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Effects of Season and Weather Patterns on Flood Frequency: Hakataramea River, New Zealand

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Abstract

There is an unresolved debate about the comparative merits of parametric and non-parametric approaches to single-site flood frequency analysis. The series of annual maximum floods usually analysed in parametric approaches often comprise few events, by comparison with data series used in other statistical modelling and inference. Previous analyses, including some for the Hakataramea River, have had unexplained systematic departures of the flood data from the distributions used to fit them. The Hakataramea catchment has a distinctive topography and climate. Annual flood maxima occurring in Spring and Autumn differ from those occurring in either Summer or Winter. The Spring and Autumn data are better fitted by an EV2 distribution, while each of Summer and Winter series are better fitted by different EV1 distributions. Although distinct categories of weather patterns are identified, the annual maximum flood events associated with them are not clearly different, and do not conform well to EV1 or EV2 distributions.

Introduction

Many design and management tasks in a river catchment require estimates of the largest magnitude flood which might occur in a certain future time period, or of the probability of occurrence of smaller magnitude floods. In New Zealand, there will often be historical and current information on weather, including rainfall, for the catchment, and sometimes records of historical floods. Less often, there will be data for river discharge estimated from water levels; such a record could be up to about 40 years in length, but is usually much less (Walter, 1990).

In estimating the frequency of occurrence of future floods, especially those outside the measured range, there are too many unidentified and unmeasured variables for a deterministic solution and too few data for standard methods of statistical inference. Such problems can be treated by system modelling techniques (Ibbitt & McKerchar, 1992) but these are not commonly used for operational flood frequency analysis.

Single-site flood frequency analysis is commonly used for analysis of long discharge records and regional (lumped records) flood frequency analysis for shorter discharge records or where records are lacking (Pilgrim & Cordery, 1993). Runoff can be estimated from rainfall records if runoff records are very short or non-existent. The "probable maximum precipitation" (Tomlinson, 1992) can be used to estimate the largest magnitude flood, but not the probability of occurrence of lesser-magnitude floods.

Single-site analysis can be approached parametrically, assuming particular distributions and estimating their parameters, or non-parametrically, by subjectively extrapolating the largest historical floods and making no claim to general applicability of the particular distribution and fitting procedures used. In New Zealand, current agency practice and one scientific viewpoint (e.g. McKerchar and Pearson, 1989; Pearson, 1992) favour parametric methods while other opinion (e.g. Bardsley, 1988, 1994) strongly prefers non-parametric methods, or at least more realistic expression of the uncertainty involved (Young and Davies, 1989). Griffiths (1989) argues that both approaches should be used jointly.

Parametric single-site analysis uses statistical modelling and inference, in spite of few data points in a time series, typically of the annual maximum floods (a complete duration series). The integer rank of events which have occurred (largest = 1, etc.) is used to estimate annual exceedance probability (AEP) from a plotting position formula known to suit the chosen analytical distribution function. In New Zealand, the Extreme Value Type 1 (EV1, Gumbel) distribution, widely used for rainfall extremes, suits many river discharge records; a smaller number are fitted by the EV2 distribution.

Previous criticism of this approach is not because the idea of using the frequency of occurrence of previous floods to estimate the probability of future floods of these and other magnitudes is faulty. Rather, it has been because the choice of what is a "flood" has been debatable, unsuitable statistical models have been used, the uncertainty in the estimates has been misrepresented, or because the nature of the estimates made has been misunderstood.

Estimates made using parametric methods are still uncertain, even with several decades of information and with lumped, regional data sets. This paper illustrates some effects of season and weather patterns on floods in a part of New Zealand where parametric single-site analysis has indicated that the fitted distribution differs from most of the rest of New Zealand (McKerchar and Pearson, 1989; Pearson, 1991). The paper examines the hypotheses that:

1. Samples of annual maximum floods occurring in different seasons come from different populations, different from each other and from an annual sample.

2. Samples of annual maximum floods arising from identifiably different weather patterns come from different populations.

Absence of "Best-fit" Lines and AEP or Return Period Axes

Although this paper takes a parametric approach, with EV1 and EV2 distributions and appropriate plotting position formulas used, the theoretical model lines have been omitted from the exceedance probability graphs to emphasise differences in sample **data**; the EV1 or EV2 distributions are merely conventional and convenient models.

Similarly, for clarity and to prevent unwise extrapolation, the flood frequency graphs have been left with reduced variate abscissae, rather than converting them to, or adding, AEP or return period axes.

The obvious limitations of using a parametric approach with extremely few data points are accepted.

