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A GUIDE TO PROBABLE MAXIMUM PRECIPITATION IN NEW ZEALAND

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Craig S Thompson and Alaric I Tomlinson

1. Introduction

The concept of an upper limit to precipitation potential for use in hydrological design purposes has been around since the 1930's. Such precipitation is known as the probable maximum precipitation (PMP) and is defined (WMO, 1986) as the theoretically greatest depth of precipitation for a given duration that is meteorologically possible over a given storm area at a particular time of the year. This definition applies to the maximum depth at the centre of the storm. Such values cannot be applied directly to catchments to evaluate the potential runoff under such conditions, but must be modified to obtain catchment-averaged estimates of PMP.

A comprehensive review of procedures to estimate PMP has been undertaken under the aegis of WMO (WMO, 1986). However, PMP estimates are still regarded as approximations, whose accuracy and reliability depends largely on the amount and quality of the data available. All but one of the procedures presented in the WMO manual are based on a comprehensive meteorological analysis, known as the physical or synoptic method. The one exception is a statistical procedure.

A method to provide estimates of synoptic scale PMP for New Zealand using generalised procedures was presented in Tomlinson and Thompson (1992). Generalised procedures refers to any suitable method to estimate the spatial and temporal pattern of PMP over large regions encompassing numerous techniques. This approach to PMP estimation has several advantages. These are, that maximum use can be made of all the data for the region; that any regional, durational and areal smoothing is done in a consistent fashion; and that regional consistency is maintained in the PMP estimates. The purpose of this publication is describe the assumptions and procedures used by Tomlinson and Thompson (1992) to estimate generalised PMP in New Zealand.

Generalised methods of estimating PMP require a large amount of preparatory work but are then relatively simple to apply. The generalised technique used here has been to estimate the non-orographic or convergence component of PMP and the envelopment of the depth-area-duration statistics followed by an adjustment to the estimate for any variations in the regional orography. This method is now explained.

2. Selection of storms and analyses

A fundamental need for developing generalised PMP is the selection and analysis of severe storms that have occurred. A computer survey of the national rainfall archive for dates and locations of high rainfall totals were extracted for all regions of New Zealand. Most of the storms initially selected were also found to be hydrologically important, in that they resulted in flooding.

A final storm database of 94 storms was assembled. Each of these storms were classified according to the type of storm producing the precipitation. This classification was used to aid the delineation of regions in New Zealand having similar weather systems leading to high rainfalls and floods. However, for 20 of the largest storms, detailed spatial and temporal analyses were undertaken for use in developing the PMP estimates.

Maximum persisting 12 hour dew point temperatures were also extracted for the 94 storms. In large storms, they are representative of the inflow of moisture into the storm system, and are usually converted into estimates of precipitable water (see for example Wiesner, 1970). However, when the storm precipitable water, W_S, is compared with the maximum amount that could occur in the storm area for the time of year, W_X, the ratio of the two quantities, W_X / W_S, gives the level of moisture maximisation and an indication of the potential limit to PMP.

3. Estimation of generalised PMP for New Zealand

3.1 Effect of orography on severe storms and storm separation

A difficult problem in the estimation of PMP is to use a consistent and suitable method for normalising severe storms for the effect of orography on the rainfall. Orography dominates New Zealand's rainfall and its effect is very largely *not* storm dependent. At any particular point in New Zealand the orographic component of precipitation in a storm is, for a given moist airstream, a function of position alone. United States and

Australian hydrometeorologists (Hansen et al., 1988; Kennedy et al., 1988) have developed procedures to separate storm precipitation into orographic and non-orographic or convergent components which reflect the two principal mechanisms of precipitation production; uplift by the weather system itself, and uplift by the mountains.

One technique to normalise the orographic influences on the amount of precipitation in individual storms makes use of the following relation (Hansen et al., 1977, 1988; Miller et al., 1984)

$$P = FAFP\ (T/C) \qquad (1)$$

where P is the total storm precipitation, FAFP is the free atmospheric forced precipitation or non-orographic component of precipitation, and T/C is the orographic factor representing the broad-scale orographic influences on storm precipitation.

FAFP is an idealised concept and is the precipitation that results from the dynamic processes in a weather system and is assumed to be largely independent of the orographic enhancement processes (Hansen et al., 1988). For a specific location, FAFP is calculated directly from (1) by dividing the orographic factor into the total storm precipitation. It is also the component of precipitation that is maximised with respect to moisture in the estimation of PMP.

