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PROBABLE MAXIMUM PRECIPITATION IN NEW ZEALAND FOR SMALL AREAS AND SHORT DURATIONS

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ABSTRACT

Probable maximum precipitation (PMP) in New Zealand for small areas and short durations is estimated, based on the maximisation of a few severe localised storms. The observed storm depths are similar to those experienced in south-east Australia. Maximisation of storm rainfalls to a common reference level of Northland, and a dew point temperature of 24.5°C, provides the basis from which nationwide PMP estimates can be made. The reference level one-hour point estimate of PMP for New Zealand is 220mm. For any location in New Zealand, applications are presented which can be used to determine PMP for a range of areas up to 1,000km^2 and durations up to six hours.

INTRODUCTION

Probable maximum precipitation (PMP) is defined by the World Meteorological organization (WMO, 1986) as being theoretically the greatest depth of precipitation for a given duration that is meteorologically possible over a given area, at a particular time of the year. This definition has remained largely unchanged since first being introduced by United States meteorologists in the middle 1930's, and makes no allowance for the effects of climate change.

In many regions of the world, severe localised rain-storms and subsequent flash flooding are problems. Severe localised storms affect the level of PMP over small catchments (up to 1,000km^2) and short durations (up to six hours). They result from mesoscale weather phenomena, which exist in many forms. At one end of the spectrum is the single cell (thunderstorm type) storm; at the other end is the multi-cellular complex with large-scale synoptic forcing. The intensity and duration of rainfall is strongly related to the proficiency of convective processes (Schaefer et al., 1985), as well as the extent to which there is interaction with the large-scale synoptic situation (Maddox et al., 1979; Shepherd and Colquhoun, 1985). Meteorologists have identified a number of factors which lead to exceptional heavy rainfalls. These include airmasses with high moisture contents; weak vertical wind shear through the cloud layer; a closed circulation extending through most of the troposphere; repeated formation of convective cells over the same storm area; synoptic scale confluence and mesoscale convergence; and orographic uplift by hills and mountains. In addition to locally heavy rainfalls, these storms can be accompanied by thunder, lightning, high winds, hail and occasionally tornadoes.

This report provides a method by which estimates of mesoscale PMP can be made quickly and consistently for areas up to 1,000km^2 and for durations up to six hours. In Tomlinson and Thompson (1993) is a procedure for estimating synoptic scale PMP for durations of 12 hours up to 96 hours and for areas up to 15,000km^2.

In developing a method for estimating PMP in New Zealand over small areas and for short durations, it was necessary to draw on the extensive body of published literature on the subject, notably from the United States and Australia. A comprehensive bibliography is provided in the World Meteorological Organization's PMP manual (WMO,1986). It is possible to take this approach because the spectrum of mesoscale storms is not confined to a few specific locations of Earth. Meteorological processes producing high-intensity rainfalls and their associated spatial patterns are the same regardless of location (Court and Griffiths, 1985).

STORM RAINFALLS

Estimates of PMP are approximations which depends on the amount and quality of data available. Record high-intensity short-duration point rainfalls have been used as a basis of determining the level of PMP in New Zealand. They were extracted from archives of extreme rainfall, provided there was evidence that the rainfall was associated with convective processes. Indicators of convective processes are reports of thunder, lightning or hail.

Unusually heavy rainfalls in New Zealand exceeding 70mm in one hour (or less) were initially extracted. As very few such storms were recorded, the threshold was relaxed to 50mm. The most intense short-period rainfalls recorded in New Zealand, satisfying the above criterion are listed in Table 1. Also included in this table, for comparison, is a recent severe thunderstorm occurring at Roxburgh.

The data are nearly all from the North Island. Significant mesoscale storms do occur in the South Island: the South Canterbury storm of March 1986 (Thompson and Osborn, 1986) is one example, as is the severe thunderstorm at Roxburgh in November 1992. Many such storms also occur in the Southern Alps, in sparsely instrumented regions, and are often embedded within large-scale synoptic features such as cold fronts. For example, during 10-12 October 1978, when the Clutha River was in high flood, widespread thunderstorm activity was observed in south Westland.