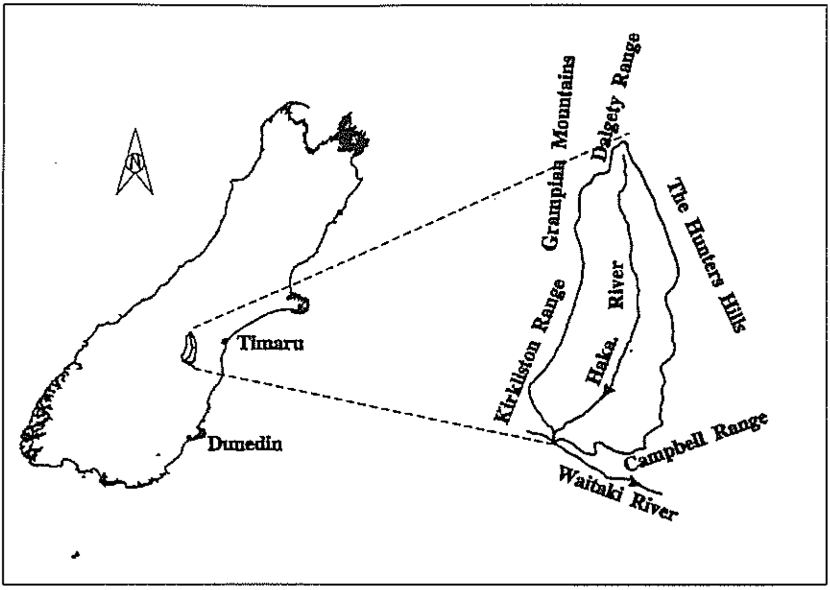

FIG 1 — Location of Hakataramea catchment in South Canterbury, South Island, New Zealand.

Hakataramea River and Catchment

The Hakataramea River runs approximately north to south, joining the west-east Waitaki River about 60 km inland from the Pacific Ocean (Fig. 1). The catchment has an area of 899 km^2 above the river-level recording site and a mean annual rainfall about 650 to 850 mm. Annual rainfall is highly variable, both between years and over the catchment. River water level is recorded near the catchment outlet (Site 71103, (Walter, 1990)) and, together with appropriate stage-discharge rating curves, provides discharge records for 1964-1993. Mean discharge for the 24 years during the record which have no missing data is 6 m^3/s. The discharge record is unusual in several ways: floods are less frequent than in many other New Zealand rivers, the annual flood maximum series is better fitted by an EV2 than an EV1 distribution, and the coefficient of variation of the annual maxima was the highest of 343 sites included in the study by McKerchar and Pearson (1989) (1.36 based on 1964-1987 data; only 18 of the 343 sites had $C_v > 1$).

The Hakataramea catchment tends to be dry in summer, and floods, although infrequent, can be very large: the mean annual flood is 172 m^3/s, but a 1352 m^3/s flood occurred in March 1986. The catchment is mostly developed for pastoral farming, with some cereal and other cropping. A number of farmers keep daily-read rainfall gauges; some of the data from these contribute to the national archive kept by the former New Zealand Meteorological Service (now part of the National Institute for Water and Atmospheric Research, NIWA).

Previous Single-Site Flood Frequency Studies

The Hakataramea River record has been included in single-site flood frequency studies by Beable and McKerchar (1982), McKerchar and Pearson (1989) and Pearson (1991). In McKerchar and Pearson (1989), the procedure being used depended on the EV1 distribution. The Hakataramea site was considered to be more like EV2 than EV1; in order to include its data in the analysis, the biennial maximum flood was selected to form a new series with fewer floods and these data were then accepted as fitting a biennial EV1 distribution. Figures 2 and 3 illustrate these distributions for 1964-1993 data. In Figure 2, y_1 is a reduced variate which is both linearly related to flood magnitude, Q, and a transform of AEP, so that the EV1 distribution is a straight line on these axes. y_{1b} is modified to suit a biennial distribution but the only real change is that there are fewer data points (Fig. 3). Similarly, y_2 is an equivalent reduced variate which has the same role for EV2 (in fact for General Extreme Value) distributions. The estimate of AEP used in both previous studies and the present study is from the Gringorten (1963) formula (see Stedinger, Vogel & Foufoula-Georgiou (1993)). For example, an annual maximum flood with a 5% probability of being equalled or exceeded has $y_1 = 2.9702$ and $y_{1b} = 2.7770$. y_2 depends on the GEV shape parameter; for $k = -0.55$ as used here later, a 5% AEP corresponds to $y_2 = 7.495$. The x variate represents Q; u and a are location and scale parameters.

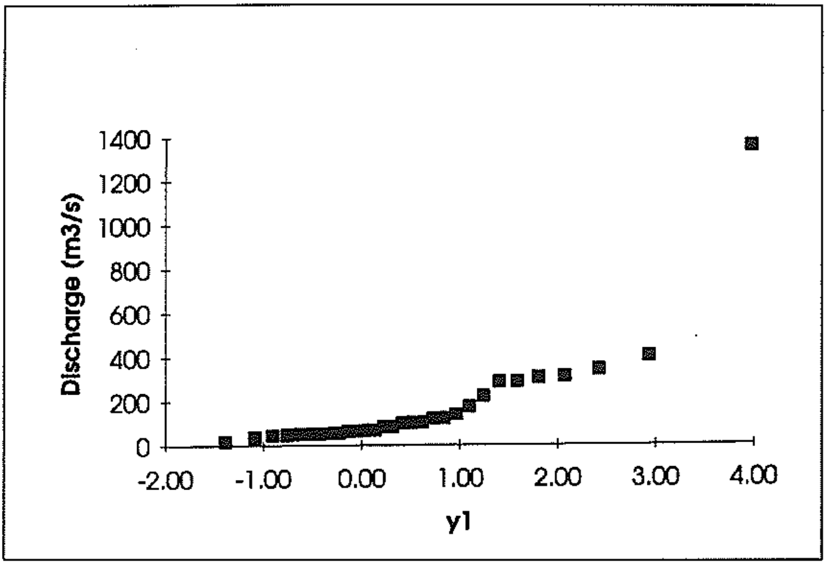

FIG 2 — Maximum annual floods 1964-1993, Hakataramea River [Site 71103], EV1 abscissa.

