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STORM RAINFALLS

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ABSTRACT

The theory of extreme values is well advanced and widely accepted in its application to point extreme rainfalls, even though the physical basis of the application is sometimes weak. By examining the weather systems that produce heavy rainfall it is possible to do two important things. Firstly, by recognising different distributions from which the extremes are taken, misapplication of the theory can be avoided. Secondly, a reasonable approach can be made to the problem of the areal extent of the extreme rainfall. Examples are given for each of these points.

Brief mention is made of the distribution of extreme rainfalls in time. It is concluded that though extremes are not always randomly distributed in time, it is generally most appropriate to assume that they are, unless specific evidence exists to the contrary.

INTRODUCTION

One of the major problems in the application of extreme value theory to rainfall values is associated with the interpretation of recorded extremes, that are very much larger than the general value of the remaining extremes. This is often colloquially referred to as the problem of 'outliers'.

In New Zealand the application of extreme value theory to rainfall events has followed the Gumbel method (1958) and has been explained by Robertson (1963). In this procedure the annual extremes are extracted for analysis. This

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sometimes results in the analysed samples containing one or two cases of extremes which are much larger than the others in the sample. Such cases may relate to quite different meteorological populations and in moderate sized samples (about 20 years) it may not be possible to assess the average frequency of occurrence of such cases. These infrequent large extremes may belong to the same extreme value distribution as the other extremes in the sample, but in estimating return period statistics for say 50 or 100 years from samples of about 20 years such an assumption can lead to very poor estimates.

The second major difficulty in assessing the return period of rainfalls involves the treatment of area rainfalls. Extreme value theory is readily applied to existing point data but comparable data for area storm rainfalls are not available. Furthermore, such data have never been collected, and accordingly the only approach to the problem of the return period of storms is via the treatment of point rainfall records. A now conventional approach to this problem is to use the set of area reduction curves devised by the U.S. Weather Bureau (1958) to relate point rainfalls of various durations to comparable area figures. While this procedure is not an unreasonable one, an examination of the spatial rainfall distribution in any extreme storm, and particularly in very extreme ones, often shows that the procedure involves considerable error.

In order to refine the U.S. Weather Bureau curves it is necessary to either have a denser network of raingauges, or to look at a number of historic extreme storms that are well documented both from the point of view of the atmospheric systems that gave rise to them and the rainfall they produced. Later in this paper an examination is made of several such storms in an attempt to find characteristic patterns of area rainfall in severe storms.

DATA

The data available for a study of storm rainfalls in New Zealand are of two types. Firstly, daily (0900 to 0900 hours) rainfalls recorded at a large number of stations in New Zealand, and secondly, autographic rainfall records from stations equipped with recording gauges. There are considerably more daily than recording stations and, in addition, the daily records furnish many long series and these are obviously of greater value in the estimation of the longer return period values. Estimates of return periods of daily values can readily be converted to those for 24 hour period rainfalls by multiplying by 1·14. This factor is established on the assumptions that rainfall is uniformly distributed throughout the 24 hours of maximum (annual) rainfall and that each time of the day is equally likely to be the start time for a period of 24 hour maximum (annual) rainfall. Over long data series both of these assumptions are likely to be quite reasonable. Similar factors of 1·07 and 1·04 relate 2–day to 48 hour rainfalls and 3–day to 72 hour rainfalls.

Data routinely extracted from the recording raingauge charts for the calculations of return periods include the maximum monthly and hence annual rainfalls of durations 10, 20 and 30 minutes, and 1, 2, 6, 12, 24, 48 and 72 hours.

SPATIAL AND TEMPORAL DISTRIBUTIONS

The distribution of heavy rainfalls in New Zealand can be described by maps of items such as the maximum 24–hour rainfall which it is expected will be equalled or exceeded on the average of once in 20 years, Tomlinson (1976). These maps show that the precipitation amounts increase from south to north, from east to west and to some extent increase with altitude. This spatial distribution relates to the fact that heavy rainfalls (of durations greater than a few hours) are often of the type that accompany active troughs of low pressure that move eastwards over the country, and that the air over the north of the country generally carries more moisture than that over the south.

The effect of altitude on heavy rainfalls is only partially known largely because of the difficulty of measuring precipitation at higher levels. However, for altitudes up to 1500 m and for all but the short duration rainfalls (less than just a few hours) it appears that rainfall intensities do increase with altitude.

There is some known temporal variation in heavy rainfall. For example, that associated with thunderstorms shows a marked diurnal variation with a pronounced peak in the late afternoon and a second smaller peak in the early morning. An annual cycle is also apparent in the frequency of most durations of heavy rainfall, with the greatest number occurring in the summer half year when the air is warmer and can carry more moisture. Other temporal variations have been noted but are less substantially documented. They have arisen in some samples of data and not in others and represent temporal variations of smaller amplitude than the two mentioned above. Notable amongst them are those related to phases of the moon, for example O'Mahony (1965). More recently Tomlinson (1977a) has noted that intense rainfalls of 1–3 days duration in Canterbury, tend to occur at the peaks in a 27–28 day period oscillation in daily rainfall series which is itself related to variations of solar flux at 2800 MHz. This result whilst being statistically significant is probably quite sample dependant, as are the lunar results.

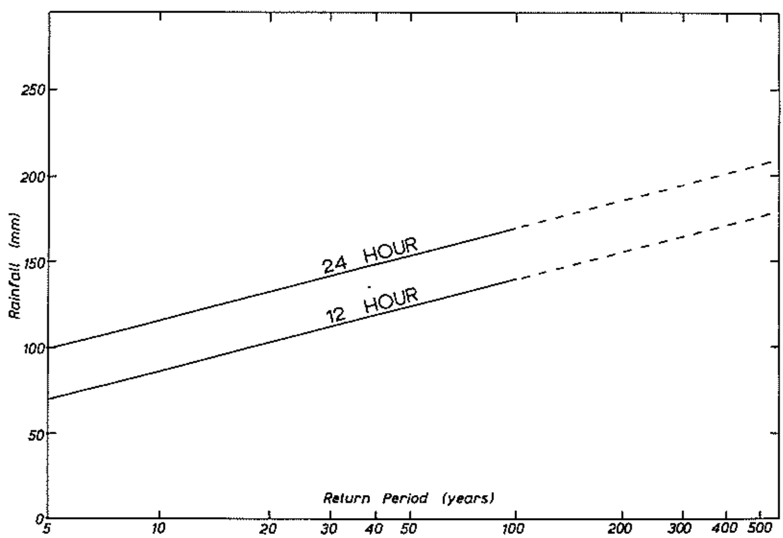


FIG. — 1 Graphs of the return period of 12 and 24 hour rainfalls at sites on the floor of the Lower Hutt Valley (and not immediately adjacent to the hills). For return periods over 100 years the graphs must be interpreted with caution.