A comparison of extreme rainfalls listed in Table 1 with notable events in Australian states of Victoria and Tasmania, and coastal New South Wales (Pierrehumbert and Kennedy, 1982; Bureau of Meteorology, Australia, 1985) shows that rainfalls there are very similar to those experienced in New Zealand, especially in the two southern states. However the New Zealand storm database has no storms that reach the severity or depth of the Dapto, New South Wales storm of February 1984, where in just six hours 515mm of rain was recorded (Shepherd and Colquhoun, 1985).

The data in Table 1 represent observed rainfall depths. Actual maximum depths are very rarely measured (Foufoula-Georgiou, 1989), although we believe the observed rainfall at Whenuapai (February 1966) is the only instance in our storm catalogue where a thunderstorm, embedded within a shallow trough of low pressure over northern New Zealand, sat over (or at least very close) to a well maintained autographic rain gauge for several hours. Differences between the actual and recorded maximum depths can be large. It is a sampling problem, common to many databases, and depends on the rain gauge density, the spatial rainfall pattern, and whether the observed maximum is recorded at or near the storm centre.

In many extreme storm rainfall catalogues and databases (see for example Hansen et al., 1988), the accuracy of the maximum rainfall is resolved to a large extent by making the maximum observed rainfalls not point falls, but rather an average depth over a small area surrounding the observation. For synoptic-scale storms the area is 25km^2; for thunderstorms and other severe localised storms the area is 2.5km^2. Maximum observed rainfalls are therefore used throughout this study as being representative of the average storm centre depth over an area of 2.5km^2. The maximum point rainfall will be larger, and synoptic meteorological studies over many years have indicated the need to increase observed rainfall depths (by an average of about 15 percent) to estimate the actual maximum (see for example Horton, 1924; Huff, 1968; Wiesner, 1970; Kennedy et al., 1988; Richards et al., 1988; Foufoula-Georgiou, 1989).

TABLE 1—Notable extreme rainfall events in New Zealand

Location	Latitude (°S)	Longitude (°E)	Date	Duration(hours)			6/1 hour ratio
				1	2	6	
Tauranga	37.6	176.1	17/04/1948	95	146	212	2.23
New Plymouth	39.1	170.1	13/02/1949	81	90	93	1.15
Tauranga	37.6	176.1	27/10/1952	64	82	125	1.95
Glenbervie	35.6	174.3	07/04/1956	75	85	121	1.61
Tauranga	37.6	176.1	06/05/1961	95	104	111	1.17
Opotiki	38.0	177.2	03/02/1960	58	75	100	1.72
Kaitaia	35.0	173.2	18/05/1962	77	84	97	1.26
Rautangata*	35.6	174.2	16/02/1966	140	195	250	1.79
Whenuapai	36.7	174.6	16/02/1966	107	150	194	1.81
Haast	43.8	169.0	29/03/1966	70	109	148	2.11
Waihi	37.3	175.8	28/02/1966	91	132	174	1.91
Glenbervie	35.6	174.3	08/08/1972	50	59	73	1.46
Stratford	39.3	174.3	08/12/1974	77	83	83	1.08
Taita, Lower Hutt	41.1	174.9	20/12/1976	50	89	181	3.62
Auckland	36.8	174.7	17/02/1979	52	66	108	2.08
Roxburgh	45.4	169.3	23/11/1992	80			1.00

*Estimated rainfall depths

ESTIMATION OF PROBABLE MAXIMUM PRECIPITATION FOR ONE HOUR

We present a procedure estimating nationwide one-hour PMP by maximising the storm rainfalls to a common reference region, Northland, where the moisture potential in storms is greatest (Tomlinson and Thompson, 1992). Estimates of PMP for other locations in New Zealand are then made by adjusting the moisture potential from the reference region.

Maximisation is a procedure by which storm rainfalls are adjusted by the ratio of the maximum atmospheric moisture which has been recorded under storm conditions, to that actually observed during the storm (WMO, 1986). Precipitable water is used as a moisture index to determine the level of adjustment. Surface dew point temperatures are used extensively as a proxy value for storm and maximum values of precipitable water as they are recorded at a large number of locations. The moisture index is determined by the surface dew point temperature of a storm in a saturated column of air with a pseudo-adiabatic lapse rate.

Monthly sea-level dew point temperatures from locations in New Zealand and adjacent offshore islands (Tomlinson and Thompson, 1992) were analysed to define the limits of the maximum values. It varied from 24.5°C in Northland to 19°C over southern New Zealand. The reference dew point temperature for New Zealand was therefore set at 24.5°C.