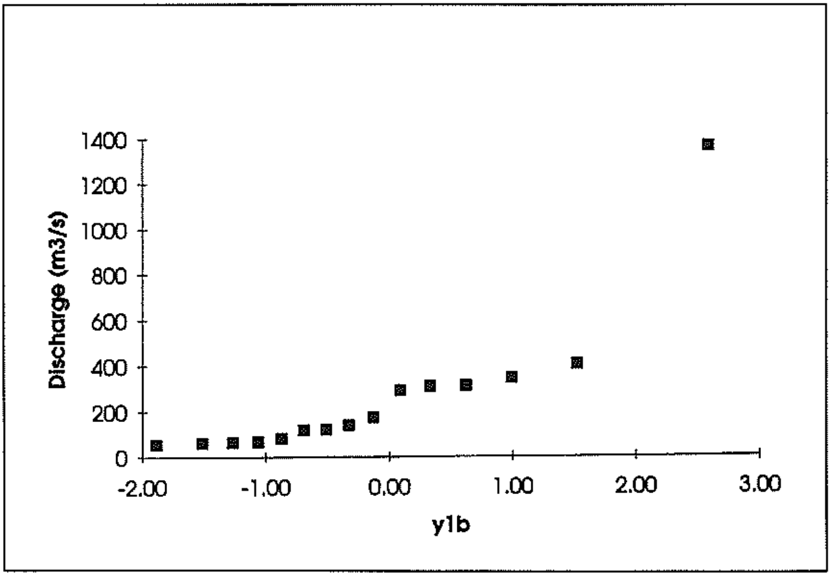

FIG 3 — Maximum biennial floods 1964-1993, Hakataramea River [Site 71103], biennial EV1 abscissa.

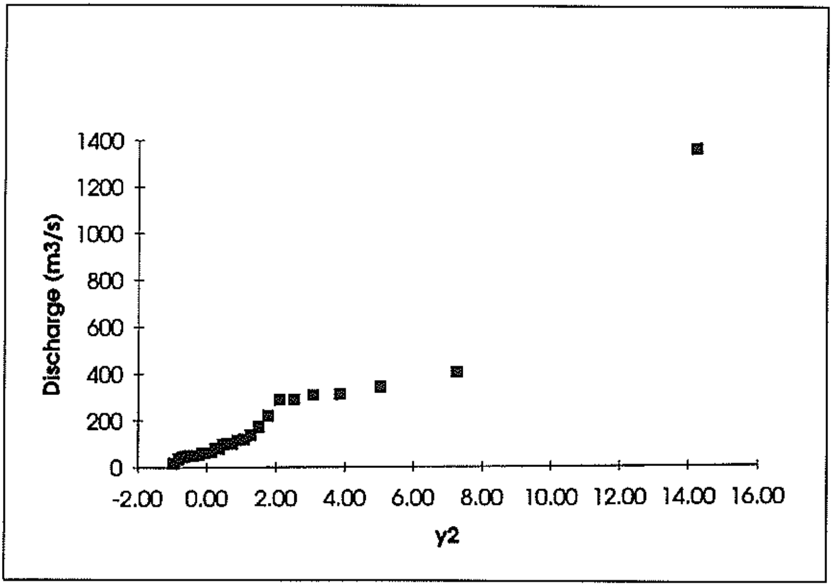

FIG 4 — Maximum annual floods 1964-1993, Hakataramea River [Site 71103], EV2 abscissa k = -0.55.

$$y_1 = [x - u]/a = -LN[-LN(1 - AEP)]$$

$$y_{1b} = [x - u]/a = -LN[-2LN(1 - AEP)]$$

$$y_2 = 1 - k[x - u]/a = \{1 - [-LN(1 - AEP)]^k\}/k$$

$$AEP = [RANK - 0.44]/[PERIOD + 0.12]$$

Pearson (1991) re-analysed the 275 New Zealand sites used by McKerchar and Pearson (1989) for flood frequency analysis, using linear moments (L-moments) in a regional approach. Statistical tests "indicated that South Canterbury", including the Hakataramea catchment, "was a reasonably homogeneous region and that the EV2 distribution was the best statistical distribution for this region". Figure 4 shows the 1964-1993 data plotted with a shape factor estimated using L-moments. An EV2 distribution would be linear on these axes.

Present Analysis

Two striking features of the Hakataramea annual maximum flood data (Table 1) are the 1986 event of 1352 m^3/s and the relative paucity of flood magnitudes between about 170 m^3/s and 280 m^3/s. The plotting position approach can do no more than assign rank 1 to the 1986 event, even though it is 3.4 times the magnitude of the rank 2 event (1978), leading to a systematic departure of the formula-plotted data from EV1, biennial EV1 and EV2 distributions (Figs 2, 3, 4) in the form of a distinct step. Such steps are a direct consequence of the integer ranking/plotting procedure used. Perhaps what is surprising is the absence or small magnitude of such steps in a large number of single-site analyses using only 20 to 30 years of data.

TABLE 1 — Annual Maximum Floods, Hakataramea River above Main Highway Bridge [Site 71103], 1964-1993.

