are presented in a similar way (Matuschka et al, 1985).

For ungauged catchments the revised method uses information from contour maps only to provide flood peak estimates with specified return periods. For gauged catchments the revised method pools map estimates with those from at-site analyses to give more reliable estimates.

2. OUTLINE OF THE REVISED METHOD

Conventional regional flood frequency methods, as applied in Beable and McKerchar (1982), use catchment mean rainfall statistics, and require that "homogeneous" regions be defined. We found that for a significant number of catchments the density of raingauges was too sparse to develop satisfactory rainfall statistics, and that maps of the flood statistics suggested smooth changes from place to place, rather than regional homogeneity.

The revised method makes use of two factors estimated from measured annual flood discharge data and then contoured on maps. One factor is a "specific discharge" $\bar{Q}/A^{0.8}$ where $\bar{Q}$ is mean annual flood (m^3/s) and A is catchment area (km^2). The other is a flood frequency factor q_{100}, which is the ratio of the 100 year return period flood Q_{100} to $\bar{Q}$. From the contour maps, values of $\bar{Q}/A^{0.8}$ and q_{100}, and the EV1 theory, facilitate estimates of Q_T, where T is return period in years, the reciprocal of annual exceedance probability. Formulae are provided for evaluating the precision of a map estimate of Q_T, and for pooling a map and an at-site estimate, and for evaluating the precision.

3. APPLICABILITY

The method is applicable to all catchments in the country except those in which snowmelt, glaciers, lake storage, ponding or urban development significantly affect the flood peak characteristics. Areas of catchments used in developing the maps ranged from 0.014 km^2 to 6350 km^2, but less satisfactory results were obtained for small (less than 10 km^2) catchments. We postulate that this is because stage/discharge rating curves for weirs and flumes on many small catchments are not reliable in floods because the curves have to be extrapolated beyond the range permissible by theory, and it is difficult to make direct measurements of flood discharges to guide the extrapolations. The method does not predict the effects of forest cover on flood peak.

We checked 13 records of more than 50 years length for trends in annual flood peaks. As we found no convincing evidence of trends, we assume that the flood series are stationary, and independent from year to year.

4. SPECIFIC DISCHARGE FACTOR

The mean annual flood $\bar{Q}$ was estimated for 343 annual maxima

**Hydrology Centre, DSIR Marine and Freshwater, Christchurch.*

This paper was first received on June 26, 1989. It was received for publication in revised form on September 18, 1989.

flood series from around the country. $\bar{Q}$ is the arithmetic mean of each series. That is,

$$\bar{Q} = [Q_1 + Q_2 + \ldots + Q_n] / n \qquad 1$$

where $Q_1, Q_2, \ldots, Q_n$ are individual annual flood peaks and n is the length of record. The sample variance of $\bar{Q}$ is the usual standard deviation estimator squared and divided by n.

A log-log plot of $\bar{Q}$ against catchment area A (Fig 1) had a least squares slope of 0.8. The specific discharge factor $\bar{Q}/A^{0.8}$ was entered on a map of New Zealand at the centroid of each catchment. Contours of $\bar{Q}/A^{0.8}$ are shown in Fig 2. The map estimator for $\bar{Q}$ is obtained by reading from the contour map the catchment mean value of $\bar{Q}/A^{0.8}$ and multiplying by $A^{0.8}$. The map prediction standard error for $\bar{Q}$ is ±22%. By comparison, Beable and McKerchar (1982) $\bar{Q}$ errors averaged ±30%.

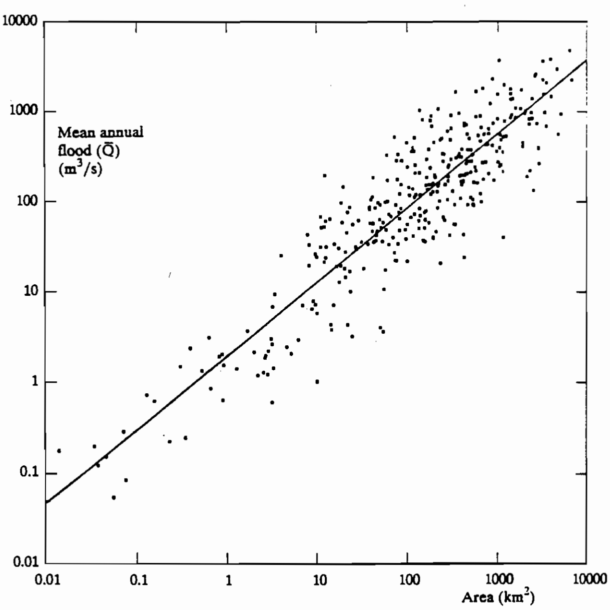

FIGURE 1: Plot of mean annual flood versus catchment area. The fitted straight line has the equation $\bar{Q} = 2.04\ A^{0.808}$.