Fig. 1 shows the return period of 12 and 24–hour rainfalls in the lower Hutt Valley. It is based on all the records accumulated in this area since about 1900. The 100 year return period value of 24–hour rainfall is estimated to be 170 mm. During 19 and 20 December 1976, 264 mm was recorded in 24 hours in this area. Assigning a return period to this recorded rainfall is not an easy matter. Before extrapolating the graph to a return period whose rainfall value is 264 mm, it is necessary to first look to see if the extreme value of December 1976 can be appropriately compared with previously recorded extremes. The weather situation on 20 December 1976 was not uncommon in its broad features although the intense rainfall resulted from a quite local airflow convergence which was largely orographically induced. Such local convergence in the Cook Strait area is probably not unusual, and indeed there is no apparent reason why the situation on 20 December 1976 cannot be compared with weather situations on previous

TABLE — 1 Annual maximum 2–day rainfalls (mm) at Stratford Mountain House

Year	*Maximum 2–day rainfall*	*Year*	*Maximum 2–day rainfall*
1963	316	1970	531
1964	323	1971	796
1965	564	1972	428
1966	492	1973	194
1967	794	1974	385
1968	344	1975	316
1969	368	1976	330
		1977	302

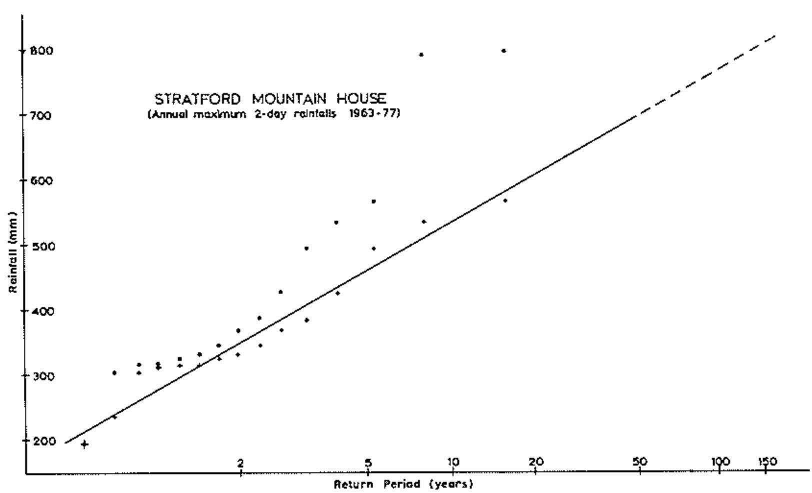


FIG. — 2 Annual maximum 2–day rainfalls for Stratford Mountain House plotted on Gumbel probability paper.

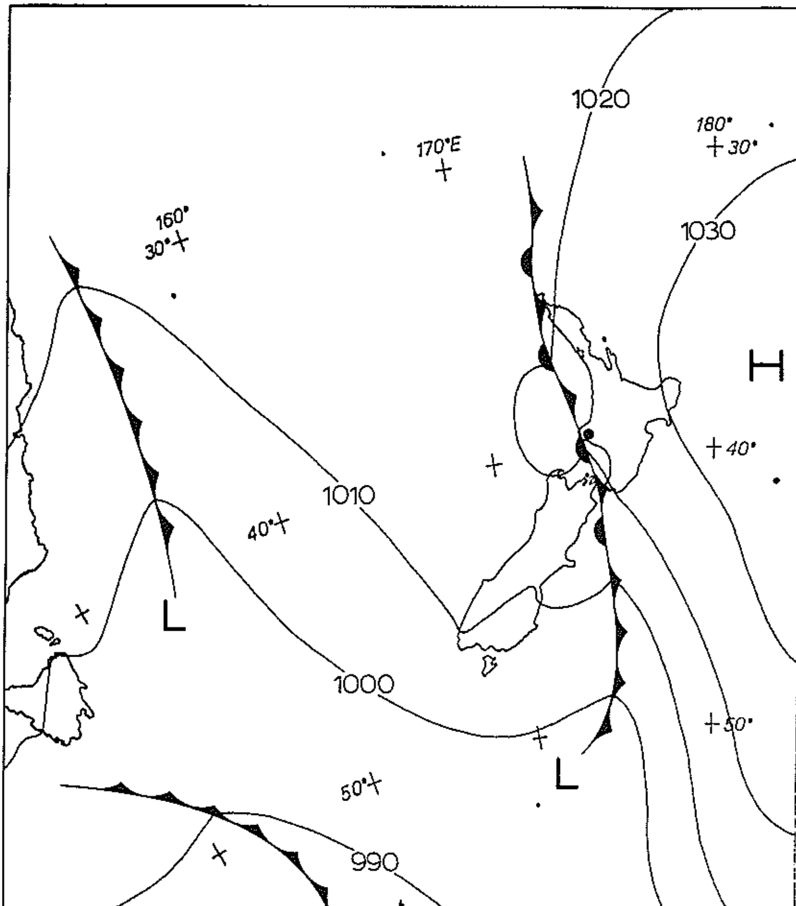


FIG. — 3a Weather situation at 0000 hours 11 August 1967. On 10–11 August 794 mm of rain was recorded at Stratford Mountain House.

occasions of intense rainfall. In a report about this storm, Tomlinson (1977b) noted that a similar intense rainfall occurred in 1939 in the Wellington area. It would seem that with present knowledge of weather systems the storm of 20 December 1976 must be considered to have an extremely large return period *in the small area it affected.*

The above situation can be contrasted with the following one. Listed in Table 1 are the annual maximum 2-day rainfalls (0900–0900 hours) for Stratford Mountain House on Mount Egmont. These values are plotted in Fig. 2 as the black dots. It is obvious that the two largest values (1967, 1971) would cause difficulty in attempting a linear fit to the points. An inspection of the weather situations reveals that these rainfalls arose from situations quite unlike those of the remaining 12 cases. An inspection of the situations can be made, to a first

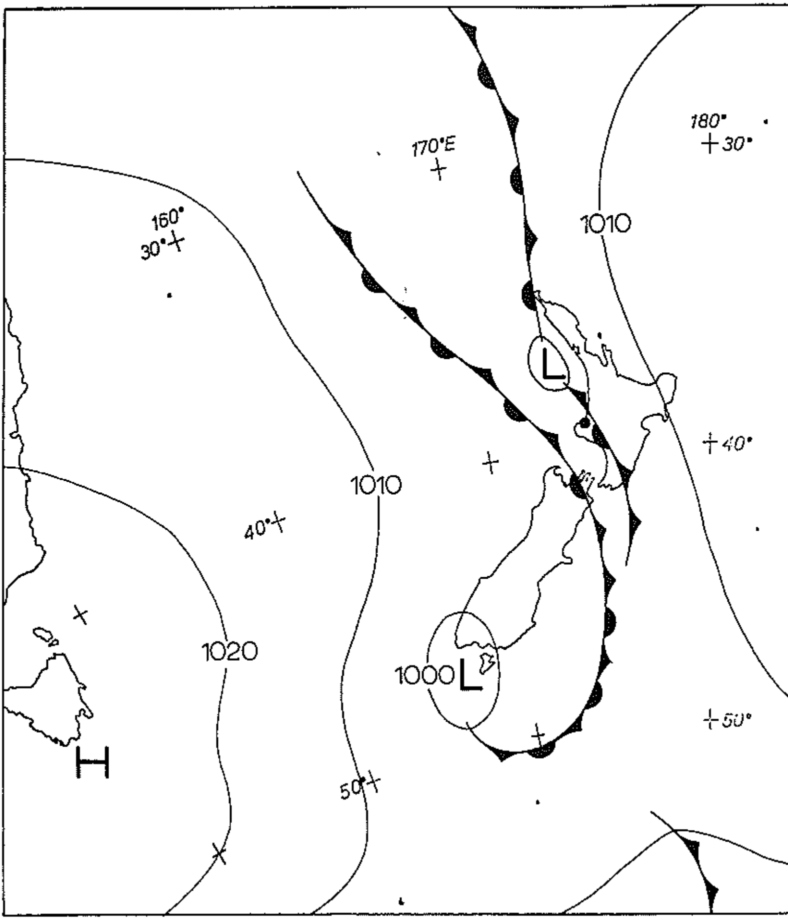


FIG – 3b Weather situation at 0000 hours on 25 February 1971. On 23–24 February 796 mm of rain was recorded at Stratford Mountain House.

approximation, by studying the surface weather maps. These are shown in Fig. 3. Each produced heavy rainfall over a large part of Taranaki and involved a long fetch of moist air from the north. If the extremes of 1967 and 1971 are removed from the sample and replaced by the next largest values in those years, then the crosses in Fig. 2 represent the resulting sample. A linear least squares fit of these points is given by the solid line.