The orographic factor, T/C, is the ratio of the 24 hour 100 year precipitation (T) to the 24 hour 100 year sea level precipitation in the absence of orography over New Zealand (C). It is assumed that in large storms the ratio Total to Convergent precipitation is the same as in the 24 hour return period statistics (WMO, 1986).

The return period of 100 years was chosen since the storms that are maximised to obtain PMP values are commonly of an intensity similar to the 100 year values. The T/C ratios at 100 year return period are assumed to apply to PMP storms. This assumption implies an equivalence between processes in severe and PMP storms.

Twenty-four hour, 100 year return period values were calculated for all stations with at least 10 years of records and plotted on 1:250,000 scale maps. Isohyets were drawn manually using additional information from Chinn (1979), Griffiths and McSaveney (1983a, 1983b), Whitehouse (1985), Griffiths et al. (1989) and Horrell

(1990). Grid point data were extracted on a 10 km square grid for computer contouring.

The 24 hour, 100 year return period convergence precipitation field (Figure 1) was constructed at a constant level (sea level), and is related to persisting dew point temperature. The amount of convergence precipitation is calculated using the dew point temperature and a model for precipitation which includes an estimate of the lifting of atmospheric moisture through convergence mechanisms (Haltiner and Williams, 1979). Convergence precipitation is a smooth field ranging from 160 mm in the north New Zealand to 110 mm in the south. It does not show the complex pattern that results from orography. A map of the orographic factor (T/C) is shown in Figure 2 and strongly reflects the pattern of orographic precipitation.

3.2 Estimation of convergence PMP

The approach for computing the convergence component of PMP (or maximised values of FAFP) follows, but is not identical with the method of the US Weather Bureau (1966) and Hansen et al., (1977). A key component of that procedure is that convergence precipitation from the 94 storms would be maximised for moisture and then enveloped. This study estimated a limit to the ratio of PMP convergence precipitation to the 100 year convergence precipitation.

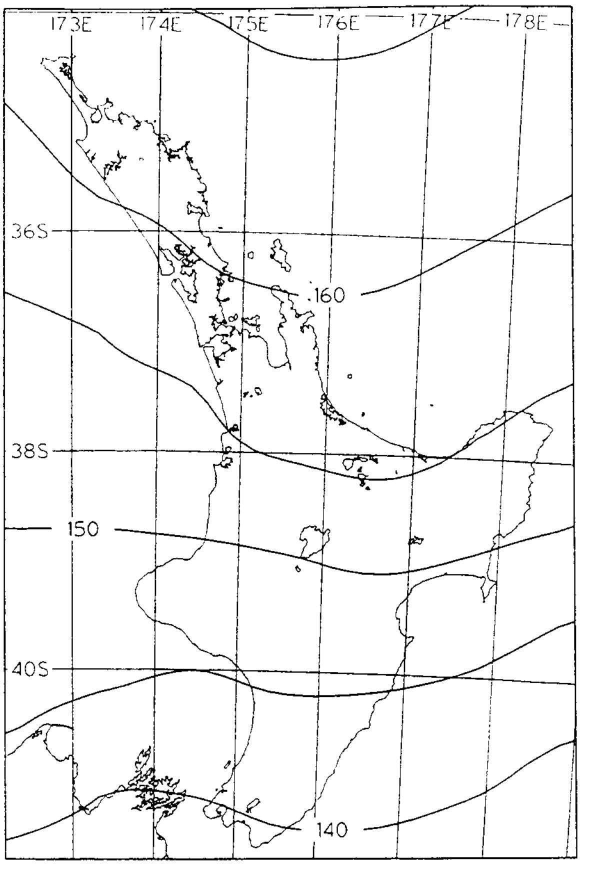
The following steps outline the procedure used to estimate the convergence component of PMP for a duration of 24 hours and an area of 25 km^2. This is referred to as the index value of PMP. Convergence PMP estimates for other durations and areas were derived from these index values. Point values have been taken as 25km^2 values (WMO, 1986).

1. Twenty-four hour point precipitation was maximised in situ for moisture, and the convergence component of precipitation was calculated from equation (1).