The maximisation procedure involved two steps. First, storm rainfalls were maximised in situ for the maximum monthly dew point temperature for the location. Moisture maximisation is based on the assumption that moisture supply during a storm can be increased without altering the dynamic structure of the storm. An upper limit of 180 percent was set for this maximisation to minimise excessive adjustments, and is based on the arguments of Hansen et al. (1988) and follows current Australian practice (Kennedy, pers. comm.). Firstly, if the moisture increase is extremely large, it may result in unreasonable changes to the storm dynamics. Secondly, excessive maximisations can result if surface dew point temperatures are not representative of the low-level atmospheric moisture feeding into storms. This can occur if storm dew points are not adequately sampled by the climatological recording network.

The restriction of 180 percent on the adjustment for moisture maximisation affected five of the 16 storms listed in Table 1.

Second, a transposition adjustment was made for geographic location from the place of origin to the Northland reference location. In terms of the meteorological processes causing severe mesoscale storms, New Zealand can be considered as a single homogeneous region since such storms are observed in most locations of the country. Variations in rainfall are therefore accounted for solely by differences in

TABLE 2—Moisture maximised storm rainfalls to reference dew point level of 24.5°

Location	Date	Duration (hours) 1	2	6	Dew Point (°C)
Tauranga	17/04/1948	187	288	417	16
New Plymouth	13/02/1949	131	145	150	19
Tauranga	27/10/1952	126	161	246	15.5
Glenbervie	07/04/1956	111	126	180	20
Tauranga	06/05/1961	187	204	218	13
Opotiki	03/02/1960	72	105	125	22
Kaitaia	18/05/1962	136	148	171	18
Ruatangata	16/02/1966	185	265	340	21
Whenuapai	16/02/1966	145	204	263	21
Haast	29/03/1966	154	239	325	15.5
Waihi	28/02/1966	161	233	307	18
Glenbervie	08/08/1972	90	106	131	10
Stratford	08/12/1974	169	182	182	15.5
Taita	20/12/1976	105	187	381	16
Auckland	17/02/1979	70	89	146	21
Roxburgh	23/11/1992	192			13.5

moisture potential, derived from ratios of the moisture indexes between the reference and origin locations.

Rainfalls, maximised to the common dew point temperature for Northland of 24.5°C, are given in Table 2. From the table, the maximised rainfall for one hour (rounded up to the nearest 20mm) is 200mm. It also represents the average PMP depth over an area of 2.5km^2. For two and six hours the maximised rainfalls are 300 and 420mm respectively. The one-hour maximised value derived from Table 2 is significantly less than the world maximum level of 421mm (WMO, 1986).

DEPTH-AREA RELATIONSHIPS

Thus far, in the development of PMP in New Zealand for small areas and durations, PMP has been estimated only for an area of 2.5km^2. It is necessary to produce relations to enable PMP estimates to be made over a range of areas. Horton (1924) observed that in many storms there was an exponential dependence of rainfall upon area, with a depth-area relationship taking the form

$$P = P_o \exp(-k A^{0.5}) \qquad (1)$$

where P_o is the point value for PMP at the centre of the storm, A is the area, and k is a coefficient determined from enveloping storm depth-area statistics.

In our study, depth-area data were available from Northland (February 1966), Taita, Lower Hutt (December 1976) and South Canterbury (March 1986). The statistics for these storms are given in Table 3. The storm data have been standardised and presented as the mean rainfall for a given area expressed as a percentage of the 2.5km^2 rainfall. The data, being extracted from 24-hour isohyetal analyses (except at Taita where a 6-hour analysis was available), do not permit a direct analysis of depth-area relations for durations up to six hours. However, on the basis of United States studies (Schwarz, 1965; USWB, 1966; Schwarz and Helfert, 1969; Hansen et al., 1977; Zurndorfer et al., 1986) relationships clearly exist between 24-hour, 6-hour and 1-hour depth-area curves. As storm area increases, the 24-hour rainfall decreases at a lesser rate than does the 6 or 1-hour rainfall. Storms of 24 hours or more have a much more uniform rainfall distribution over a large range of areas, than does a storm with a one- or six-hour duration, where the rates of decrease of rainfall away from the storm centre are larger. From these studies a one-hour depth-area curve (DA_{1h}) can be estimated from the 24-hour curve (DA_{24h}) by an equation which is also dependent upon area; i.e. $DA_{1h} = DA_{24h} \exp(-0.02 A^{0.5})$. This relation can also be used to derive one-hour depth-area values, from six-hour storm data. For areas up to 1,000km^2, six-hour depth-area statistics are five percent smaller than the 24-hour values.