5. FLOOD FREQUENCY FACTOR

The 100 year return flood peak Q_{100} was estimated for 275 annual maxima series with length of 10 or more years from around the country. In the majority of cases (228 series) the EV1 distribution gave satisfactory at-site flood frequency results. The test used (McKerchar and Pearson, 1989) distinguishes the EV1 distribution from the alternative three parameter EV2 and EV3 distributions which respectively are curved upward and downward on Gumbel probability paper. Australian and North American practice is to use the empirical three parameter log Pearson type 3 distribution, which gives results that are similar to those from the EV2 or EV3 distributions.

The method of probability weighted moments (PWM) was used to fit the EV1 distribution to the annual series (Phien, 1987). The resulting at-site EV1/PWM estimate for Q_T is given by,

$$Q_T = 1.8327\ \bar{Q} - 1.6654\ \text{PWM} + [2.8854\ \text{PWM} - 1.4427\ \bar{Q}]\ y_T \qquad 2$$

where y_T is the Gumbel reduced variate,

$$y_T = -\ln[-\ln(1 - 1/T)] \qquad 3$$

and PWM is the first probability weighted moment defined by,

$$\text{PWM} = [Q_2 + 2Q_3 + 3Q_4 \ldots + (n\text{-}1)Q_n] / [n(n\text{-}1)] \qquad 4$$

where $Q_1 \leqslant Q_2 \leqslant Q_3 \leqslant \ldots \leqslant Q_n$ are the ordered individual flood peaks. The sample variance of Q_T is,

$$\text{var}(Q_T) = (2\text{PWM}\text{-}\bar{Q})^2\ [(2.3161n\text{-}1.8870) - (0.9520n - 2.4398)\ y_T + (1.6747n - 0.3861)\ y_T^2] / [n\ (n\text{-}1)] \qquad 5$$

From equation 2, Q_{100} was obtained for the satisfactory EV1 sites and divided by $\bar{Q}$ to give the flood frequency factor q_{100}. For the remaining 47 series, 32 showed EV2 tendencies, that is the data suggested a distribution that curved upward on a Gumbel probability plot, and 15 showed EV3 tendencies. There was some possible grouping of EV3 sites on the West Coast of the South Island, but the groupings of EV2 sites on rivers draining the drier East Coast of the South Island and pumice regions in the North Island were more pronounced. We postulate that this occurs because dry years contain only a few minor flood events, and hence the requirements of the extreme value theory for the EV1 distribution are not satisfied (Leadbetter et al, 1983). Biennial time partitioning for selecting flood peaks generally worked because it provides samples more in accord with the requirements of the theory. The number of EV3 sites (15) is somewhat more than the seven we expect from a sample of 275 if New Zealand flood series all derive from EV1 distributions and we use 95% confidence limits. However, in practice, the biases incurred in applying the EV1 distribution to the 15 EV3 records were small, and their Gumbel plots looked acceptably EV1.

The Q_{100} estimates were divided by $\bar{Q}$ to give q_{100}. Each q_{100} value was entered on a map of New Zealand at the centroid of each catchment. Contours of q_{100} are shown in Fig 3. The map estimator for q_{100} is obtained by reading off the contour map value of q_{100}. The map prediction standard error for q_{100} is ≤17%. By comparison, Beable and McKerchar (1982) q_{100} errors averaged ≤20%.

6. MAP ESTIMATION OF Q_{100} AND ITS PREDICTION ERROR

The contour map estimate for the 100 year flood peak Q_{100} for any catchment in the country is obtained by using the contour $\bar{Q}$ and q_{100} estimates from maps (Figs 2 & 3) and combining them to give,

$$Q_{100} = \bar{Q}\ q_{100} \qquad 6$$

Provided estimates of $\bar{Q}$ and q_{100} are independent, the variance of Q_{100} can be written as,

$$\text{var}(Q_{100}) = q_{100}^2\text{var}(\bar{Q}) + \bar{Q}^2\text{var}(q_{100}) + \text{var}(\bar{Q})\ \text{var}(q_{100}) \qquad 7$$

When $\bar{Q}$ and q_{100} are estimated from the maps, their prediction standard errors are ±22% and ±17% respectively, so that equation 7 yields,

$$\begin{aligned}\text{var}(Q_{100}) &= q_{100}^2(0.22\bar{Q})^2 + \bar{Q}^2(0.17q_{100})^2 + (0.22\bar{Q})^2(0.17q_{100})^2 \\ &= [0.281\ \bar{Q}\ q_{100}]^2\end{aligned}$$

and so the prediction standard error of estimate for Q_{100} from the maps is ±28%.

