Bureau of Meteorology, Australia

HYDROLOGY REPORT SERIES

HRS Report No. 4

DEVELOPMENT OF THE GENERALISED SOUTHEAST AUSTRALIA METHOD FOR ESTIMATING PROBABLE MAXIMUM PRECIPITATION

Hydrology Unit
Melbourne
August 1996

Hydrometeorological Advisory Service
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1. INTRODUCTION

Probable Maximum Precipitation (PMP) is defined as *'the greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends.'* (WMO, 1986). It is the primary input to the estimation of the Probable Maximum Flood (PMF), which is a design standard for the spillways of large dams. If a spillway cannot safely pass the PMF, breaching of the dam wall or erosion of the abutments due to overtopping may occur.

Since the 1950s a number of methods have been developed for estimating PMP in Australia (Pearce and Kennedy, 1993). Early estimates based on the highest recorded rainfalls at a location, suffered from the shortness of the record: PMP estimates for locations in the same general area differed greatly. From the mid-1970s more 'generalised' methods which utilise the rainfalls recorded over a large region have been developed. Such methods separate the portion of the storm rainfall consistent with 'regional' meteorological conditions from that portion attributable to 'site-specific' conditions. The 'regional' or 'general' portion may then be transposed to any location within the region and the 'site-specific' effects of the location factored in. The Generalised Tropical Storm Method (GTSM), for regions of Australia affected by tropical storms, was developed during the 1970s (Kennedy, 1982; Kennedy and Hart, 1984). The Generalised Short Duration Method (GSDM), for small-area PMP estimation, was developed in the early 1980s (Bureau of Meteorology, 1985; Bureau of Meteorology, 1994).

In 1985 the Hydrometeorological Section of the Bureau of Meteorology embarked on the development of the Generalised Southeast Australia Method (GSAM) for estimating PMP in the region of the country where tropical storms are not the source of the greatest depths of precipitation, and where 'site-specific', topographic effects vary markedly (Kennedy et al, 1988). Development was completed in 1992. This document records that development.

2. THE PMP CONCEPT

The concept of PMP assumes the simultaneous occurrence in the one storm of (i) a maximum amount of moisture, and (ii) a maximum conversion rate of moisture to precipitation. The concept derives from an understanding of the processes involved in precipitation and from models of storm dynamics (Paulhus and Gilman, 1953; Gibbs, 1958; United States Weather Bureau, 1960; Weisner, 1970; WMO, 1986).

Maximising the *moisture content* of a storm to create a PMP storm relies on a simple, empirical relationship between surface dewpoint temperature and storm moisture content. The technique is traditionally referred to as **Moisture Maximisation**.

Maximising the *rate of conversion* of storm moisture to storm precipitation is more difficult: there is neither an empirical, nor a satisfactory theoretical, approach to estimating this component of a PMP storm. Instead, a further assumption is made that, in a large sample of storms, recorded over a long period, at least one storm would operate at maximum ‘efficiency’. Obtaining a sufficiently large sample of storms requires transposing storms from their original location to the location of the PMP storm. **Storm Transposition**, as it is termed, further requires considered and consistent treatment of the ‘site-specific’ details of the original and the transposed storm.

These two components of the creation of the PMP storm are detailed in the context of the GSAM in the next section.

3. DEVELOPING THE GSAM

In developing the GSAM the concept of moisture maximisation was adopted without challenge, and the traditional technique employed. The concept of storm transposition however was greatly generalised. Entirely new techniques were developed to enable the assemblage of a large sample of storms from diverse topographic conditions. From this assemblage, a fictitious ‘storm’ of maximum efficiency was determined. This ‘storm’ could then be transposed to the location where the PMP estimate was required. Because the PMP storm could no longer be identified with any one real event, spatial and temporal distributions of the PMP depths had to be designed.

This section documents the development of
(i) the GSAM Storm Database
(ii) the GSAM PMP Estimation Technique

3.1 GSAM STORM DATABASE

The foundation of PMP estimation is a large storm sample. In the United States PMP estimates are drawn from a catalogue of about 800 storms (US National Weather Service, 1988). Prior to the development of the GSAM no such catalogue existed for Australian storms. The first task in the project therefore was to construct one. Having done so, it was then necessary to generalise this storm database by removing the ‘site-specific’ components of each of the storms, maximising their moisture content, and determining the ‘storm’ of maximum efficiency.

3.1.1 Storm Catalogue

The following describes how the storm catalogue was constructed. It includes the following topics:

1. Storm Selection
2. Data Quality Control
3. Storm Analysis and Gridding
4. Storm Temporal Distributions
5. Depth-Duration-Area Analysis
6. Storm Dewpoint Temperatures

The catalogue itself is available as a Bureau of Meteorology internal report in the Hydrology Report Series (Meighen and Kennedy, 1995).

3.1.1.1 Storm Selection

Over the course of about 3 years a number of storm selection techniques were employed:

(i) Published Reports
The dates of many storms came from published reports including: storm descriptions, tropical cyclone reports, lists compiled for other projects, flood damage reports.