On this line the events of 1967 and 1971 would have a return period of about 120 years and the probability of getting two such events in 14 years is less than 0.5%. However, it would be quite misleading to conclude that their return period was 120 years since the line in Fig. 2 does not refer to extremes of the types experienced in 1967 and 1971. The return period of these extremes remains unknown, but the existence of two of them in a 14 year sample would suggest a

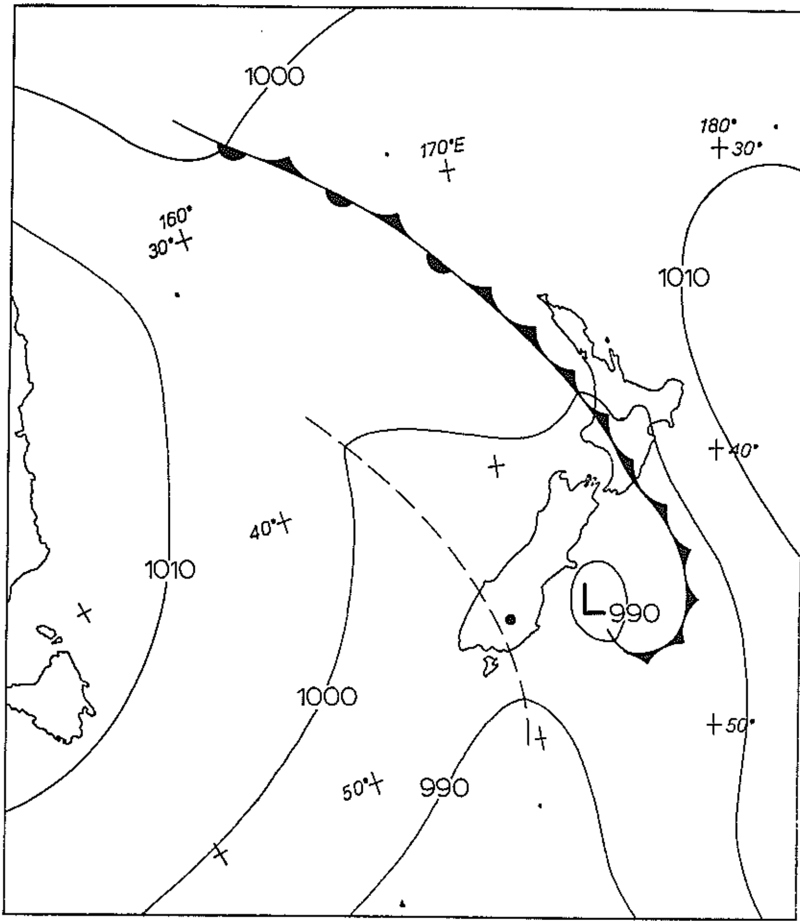


FIG — 4 Weather situation at 1200 hours 22 February 1935. On 22 February 82 mm of rain was recorded at Moa Creek and this is 1·28 times the 50 year return period value.

value considerably less than 120 years.

It should be noted that in both the cases discussed so far (lower Hutt Valley and Stratford Mountain House) the situation is not substantially changed if the extreme value distribution is changed. When different distributions are used it is necessary to consider the spatial consistency of estimates from adjacent stations.

To identify outliers it is convenient to know the ratio of the 100 to 50 year return period values for different durations of rainfall. For daily rainfalls an analysis of the records from 80 stations in New Zealand, with records of at least 50 years each, showed that this ratio varied from 1·09 to 1·13 with a mean value of 1·11. This ratio increases with decreasing duration of rainfall. For durations 48 and 72 hour the ratio averages 1·10 to 1·09.

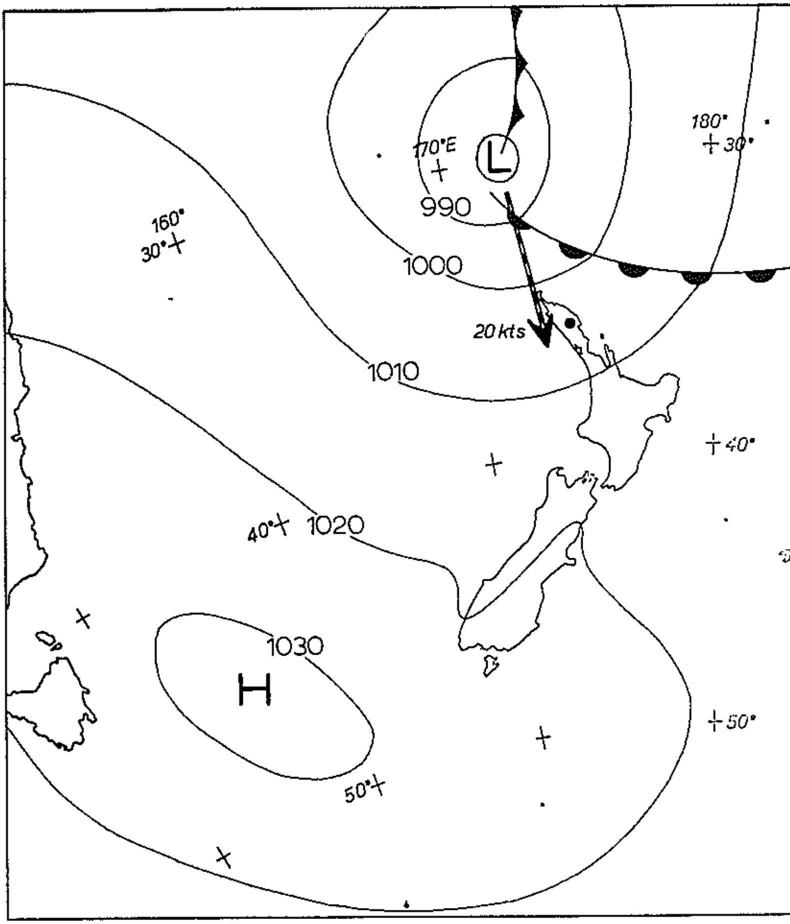


FIG — 5 Weather situation at 1200 hours 1 February 1936. On 1 February 350 mm of rain was recorded at Puhipuhi and this is 1·20 times the 50 year return period value.

Figures 4 to 7 give further examples of outliers and notes on the interpretation of these follow. Each resulted in exceptionally heavy rain being recorded at a manual raingauge site, and accordingly the notes are based only on daily rainfall totals.