7. RETURN PERIODS OTHER THAN 100 YEARS

The contour map estimate for the T year flood peak Q_T, where T is

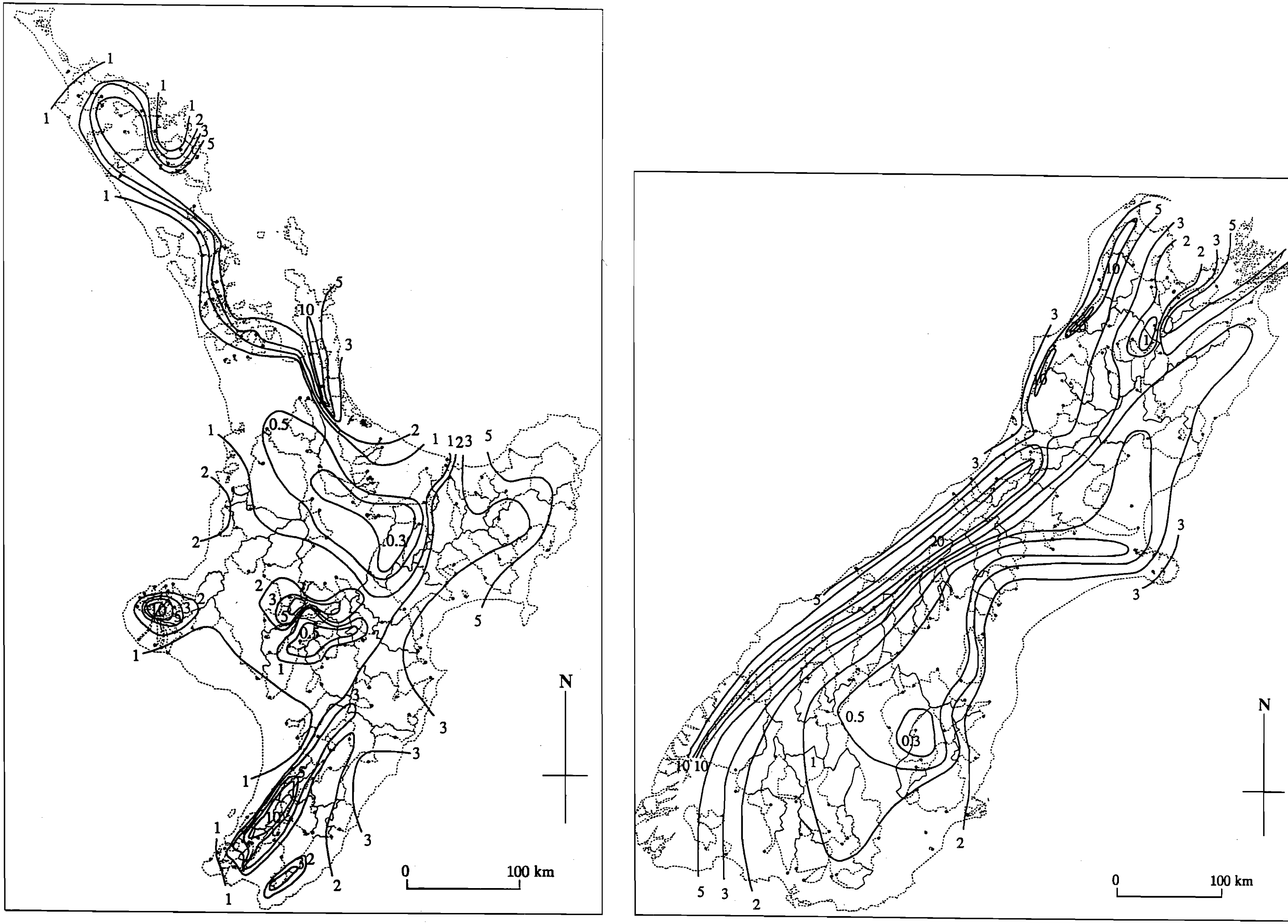

FIGURE 2: Contour maps of specific discharge factor $\bar{Q}/A^{0.8}$ for New Zealand. The contours have been fitted by eye to $\bar{Q}/A^{0.8}$ values located mostly at the centroids of catchments. Standard error of estimate of $\bar{Q}$ from the maps is $\pm$ 22%. Dots show location of recorder stations, and catchment boundaries and coastlines are dotted.