Date (D/M/Year)	Discharge (m^3/s)	Rank (1=highest)	Season	Scenario (See text)
21/7/64	46.59	26	W	N
1/2/65	119.6	10	Su	N
24/1/66	43.72	27	Su	S
27/11/67	61.66	20	Sp	N
8/6/68	306.8	4	W	S
1/2/69	66.16	18	Su	F
24/9/70	67.34	17	Sp	-
30/6/71	53.74	22	W	S
17/5/72	289.3	5	A	-
31/8/73	101.8	13	W	N
17/4/74	138.3	9	A	N
20/8/75	102.2	12	W	S
22/12/76	50.72	24	Su	F
6/1/77	64.46	19	Su	S
26/8/78	401.7	1	W	S
6/5/79	97.14	14	A	F
6/6/80	341.9	2	W	N
15/6/81	219.7	7	W	N
27/10/82	51.32	23	Sp	S
27/6/83	80.43	16	W	-
12/12/84	16.99	29	Su	S
26/12/85	116.8	11	Su	N
13/3/86	1352	Outlier	A	N
11/3/87	287.7	6	A	N
20/1/88	36.43	28	Su	S
9/10/89	54.35	21	Sp	N
24/8/90	311.2	3	W	N
20/9/91	50.39	25	Sp	N
23/10/92	80.92	15	Sp	S
17/5/93	172.9	8	A	N

Testing for Outliers

Single data points such as the 1986 flood are often removed from the analysis as an "outlier" (Stedinger, Vogel and Foufoula-Georgiou, 1993). Tests have been recommended (US Water Resources Council, 1981) for deciding whether such a high outlier should be discarded as "historic" flood data, if information indicates that it is the maximum which has occurred over a very long period, or retained in the analysis when there is no such information.

Another attitude which could be taken is that the flood did occur, and therefore provides useful information. It is a failing of the conventional analysis that the highest-ranked flood has a plotting position given by the formula, even if it is "actually" a flood of very much smaller probability of exceedance which happened to occur in the sample time period.

In a conventional approach, the threshold value for high outliers, for a series of 30 annual floods as in Table 1, is calculated from

$$[10]\exp[\mathrm{MEAN}(\log_{10}Q) + 2.563\mathrm{SD}(\log_{10}Q)] = 1114.5 \text{ m}^3/\text{s}$$

in which Q are the annual floods and SD is the standard deviation of their base 10 logarithms. The 1986 flood is 20% greater than this threshold value and is reputed to be the largest flood in living memory in the catchment (60 years?). Current technical wisdom would therefore exclude the 1986 event from the analysis. A comprehensive discussion of treating historic floods, and further references, are given by Stedinger, Vogel and Foufoula-Georgiou (1993). Criticism of this and similar techniques is provided by Bardsley (1988, 1994), Young and Davies (1989), Griffiths (1989) and Davies (1993).

A Synoptic Weather Explanation of the Outlier

High rainfall on the Hakataramea catchment can be associated with moist north-easterly airflows (see *Synoptic Weather Patterns and Floods).* The event of 13 March 1986 was unusual because a depression in the Tasman Sea became associated with the remains of a tropical depression decaying near the Kermadec Islands (Fig. 5), causing an unusually high amount of moisture in the north-easterly flow onto the catchment. At the same time a very slow-moving cold front lifted the moist, unstable air at the frontal surface. The front became slow-moving, or even stationary over the catchment on 13 March, resulting in very heavy rainfall.

Only one other tropical depression occurs in synoptic weather maps preceding annual floods in the 30 years of record, a trough of low pressure around Norfolk Island on 15 May 1972 which might have developed into a tropical depression, contributing to a flood on 17 May of 289 m^3/s. This was associated with easterly rain on 17 May following south-west frontal rain on 13-14th May.

Tropical depressions thus rarely influence floods in the Hakataramea River; those associated with a slow-moving or stationary front, as on 13 March 1986, are rarer still. The 1986 flood might thus be from a different population of rainfall events from most of the other floods. An alternative is that the event which happened to occur in this short sample is of such low exceedance probability that it accentuates the weakness of the usual plotting position formula. Either explanation gives some support to the exclusion of the event as a high outlier from a conventional analysis which would try to fit all of the "floods" by one distribution. This does not of course deny the relevance of the information to planning to cope with future floods.