(ii) Previous PMP studies

(iii) Computerised Searches of the Rainfall Archive

Early in 1985 a set of computer programs was run to extract storm data from the Bureau of Meteorology's archive of daily rainfall data. The first of these programs simply listed all the rainfall recording stations within a defined latitude-longitude box. The second program examined the records of selected stations and ranked the dates of the highest falls. The final program produced isohyetal plots of the 50 largest 1, 3 and 5 day storms. A large sample of storms was obtained with this technique. It was, however, very time-consuming and internal program limits, on the size of the box and the number of stations that could be examined in one program run, meant that large-area storms were not handled well. Also, the selection criterion (highest rainfall totals) biased the storm sample: storms in locations of high topographic influence far outnumbered those in locations of low topographic influence.

In 1987 a new selection technique was devised which streamlined the process and addressed the selection criterion concerns. An archive of the ten highest 1-7 day falls was created for every station in SA, NSW, VIC and TAS. This archive was then edited so that only dates that were common to a number of stations were kept. The station rainfall totals for the edited list of dates were then compared to the 72hr 50yr rainfall intensities at the station location, and a final list of storm dates and general locations produced. Many of the storms previously identified were selected with this technique, but some new storms were also identified.

A total of 110 storms were finally selected for inclusion in the storm catalogue. The dates of their occurrence cover the period from 1889 to 1990. The location of their centres is given in Figure 1.

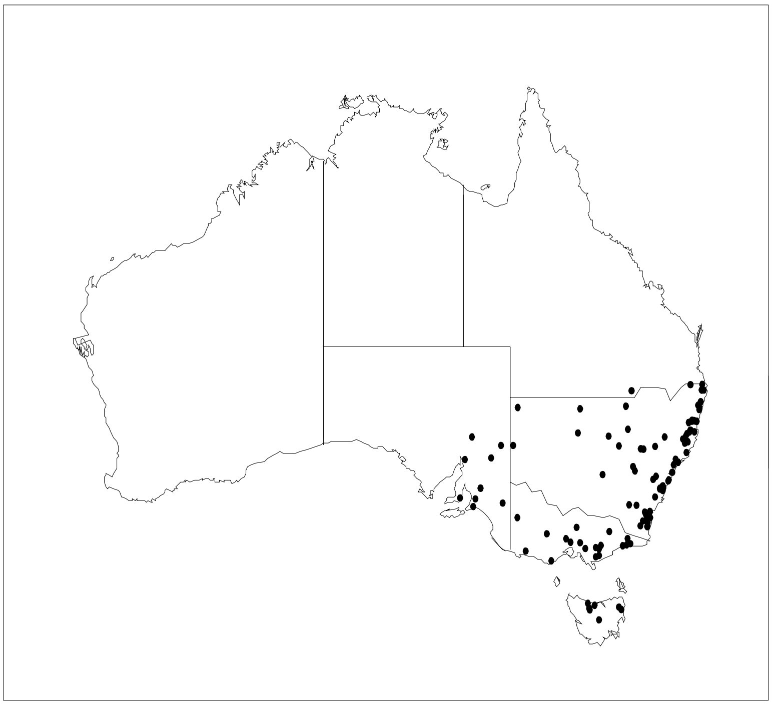

Figure 1: Locations of the Rainstorm Centres of the GSAM Storm Catalogue

3.1.1.2 Data Quality Control

After the storm dates were identified the rainfall totals for all stations within the area of the storm were printed and scrutinised for temporal and spatial consistency. Many instances were found of rainfall totals being recorded on the wrong date, or accumulated over more than 24 hours. Sometimes it was found that the location of a station had changed over the period of the station’s record and that current location details were not those at the time of the storm. Corrections were made to the data where it was obvious what should be done. The original rainfall observation booklets were also retrieved from the Commonwealth Archives for stations at the centre of the largest storms; comments by observers of raingauge overflow were particularly noted. Rainfall data were sometimes also available from other sources: a large pluviograph archive was provided by the Hydro-Electric Commission of Tasmania and a number of reports from various state authorities investigating high rainfall, flood damage, dam breaks etcetera, included extra data. These extra data were vetted and added to the Bureau of Meteorology data and assigned their own station number and location. This quality control of the storm data was a time-consuming, but essential, component of the construction of the storm catalogue.

3.1.1.3 Storm Analysis and Gridding

The rainfall totals for the total storm duration were then plotted at a scale suitable for overlay on a topographic map; typically 1:250 000. The storm was then analysed manually by an experienced meteorologist.

The isohyets of the analysed storm were then digitised on a large upright digitising pad. The strings of latitude and longitude values representing the isohyets were interpolated to a regular grid using a spline function, in the manner of Canterford et al (1985). The gridded data were contoured and replotted at the scale of the original analysis and overlaid on it for direct comparison. The parameters of the spline function were adjusted and extra, ‘shaping’ isohyets were digitised, in a recursive procedure, until a satisfactory reproduction of the original analysis was achieved. For storms with isohyets extending across the coastline and over the sea where no data existed, a land-sea mask was applied to the gridded data which set the sea values to zero. An example of a gridded storm is given in Figure 2.

3.1.1.4 Storm Temporal Distributions

Rather than creating separate analyses for each day of a storm it was decided to determine the variation in rainfall depth with time as a proportion of the total storm depth. These storm temporal distributions could then be used to determine the maximum rainfall depth at any duration within the total storm duration.