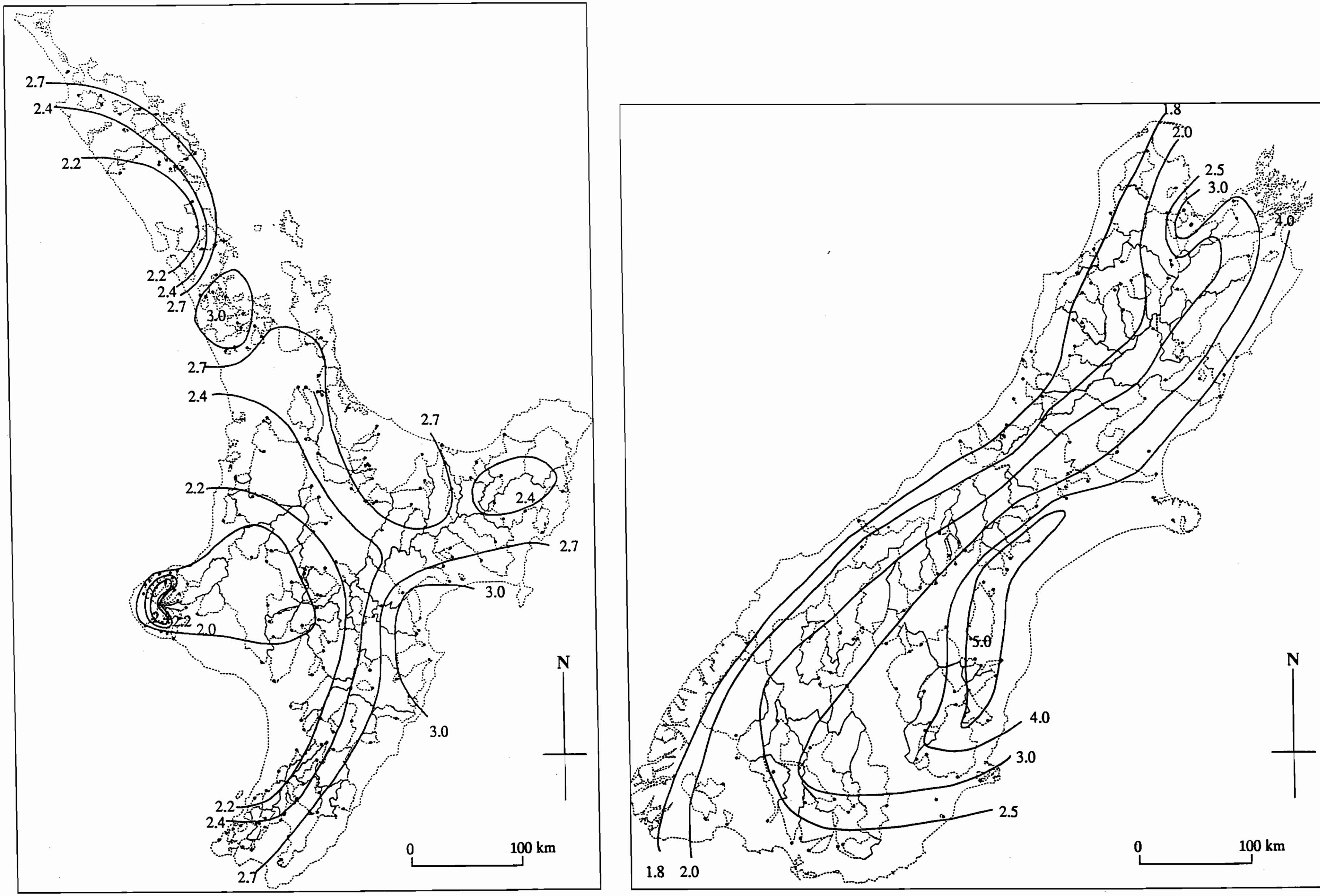

FIGURE 3: Contour map of flood frequency factor q_{100} for New Zealand. The contours have been fitted by eye to $q_1{}^0{}_0$ values located mostly at the centroids of catchments ($q_{100} = Q_{100}/\bar{Q}$, with Q_{100} estimated by EV1/PWM analysis). Standard error of estimate of q_{100} from the maps is ± 17%. Dots show location of recorder stations, and catchment boundaries and coastlines are dotted.

other than 100 years, for any catchment in the country is obtained by using the contour $\bar{Q}$ and q_{100} estimates from maps (Figs 2 & 3) and combining them to give,

$$Q_T = \bar{Q}[x_T + (1 - x_T)q_{100}] \qquad 8$$

where

$$x_T = 1.1435 - 0.2486\, y_T \qquad 9$$

and y_T is the Gumbel reduced variate (equation 3). From equation 8, the quantity $Q_T/\bar{Q}$ is shown for a range of q_{100} and T values in Figure 4.

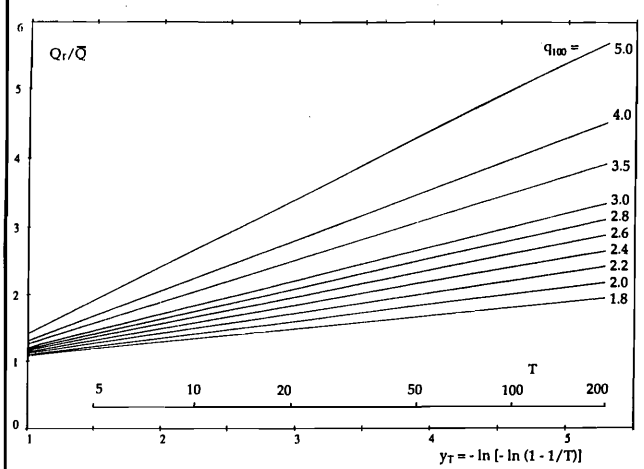

FIGURE 4: Graph of $Q_T/\bar{Q}$ versus y_T and T for q_{100} ranging from 1.8 to 5.0.