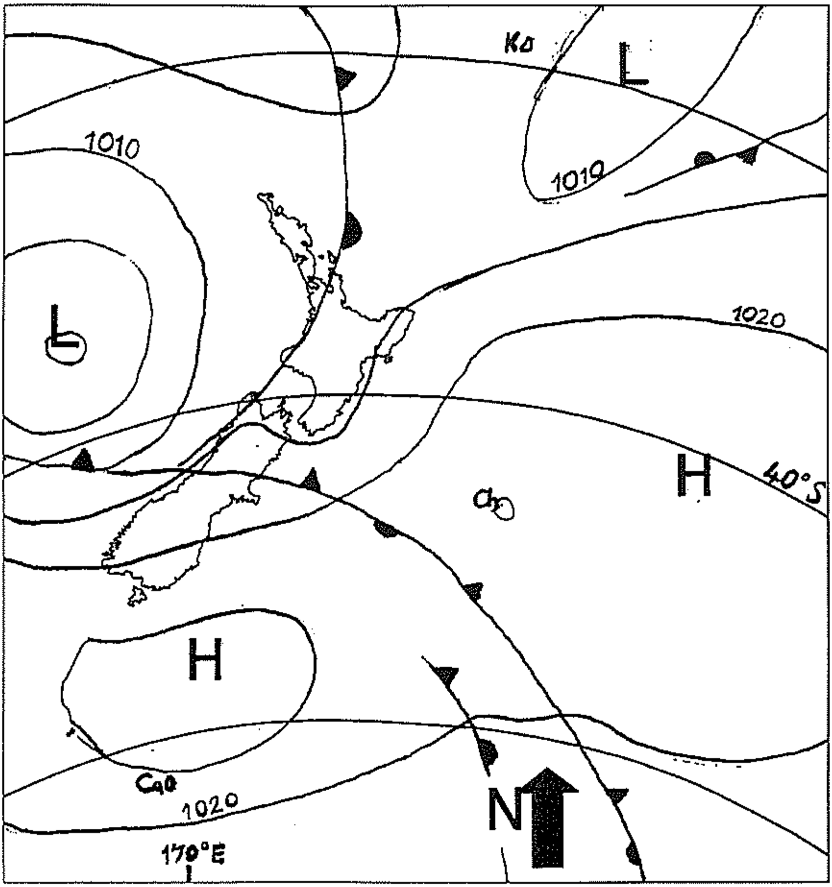

FIG 5 — Simplified synoptic weather map for 13 March 1986 with a tropical depression near the Kermadec Islands [K, top right].

Bi-modal Data Distribution

The 29 data values remaining when the 1986 value is excluded depart systematically from the usually-chosen distributions primarily because they are bi-modal (Fig. 6). Data of magnitude up to 173 m^3/s (22 points) plot acceptably as EV1 (Fig. 7). Data of greater magnitude, 220 to 402 m^3/s (7 points) are similarly linear against the EV1 reduced variate, y_1, although with too few points for great confidence. But the combined series conventionally plotted have a distinct step causing them to depart systematically from EV1.

Data drawn from two parent EV1 distributions having different parameters would plot with such a systematic departure from a single "lumped" EV1 distribution. A Two-component Extreme Value distribution could be fitted to such data (Fiorentino, Versace and Rossi, 1985; Arnell and Gabriele, 1988).

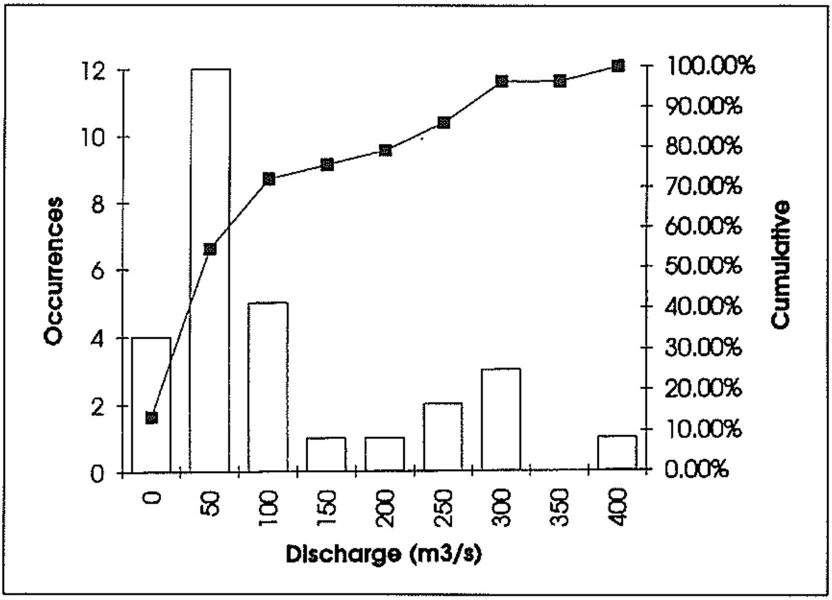

FIG 6 — Frequency of occurrence and cumulative distribution of maximum annual floods, Hakataramea River [Site 71103], 1964-1993 excluding 1986.

But such approaches do not explain why the data depart from EV1 nor enhance flood probability prediction.

Not all annual maxima are "floods"; the Hakataramea catchment often has long periods without appreciable rainfall. Series excluding low values could be used, but the results would be similar to those in this study. Excluding all except the few largest values and fitting these subjectively would effectively be changing to a non-parametric approach.

A Seasonal Correlation with Systematic Departures

The 1986 "outlier" flood might well be from a different population of rainfall events, and therefore possibly from a different population of floods, from most others in the catchment. Other floods might also be drawn from two or more distinct populations which have distinct causal rainfall and weather patterns.

Flood analysis may be more simply based on quarterly "seasons" of the year. Annual maxima which occur in each season are considered as sub-sets of the original data. The austral "Summer" used here comprises December, January, February; "Autumn", "Winter" and "Spring" follow 3-monthly.

