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Frequency distributions of annual maximum storm rainfalls in New Zealand

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Abstract

Tomlinson (1980) used the Extreme Value Type I (EV1) or Gumbel distribution to estimate frequencies of annual maximum storm rainfalls in New Zealand. This distribution did not satisfactorily fit all annual maximum series unless outlying values that did not conform with the EV1 distribution were deleted from the analysis. For hydrological design, deleting these "outliers" and using the EV1 distribution leads to underestimates of design storm rainfalls for some regions: in the drier, eastern regions of New Zealand, and Southland, Taranaki and Auckland, annual maxima of 24-hour rainfalls tend toward Extreme Value Type II (EV2) distributions. A map identifying regional tendencies toward EV2 rainfall distributions is presented and can be used to supplement Tomlinson's method for estimating annual maximum storm rainfall frequencies in New Zealand.

Introduction

The frequency distribution of maximum rainfalls is a useful measure of storm rainfall for hydrological flood studies. Tomlinson (1978, 1980) provided frequency estimates of New Zealand storm rainfalls for durations from 10 minutes to 72 hours for return periods up to 100 years (annual exceedance probabilities down to 1%), using the Extreme Value Type I (EV1, or Gumbel) distribution.

Tomlinson documented some rainfall values that were better fitted by an Extreme Value Type II (EV2) distribution for the annual maxima he analysed. These values were defined as "outliers" and removed from the analysis; for the remaining data the EV1 distribution was acceptable.

In this study, methods for estimating the frequency of maximum storm rainfalls are reviewed and the appropriateness of deleting extreme rainfall values is discussed. It is argued that the EV2 distribution tendencies found by Tomlinson for some New Zealand annual maximum storm rainfalls are valid, and their spatial pattern is investigated.

Extreme rainfall frequencies

Methods are required to estimate extreme storm rainfalls for flood design work (e.g. Foufoula-Georgiou, 1989). Both the physical processes underlying storm rainfalls and the recorded data must be considered to advance knowledge of the probabilities of extreme rainfalls (e.g. understanding orographic effects on extreme rainfall and its frequency in the Southern Alps, Henderson, 1993). It has been hypothesised that a storm rainfall frequency distribution will converge to a maximum value – the "probable maximum precipitation" (Thompson and Tomlinson, 1993).

For hydrological design, estimates of frequencies of storm rainfalls of a fixed duration are derived from all records of storms of that duration, regardless of storm type. The type of storm is irrelevant as a raingauge does not discriminate between different storm types; it simply measures the total rainfall for a fixed duration. To estimate the spatial distribution of storm rainfall does, however, require knowledge of the storm type.

The methods used in analysis of storm rainfall frequency for a location are based on a number of assumptions, such as the stability of the underlying climate, the reliability of the recorded data, and independence between defined storm events.

Storm events can be analysed using maximum rainfall for a specified duration (e.g. 12 hours) from fixed intervals (e.g. months, seasons, years). For example, Revfeim (1982, 1983, 1991) has developed analysis methods based on monthly and annual rainfall maxima; Tomlinson (1980) used annual maxima. Alternatively, the largest rainfalls over a fixed threshold amount can be analysed; this method is equivalent to the partial duration series method of flood frequency analysis (e.g. Madsen *et al.*, 1997). Selection rules are needed with this approach to ensure the maxima analysed are independent storm events.

This paper focuses on the analysis of annual maximum storm rainfalls. There are many frequency distributions which may fit recorded annual maxima well. Some distributions, such as extreme value distributions and those developed by consideration of the physical processes of storm rainfalls (e.g. Revfeim, 1982), have more theoretical justification than others. Series of annual maxima storm rainfalls may comprise values from storms of more than one type, which complicates developing theoretical distributions.

Buishand's (1991) analysis of Dutch storm rainfalls shows that the frequency distribution of annual maxima passes smoothly from EV2 to EV3 as storm duration increases. The crossover point is the EV1 distribution; it occurs for the Dutch data at a duration of around 4 days. This is consistent with an analysis of Christchurch storm rainfalls by Griffiths and Pearson (1993), where they found an EV2-like curvature for durations ranging from 30 minutes to 72 hours; in fact the same dimensionless distribution was appropriate for all of their Christchurch data.

Schaeffer (1990) showed that the frequency distribution of annual maximum storm rainfalls in Washington State was EV2 for short duration events (2 hours) and for arid regions (mean annual precipitation less than 500 mm), and tended towards EV1 with increasing duration and mean annual precipitation.