From equations 8 and 9 the prediction variance for Q_T is,

$$var(Q_T) = x_T^2 var(\bar{Q}) + (1-x_T)^2 var(Q_{100}) \qquad 10$$

and when $\bar{Q}$ is estimated from the contour maps this becomes,

$$var(Q_T) = x_T^2[0.22\bar{Q}_{map}]^2 + (1-x_T)^2[0.281\, \bar{Q}_{map}\, q_{100,map}]^2 \qquad 11$$

Hence the prediction standard error of estimate for Q_T is the square root of this equation. The percentage standard error of Q_T estimated from the maps alone (Figs 2 & 3) ranges from 17 to 19% for T = 5 years, to 29 to 30% for T = 200 years.

8. COMBINATION OF AT-SITE AND MAP ESTIMATORS

In design situations where there are some annual maxima flood data available for a site, it is possible to combine the at-site and map estimators to provide pooled estimators for $\bar{Q}$ and Q_T. For the statistic Q (either $\bar{Q}$ or Q_T), we assume there is an at-site estimate Q_{site} and a map estimate Q_{map} available, both with variances $var(Q_{site})$ and $var(Q_{map})$. Assuming that these estimates are normally distributed, then the pooled estimate is an empirical Bayes estimate (Kuczera, 1983). It is,

$$Q_{pool} = s\, Q_{map} + (1-s)Q_{site} \qquad 12$$

where s, called the shrinkage factor (Kuczera 1983) is defined by,

$$s = var(Q_{site}) / [var(Q_{site}) + var(Q_{map})] \qquad 13$$

and the prediction variance for the pooled estimate is,

$$var(Q_{pool}) = s\, var(Q_{map}) \qquad 14$$

Therefore the prediction standard error for the pooled estimate Q_{pool} is the square root of equation 14. Equation 14 shows the meaning of the term "shrinkage"; s is the ratio of the final variance [$var(Q_{pool})$] over the initial variance [$var(Q_{map})$], and this reduction is achieved through use of data recorded at the site.

To facilitate pooling, as well as the map variance estimates (which we have), we need the at-site variance estimates. The at-site variance estimate for Q_T is given by equation 5. For $\bar{Q}_{site}$ it is the sample variance of the annual maxima series divided by n the length of the series. For $n \leq 5$ this has low reliability. It is recommended in this case that the $\bar{Q}$ and q_{100} contour values are extracted from the maps (Figs 2 & 3) and used with the method of moments estimation procedure for the EV1 distribution (Phien, 1987) to give the alternative $var(\bar{Q}_{site})$,

$$var(\bar{Q}_{site}) = 0.1017\, \bar{Q}_{map}^2\, (q_{100,map} - 1)^2/n \qquad 15$$

9. METHOD OF APPLICATION

The steps in an application of the revised method are as follows:

(1) Decide on the return period T of the flood. The choice of return period depends on factors such as the expected life and cost of the structure and the consequences of exceedance.

(2) Collect all the annual flood peak data for the catchment (n years). This entails cross checking that the largest events are included in the record of years which have parts of the record missing and that the stage/discharge rating curve has been extrapolated to high discharges in a consistent manner (see McKerchar and Henderson, 1987).

(3) For the ungauged catchment case (n = 0) the contour maps must be used on their own to estimate Q_T: $\bar{Q}/A^{0.8}$ is read from Fig 2 and multiplied by $A^{0.8}$ (A in km^2) to give the map $\bar{Q}$ estimate ($\bar{Q}_{map}$) in m^3/s. The variance of this estimate is $(0.22\bar{Q})^2$, and hence its standard error (se) is $\pm$ 22%. The flood frequency factor q_{100} is read from Fig 3. $\bar{Q}$ and q_{100} are combined as in equation 8 to give the design flood peak estimate Q_T. Its variance is given by equation 11.

(4) For less than 10 years of at-site data ($n < 10$) there is some data available, but not enough to perform an at-site flood frequency analysis. The map $\bar{Q}$ and q_{100} estimates are obtained as in (3) above. The at-site estimator for $\bar{Q}$ is the usual arithmetic mean (equation 1). $\bar{Q}_{site}$'s variance is the usual sample variance divided by n, if $n > 5$, and equation 15 if $n \leq 5$. The two $\bar{Q}$ estimates are pooled as in equations 12 to 14. $\bar{Q}_{pool}$ is used with q_{100},map as in equation 8 to give the design flood peak estimate Q_T, and its variance is given by equation 10.