Analysed conventionally (in spite of now having only 8 data points), "Summer" data do not depart systematically from a linear plot against the EV1 variate (Fig. 8). The relatively poor fit of the high-y_1 (low AEP) events is an expected feature of the technique. The "Winter" data (Fig. 8) do suggest a step-like systematic departure to the original data (Fig. 7), but with reduced magnitude. "Spring/Autumn" data (8 points) show a concave upwards curve suggestive of how an EV2 distribution plots against the EV1 variate. Re-plotted against the EV2 variate, y_2, all but the two or three lowest magnitude events in the "Spring/Autumn" data become quite linear (Fig. 9).

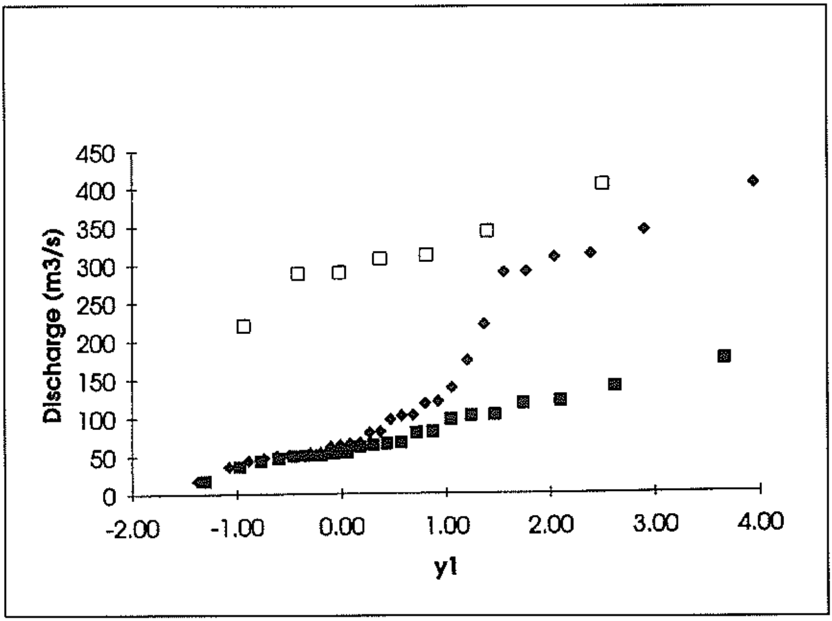

FIG 7 — Maximum annual floods 1964-1993 excluding 1986, Hakataramea River [Site 71103], plotted as two separate series of magnitude greater or less than 200 m³/s [□,■] and as a combined series [◆].

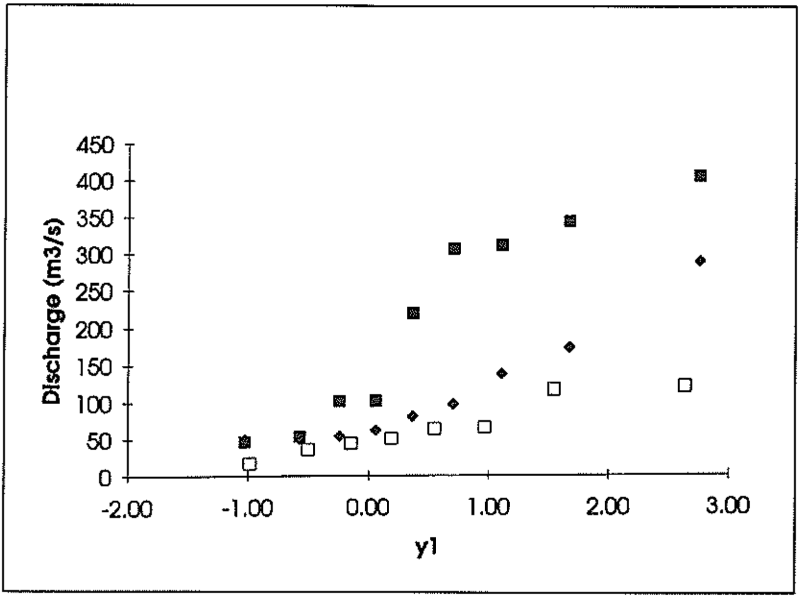

FIG 8 — Maximum annual floods 1964-1993 excluding 1986, Hakataramea River [Site 71103], plotted as three EV1 series: Summer [□], Winter [▨] and Spring/Autumn [◆].

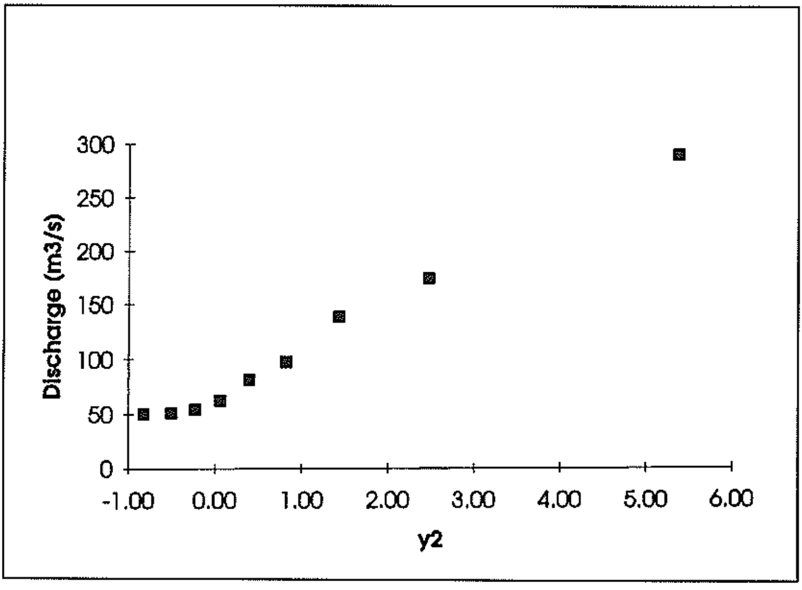

FIG 9 — Maximum annual floods in Spring or Autumn 1964-1993 excluding 1986, Hakataramea River [Site 71103], EV2 abscissa k = -0.438.