Figure 4 shows the weather situation at noon on 22 February 1935. A trough of low pressure was crossing Southland and Fiordland at this time. During the period 0900 hours 22 February to 0900 hours 23 February there was a period of several hours of rainfall and a total of 82 mm was recorded at Moa Creek. While such an amount of rainfall would not be extreme in many parts of the country, it represented a daily value equal to 1·28 times the 50 year return period value for one day rainfall. The weather situation from which it resulted did not exhibit

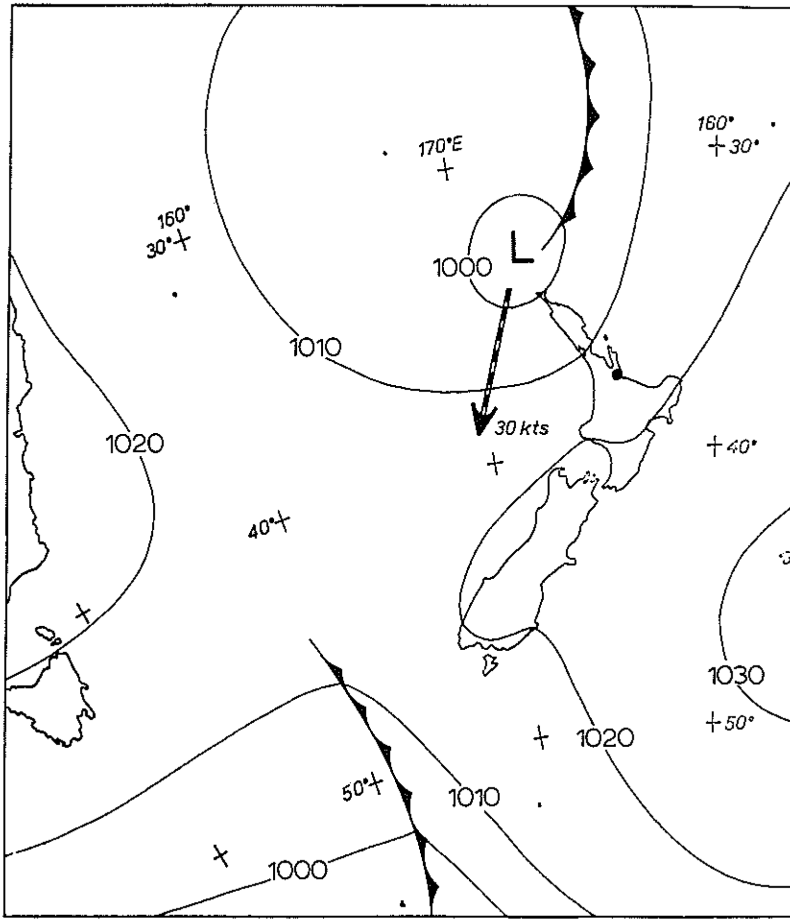


FIG – 6 Weather situation at 1200 hours 4 February 1938. On 4 February 419 mm of rain was recorded at Waihi and this is 1·29 times the 50 year return period value.

any features which would allow it to be separated from the situations that produce the general run of extremes, and accordingly it would be correct to assume that this event has a very long return period – in excess of 100 years.

Figs. 5 and 6 both depict weather situations in which a tropical depression brought extreme rainfalls to the north of the North Island. Both depressions were moving rapidly southwards, the first one on 1 February 1936 brought 350 mm in one day at Puhipuhi in Northland, and the second one on 4 February 1938 brought 419 mm on one day at Waihi. Both these rainfalls resulted from weather situations clearly separable from the normal mid-latitude weather patterns, and therefore should be treated separately from them for the assessment of their likely recurrence time.

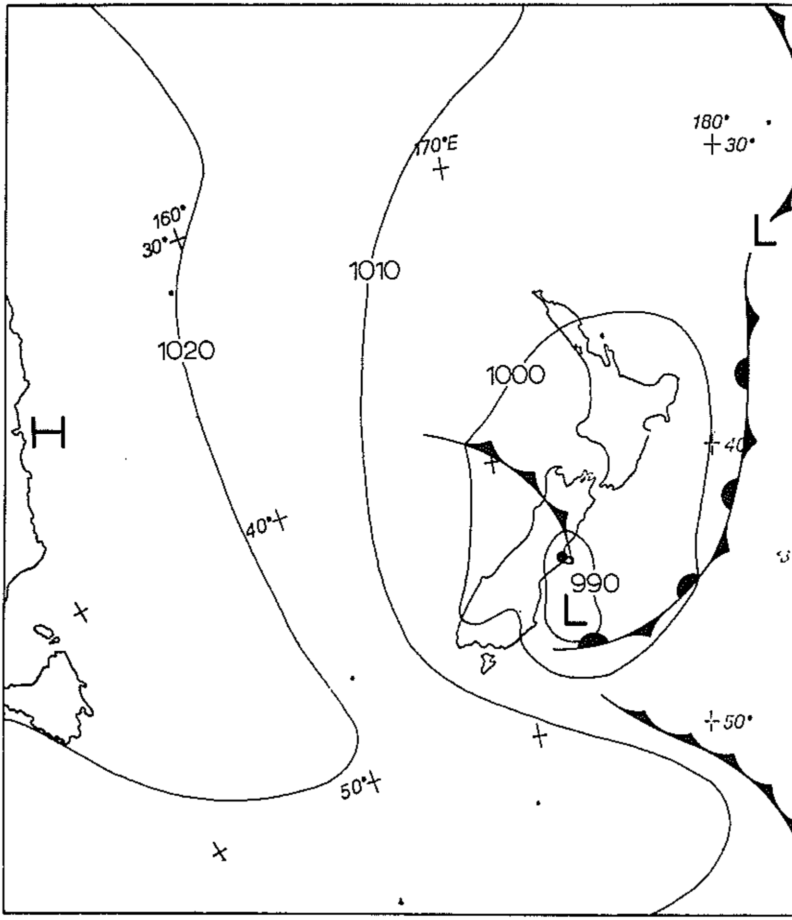


FIG — 7 Weather situation at 1200 hours on 11 April 1968. On 10–11 April 240 mm of rain was recorded at Pleasant Valley and this is 1.60 times the 50 year return period value.

Fig. 7 represents a meteorologically very complex situation which cannot be fully analysed here. The depression off the east coast of the South Island is the remains of that which produced the Wahine Storm in Wellington on 10 April 1968, and which had begun its life north of the New Hebrides on 5 April 1968. In the vicinity of New Zealand the tropical cyclone combined with an extra-tropical disturbance to produce an extremely vigorous depression. The structure of this depression has not been fully explored and indeed it may not be possible to do so. The rainfall recorded at Pleasant Valley near Christchurch was 240 mm on 10 and 11 April and this amount is 60% above the 50 year return period value. This value would lie at several thousand years, if placed on the return period graph for 2–day rainfalls at Pleasant Valley. Such an interpretation would be