(5) For 10 or more years of at-site data ($n \geq 10$) there is enough data to perform an at-site flood frequency analysis. The map Q_T and its variance are obtained as in (3) above. The site Q_T estimate and its variance are obtained from an EV1/PWM analysis (Section 5) of the available annual maxima (equations 2 to 5). The two Q_T estimates are pooled as in equations 12 and 13. $Q_{T,pool}$ is the design flood peak; its variance is given by equation 14.

10. EXAMPLE

The Branch River (station number 60112) is a tributary of the Wairau River in the northern South Island. Catchment area is 551 km^2 and elevation ranges from 400 m to 2200 m. This station was not used in preparing the flood estimation contour maps because the channel aggrades and degrades frequently, flood gaugings were few, and stage/discharge ratings were not available. All the stage/time records and gauging data were recently supplied to S M Thompson by the Marlborough Catchment Board and he prepared stage/discharge rating curves for estimating flood magnitudes (Fig 5). The shifts in these ratings are typical of many New Zealand gravel bed rivers. With the methods of Ibbitt and Pearson (1987), we can state with 90% confidence that all the shifts in ratings, implying mean bed level changes of 100 mm or more, have been detected. Therefore we have reasonable confidence in the flood discharge series. The annual maxima discharge obtained with these ratings were:

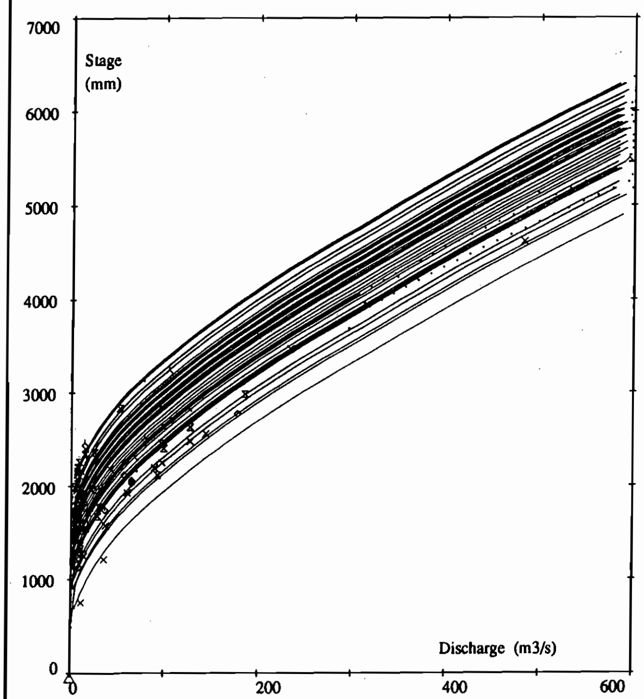

FIGURE 5: Branch River stage/discharge rating curves prepared by S M Thompson. An outline of the procedures and computer software used to prepare these curves is in McKerchar and Henderson (1987).

Date (yymmdd)	*Peak discharge (m3/s)*	*Date (yymmdd)*	*Peak discharge (m3/s)*
590918	252	710513	427
600311	151	721008	450
610305	286	731121	420
621024	603	740405	783
630529	538	750401	721
640108	542	760127	507
651118	320	770119	317
660409	324	780514	551
670810	717	790507	383
680409	950	800816	243
690911	555	811006	360
700917	483	820522	250

Three scenarios for estimating the 50 year return period flood for the Branch are used to illustrate the application of the procedure: no data for the station; just five years of record 1959-1963; and the full record of 24 years 1959-1982.

The following information is first compiled: A = 551 km^2, $\bar{Q}/A^{0.8}$ = 2.6 (Fig 2), q_{100} = 2.4 (Fig 3), y_{50} = 3.90 (equation 3), x_{50} = 0.174 (equation 9), and $Q_{50}/\bar{Q}$ = 2.16 (from either Fig 4 or a rearrangement of equation 8).

Case 1: No data

From the above data $\bar{Q}_{map}$ = 2.6 x 551$^{0.8}$ = 405 m^3/s and from Section 4, the ± 22% standard error for $\bar{Q}_{map}$ implies that var($\bar{Q}_{map}$) = (0.22 x 405)^2 = 7940. The map or "no data" design flood peak estimate is $Q_{50,map}$ = 405 x 2.16 = 875 m^3/s. From equation 11, var($Q_{50,map}$) = 0.174^2 (0.22 x 405)^2 + (1-0.174)^2 (0.281 x 405 x 2.4)^2 = 51100 and so the prediction error of $Q_{50,map}$ is ± 26%. The frequency curve inferred from these results is shown dashed in Fig 6.