Tomlinson (1980) reported that the EV2 distribution is applicable for some New Zealand annual maximum storm rainfalls, using the Otten and van Montfort (1978) statistical hypothesis test. However, by assuming an EV1 distribution, Tomlinson could identify nearly 300 annual maxima "outliers". A second analysis omitting these outliers fitted an EV1 distribution. Tomlinson justified this method by arguing that outliers are to be expected in samples, and that these outliers should be assigned very long return periods. If it is known through comparison with other historical records that an annual maximum rainfall event from, for example, a 30-year record was the largest event in the last 100 years, then an adjustment to its return period is justified. But to exclude these values altogether is equivalent to saying they never occurred, which ultimately has the effect of underestimating the extreme quantiles.

Balancing annual maximum rainfall series with one or two extremely large values, there are usually others with no outstandingly large values. The regional approach used in this paper (Wallis, 1988; Schaeffer, 1990; Pearson, 1991b) effectively averages the extremes of individual samples (without deleting "outliers") to provide a balanced and unbiased picture of the dimensionless frequency distribution for a region.

Some of the "outliers" may be caused by storms of different types, such as thunderstorms. A mixed distribution may thus be required to account for the occurrence of all storm types (e.g. the two-component extreme value, TCEV, distribution, Rossi *et al.*, 1984).

In the flood study of McKerchar and Pearson (1989) annual maximum flood series from 275 catchments were shown to be reasonably EV1-distributed. Pearson (1991a) showed however that drier regions (South

Canterbury) were better fitted by the EV2 distribution (upward curvature on a Gumbel plot, whereas a true EV1 distribution plots as a straight line). Also, in a study of small catchments, Pearson (1991b) showed that the EV1 distribution underestimated high return period flood peaks, particularly in dry regions.

Therefore, if annual flood peaks tend to be more EV2-distributed as catchment size decreases (and if a raingauge may be considered as an extremely small catchment), do New Zealand storm rainfalls have EV2 tendencies?

EV2 rainfall distributions in New Zealand – regional variations

Method

A hypothesis test based on the shape parameter of the Generalised Extreme Value (GEV) distribution (Jenkinson, 1955; Hosking *et al.*, 1985) was used to investigate EV2 tendencies of annual maximum storm rainfalls in New Zealand. The GEV distribution function $F(x)$ is:

$$F(x) = \exp\{ - [1 - k(x - u)/a]^{1/k}\}$$

where x is the random variable of interest (annual maximum rainfall), u is the location parameter, a is the scale parameter and k is the shape parameter which specifies one of three asymptotic extreme-value distribution types (Fisher and Tippett, 1928): EV1 ($k = 0$), EV2 ($k < 0$) or EV3 ($k > 0$). The EV1 or Gumbel distribution function $F(x)$ is:

$$F(x) = \exp\{ - \exp [-(x - u)/a]\}$$

The EV1 distribution is a two-parameter distribution (parameters a, u), as k is implicitly fixed at zero, whereas the GEV distribution has three parameters (a, u, k).

The parameters of the GEV distribution are estimated using probability-weighted moments (Hosking *et al.*, 1985; McKerchar and Pearson, 1989). This is equivalent mathematically to the method of L-moments (Hosking, 1990; Pearson, 1991a).

The focus of this paper is the shape of New Zealand annual maximum rainfall frequency distributions, not their dimensions (as specified by the series mean).

The statistical test developed by Hosking *et al.* (1985) is used to test whether the EV1 is acceptable against the EV2 or EV3 alternatives for each annual maximum storm rainfall series. The test statistic (z) based on the GEV distribution's shape parameter k is:

$$z = k\,(n / 0.5633)^{0.5}$$

which is asymptotically standard normally distributed, where n is the sample size of the series and k has been estimated by the method of probability-weighted moments. If z, and hence k, is significantly negative or positive the EV1 distribution is rejected in favour of the EV2 or EV3 distribution, respectively. If k is not significantly different from zero, the EV1 distribution is acceptable. Significance levels for z are taken from standard normal distribution tables.

This test is applied to each New Zealand annual maximum storm rainfall series, and spatial variability in k is investigated by mapping and contouring k values.

For regions that depart from the EV1 distribution (such as Christchurch, Griffiths and Pearson, 1993), the data can be tested to determine if one distributional shape can used for the region, and to determine the best three-parameter distributional shape for it. To illustrate the method, L-moments hypothesis testing (method given by Hosking and Wallis, 1993) is applied to 24-hour duration rainfalls for eastern Southland.