To construct the storm temporal distributions the daily rainfall records and the pluviograph archive were used, and where available, the 3-hourly rainfall observations from the Bureau of Meteorology synoptic station network. Individual storm studies were another source of temporal information.

As with the storm analyses, the data used to construct the temporal distributions were checked for temporal and spatial consistency. In this procedure, however, stations recording anomalous rainfall depths were deleted from the list.

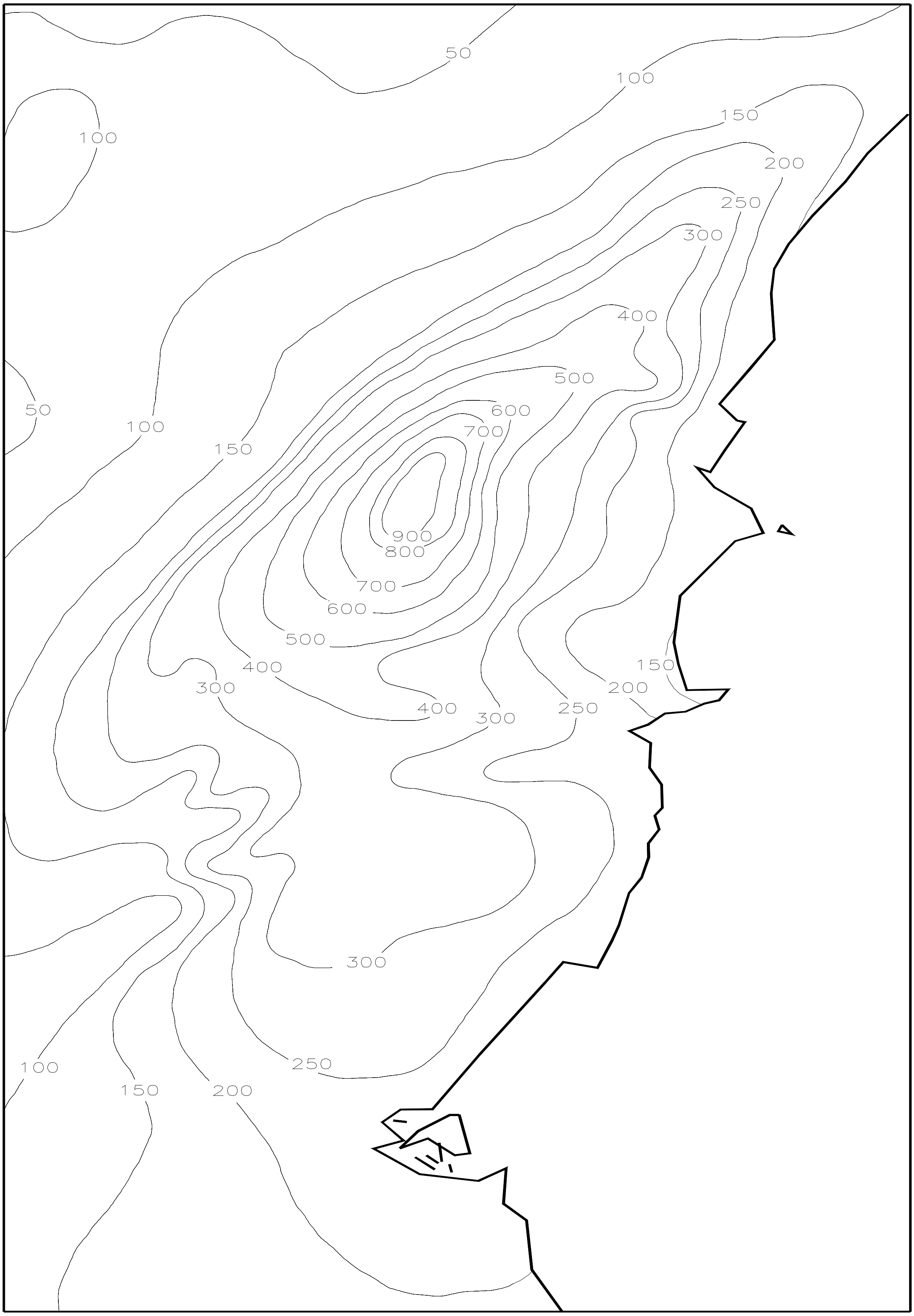

Figure 2: Example of an Analysed and Gridded Storm: Dapto, 2 days to 19/2/1984. Isohyets are in mm.

Temporal distributions were determined for a number of standard-sized areas surrounding each storm centre. The chosen standard areas were: 100; 500; 1,000; 2,500; 5,000; 10,000; 20,000; 40,000 and 60,000 km^2. No storm temporal distributions were constructed for areas smaller than 100 km^2 since these would in general have been based on just a single station and unlikely to be representative of the true storm peak. For each storm, parallelograms of areas approximating the standard areas were drawn about the centre of the storm in such a way as to enclose the maximum number of high rainfall totals. An outer parallelogram was also specified to allow for the influence of rainfall stations near the border of the standard area parallelogram. An example of this procedure is given in Figure 3.