Case 2: Five years of record 1959-1963

From the first five years of record, $\bar{Q}_{site}$ = 366 m^3/s. Since n ≤5, the variance of $\bar{Q}_{site}$ is estimated using equation 15: var($\bar{Q}_{site}$) = 0.1017 x 405^2(2.4 - 1)^2 / 5 = 6540. The $\bar{Q}_{site}$ estimate is combined with the map estimate $\bar{Q}_{map}$ from Case 1 above to get a pooled estimate of $\bar{Q}$, using equations 12 and 13. First from equation 13, s = 6540 / (6540 + 7940) = 0.452, and then with equation 12, $\bar{Q}_{pool}$ = 0.452 x 405 + (1 - 0.452) x 366 = 384 m^3/s and var($\bar{Q}_{pool}$) = 0.452 x 7940 = 3590 (equation 14), so that $\bar{Q}_{pool}$'s standard error is ± 16%. Finally, the design flood peak estimate is Q_{50} = $\bar{Q}_{pool}$ Q_{50}/Q = 384 x 2.16 = 829 m^3/s, where $Q_{50}/\bar{Q}$ is from Fig 4. To estimate var(Q_{50}), we first require var(Q_{100}). From equation 7, using $\bar{Q}$ = 384 and var($\bar{Q}$) = 3590, var(Q_{100}) = 46300, so that from equation 10, var(Q_{50}) = 31700 and hence Q_{50}'s standard error is ± 21%.

Case 3: Full record 1959-1982

In this case the map estimate $Q_{50,map}$ from Case 1 is combined with the $Q_{50,site}$ obtained from frequency analysis of the 24 years of record. EV1/PWM at-site flood frequency analysis (equations 2 to 5) of the annual maximum provides an excellent Gumbel plot (Fig 6). The analysis gives $\bar{Q}_{site}$ = 464 m^3/s, PWM = 287, $Q_{50,site}$ = 994 m^3/s with var($Q_{50,site}$) = 12800 and so $Q_{50,site}$'s standard error is ± 11%. Combining the variances from the map and site estimates in equations 13 and 14, s = 0.203 and var($Q_{50,pool}$) = 10200. Hence the design flood peak estimate from equation 12 is $Q_{50,pool}$ = 970 m^3/s and its standard error is ± 10%.

TABLE 1 Summary of Branch River results

	Case 1 (n = 0)	*Case 2 (n = 5)*	*Case 3 (n = 24)*
$\bar{Q}_{map}$	405±22%	405±22%	405±22%
$\bar{Q}_{site}$	–	366±22%	464±9%
$\bar{Q}_{pool}$	–	384±16%	–
$Q_{50,map}$	875±26%	875±26%	875±26%
$Q_{50,site}$	–	–	994±11%
$Q_{50,pool}$	–	829±21%	970±10%

In summary, the results (Fig 6 and Table 1) show good agreement: $Q_{50,map}$ differs from $Q_{50,site}$ (from 24 years of record) by 119 m^3/s (12%), despite the shifts in the rating curves. Note however that the standard error of estimate for $Q_{50,map}$ is ± 26%. Combination of the five years of record with the map estimate (Case 2) gives a relatively low $Q_{50,pool}$ = 829 m^3/s (± 21%). This occurs through inclusion of the first five years of record which has a low $\bar{Q}_{site}$ = 366 m^3/s, compared with $\bar{Q}_{site}$ = 464 m^3/s for the full record of 24 years. With 24 years of record, $Q_{50,site}$ is 994 m^3/s ± 11%, and pooling this estimate with $Q_{50,map}$ gives $Q_{50,pool}$ = 970 m^3/s ± 10%. Thus with 24 years of record only a modest reduction in standard error occurs when the map or regional information is incorporated, which is intuitively reasonable.

11. CONCLUSION

The extreme value type 1 (EV1 or Gumbel) distribution fitted 228 of the 275 annual maxima series (of length 10 or more years) satisfactorily. Of the remaining 47 series, 32 showed EV2 tendencies, but the EV1 distribution satisfactorily fitted the biennial maxima series. EV1 Gumbel plots for the remaining 15 records which showed EV3 tendencies were judged satisfactory. Many of the series with annual maxima showing EV2 tendencies were from rivers draining drier regions which did not experience several floods each year. The EV1 distribution has a supporting theory and its continued use for flood frequency analysis is recommended.

The EV1 distribution can be specified by the quantities $\bar{Q}/A^{0.8}$ and q_{100} (= $Q_{100}/\bar{Q}$). Contours of these quantities drawn on maps enable estimation of the flood frequency regime for any river without records. Although the maps for $\bar{Q}/A^{0.8}$ reflect patterns of rainfall shown on maps of mean rainfall and rainfall intensity, they appear to provide more robust flood estimates than is possible from methods which first require estimation of catchment mean rainfall statistics.