Data

Rainfall recording sites were selected from the Climate Database and the Water Resources Archive, both nationally important databases maintained by NIWA. Annual maximum storm rainfall intensities (in mm) were extracted for each site, for durations of 1, 6 and 24 hours. Most of the raingauges were read daily, so only 24 hour durations were available. As this study was concerned only with the shape of the frequency distribution, not its mean, daily rainfalls recorded at 9am were not adjusted to 24-hour maxima (as was done in Tomlinson, 1980).

Annual maximum series for each site were acceptable if each annual value came from a year with at least 11 months of record (i.e., gaps totalled less than 1 month per year), and if the total number of annual maxima in each series totalled 10 or more years (i.e., $n \geq 10$).

Table 1 provides statistics of the annual maximum rainfall series analysed.

Table 1– Statistics of the annual maximum storm rainfall series (each of sample size *n*) assembled for analysis.

Duration:	1-hour	6-hour	24-hour
No. of Sites:	153	154	1933
Min. *n*	10	10	10
Mean *n*	17	17	31
Max. *n*	32	32	120

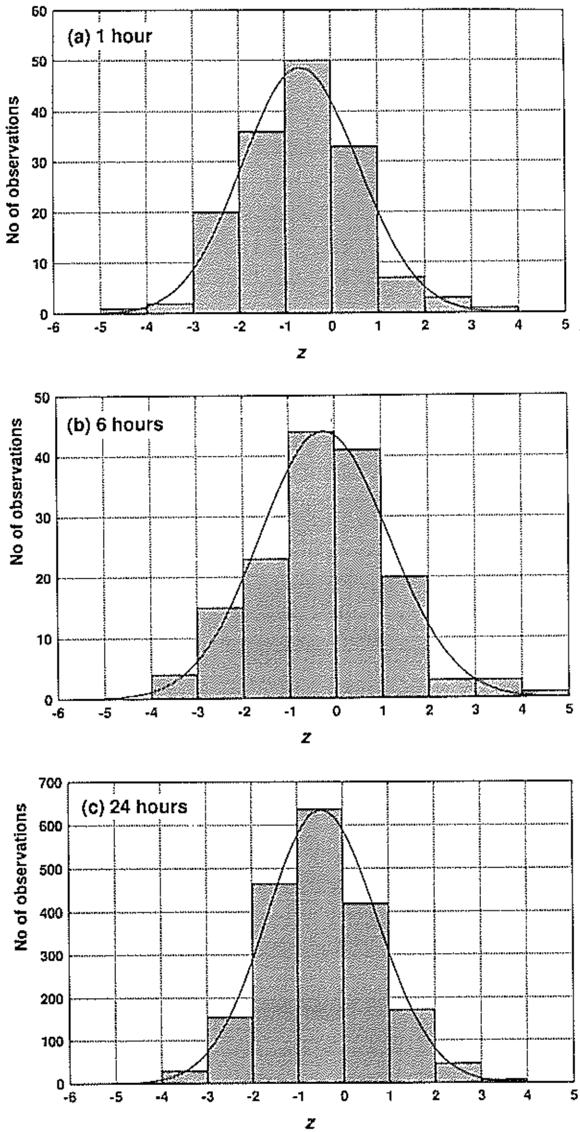
Results

The results of application of Hosking *et al.*'s (1985) test are presented in Figure 1 and Table 2. Figure 1 shows the overall distribution of the test *z* statistics. For each duration a normal distribution fits the *z* data well. But in each case the mean is less than zero, indicating an EV2 tendency. From Table 2, at the 95% significance level, the number of observed EV2 occurrences was four times the number expected (2.5%) for each duration. For two of three durations, the EV3 distribution matched its expected number of observations (2.5%), and for the other duration (6 hours) the observed number (4.5%) may be within sampling fluctuations. These results are almost identical to those of Tomlinson (1980). Clearly the use of the EV3 distribution for New Zealand storm rainfalls for durations of 24 hours or less would provide underestimates. At the very least the EV1 distribution should be used, and in a significant number of cases, an EV2 (or similar) distribution should be used (e.g. EV2, log-Normal, log-Pearson, TCEV, Pareto distributions). The overall conclusion of the tests is that the EV1 distribution, although satisfactory for most annual series (over 80 %, Table 2), does not fit all New Zealand annual maximum storm rainfalls of durations of 24 hours or less.