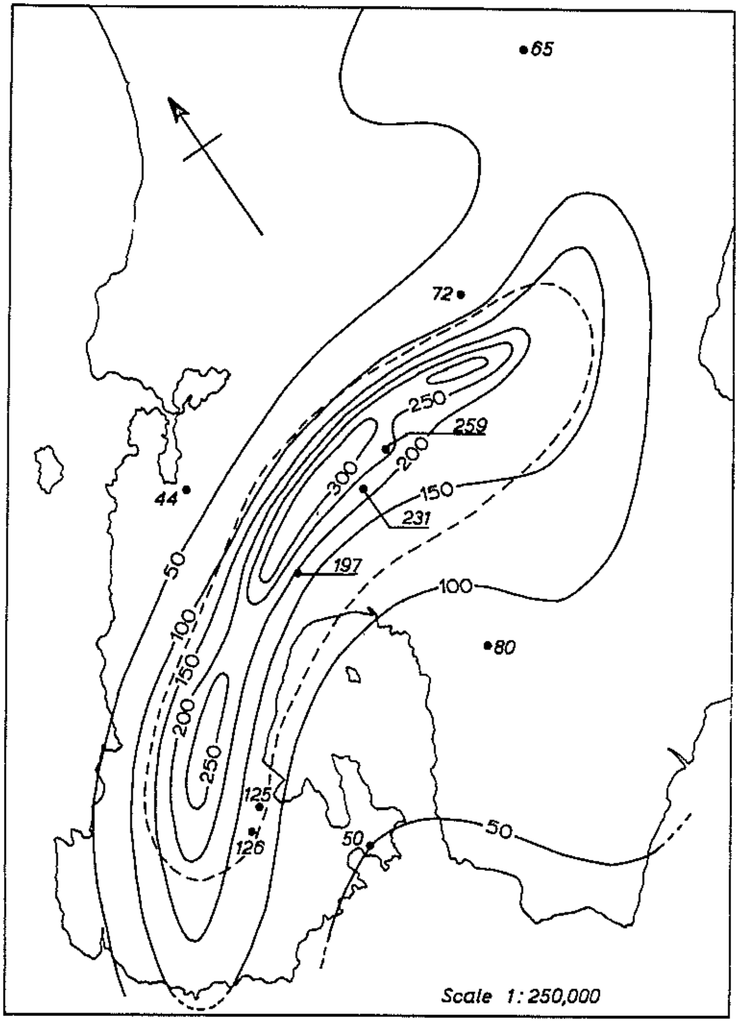


FIG – 8 The maximum recorded rainfalls in 12 hours on 20 December 1976. The isohyets are drawn at 50 mm intervals. The locations of autographic rainfall recording stations are indicated by dots and the values recorded at these stations are plotted. All points within the dashed line received 12 hour rainfalls of return period greater than 50 years.

doubtful, but the complexity of the situation is such that the case cannot be separated from other cases of extreme rainfall and the return period of this rainfall can only be assessed as large and of the order of several hundred (or even thousand) years.

Application of the area reduction curves of the U.S. Weather Bureau (1958) to intense rainstorms in New Zealand leads to a considerable error in many cases. Fig. 8 shows the distribution of the maximum 12 hour rainfall in the 20 December 1976 storm in the Wellington area. In this storm the reduction of rainfall with area was very large and far in excess of that indicated by the U.S. Weather Bureau curves. However, this storm was a very extreme event and it is likely that for less severe storms the curves are rather more realistic. For many design purposes it is the extreme events that are of concern, and it is proposed that for these the depth area relations can be assessed in a different way.

It has been shown in the previous section that extreme rainstorms can involve point rainfalls whose return periods are very long, and certainly well in excess of 50 years. Such storms can be well characterised by their duration, the largest rainfall recorded over this duration (at any station affected by the storm) the ratio of this rainfall to the 50 year return period value at the site, and the area within which the rainfall at all points has a return period in excess of 50 years. The duration of the storm is that which maximises the third of the four characteristics, namely, the ratio of the rainfall to the 50 year return period value.

These four characteristics give a very condensed and standard format which will allow very intense rainstorms in different parts of the country to be compared. By looking at the area enclosed by the 50 year return period isopleth instead of the depth area reduction curves, the climatic effects of spatial rainfall variability through the country are built into the analysis and are not left to cloud any further analysis concerned with the temporal distribution of such storms. Also, since very extreme storms are by their nature very rare events there are likely to be too few of them in any area to allow meaningful average area reductions curves to be computed. In a country like New Zealand with very large spatial distributions of mean rainfall it would be unrealistic to expect one set of area reduction curves to serve the whole country. By considering just the four characteristics listed above, regional differences are removed and we can look nationally at severe rainstorms.

Rainfall maps, such as that shown in Fig. 8, are not based on just the recorded rainfalls. In drawing them account should be taken of the weather systems that produce them, to ensure compatibility between the recorded rainfall and the associated atmospheric processes. In the following examples of area rainfall distributions in extreme rainstorms this has been done.

Fig. 9 shows the rainfall distribution on 17 April 1948 and the accumulation of rainfall at Tauranga Aerodrome. Most of the rain in this storm fell in 6 hours and was associated with a warm front which moved southeastwards across the Bay of Plenty. The 50 year return period isopleth on the isohyetal map follows fairly closely to the 150 mm isohyet.

Fig. 10 shows an exceptional rainfall in the Tasman Mountains to the northwest of Nelson in March 1954 and the accumulation of rainfall at Cobb Dam. Most of the rainfall in this storm fell in 48 hours and was associated with a tropical depression moving slowly southeastwards over the area. At Cobb Dam 510 mm was recorded in 24 hours which is more than twice the previous maximum 24 hour rainfall recorded in 30 years. The 50 year return period isopleth on the isohyetal map ranges from 300 mm to about 400 mm.