2. Ratios of maximised convergence precipitation to the 100 year convergence precipitation were computed (Figure 3). Some of the maximised precipitation's were less than the 100 year convergent rainfall estimates, indicating that the physical processes within them were clearly inadequate to produce PMP. There was no evidence in the data plotted in Figure 3 for any latitudinal variation. The maximum computed ratio from the storm data was 2.94.

Figure 1. The convergence component of 24 hour, 100 year return period precipitation (C).

(a) North Island



(b) South Island

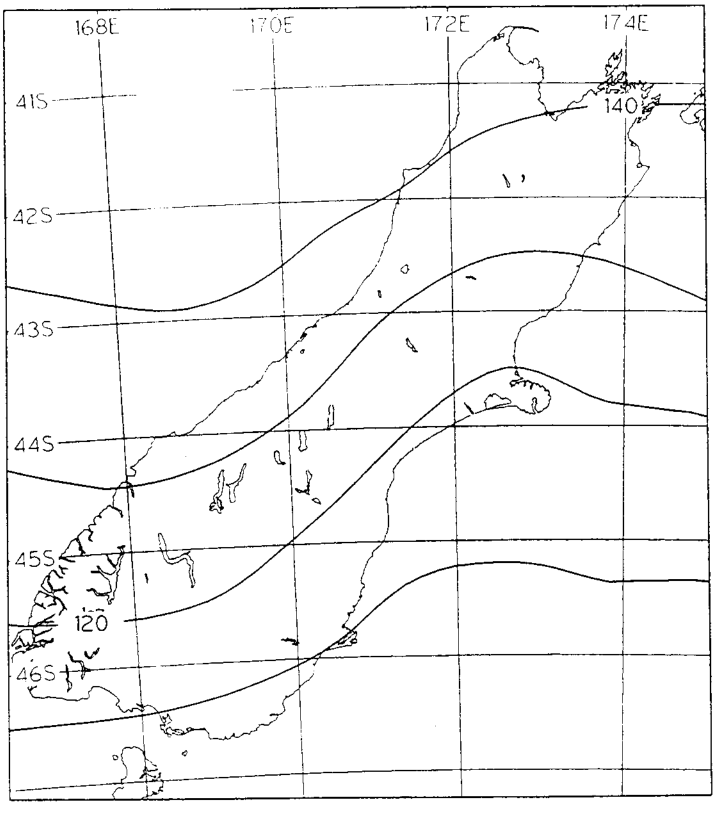


Figure 2a. The ratio of total to convergence precipitation (T/C) or orographic factor for the North Island