Table 2 – Hosking et al. (1985) hypothesis test results for the EV1 distribution at the 95% significance level. Figures in the table are the observed percentage of sites falling in each *z* category. Expected percentages if the EV1 distribution is the true parent distribution are: EV2 - 2.5%, EV1 - 95%, EV3 - 2.5%.

Duration:	1-hour	6-hour	24-hour
EV1 ($-1.96 \leq z \leq 1.96$)	81.7	82.5	87.0
EV2 ($z < -1.96$)	15.7	13.0	10.1
EV3 ($z > 1.96$)	2.6	4.5	2.9

Figure 1 – Histograms with fitted normal distributions of Hosking *et al.* (1985) z test statistic for New Zealand annual maximum storm rainfall series of durations (a) 1 hour (b) 6 hours (c) 24 hours.



An interesting pattern in Table 2 is the decreasing percentage of EV2 distributions as duration increases. This matches the findings of Buishand (1991) in that, as duration increases the appropriate GEV distribution goes from EV2 through EV1 to EV3.

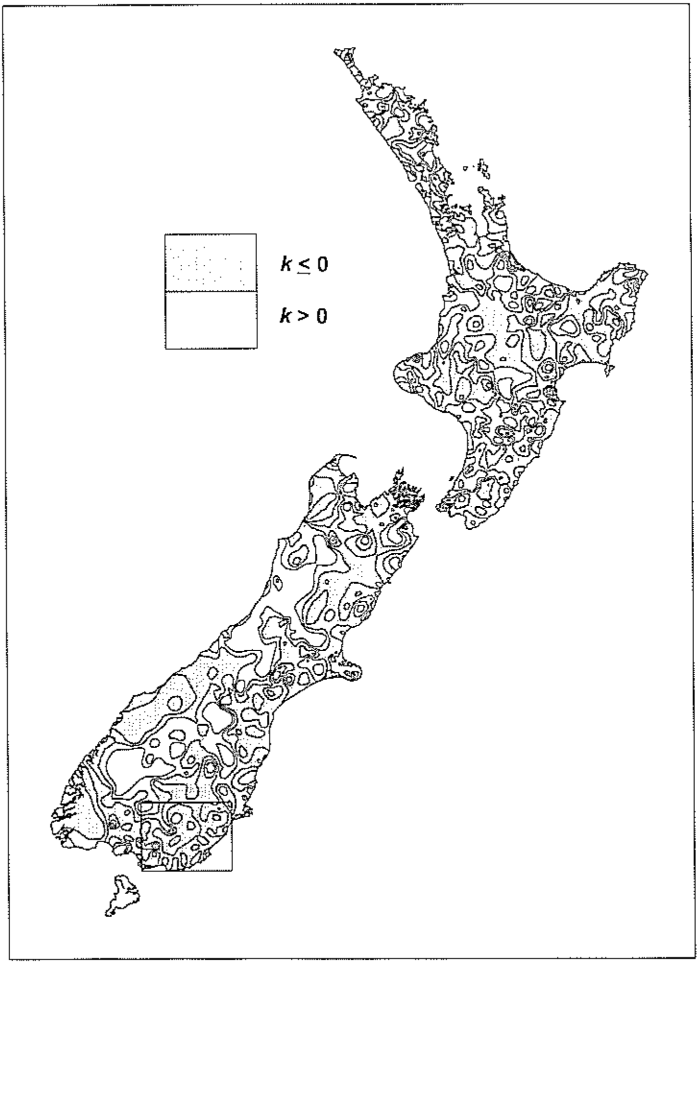
L-moment ratios (L_{CV}, L_{SK}, L_{KUR}, Hosking, 1990; Hosking and Wallis, 1993), which are alternative, more robust, coefficients of variation, skewness and kurtosis respectively, were calculated for each annual series, for each duration. The variability of these ratios over all the annual series for each duration was too great to be accounted for by one distribution. This indicates that more than one dimensionless distribution is required to describe New Zealand annual maximum storm rainfalls. To help summarise the overall trends, average statistics of the annual maximum storm rainfall series, derived using L-moment methods, are presented in Table 3. The distance of the (L_{SK}, L_{KUR}) pairs from the EV1 point in this plane (0.17, 0.15) indicated the average tendency towards the EV2 distribution. This is confirmed by the negative values of average GEV shape parameters (k). Estimators of average EV2 dimensionless (divided by series mean) T-year return period rainfalls (x_T) were calculated. The average values of the ratio x_{100} / x_5, which was used by Tomlinson (1980), were all greater than Tomlinson's values of 1.75 for durations less than 1.5 hours and 1.68 for durations greater than 1.5 hours, indicating that Tomlinson's EV1 estimates will be underestimates on average.