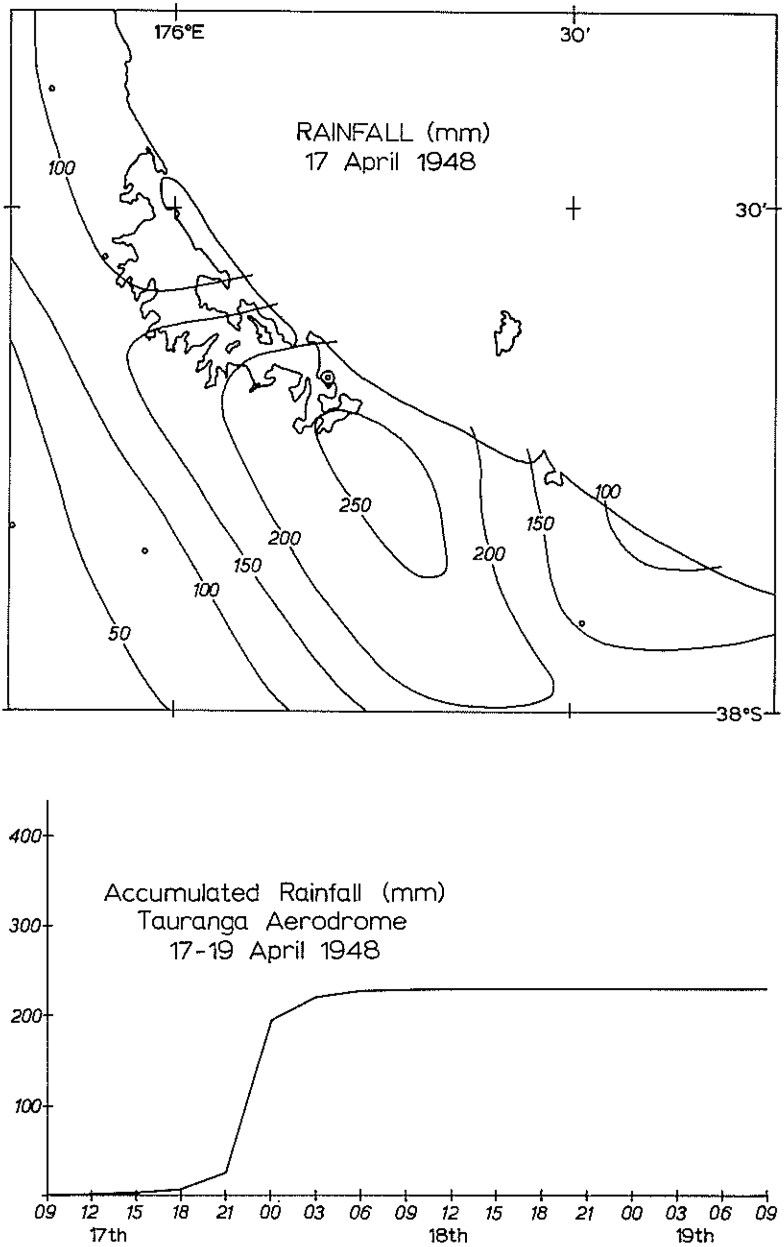
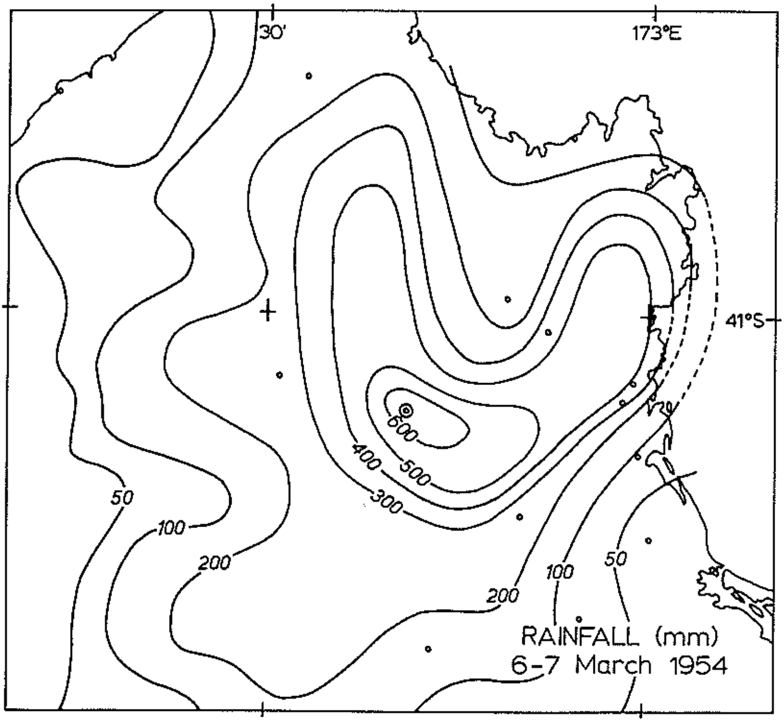


FIG — 9 Isohyetal map showing the rainfall recorded on 17 April 1948 in the Bay of Plenty area. Also shown is the accumulation of rainfall measured by the recording gauge at Tauranga Aerodrome.



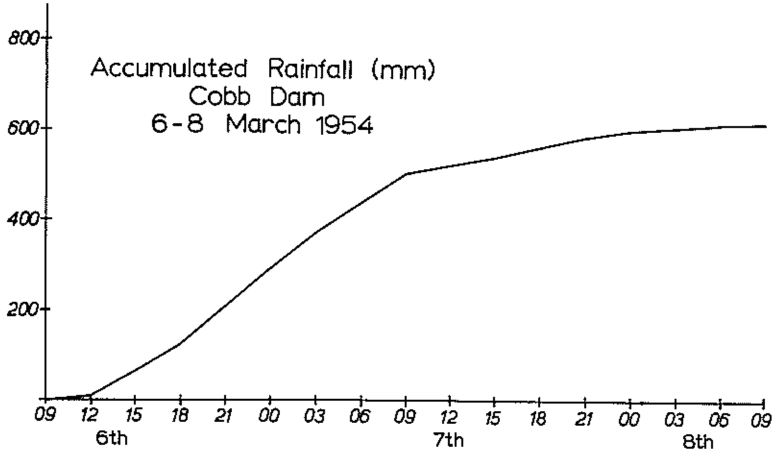


FIG — 10 Isohyetal map showing the rainfall recorded on 6–7 March 1954 in the Tasman Mountains. Also shown is the accumulation of rainfall measured by the recording gauge at Cobb Dam.

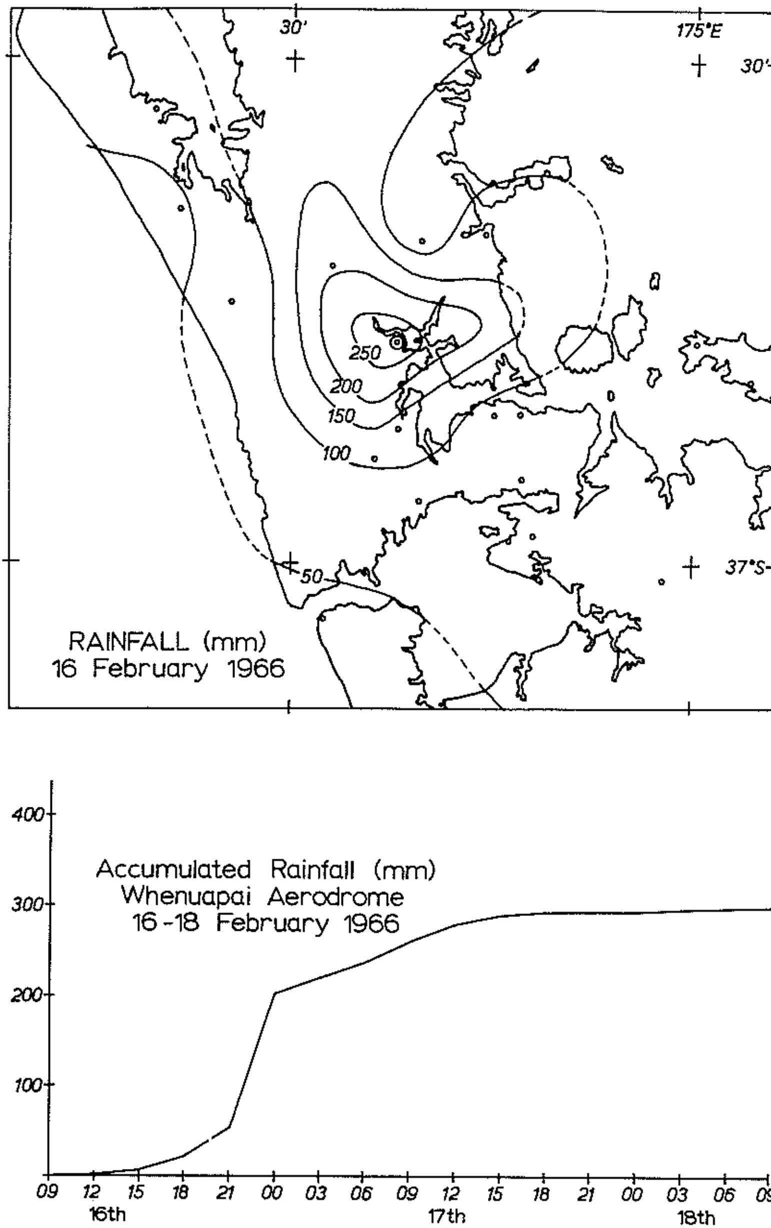
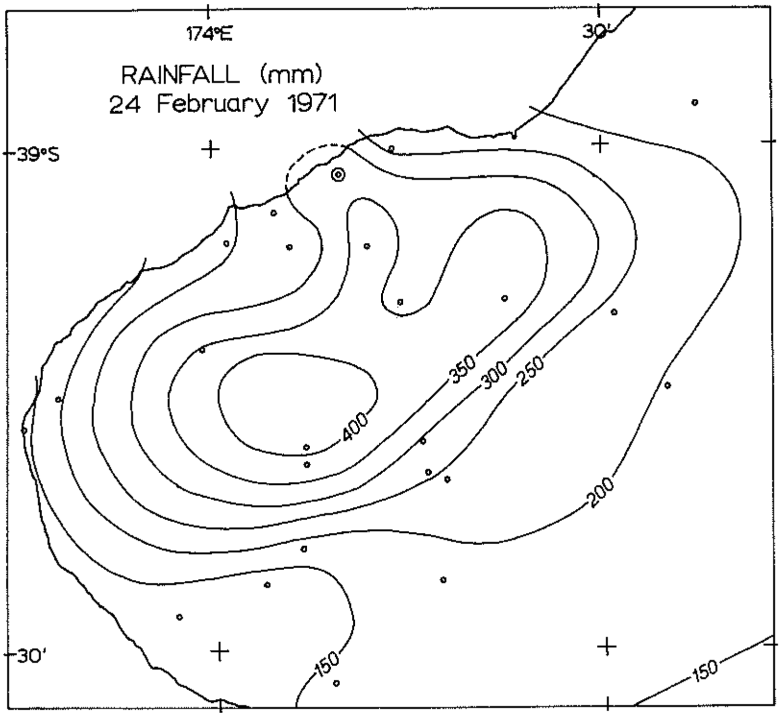