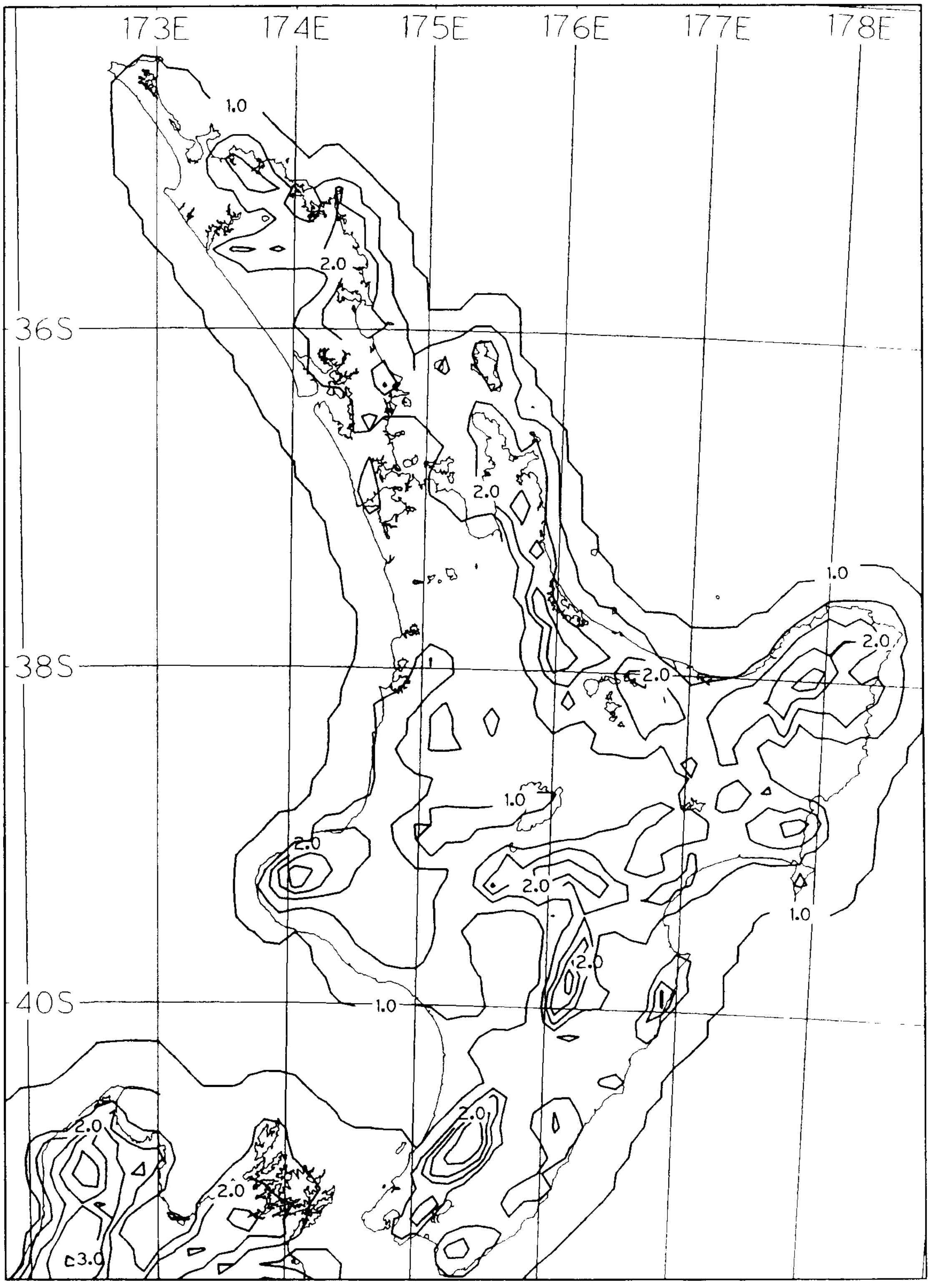


Figure 2b. The ratio of total to convergence precipitation (T/C) or orographic factor for the South Island