Classification of annual maxima by season provides a good fit to EV1 and EV2 distributions. However, it does not explain why flood behaviour varies according to season.

Synoptic Weather Patterns and Floods

Synoptic charts of weather patterns preceding the thirty floods in the 1964-1993 record could be sorted into three rain-bearing weather scenarios. As the sorting process is subjective, it was carried out by one author (SHL) at the request of the other, independently of any involvement with the rest of the analysis.

The effects of topography on rainfall in the Hakataramea catchment are important and have been taken into account. The valley is largely sheltered from westerly and north-westerly winds by the Southern Alps and the bounding Kirkliston and Grampian Mountains (Fig. 1). The lower but still important Hunters Hills and Campbell Range to NE and SE, respectively, tend to isolate the catchment from coastal winds.

“Northerly” Scenario

An active depression develops in the Tasman Sea, often to the east of Tasmania, and moves quickly across the Tasman Sea intensifying as it moves. When it is close to the west coast of middle or southern regions of the North Island, and as it travels onto the North Island, it brings a moist NE air flow into the Hakataramea catchment.

Five Winter, 2 Summer and 7 Spring/Autumn events are categorised in this way. The 13 March 1986 event, which has already been discussed, was eventually excluded. The 6 June 1980 and 11 March 1987 events differed in having more E than NE winds. Three events: 15 June 1981, 26 December 1985 and 11 March 1987 had associated occluded fronts.

These 14 (including 1986) events are marked “N” in Table 1.

“Southerly” Scenario

A depression (with one or more closed isobars) forms to the east of Cook Strait or the South Island, either as a result of a depression crossing the South Island from NW to SE and re-forming on the eastern side, or by troughing off the eastern South Island coast. This brings cool, moist winds, often from SSE, but with winds varying between SE and SW for some events.

Four Winter, 4 Summer and 2 Spring/Autumn events are categorised in this way; these 10 events are marked “S” in Table 1.

"Frontal" Scenario

A south to south-west cold front moves up the South Island east coast, bringing heavy rain.

There were no Winter events of this kind, and 2 Summer and 1 Spring/ Autumn event (6 May 1979).

The 1979 event was complicated. A SW front probably brought the initial rain, but this front seemed to slow as a depression from the mid-Tasman Sea moved onto the west South Island. Another depression east of Banks Peninsula would have produced more unstable air and this perhaps explains why the front brought heavy rain.

These three events are marked F in Table 1. There are too few points to analyse further.

Three events in the record could not be placed in the northerly, southerly, or frontal scenarios. The large flood (289 m^3/s) on 17 May 1972 has already been referred to in discussing tropical depressions and the 1986 "outlier". Beginning on 13 May there had been frontal rain, on 14 May southerly rain and what happened on 16th and 17th *might* have been northerly rain, so this event was a real mixture! On 24 June 1970 and 27 June 1983 there were westerly and north-westerly airflows onto the catchment, respectively, with SW cold fronts approaching. The westerlies probably did not provide much rain, so perhaps the fronts advanced faster than shown on the weather map.

These three events have been omitted from this part of the analysis.

The northerly scenario ("N") and southerly scenario ("S") data are shown in Figure 10, treated as two separate series but plotted together. The two series are distinct, but the northerly scenario data depart systematically from EV1 as do the original data (Fig. 7), although less so, and the two events of greatest magnitude in the southerly scenario data depart from the EV1-like plot of the other 8 points. Five of the 6 events above 200 m^3/s are Winter floods; 4 of the 6 occurred in June.

Discussion

Weather Pattern Effects

There are no strong correlations between season and weather patterns (Table 1). There are no southerly floods in Autumn in the record, but there are very few (6) Autumn events. Summer floods (8) are all below 120 m^3/s and Spring floods (6) are all below 81 m^3/s. Autumn floods (6) are all above 97 m^3/s. Winter floods (10) are the most numerous and have a wide range of discharge from 46 to 402 m^3/s.

Consistent application of the arguments already presented suggest that the two highest "S" points on Figure 10 must come from a different population than the other 8 points. They are not, however, outliers (in the sense previously discussed) from the whole record. Although they both occurred in June and are therefore winter events, this provides no useful further explanation.

Even allowing for uncertainty in the two highest "N" points on Figure 10, the other 11 points are not necessarily EV2-distributed, although that is what some recognised statistical tests would suggest. They might indicate either samples from several populations, or a sample from a population which is neither EV1 nor EV2. A good candidate would be the theoretically-based Wakeby distribution of Griffiths (1989).

There are too few data to carry out any useful analysis on frontal scenario data, and three events which could not be fitted into any of the three scenarios.

Weather patterns clearly affect flood magnitudes, but it has not been possible to classify these effects in a way which allows improved flood frequency prediction.