FIG – 11 Isohyetal map showing the rainfall recorded on 16 February 1966 in the Auckland area. Also shown is the accumulation of rainfall as measured by the recording gauge at Whenuapai Aerodrome.



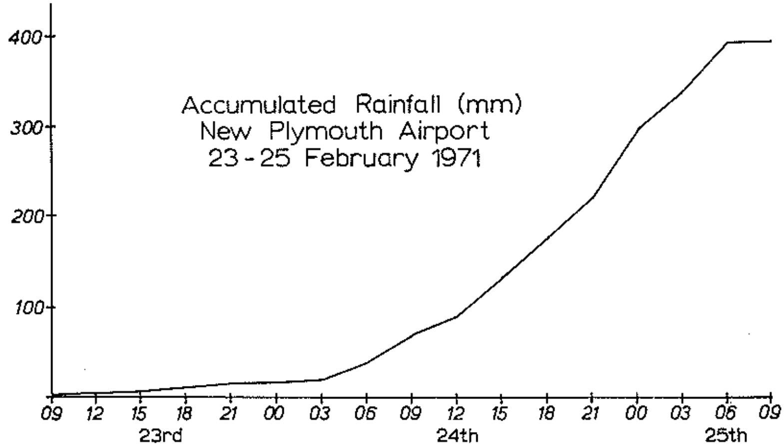
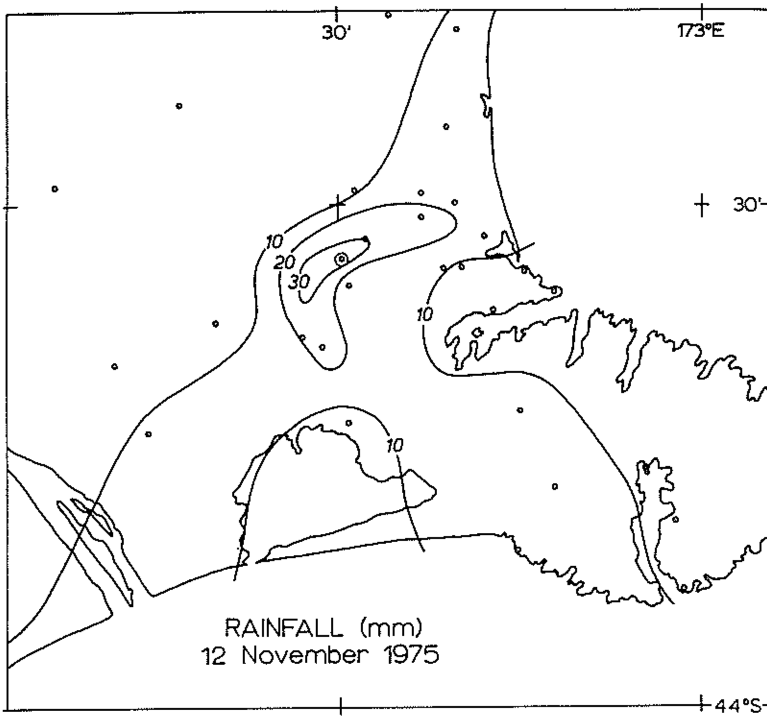


FIG — 12 Isohyetal map showing the rainfall recorded on 24 February 1971 in North Taranaki. Also shown is the accumulation of rainfall as measured by the recording gauge at New Plymouth Airport.



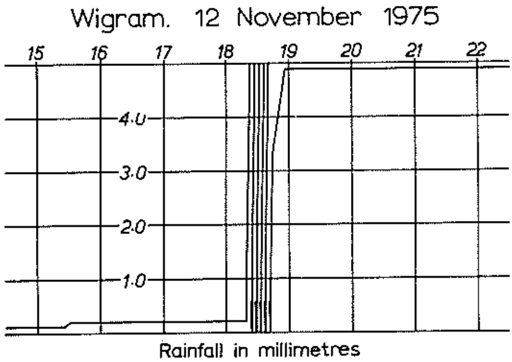
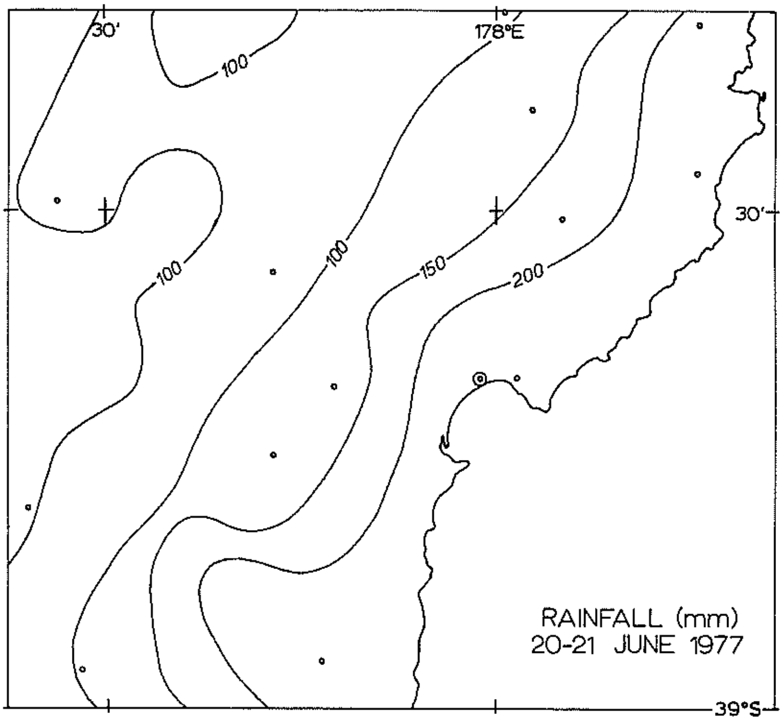


FIG – 13 Isohyetal map showing the rainfall recorded on 12 November 1975 in the Christchurch area. Also shown is a copy of a section of the recording raingauge chart from Wigram Aerodrome.