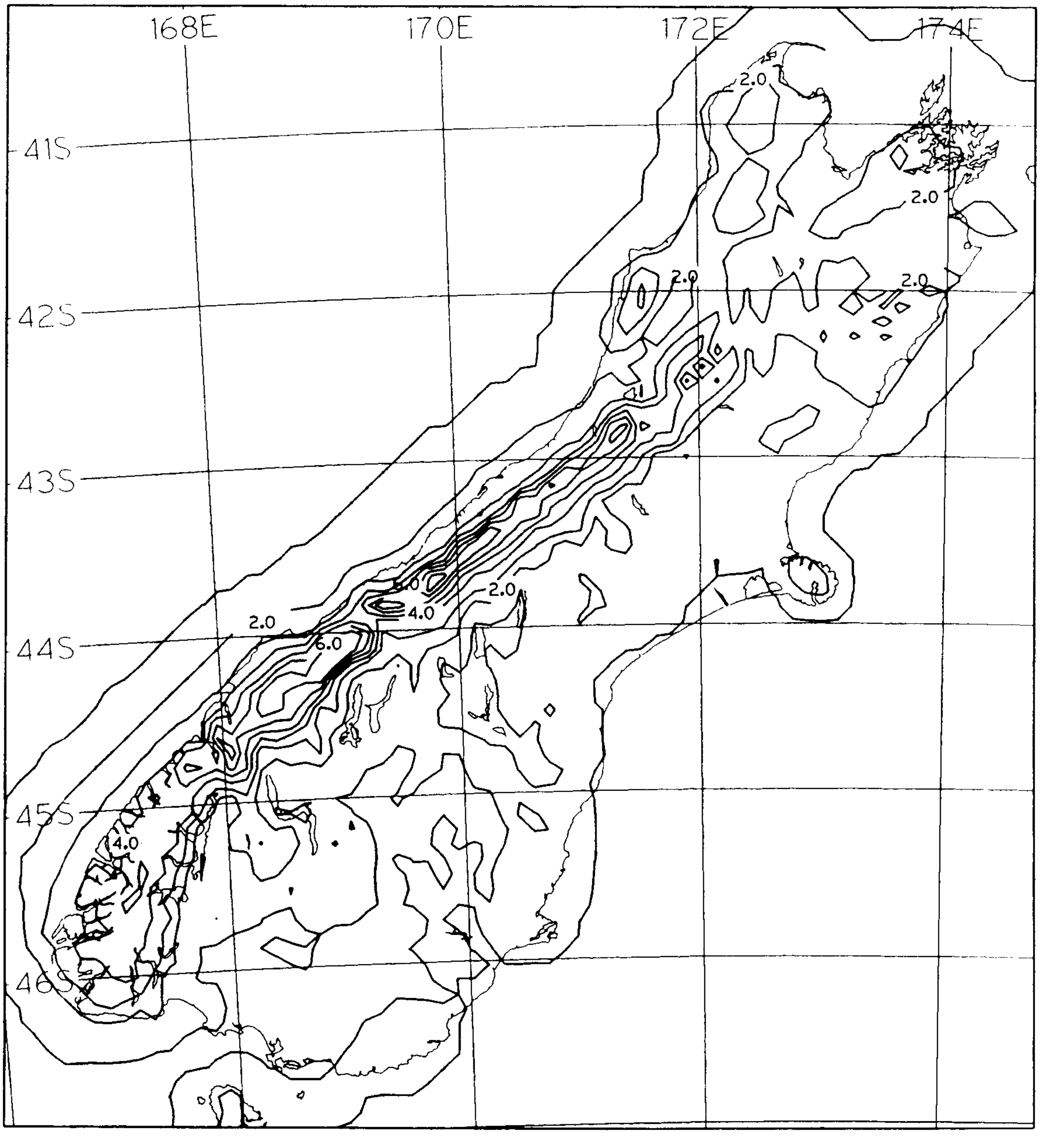
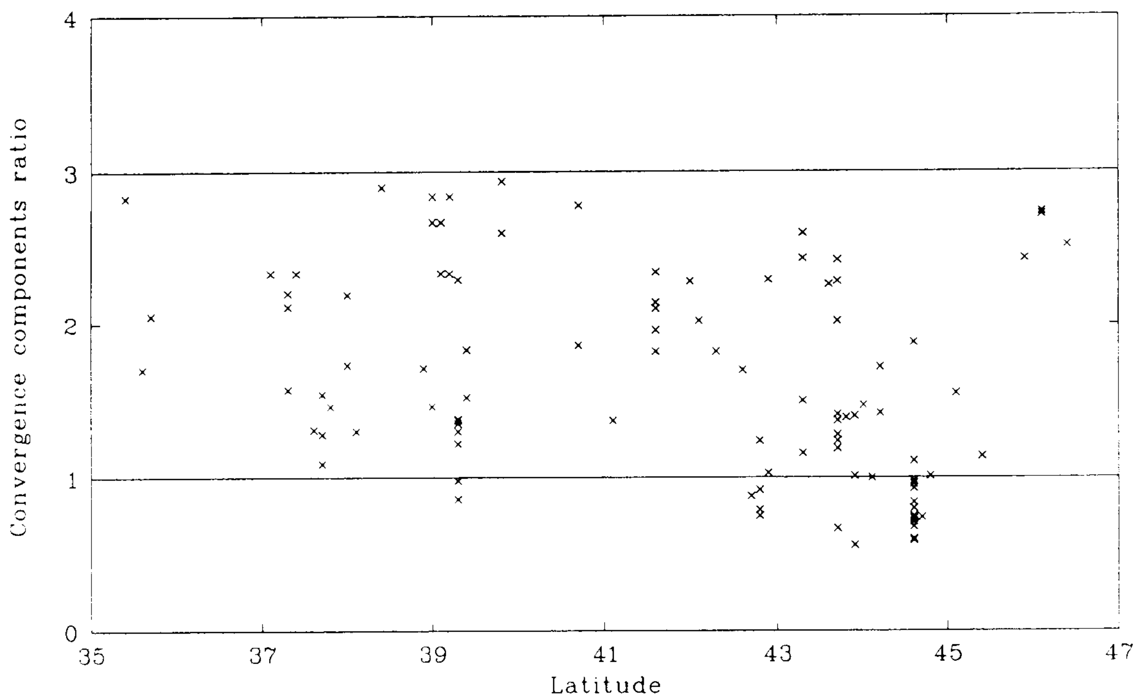


Figure 3. The latitudinal variation of the ratio of the maximised convergence 24 hour precipitation (convergence component of PMP) to the convergence component of the 24 hour, 100 year return period precipitation.