The one-hour depth-area relation for the reference region of northern New Zealand, derived from enveloping the depth-area data given in Table 3, and adjusted by the inter-duration depth-area relationship, is as follows:

$$P = 220 \exp(-0.04 A^{0.5}) \qquad (2)$$

where P is the average 1-hour PMP depth for the area A in km^2. The estimate for the point value, P_o, at the centre of the storm in equation (1) of 220mm, has been rounded to the nearest 20mm, because of the uncertain relationship between the extreme (point value) and maximum observed rainfalls. The depth-area equation can be used for areas up to 1,000km^2. For other durations, the above equation is multiplied by appropriate depth-duration values.

TABLE 3—Depth-area statistics (percent of 2.5 km^2 area) from New Zealand storms

Area (km^2)	Taita	Whenuapai	Ruatangata	SthCanty.
	Depth-area data for storm			
2.5	100	100	100	100
50	67	92	95	82
100	61	85	90	79
200	54	75	80	74
300	49	65	74	72
500	41	60	63	69
750		54	58	66
1,000		50	52	63
Analysis period	6h	24h	24h	24h

DEPTH-DURATION RELATIONS

Estimates of PMP for other durations can be computed from the one-hour value through the use of depth-duration relations, which are based on the concept that mean intensity of rainfall decreases as duration increases (Hansen et al., 1977). This is clearly evident from rainfall records. This type of relation, although useful in developing a generalised PMP procedure for small areas and short durations, does not specify the time sequence in which incremental rain will fall.

The wide range of 6/1-hour depth-duration ratios (Table 1) indicates that there is no typical relationship for storms with mesoscale and synoptic scale interaction. For example, for the Taita storm the ratio was 3.6, while during the Whenuapai storm the ratio was 1.8. Other significant storms having large 6/1-hour ratios were the South Canterbury flash flood and the Dapto, New South Wales storm, with ratios of 3.6 and 3.9 respectively. Ratios tend to be larger when mesoscale and synoptic-scale interactions are influenced by strong orographic forcing.

A family of depth-duration curves covering the range of storm variation given in Table 1 has been developed and is given in Table 4. A generalised relationship was determined using the storm data in Table 1. The depth-duration relationship covers the range from the single-celled thunderstorm in which nearly all the rain falls in the first hour (i.e. small 6/1-hour ratios) to the larger multi-cellular meso-complex embedded within the synoptic scale weather system (i.e. larger 6/1-hour ratios). Meteorological experience indicates that in inland basin regions, especially in the South Island, thunderstorms are the predominant mesoscale phenomenon, while the larger multi-celled meso-complexes are observed elsewhere in New Zealand.

Families of smoothed depth-duration curves are constrained by two limits. The first is that rain falls at a constant rate during the storm, i.e., a straight line rate from 1 to 100% at 1 hour on to 600% at 6 hours; this sets the upper limit to the depth-duration relation. The second is that all the rain falls in the first instant or is 100 percent at all durations; this sets a lower limit to the depth-duration relation. Over the range of possible 6/1-hour rainfall ratios, the depth-duration relationship can be approximated from storm data by D^R, where D is the duration in hours and $R = 0.56 \log_e$ (6/1-hour rainfall ratio). Table 4 gives the durational variation of rainfall as a percentage of the one-hour PMP.

TABLE 4—Durational variation of PMP as a percentage of the one-hour total for a range of 6/1-hour rainfall ratios

6/l-hour ratio	Duration (hours)						
	0.5	1	2	3	4	5	6
1.5	89	100	117	128	137	144	150
2.0	77	100	131	153	171	186	200
2.5	70	100	142	175	203	227	250
3.0	65	100	153	196	234	268	300
3.5	62	100	162	215	263	307	350

ADJUSTMENT OF PMP FOR LOCATION OF STORM

The one-hour estimate of PMP for northern New Zealand is 220mm. Other areas of New Zealand have lower moisture potentials (Tomlinson and Thompson, 1992). Figure 1 shows the percentage reduction in moisture potential, F_m, over North and South Islands when compared with northern New Zealand. This figure represents the variation of maximum dew point temperatures over New Zealand. It was derived from consideration of the principal moisture influxes during severe storms, and from a nationwide analysis of dew points.