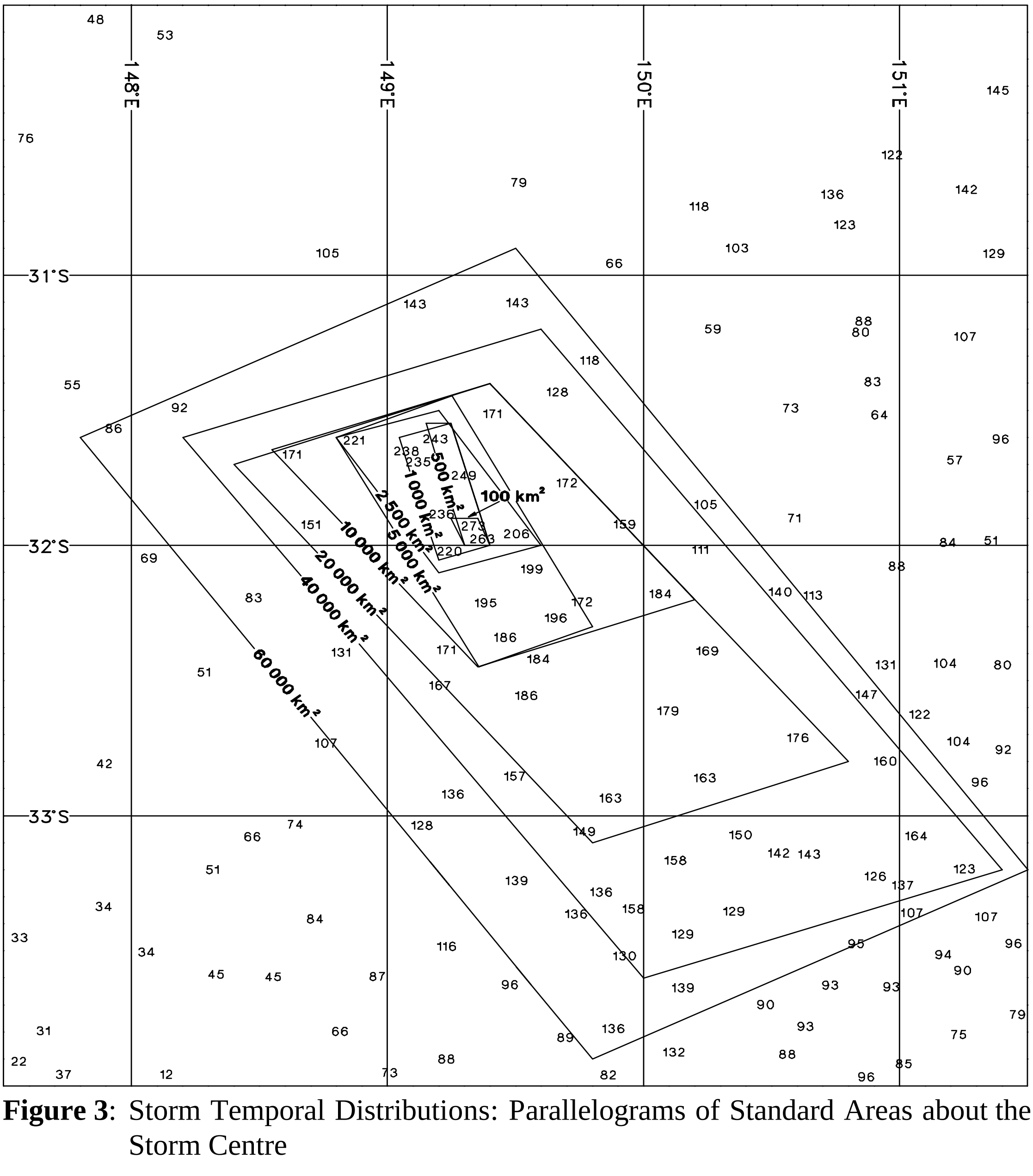

Figure 3: Storm Temporal Distributions: Parallelograms of Standard Areas about the Storm Centre

The daily rainfall depths within each specified parallelogram were then averaged using an areal weighting technique (Thiessen, 1911). The result of this procedure was a series of daily percentages of the total storm depth, for each parallelogram area. A 3-hourly temporal distribution was then imposed on this daily distribution using the pluviograph and other data. These 3-hourly data were manually weighted for (i) their consistency with the daily distributions, and (ii) the relevance of their location to the parallelogram. This procedure thus provided a series of 3-hourly percentages of the total storm depth, for each parallelogram area. Percentages at the standard areas were determined by interpolation between the parallelogram areas. The final step in the construction of the storm temporal distributions was to determine the **maximum** percentages of the total storm depth that fell within the standard durations of 6, 12, 24, 36, 48, 72, 96 and 120 hours, that is, the maximum 6 hour percentage, the maximum 12 hour percentage and so on. Although storms of up to 7 days (168 hours) duration were selected and analysed, in general almost 100% of the 7-day totals had fallen within 5 days.