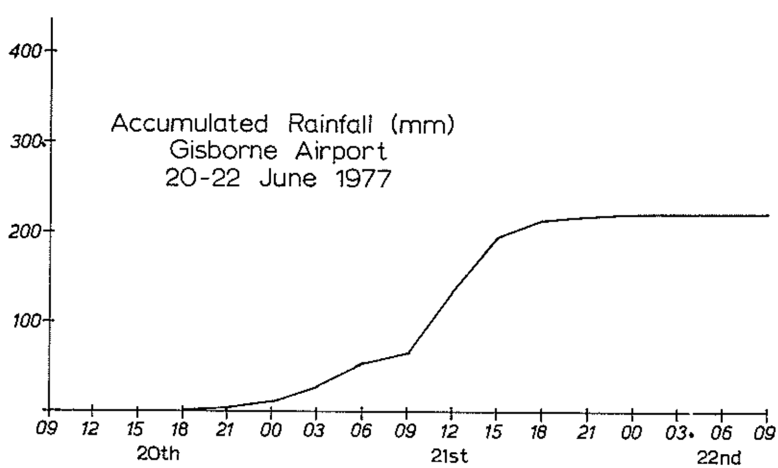


FIG – 14 Isohyetal map showing the rainfall recorded on 20–21 June 1977 in the Gisborne District. Also shown is the accumulation of rainfall as measured by the recording raingauge at Gisborne Airport.

Fig. 11 shows a rather local extreme rainfall in the Auckland area on the night of 16 to 17 February 1966 and the accumulation of rainfall at Whenuapai Aerodrome. Most of the rainfall in this storm fell in 12 hours, with a very intense fall in just 3 hours. The rain resulted from a very vigorous thunderstorm which was almost stationary over the area. The 50 year return period isopleth on the isohyetal map ranges from 130 mm to 140 mm.

Fig. 12 shows the rainfall pattern in Taranaki on 24 February 1971 and the accumulated rainfall at New Plymouth Aerodrome. The weather situation from which this rainfall resulted is shown in Fig. 3b. The 50 year return period isopleth on the isohyetal map ranges from 270 mm in the north to 230 mm in the south.

Fig. 13 shows an extremely local and short duration rainfall pattern near Christchurch on 12 November 1975 and a copy of the rainfall chart from Wigram Aerodrome. This rainfall occurred over only 30 minutes and resulted from a thunderstorm on the leading edge of a southerly change which moved over Canterbury. The 50 year return period value for 30 minute rainfall in this area is 24 mm.

Fig. 14 shows the rainfall distribution for the 2 days 20–21 June 1977 in the Gisborne district and the accumulation of rainfall at Gisborne Aerodrome. This pattern of rainfall is unusual because of the large values along the coast and also because of the decrease in rainfall inland. The rainfall was associated with a depression moving over the north of the North Island. The 50 year return period isopleth on the isohyetal map lies close to the 150 mm isohyet north of Gisborne, but turns eastward to cross the coastline about 15 km south of Gisborne.

TABLE – 2 Some characteristics of a selection of very intense rainstorms

Date	*Place*	*Length of Storm (hr)*	*Maximum rainfall at recording gauge site*		*Area enclosed by 50 year R.P. line (km²)*
			Amount (mm)	*Percentage above 50 yr R.P.**	
20.12.76	Wellington area	12	259	85	300
17.4.48	Western Bay of Plenty	6	212	50	2000
6- 7.3.54	Tasman Mountains	48	618	106	700
16-17.2.66	Auckland area	12	252	85	500
24-25.2.71	North Taranaki	24	358	94	2200
12.11.75	Christchurch area	0.5	33	40	100
20-21.6.77	Gisborne District	24	215	43	1100

*R.P. indicates return period value for rainfall of the duration equal to the length of the storm

Some of the main points depicted by Figs. 8 to 14 are shown in Table 2. The storms listed in Table 2 are all extreme and represent a very small sample of similar storms which have probably occurred in New Zealand over the last 30 years. However, they represent most of those which have passed over recording raingauges. Even this small sample should raise doubts about the generally held view that storm area usually increases with duration and also with intensity. Apart from the 30 minute rainstorm near Christchurch on 12 November 1975 where the area concerned is very small, there is considerable variability in the relationships between storm length, storm area and storm intensity for the seven very extreme cases considered.

CONCLUSIONS

This paper has been concerned with very extreme rainstorms, whose peak rainfalls would have been assessed by 'conventional' means to be considerably in excess of 100 years. Twelve such storms have been examined.

It has been shown that throughout New Zealand the 100 year return period value of daily rainfall is between 9% and 13% greater than the 50 year return period value (at places below 1000 m). The 24–hour return period values are 14% greater than the daily ones. The ratio of the 100 to 50 year return period value decreases slightly with increasing rainfall durations from 24 hours to 72 hours. For durations less than 24 hours the ratio will increase but the actual amount of this increase has not been investigated.

The spatial distribution of heavy rainfalls in New Zealand can be represented by national maps of rainfall amounts of various return periods. Several such maps exist in the literature. Some temporal variations in heavy rainfall are clearly observable such as diurnal and annual cycles. Other temporal variations are detectable in some samples and these may be related to solar or lunar variations. Great care should be exercised with these latter types, as they are commonly very transient and have an average amplitude which is quite small. In general it is most appropriate to neglect all temporal variations, other than diurnal and annual, since for design purposes they tend to be too small and too unreliable to be of any value.

By examining the weather situations that have produced very intense rainstorms, it has been shown that some outliers on the Gumbel extreme value probability graphs represent quite separate populations to those represented by the other extremes. Such values should not have a return period assigned to them on the basis of these graphs. Though this separation of populations does not particularly simplify the task of assigning return periods to outliers, it does at least ensure that the theory is not misapplied and it may lead to a more prudent assessment of the return periods of some extreme rainfalls.

The area reduction curves of the U.S. Weather Bureau can frequently lead to considerable error in assessing the area rainfall associated with point extreme rainfalls. Because of the very large spatial variations in rainfall in New Zealand (which is especially apparent in severe storms) it seems unlikely that an adequate set of area reduction curves can be constructed for New Zealand. A simpler approach is therefore proposed where only four statistics are used to characterise both the area and severity of extreme storms. These four statistics are the duration of the storm, the maximum recorded rainfall, an indication of the return period of that rainfall, and lastly, the area enclosed by the 50 year return period isopleth. Since the most severe storms do in practice set design values for engineers (even though the recurrence times of these storms may be extremely large) the seven examples given of the application of the proposed classification of storms have been cases of very extreme rainfalls. This sample of only seven cases is very small and it will be necessary to increase this to at least 50 cases before any patterns in the four statistics can be expected to emerge. To do this some storms of lesser return period (20 to 100 years) will need to be examined.

ACKNOWLEDGEMENT

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