3. Ratio data of at least 2.5 were used to estimate the envelope limit. Ten percent of the data contained in Figure 3 had a ratio which exceeded this value, and was considered a representative selection of the extreme values. This data set was first tested for normality. The skewness coefficient of -0.46 (variance 0.71) was not significantly different from normal. Sample mean and standard deviation were 2.74 and 0.14 respectively. Several levels of envelopment were computed which corresponded to normal distribution significance levels (Table 1). The level of envelopment was set at the one percent exceedance level, which occurs when the convergence ratio is 3.05. The enveloped line at 3.05 is therefore plotted on Figure 3. Convergence PMP was then computed as the product of the convergence precipitation at 100 year return period (given in Figure 1) multiplied by the convergence ratio of 3.05.

Table 1. Significance levels for envelopment values of the ratio of the maximised convergence rainfall to the convergence component of 100 year return period rainfall, for all New Zealand data.

Significance level (%)	Envelopment level
5.0	2.97
2.5	3.01
1.0	3.05
0.5	3.10
0.1	3.17

The convergence PMP just estimated is determined for sea level. In mountainous regions it needs to be adjusted for the effects of the reduction in moisture with elevation and the effect of mountains on the inflow of moisture over catchments. On windward slopes convergence precipitation processes, related to wind flow, tend to initially increase with elevation in response to wind increase with altitude. The increase is greatest in the lowest levels, where the rate of decrease of precipitable water in a column of saturated air is greatest. By combining these effects, United States meteorologists (United States Weather Bureau, 1966) adopted a relatively constant rate of decrease of convergence PMP with elevation of 15 percent per kilometre. After experimenting with several other adjustment schemes this adjustment for moisture depletion over catchments was adopted in New Zealand. This step in the PMP procedure is normally done after the calculation of the PMP estimate.

3.3 Calculation of PMP

The equation (1) used in separating the orographic and non-orographic components of precipitation forms the basis for calculating the 24 hour 25km^2 index PMP for any location in New Zealand. Following Miller et al., (1984), the following equation was developed to estimate PMP

$$PMP = FAFP_x \; (T/C - m^2 (T/C - 1)) \qquad (2)$$

where $FAFP_x$ is the convergence PMP estimate at sea level, T/C the orographic factor as before, and m is a storm intensification factor which modifies and reduces the orographic influence during a PMP storm. The storm intensification factor, m, is defined as the ratio of precipitation during the most intense portion or core of the storm to the total storm precipitation and its nature will now be explained.

It has long been recognised (Schwarz, 1972) that orographic rainfall enhancement during very severe storms is reduced. This lead to the idea for the need to modify and reduce T/C during the most intense portion of the storm (Hansen et al., 1977; Fenn, 1985; Kennedy et al., 1988) since it is thought that there is a limit to the rate of precipitation production that cannot be further increased by adding in orographic forcing. Without a storm intensification factor in (2), PMP estimates would be significantly greater.

Table 2. Estimated duration of the intense precipitation (core) event and storm intensification factor, m, for storms of 6 to 72 hour duration.

Storm Duration (hours)	Core duration (hours)	Intensification Factor (m)
6	3.5	0.67
12	6.0	0.64
24	9.0	0.61
48	12.5	0.57
72	15.5	0.56

Storm intensification factors for New Zealand are given in Table 2. An estimate of the core duration was made by taking the number of hours when the precipitation exceeded the mean intensity for the storm. As the duration increases, the magnitude of the storm intensification factor tends to decrease at a reducing rate.

Maps of 24 hour, point values of PMP have been produced (not shown). They were based on the sea level estimates of convergence PMP and were not adjusted for reduced convergence precipitation potential with elevation.

3.4 PMP depth-area relations

Depth-area relations were developed from the maximised convergent component of rainfall, and are used to reduce the index value of convergent PMP estimate to a catchment average value. Procedures to provide depth-area curves for three meteorologically homogeneous regions of New Zealand were similar to those used by WMO (1969) and Hansen et al. (1988), in which the depth-area variation was taken from representative storms in the final sample, and a smoothing curve applied. Depth-area curves, expressed as a percentage of the 25km^2 value are presented in Table 3.