Figure 1 is used in conjunction with the above generalised depth-area PMP equation. For a specific location or catchment, the initial PMP estimate is adjusted by the percentage reduction in moisture potential, F_m, taken directly from the isolines shown on the maps in Figure 1. If the location is at a high elevation, a reduction for altitude is also required. Moisture potential in severe localised storms has been found to change little with altitude up to about 1500m (Hansen et al., 1977). Above this altitude rainfall is reduced about five percent per 300m, because of the lower moisture potential of the atmosphere due to decreasing temperatures.

SPATIAL DISTRIBUTION OF PMP

Meteorological experience both here and overseas has shown that the most representative shape for severe localised storm rainfall patterns is that of an ellipse. Although storm patterns in general extend in more than one direction, mainly as a result of storm movement, in the region of heaviest rainfall an ellipse can be fitted to most storms. Idealised isohyetal patterns for PMP have been prepared from elliptical patterns for distributing PMP over small catchments. Storms at Whenuapai, Ruatangata, Taita, and Tauranga (April 1948) are examples in New Zealand, from which an idealised elliptical isohyet pattern having a 2:1 axial ratio was adopted for application within New Zealand. An idealised pattern is given in Figure 2. Isohyets are shown on this idealised pattern labelled A (1km^2) to I (1,000km^2).

Table 5 gives the isohyets labelled A to I in Figure 2 as percentages of the one-hour point PMP for successive hourly increments of PMP from one to six hours in descending order of magnitude. Isohyetal labels are given for a range of 6/1-hour rainfall ratios applicable to the range of storms identified in New Zealand. The isohyetal values have been derived directly from the depth-area relation for New Zealand. The procedure is essentially the reversal of steps used in a depth-area-duration analysis in WMO (1986). The rainfall depth along an enclosing storm isohyet label A to I can be shown to follow the equation $P=220\exp(-0.06\ A^{0.5})$. The appendix provides the derivation of this equation.