12. ACKNOWLEDGEMENT

We appreciate the willing assistance we received from staff of Catchment Authorities and the DSIR Water Resources Survey in providing and assembling the sets of data used in this study. Examination of many rating curves has demonstrated to us the very considerable efforts made by these staff to gauge rivers in flood. The Marlborough Catchment Board is thanked for providing data for the Branch River. Dr S M Thompson initiated many stimulating discussions from which we have benefitted. Ms K M Walter and Mr P D Hutchinson helped us by using POLAR software to prepare the contour maps.

13. REFERENCES

Beable M E and McKerchar A I (1982): *Regional flood estimation in New Zealand*. Water & Soil Tech. Publ. 20, Ministry of Works and Development, Wellington, 139p.

Ibbitt R P and Pearson C P (1987): Gauging frequency and detection of rating changes. *Hydrol. Sci. J. 32(1)*:85-103.

Kuczera G (1983): Effect of sampling uncertainty and spatial correlation on an empirical Bayes procedure for combining site and regional information. *J.Hydrol. 65*: 373-398.

Leadbetter M R, Lindgren G, Rootzen H (1983): *Extremes and related properties of random sequences and processes*. Springer-Verlag, New York.

Matuschka T, Berryman K R, O'Leary A J, McVerry G H, Mulholland W M and Skinner R I (1985): *New Zealand seismic hazard analysis*. Bulletin NZ Nat. Soc. Earthquake Engineering 18(4):313-322

McKerchar A I and Beable M E (1983): Regional flood estimation - a design procedure. *IPENZ Trans., 10(1)*:5-15.

McKerchar A I and Henderson R D (1987): *Drawing and checking stage/discharge rating curves*. Hydrology Centre Publ. 11, DSIR, Christchurch. 29p.

McKerchar A I and Pearson C P (1989): *Flood frequency in New Zealand*. Hydrology Centre Publ. 20, DSIR, Christchurch, 87p.

Phien H N (1987): A review of methods of parameter estimation for the extreme value type-1 distribution. *J. Hydrol. 90*: 251-268.

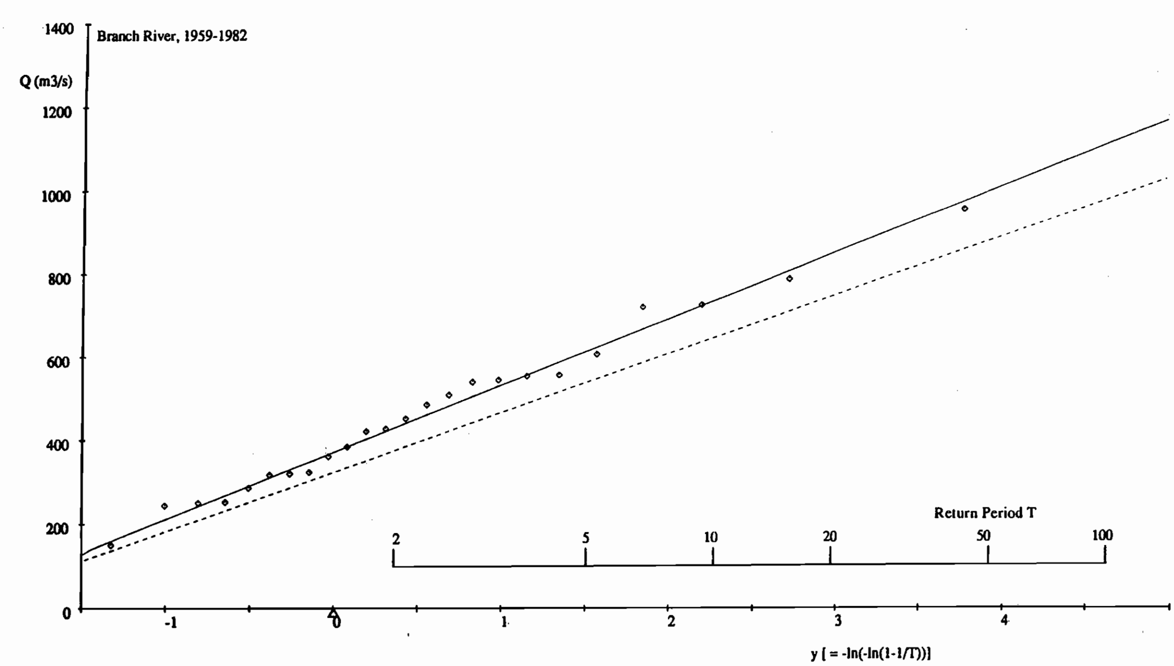

FIGURE 6: Frequency analysis of floods for the Branch River (site number 60112). The full line on the Gumbel plot is fitted by EV1/PWM method (equations 2, 3, 4) to the annual maxima for 1959-1982, and $Q_{50,site}$ = 994 m^3/s (standard error ± 11%). The dashed line is the frequency curve inferred from the maps in Figs 2 & 3, and $Q_{50,map}$ = 875 m^3/s (standard error ± 26%)