A storm temporal distribution is thus defined as ***the maximum percentages of the total storm rainfall that fell within the standard durations and the standard areas.***

3.1.1.5 Depth-Duration-Area Analysis

A storm is usually quantified in terms of its maximum analysed rainfall depths over standard-sized areas and standard durations: a set of depth-duration-area curves. The standard method for computing the maximum depth-area relationship of a storm is detailed in *Manual for Depth-Area-Duration Analysis of Storm Precipitation* (WMO, 1969). The method used in the GSAM differed slightly from the standard method in that multi-centred storms were treated as if they were single-centred. Test comparisons of the two methods found minimal differences in the calculated depth-area relationships. The program which determines the maximum depth-area curve of each gridded storm simply counts the number of gridpoints in between evenly-incremented isohyets, from the maximum to the minimum isohyet, calculates the arithmetic mean rainfall per interval and determines a running-average rainfall depth and cumulative area over all intervals. Area calculations are based upon the number of gridpoints counted and the known resolution of the grid.

Once the depth-area curve for the total storm duration had been calculated, the depths at standard areas were determined by interpolation. These were then multiplied by the percentage -depths in the storm temporal distributions to produce a set of depth-area curves at standard durations and standard areas. An example set of depth-area curves for a storm is given in Figure 4.

3.1.1.6 Storm Dewpoint Temperatures

The technique of moisture maximisation requires knowledge of the moisture content of a storm. The precipitable water of the storm is used as a measure of this moisture content. Total precipitable water is the depth of water resulting from condensation of all the water vapour in a column of air of unit cross-section, extending from the surface to the ‘top’ of the atmosphere (WMO, 1986 pg.267); in practice the ‘top’ of the atmosphere is the height to which non-negligible amounts of moisture exist, about 300hPa. With the assumption of a saturated pseudo-adiabatic atmosphere, total precipitable water can be estimated from the surface dewpoint temperature. Precipitable water values, in general, may be determined between any two levels, and in practice surface dewpoint temperatures are reduced pseudo-adiabatically to a common level of 1000hPa and storm precipitable water values determined between this level and the ‘top’ of the atmosphere. Precipitable water values above 1000hPa have been

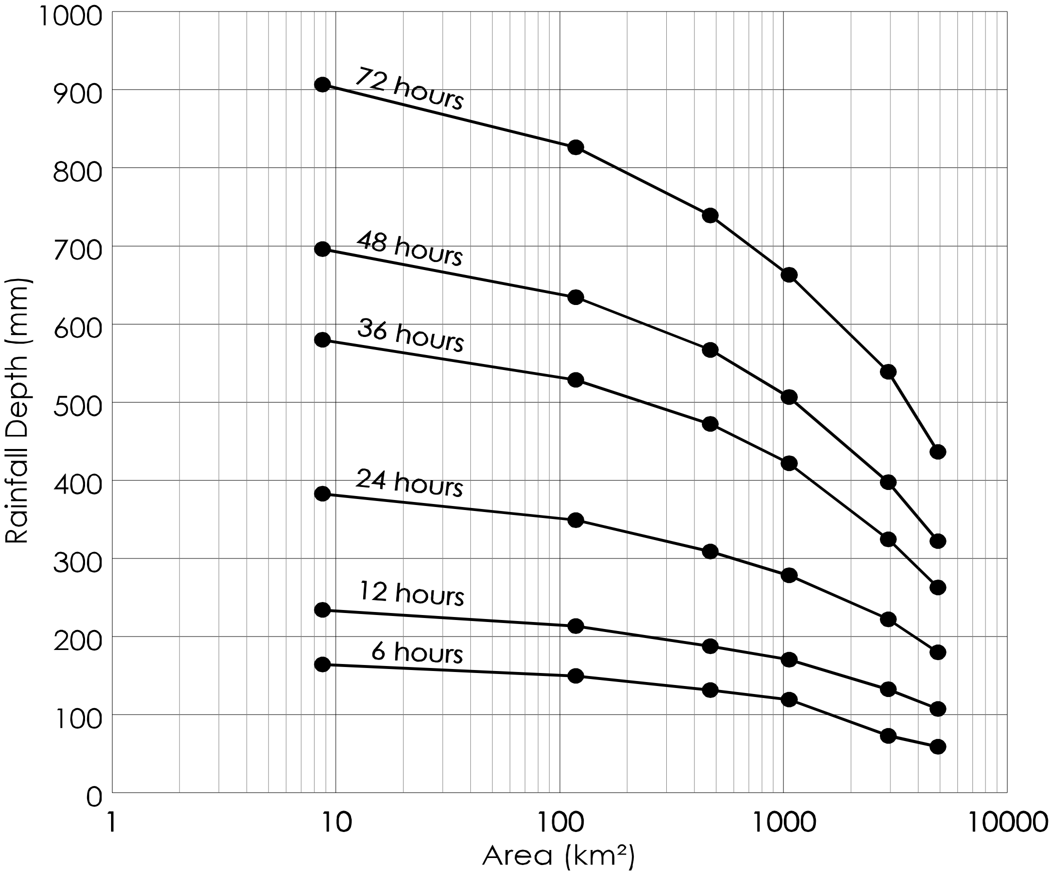

Figure 4: Example Set of Storm Rainfall Depth-Area Curves at Standard Durations

calculated for a range of dewpoint temperatures and are published as tables. The moisture content of a storm can thus be determined from the 1000hPa dewpoint temperature that is representative of the rain-producing airmass of the storm.