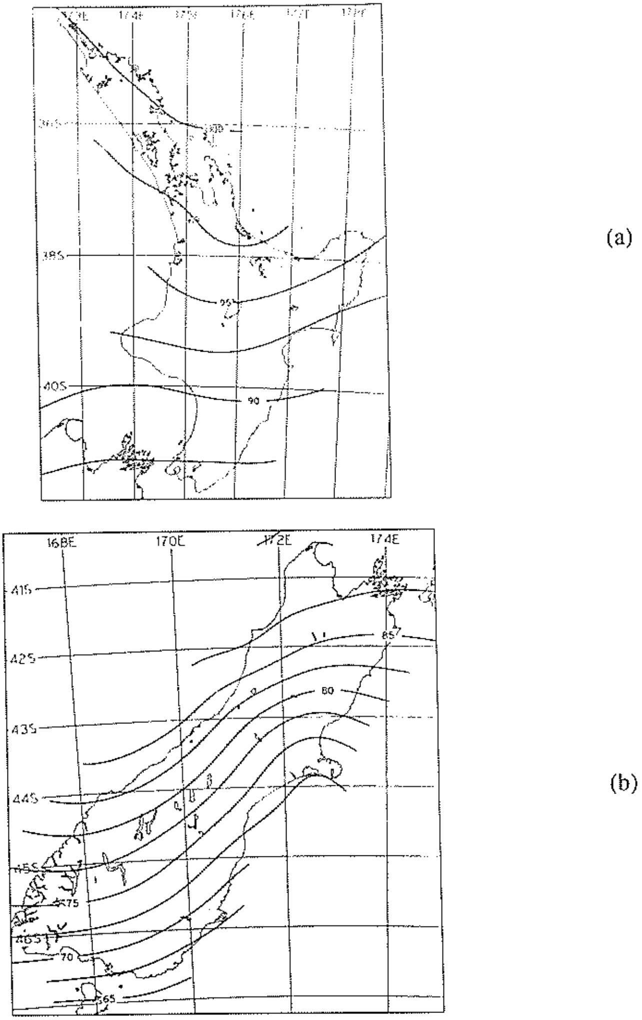
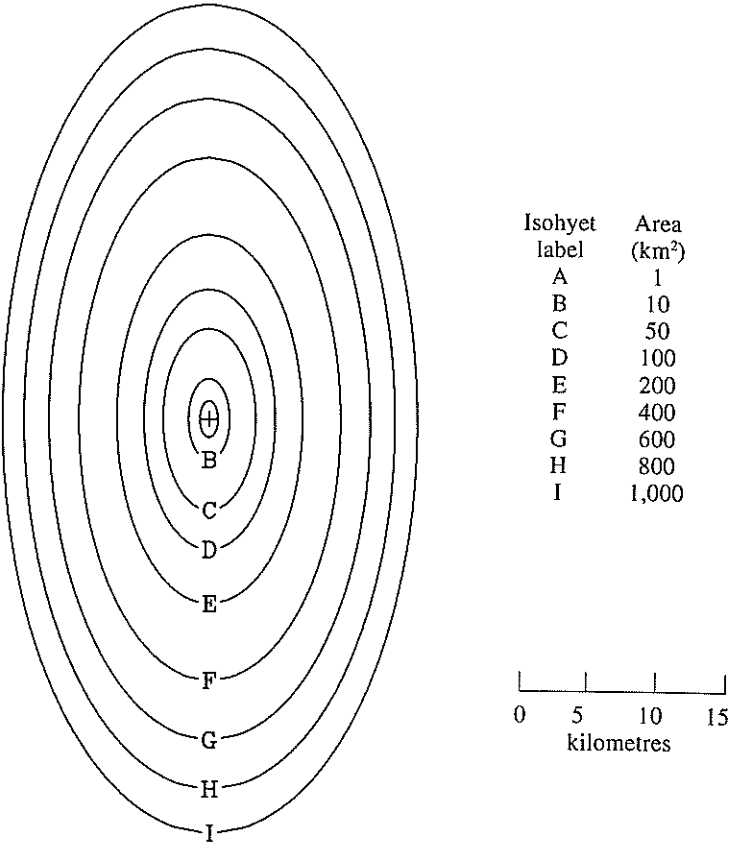


FIG. 1. Percentage reduction in moisture potential (F_m) from northern New Zealand for (a) North Island and (b) South Island.



Isohyet label	Area (km^2)
A	1
B	10
C	50
D	100
E	200
F	400
G	600
H	800
I	1,000

FIG. 2. Idealised isohyetal pattern of mesoscale PMP.

SUMMARY OF METHOD TO DETERMINE PMP

Two sets of procedures are given to estimate PMP; the first is to determine a catchment-averaged PMP, and the second is to indicate the spatial distribution of PMP within the catchment. They are summarised below and follow standard procedures described in many PMP reports (e.g. Tomlinson and Thompson 1992).

A. To estimate Catchment-averaged PMP

1. Catchment details: Determine outline, area and mean altitude of catchment.

2. Determine 1-hour reference level PMP for catchment: The reference PMP is given by the equation $P = 220 \exp(-0.04 A^{0.5})$.

3. Reduction factor for location of catchment: Determine the moisture reduction factor (F_m) from Figure 1 for the location of the catchment.

4. Adjustment for mean catchment elevation: If catchment is below 1,500m, no adjustment is required. If catchment is above 1,500m, apply an altitude reduction factor (F_a) for reduced moisture potential of five percent for every 300m increase in elevation above 1,500m.

5. Catchment-averaged PMP: The 1 -hour reference PMP in step 1 is multiplied by the appropriate adjustment factors for moisture potential (F_m) in step 3 and for altitude (F_a) in step 4, such that PMP = P $F_m F_a$.

6. Depth-duration adjustments: Depending on the type of mesoscale storm, an appropriate 6/1-hour rainfall ratio is selected and the depth-duration variation of catchment PMP, as a percentage of the one-hour PMP, is given in Table 4. As no typical ratio exists, a general rule to follow would be to use small ratios for storms with weak orographic forcing or for thunderstorms, and to use larger ratios for storms with large orographic forcing.