Table 3. Depth-area PMP as a percentage of 25 km^2 PMP.

Area (km^2)	Region		
	North Island and northeast South Island	Alpine South Island	Southeast South Island
25	100.0	100.0	100.0
100	95.2	97.1	98.2
1000	80.3	82.0	87.1
2000	75.4	79.2	80.1
5000	63.1	72.1	65.5
10000	55.6	63.5	55.5
15000	49.3	58.5	49.7

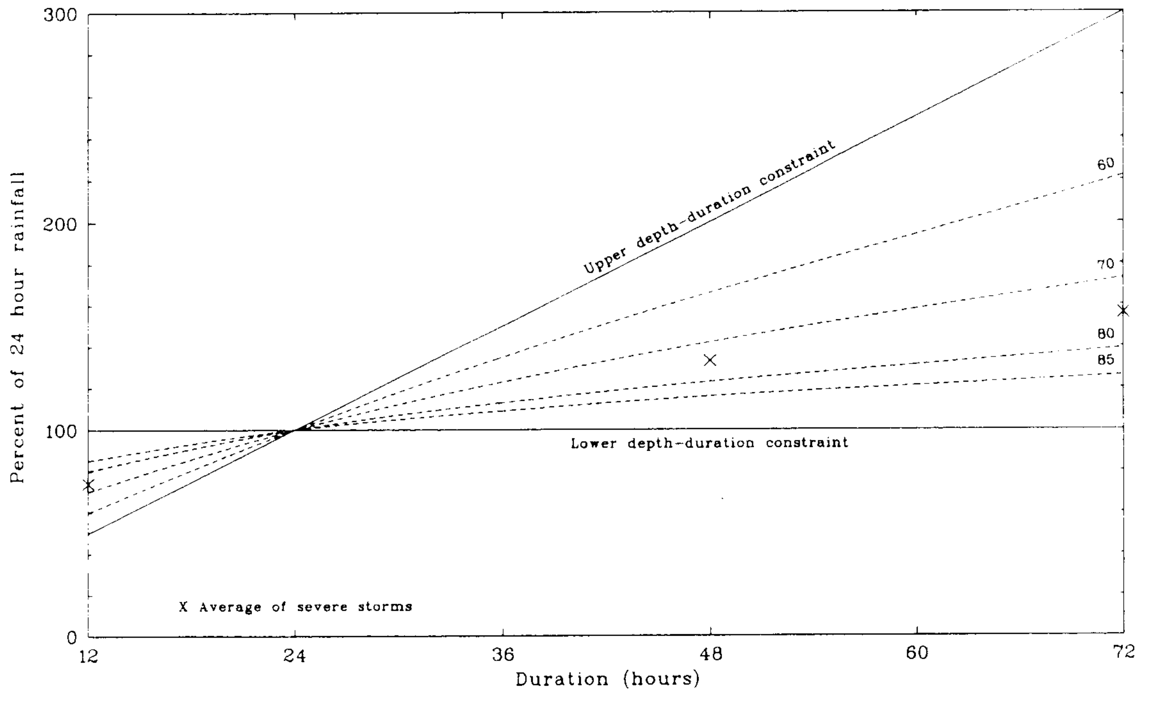
This approach reduces the convergence PMP estimate, but does not affect the orographic factor. Miller et al. (1984) and Fenn (1985) assume that the orographic component to the PMP remains constant, and this is probably a reasonable assumption in New Zealand.

3.5 Depth-duration relations

Estimates of PMP can be extended from 24 hour index values to other durations through the analysis and application of depth-duration relations. Depth-duration relationships were developed from 12/24, 48/24, and 72/24 hour ratios of precipitation.

Within storm 12/24 hour depth-duration ratios over New Zealand showed marked regional variation, mainly due to the influence of orography and storm movement. Values ranged from 0.65 to 0.85, with the smallest ratios occurring in mountainous regions on the steepest slopes were precipitation is enhanced by the orography for longer durations (Hansen et al., 1988). A family of depth-duration curves that would cover the range of 12/24 hour ratios is shown in Figure 4. In Figure 4 depth-area curves should be constrained (solid lines on the figure) by a constant precipitation rate, ie a straight line from 0 - 300 percent from 0 - 72 hours; and by the assumption that all the rain fall in the first instant of time, ie 100 percent at all durations.