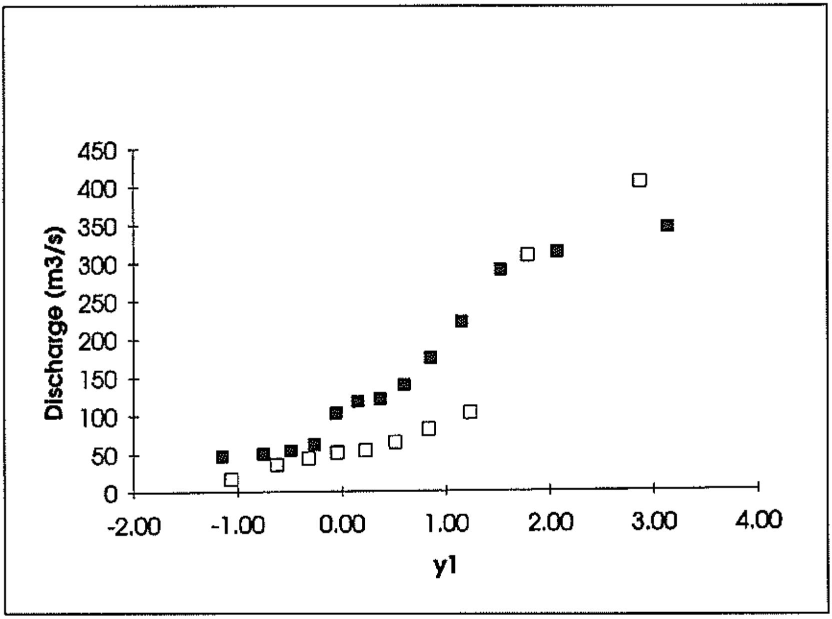

FIG 10 — Maximum annual floods from northerly scenario "N" [■] or southerly scenario "S" [□] weather 1964-1993 excluding 1986, Hakataramea River [Site 71103], as two separate EV1 series.

Seasonal Effects

The classification into Summer, Winter and Spring/Autumn events has been more successful, for two reasons:

1. The arrival of these seasons each year, unlike weather patterns, is predictable.
2. The data for these classifications, although few in number for this 29-year record, show reasonable evidence of being fitted by EV1 (Summer and Winter) and EV2 (Spring/Autumn) distributions (Figs. 8 and 9).

It might now be possible to answer the question:

"What is the likely probability of occurrence in Summer, or Winter, Spring or Autumn, of an annual maximum flood (not caused by a tropical cyclone) greater than Q m^3/s?"

Because of the better fit of the data, the uncertainty associated with predictions is reduced. More importantly, the reasons why Hakataramea data have previously appeared as poorly-fitting EV2 or biennial EV1 have been clarified.

Time and Space Distributions of Rainfall

Floods result from catchment-modified rainfall events. Weather patterns and the season affect the way in which rainfall is distributed in time and space on the catchment. In particular, rainfall which does not cover all the catchment (partial storms) could be expected to have important effects which might well be associated with particular weather patterns or with season. Antecedent moisture stored in the catchment is affected both by evaporation (solar radiation and advected energy driven) and by the time distribution of rainfall prior to flood-producing rainfall. Antecedent moisture is very likely to be strongly correlated with season, as are the effects of snowmelt.

A study of rainfall frequency distributions, time distribution of rainfall and spatial rainfall coverage for the catchment could add to understanding of the flood behaviour reported here. Such a study would not by itself, however, improve prediction of the probability of occurrence of future floods.

Relevance to South Canterbury Region

Only the Hakataramea record is examined in this paper. Pearson (1991) demonstrates, using an L-moment analysis of 275 New Zealand sites, that South Canterbury including the Hakataramea catchment is a distinct region whose flood data are best fitted by an EV2 distribution. This analysis suggests that Spring and Autumn subsets of Hakataramea data are best fitted by EV2 while the other seasons are best fitted by different EV1 distributions. It remains to be seen whether the same is true of other South Canterbury records.

Conclusions

Synoptic weather patterns prior to floods in the Hakataramea River have been analysed for the 30-year record of annual maximum floods. The relationship of these annual maxima to the four seasons has also been considered.

Annual maximum floods in the Hakataramea River which occur in different seasons of the year appear to come from different populations. Annual maximum floods occurring in Spring and Autumn are better fitted by an EV2 distribution, while those occurring in Summer and Winter are better fitted by different EV1 distributions. The annual maximum flood series for this river comprises data which depart systematically from EV1, biennial EV1 or EV2 fitted distributions.

Three distinct synoptic weather patterns bringing flood-producing rain to the catchment can be identified. The annual maximum floods from each pattern do not conform well to EV1 or EV2 distributions. An hypothesis that the events from each pattern come from different populations is not supported by the evidence.

The results of single-site flood frequency analysis improve as the record increases in length. The river level recording site used to derive the data for this study remains operational and it will be possible to reconsider the conclusions above in the light of each year's new data.

Acknowledgments

Carolyn Doughty assisted with assembling weather map information and providing preliminary synoptic summaries. Alistair McKerchar and Charles Pearson participated in useful discussion; they and Vince Bidwell reviewed the draft paper. NIWA Climate Division (Christchurch) provided access to data and a quiet place to work for the first author.

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