Although the storm dewpoint temperature is primarily a feature used in moisture maximisation, it is also an identifying characteristic of a storm and has thus been included in the storm catalogue.

Surface dewpoint temperatures are recorded at Bureau of Meteorology climate observing stations throughout Australia. To obtain sufficient surface dewpoint temperature information for all the storms in the catalogue, a number of data sources were investigated:

(i) Australian Region MSL Charts
   Surface dewpoint temperature observations are plotted, along with other meteorological information, on Australian Region MSL charts. Those for the period pre-1950 were viewed at the Australian Archives; post-1950 were available on microfiche from the National Meteorological Centre.

(ii) National Climate Centre (NCC) Archives
   From about the 1940s surface dewpoint temperature observations, along with other meteorological information, were relayed from observing stations via a coded transmission to the Bureau of Meteorology Head Office. These transmissions were then digitally archived. A number of standard NCC programs were run to extract the requisite surface dewpoint temperature observations from this digital archive.

(iii)Observers' Logbooks

Many of the early surface observations (pre-1950) were neither plotted on MSL charts nor digitally archived, and are recorded solely in the original observer's log. These are archived in each of the State Regions. The requisite logbooks were requested and loaned to the Hydrometeorological Section for the purposes of the project.

To ensure that a storm dewpoint temperature is representative of the rain-producing airmass of a storm, surface dewpoint temperatures from a number of stations were averaged. Suitable stations were either on the trajectory of the moisture inflow to the storm or in the area of the storm peak itself, and had recorded high dewpoint temperatures persisting over a period of 6 to 24 hours. Where the station elevation was above 100m, surface dewpoint temperatures were reduced pseudo-adiabatically to 1000hPa values (US Weather Bureau, 1951). It was particularly important to ensure that the surface dewpoint temperatures used had not been rain-contaminated: observations indicating atmospheric saturation are representative of the rain and not the rain-producing airmass.

In the process of estimating a storm dewpoint temperature a considerable amount of judgement was required: in determining the moisture inflow direction, the influences of local topography, the timing of the precipitation process, the relevance of dewpoint temperature persistence, the representativeness of surface measurements to the layer where precipitation is forming, and the quality of individual observations. Weighing these various factors and determining a single estimate of storm dewpoint temperature was very subjective. Given that all other sources of inaccuracy had been minimised, no more accuracy than about 2°C could be achieved.

3.1.2 Generalising the Storm Database

The task of generalising the storm database was primarily one of identifying and removing the 'site-specific' components of each storm so that the storm could be transposed to other locations.

For the purposes of the GSAM, the 'site-specific' features of storm rainfall were identified as:

(i) Storm Type
(ii) Storm Spatial Distribution
(iii) Topographic Influences
(iv) Moisture Content

Clearly these features are interrelated, as are the techniques that were developed to remove them. The following describes the development of these techniques and includes the topics:

1. Regions, Zones and Homogeneity
2. Depth-Duration-Area Analysis
3. Storm Separation: Estimating the Topographic Component of a Storm
4. Moisture Maximisation and Standardisation
5. Enveloping the Depth-Duration-Area Curves

3.1.2.1 Regions, Zones, and Homogeneity

The region of GSAM applicability was originally defined, by default, as that part of Australia outside the region of applicability of the GTSM. The geographical boundary between the two methods follows the boundaries of certain drainage basins.

The GSAM region was subsequently divided into two zones, Coastal and Inland, separated by the Great Dividing Range. This zonal division reflects a working hypothesis that within the two zones the mechanisms by which large rainfalls are produced are genuinely different. The corollary is that within each zone there is an assumed homogeneity: storms in the zonal database can occur anywhere within the zone.

Due to the lack of data and hence understanding of heavy rainfall events in the area, the West Coast of Tasmania has been excluded from the region of GSAM applicability.
By dividing the country into these regions and zones the effects of **storm type** were effectively removed from the database.

The boundaries between the methods and the zones are shown in Figure 5.