Figure 4. Depth duration curves expressed as a percentage of 24 hour precipitation.



3.6 Temporal patterns of PMP

Temporal patterns (distributions) of extreme precipitation events, such as those associated with tropical cyclones, tend to be more uniform than those of storms which occur more frequently (IEA, 1987) and to show a single peak intensity (Miller et al., 1984). Derivation of PMP temporal patterns were also based on two other considerations proposed by Pilgrim and Cordery (1975). The first is that temporal patterns may not represent the precipitation in complete storms, but rather cover a period of intense rainfall which occurs at some stage within the storm. The second is that there is an assumed equality between the PMP and PMF if the temporal patterns incorporate average variability of precipitation intensities.

The analysis technique for determining PMP temporal patterns was based on the method of average variability (Pilgrim et al., 1969; Pilgrim and Cordery, 1975). This method produces, from the recorded maxima of a given duration, a temporal pattern with an average variation in intensities together with a most likely sequence of these varying intensities. Temporal sequences, derived for nine durations from 6 to 96 hours by the above technique, were smoothed with respect to the time of maximum intensity within a storm to reduce inconsistencies not only within the temporal pattern, but also in inter-duration relationships. These may arise from random variations in the data due to the relatively small sample of PMP storms. Smooth PMP temporal patterns for durations from 12 to 72 hours are shown in Table 4. Temporal patterns for 84 and 96 hours were identical with the values for 72 hours.

Table 4. Percentage accumulation of PMP for storm durations of 12, 24, 48 and 72 hours.

(a) North Island

Duration	Percentage accumulation during storm										
(hours)	5.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	95.0
12	3.3	6.8	14.8	24.1	35.4	48.2	64.1	77.0	86.8	94.8	97.5
24	1.9	4.1	10.8	19.1	29.7	43.1	61.3	75.5	86.8	94.8	97.5
48	1.5	3.5	9.4	18.0	30.2	45.5	65.7	79.4	88.9	95.7	98.1
72	0.5	1.8	7.1	15.3	27.5	46.3	68.2	82.0	91.2	97.2	99.1

(b) South Island

Duration	Percentage accumulation during storm										
(hours)	5.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	95.0
12	2.2	4.6	10.8	18.5	27.4	38.3	51.2	66.6	81.8	93.1	96.9
24	1.4	3.1	7.9	14.9	25.3	38.5	55.8	76.8	90.7	97.3	98.9
48	0.5	1.4	4.0	8.4	15.7	27.2	46.9	76.1	92.1	98.0	99.3
72	0.4	1.2	3.6	7.3	13.8	24.9	47.8	81.5	93.8	98.3	99.4

4. Summary of method to estimate PMP

The steps to compute PMP estimates where then as follows:

1. Determine the outline of the catchment and the area of the catchment or sub-catchment.

2. Obtain a representative average 24 hour index PMP within the catchment. This can be achieved by application of equation (2), Figure 2 and Table 1.

3. Estimate the effective height of any barrier impeding the flow of moisture into the catchment. (NB: The effective height of the barrier is less than the actual barrier height and can be taken as the elevation 5 to 8 km on the windward side

of the divide.) Apply a reduction factor for reduced moisture potential. This is approximated by $\exp(-0.0002\,x)$ where x is the height in metres.

4. Select the depth-area relation from Table 3 for the region of New Zealand under study. Determine the appropriate reductions for the catchment area to apply to the index averaged depths from step 2.

5. Multiply the percentage reductions in steps 3 and 4 by the average index PMP from step 2.

6. From the maps of 12/24 hour depth-duration ratios (not shown in this report) make an estimate of a representative ratio for the catchment.

7. For the representative 12/24 hour durational ratio in step 6 extract from Figure 4 the ratios for other durations as percent of the 24 hour value.

8. Multiply the resulting percentage adjustments in step 7 by the average 24 hour catchment estimates of PMP in step 5.

9. The temporal distribution of PMP is gained from Table 4.

Applying the above method requires some degree of meteorological knowledge. All PMP estimates involve uncertainty as there is no absolute standard by which to judge the level of the PMP. Further, the scale of the maps presented in Figure 2 are too large for the practical calculation of PMP. Because of these two factors, people wishing to get assistance with PMP calculations should contact the authors.

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