7. PMP estimates for range of durations: Multiply percentage depth-duration adjustments of step 6 by the catchment-averaged PMP in step 5.

B. Spatial distribution of PMP

1. Determine 1-hour PMP: For the catchment, calculate the 1-hour PMP from steps 1-5 of the catchment-averaged PMP procedures given above.

2. Determine isohyetal patterns for catchment: Lay the isohyetal pattern (Fig. 2) over the catchment outline of the same scale. Centre and rotate pattern to provide the greatest average depth. In some catchments, especially in the lee of mountain ranges, the anchoring of storms onto windward slopes may preclude centring the isohyetal pattern over the catchment.

3. Extract isohyet labels and corresponding storm values: For a given 6/1-hour rainfall ratio, obtain isohyet labels from Table 5 for isohyets up to the minimum size required to entirely enclose the catchment. Multiply the 1-hour PMP in step 1 by the isohyetal percentages (Table 5) to obtain isohyetal values.

4. Calculate average depth over catchment: Determine average depth of rainfall over catchment. The average rainfall over the catchment should agree closely with the value determined by the procedures outlined in Part A.

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TABLE 5—Isohyetal labels in percent of point 1-hour PMP for a range of 6/1-hour rainfall ratios

a. One hour PMP

Isohyet label	A	B	C	D	E	F	G	H	I
Area km^2	1	10	50	100	200	400	600	800	1,000
PMP (%1 hr)	98	86	67	56	42	28	20	15	11

b. Isohyetal labels for second to sixth hourly incremental PMP

6/1 hour ratio	A	B	C	D	E	F	G	H	I
				Second highest hourly PMP increment					
1.5	17	15	11	10	7	5	3	2	2
2.0	30	27	21	17	13	9	6	4	3
2.5	42	37	29	24	18	12	9	6	5
3.0	52	46	36	30	23	15	11	8	6
3.5	61	54	42	35	27	18	12	9	7
				Third highest hourly PMP increment					
1.5	11	10	8	6	5	3	2	2	1
2.0	22	19	15	12	9	6	4	3	2
2.5	32	28	22	18	14	9	7	5	4
3.0	42	37	29	24	18	12	9	6	5
3.5	52	46	36	30	23	15	11	8	6
				Fourth highest hourly PMP increment					
1.5	8	7	6	5	4	2	2	1	1
2.0	18	16	12	10	8	5	4	3	2
2.5	27	24	19	16	12	8	6	4	3
3.0	37	33	26	21	16	11	8	6	4
3.5	47	41	33	27	20	14	10	7	5
				Fifth highest hourly PMP increment					
1.5	7	6	5	4	3	2	1	1	1
2.0	15	13	10	9	7	4	3	2	2
2.5	24	21	17	14	10	7	5	4	3
3.0	34	30	23	19	15	10	7	5	4
3.5	44	38	30	25	19	13	9	7	5
				Sixth highest hourly PMP increment					
1.5	6	5	4	3	3	2	1	1	1
2.0	13	12	9	8	6	4	3	2	1
2.5	22	9	15	12	9	6	4	3	2
3.0	31	27	22	18	14	9	6	5	3
3.5	41	36	28	24	18	12	9	6	5

APPENDIX

Derivation of the value of a storm isohyet for a given storm area from the depth-area equation

The depth-area equation derived from New Zealand data (Table 3) is

$$P = 220 \exp(-0.04 A^{0.5}). \qquad (A1)$$

This equation can also take the form (United States Weather Bureau, 1945):

$$PA = \int_0^A P_i dA \qquad (A2)$$

where P_i is the depth along the enclosing storm isohyet label A to I in Figure 2 and is the quantity we wish to derive and evaluate.

From equation (Al), $Adp/dA = 220(-0.02 A^{0.5}) \exp(-0.04 A^{0.5})$

Therefore, differentiating both sides of equation A2 and solving for P_i gives

$$P_i = 220 \exp(-0.04 A^{0.5}) (1.0 - 0.02 A^{0.5}) = P + AdP/dA \qquad (A3)$$

Now $1.0 - 0.02 A^{0.5} \sim \exp(-0.02A^{0.5})$

Hence

$$P_i \sim 220 \exp(-0.06 A^{0.5}) \qquad (A4)$$

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