Table 3 – Average statistics of the annual maximum storm rainfall series, including L-moment ratios (L_{CV}, L_{SK}, L_{KUR}), and dimensionless (divided by series mean) quantiles x_T of return period T. Theoretical values for the EV1 distribution are given for comparison.

Duration:	1-hour	6-hour	24-hour	EV1
No. of Sites:	153	154	1933	
L_{CV}	0.204	0.175	0.197	
L_{SK}	0.256	0.212	0.223	0.17
L_{KUR}	0.184	0.180	0.174	0.15
GEV k	-0.130	-0.064	-0.080	0.0
x_{100} / x_5	1.96	1.73	1.85	

The 6-hour duration results are on average less EV2-oriented than those for the other two durations (Figure 1 and Table 3). For example, the average EV1 test z value for 6 hours (Figure 1) is closer to zero than it is for the 1 and 24 hours. Similarly, x_{100} / x_5 is less for 6 hours than it is for the other

Figure 2 – Smoothed shape parameter (k) of the GEV distribution fitted to 1933 series of New Zealand annual maximum 24-hour duration storm rainfalls. Contours are shown for k = -0.2, -0.1, 0, 0.1, 0.2. The eastern Southland region is indicated by the box at the southern end of the South Island.



two durations in Table 3. This result may be explained by the smaller sample size and hence greater sampling variability for averages of the 1 and 6 hour durations. The 24-hour duration averages are derived from more than ten times the number of annual series, and nearly twice the length of record (n), and so are more reliable.

Regional variations of the 24-hour duration series are shown in Figure 2 as maps of estimated GEV shape parameter (k) for each of the New Zealand series. The values have been smoothed using a kriging algorithm (Delhome, 1978). Note that the density of raingauges is not uniform – there are more raingauges in heavily popoulated areas and few in mountain regions. This uneven coverage needs to be considered when analysing the regional variability in k shown in Figure 2.

Overall, regions where the EV1 distribution was applicable (say $-0.1 < k < 0.1$ areas of Figure 2) predominate. However there are some large areas with EV2 tendencies ($k < -0.1$, Figure 2) where the distribution is supported by data from dense raingauge networks: southern Auckland, northern Taranaki and eastern areas of the North Island, and eastern regions of the South Island. Eastern Southland in particular has EV2 tendencies. Regions with EV3 tendencies ($k > 0.1$, Figure 2) are in alpine areas with few raingauges (e.g. Southern Alps of the South Island) and hence the distributions may be artefacts of limited sampling. As discussed above, the EV1 distribution is recommended for design use rather than the EV3 distribution. The map (Fig. 2) provides an overview of regional variations, and should be of use in selecting homogeneous regions for engineering design studies.

To illustrate a regional approach and to show the underestimates that result from using an EV1 distribution when EV2 tendencies are present, storm rainfalls for the eastern Southland region are analysed. This region was defined arbitrarily by a rectangle extending north from Invercargill and westward from a point just west of Dunedin (shown in Figure 2). The 83 annual maximum 24-hour duration storm rainfall series from within this rectangle were analysed using L-moments methods. The variability of L-moment ratios (L_{CV}, L_{SK}, L_{KUR}) from individual series around the regional average values (as shown for L_{SK} versus L_{KUR}, in Figure 3) was significantly small (Hosking and Wallis, 1993 tests), indicating that the dimensionless annual series (each divided by its mean) could have come from one distribution for the region. Hosking and Wallis (1993) goodness-of-fit z statistics for five three-parameter distributions are given in Table 4. The EV2 distribution was the best fit, with estimated regional shape parameter of $k = -0.16$. This distribution is plotted with the annual series on Gumbel paper in Figure 4. Also plotted is the EV1 distribution, fitted to this data. The curvature of the EV2 distribution away from the EV1 line indicates the extent to which use of the EV1 distribution would result in underestimation of maximum rainfalls for this region for return periods of greater than 50 years (Gumbel reduced variate greater than 3.9). Use of the EV1 distribution will, however, provide good first approximate estimates, which can then be refined upwards using the EV2 distribution.

Figure 3 – L-moment ratios of 83 series of eastern Southland annual maximum 24-hour duration storm rainfalls. Regional means are shown (L_{SK} = 0.276, L_{KUR} = 0.194).