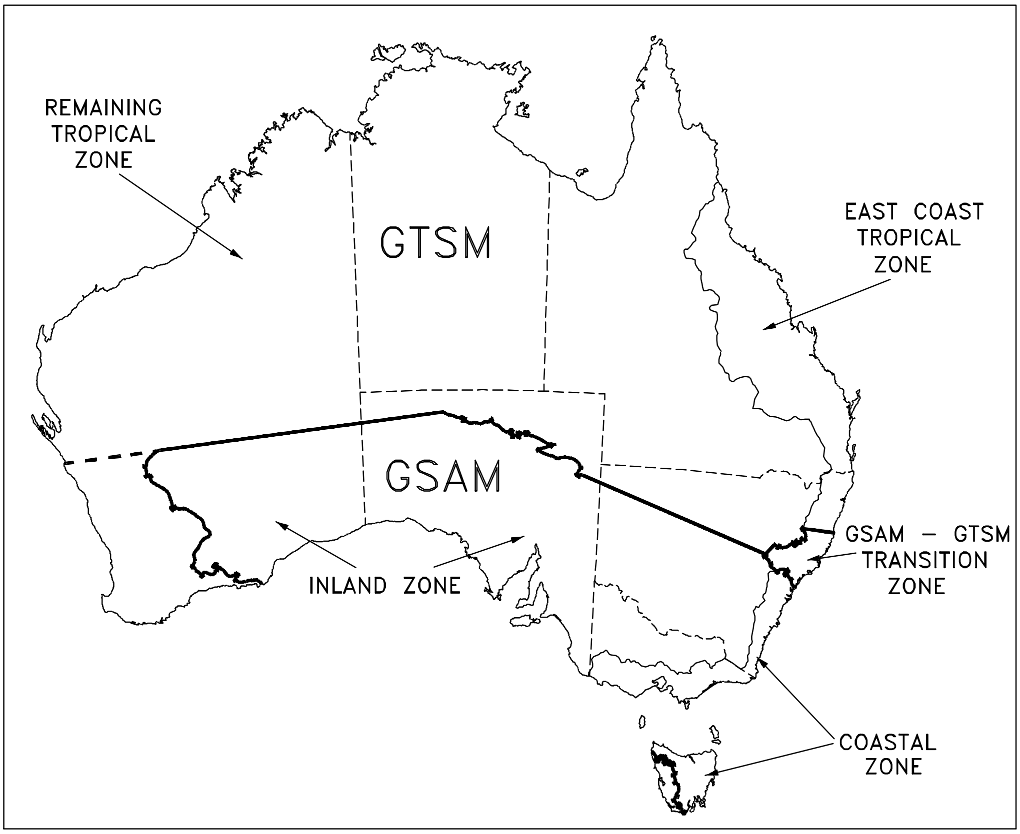

Figure 5: Boundaries between PMP Methods and Zones

3.1.2.2 Depth-Duration-Area Analysis

The size, shape and orientation of the analysed isohyets of a storm are influenced by a number of 'site-specific' features including: topographic influences, moisture inflow direction, and storm movement. Quantifying each storm in terms of a set of depth-duration-area curves, as outlined in section 3.1.1.5, effectively removes the specifics of the **spatial distribution** of each storm.

3.1.2.3 Storm Separation: Estimating the Topographic Component of a Storm

The most original feature of the GSAM is the technique developed for estimating the topographic component of the total storm rainfall. The technique is based, loosely, on concepts and practices expressed in various US Hydrometeorological Reports (US Weather Bureau, 1966; US National Weather Service, 1977; US National Weather Service, 1984), and in Wang (1986).

The primary concept is that precipitation results from the convergence and vertical motion of moist air, and that these motions are due to (i) synoptic-scale atmospheric disturbances, and (ii) topographic influences. The synoptic-scale disturbances are situations such as non-geostrophic wind flow and frontal lifting, as well as large-scale instability in an airmass (WMO, 1973). Precipitation due to these mechanisms, and any atmospheric process unaffected by terrain, is termed **convergence precipitation**. The portion of rainfall within a storm that is convergence precipitation is termed, within the GSAM, the **Convergence Component** of the storm. Conversely, the portion of rainfall within a storm that is not entirely due to these convergence mechanisms is attributed to topographical influences, and is termed the **Topographic Component** of the storm.

The secondary concept is that rainfall frequency analyses can be used as a measure of the topographic influences operating in an area. This concept is expressed in WMO(1986, pg.54) thus: ‘If storm frequency, moisture availability, and other precipitation producing factors do not vary, or vary only slightly over an orographic region, differences in precipitation-frequency values should be directly related to variation in orographic effect’.

Rainfall frequency analyses have been constructed for the Australian region as part of a major revision of *Australian Rainfall and Runoff* (IEAust, 1987) and a gridded version of the maps is held by the Bureau of Meteorology in a package known as CDIRS: Computerised Design IFD (Intensity-Frequency-Duration) Rainfall System. An example of these data is given in Figure 6.

Differences in rainfall intensity over the area of this figure are an indication of the average variation in the topographic influences on rainfall production, in relatively rare (50-year Average Recurrence Interval), medium duration (72-hour) rainfall events. The rainfall intensities over areas which are not affected by topography can be considered as deriving from convergence precipitation alone. Those values over areas that are affected by topography derive from both convergence and topographic precipitation. The ratio of values from topographic and non-topographic areas, in the same general region, is a measure of the average enhancement of rainfall due to the presence of topography.