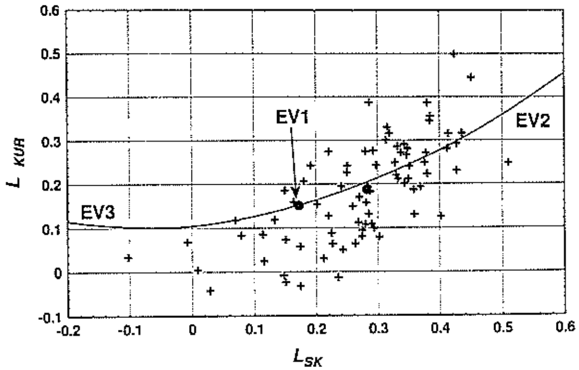
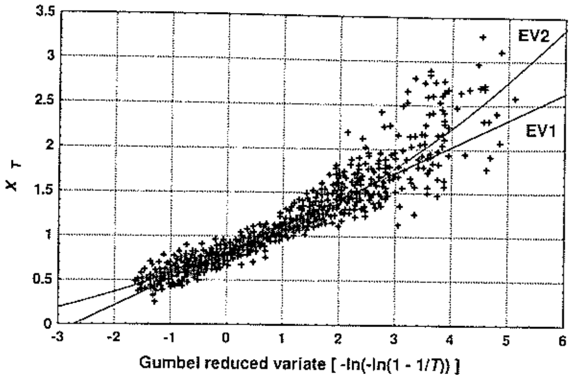


Table 4 – Hosking and Wallis (1993) goodness-of-fit test *z* results for 83 annual maximum 24-hour duration storm rainfall series for eastern Southland, where *z* is a standard normal test statistic (different test to the EV1 test in Table 2).

Distribution	*z*
Generalised Logistic	2.62
GEV	-0.08*
Generalised Normal (log-Normal)	-1.76*
Pearson Type III	-4.69
Generalised Pareto	-7.07
EV1	-4.71

* $-1.96 < z < 1.96$, significant at 95% level

Figure 4 – Dimensionless (maxima divided by mean) Gumbel plot of 83 series of eastern Southland annual maximum 24-hour duration storm rainfalls, with fitted EV2 (curve) and EV1 (line) distributions.



Discussion

The results showed that for a number of regions e.g. eastern Southland, the occurrence of EV2 tendencies was not random spatially. To check that the Southland data were not just a result of a cluster of severe events since 1980 (see e.g. Riddell, 1984), the regional analysis for the 83 sites was re-run using only annual maximum 24-hour duration rainfalls recorded before 1980. The number of sites reduced to 76, as seven sites no longer had ten or more years of annual maxima. The most appropriate GEV distribution for this pre-1980 data set was the EV2 distribution, with an average shape parameter of $k = -0.15$, compared with $k = -0.16$ for the full data set. This confirms that the EV2 tendencies in Southland are not caused by a spate of severe events after 1980.

Contours of the GEV distribution's shape parameter k for the 24-hour duration data (Fig. 2) bear some relation to contours of topography and to mean rainfalls. The EV2 distribution is more common for areas at lower elevations, such as in river valleys, and in drier regions. In Southland, the more negative k values coincide with the Mataura River valley, whereas k values are closer to zero for areas at the perimeter of the catchment. In higher elevation regions, such as the Southern Alps of the South Island, where mean rainfalls are extremely high and storms are frequent (Whitehouse, 1985), maximum rainfall distributions show few EV2 tendencies.

Negative values of the GEV distribution's k parameter (i.e. indicating an EV2 distribution) for annual maximum rainfalls may occur simply because no one storm type is sufficiently dominant to provide a satisfactory EV1 fit. The annual rainfall maxima are the product of concurrent processes involving seasonality and storm type, plus larger-scale climate phenomena such as the El Niño Southern Oscillation phenomenon. Revfeim (1991) gives a general framework to account for these processes.

Conclusions

The EV1 distribution is acceptable for describing the frequency of most New Zealand annual maximum storm rainfall series of durations of 1, 6 and 24 hours, however, for some regions the EV2 distribution is a better fit. These areas include southern Auckland, northern Taranaki and eastern areas of the North Island, and eastern regions of the South Island.

In most regions Tomlinson's (1980) and Thompson's (1993) EV1 distribution estimates are satisfactory for hydrological design purposes. The map (Fig. 2) should be checked to see if maximum rainfalls in the region of interest tend toward the EV2 distribution. A regional study of either annual maximum storm rainfalls, as presented for eastern Southland, or partial duration series storm rainfalls, is recommended to estimate the shape of the frequency distribution for such regions, to improve upon Tomlinson's EV1 estimates.

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