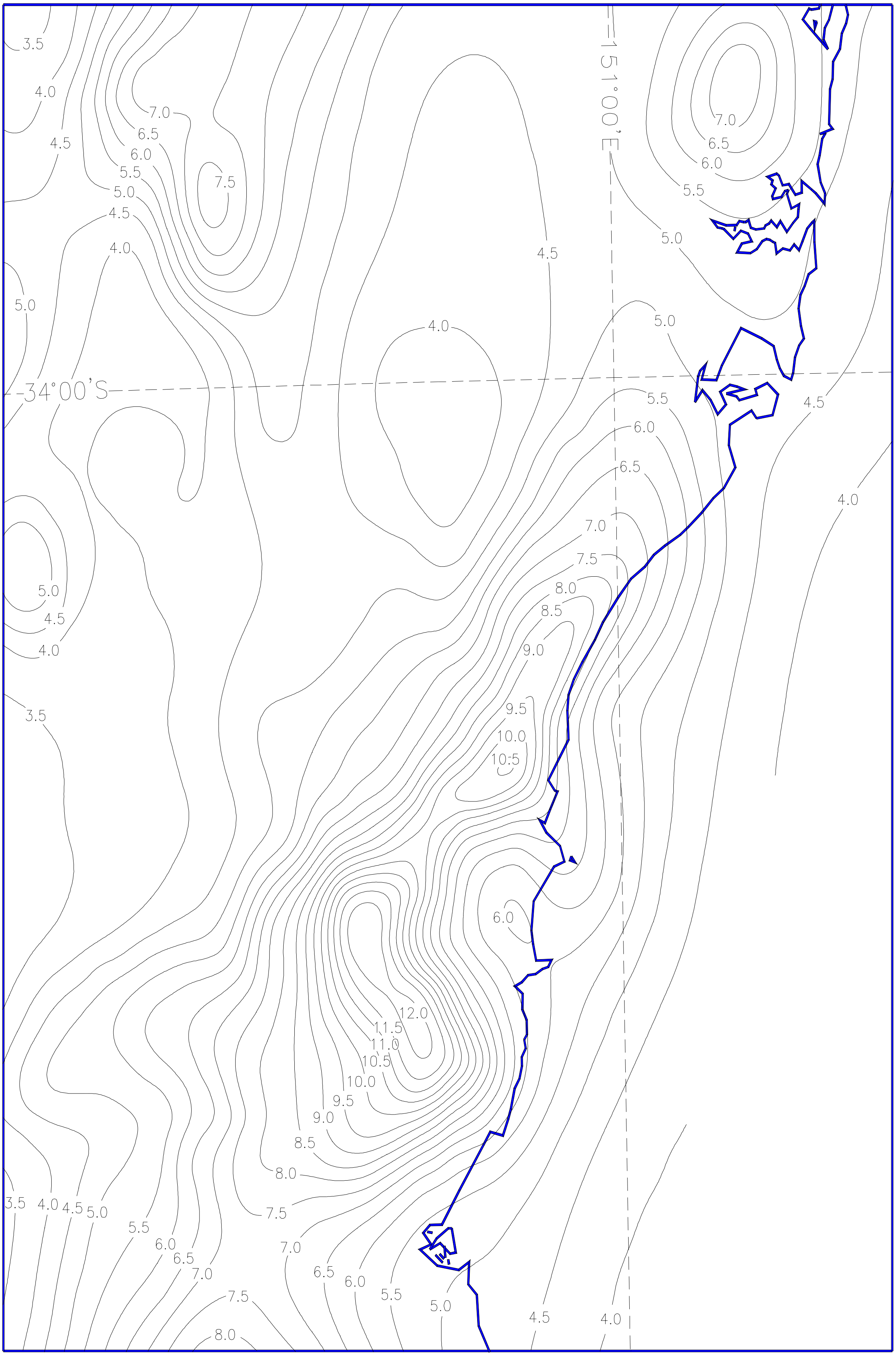

Figure 6: 72-Hour, 50-Year Rainfall Intensities over Central NSW Coast. Isopleths are in mm/hr.

To estimate the **Topographic Enhancement Factor** of a storm the following approximate equality has been used:

$$\frac{\text{Total Rainfall Intensity}}{\text{Conv. Rainfall Intensity}} \approx \frac{\text{Total Storm Depth}}{\text{Conv. Storm Depth}}$$

In practice, the ≈ was replaced by = , but the approximate nature of the relationship was kept in mind. Thus the Convergence and Topographic Components of a storm were defined as:

$$\text{Conv. Storm Depth} = \text{Total Storm Depth} \times \frac{\text{Conv. Rainfall Intensity}}{\text{Total Rainfall Intensity}}$$

$$\text{Topog. Storm Depth} = \text{Total Storm Depth} - \text{Conv. Storm Depth}$$

While the concept of convergence and topographic precipitation has been widely used, their definition is strictly method dependent, and the GSAM definitions differ from those used by others (US Weather Bureau, 1966; US National Weather Service, 1977; US National Weather Service, 1984; Wang, 1986).

Calculating the convergence component of a storm thus requires a value for the convergence component of the rainfall intensity field. In the course of the development of the GSAM a number of approaches to evaluating this component were tried. Ultimately it was decided to construct a map of the convergence component of the 72-hour 50-year rainfall intensities over the whole region of the GSAM. This was done by pin-pointing those locations where values were considered to be unaffected by topographic influences and manually interpolating between these points. Over the Inland Zone this was a relatively simple task. Over the mountainous areas of the Coastal Zone far more judgement was required. A section of the resulting field is shown in Figure 7.

The isopleths of this field were then digitised and gridded using the technique established for the gridding of the storm isohyets. The ratio of the total rainfall intensity field to its convergence component could then be calculated on a point-by-point basis. Likewise the convergence component of each storm could be calculated by dividing the total storm rainfall depth at each storm gridpoint by the coincident rainfall intensity ratio.

The decision to use the 72-hour, 50-year rainfall intensity field to estimate the topographic enhancement factor for all storms was based on the following considerations:

(i) the 72-hour, 50-year field is the most accurate of the six basic rainfall frequency analyses developed for *Australian Rainfall and Runoff*
(ii) a duration of 72 hours is about the middle of the duration range required for the GSAM

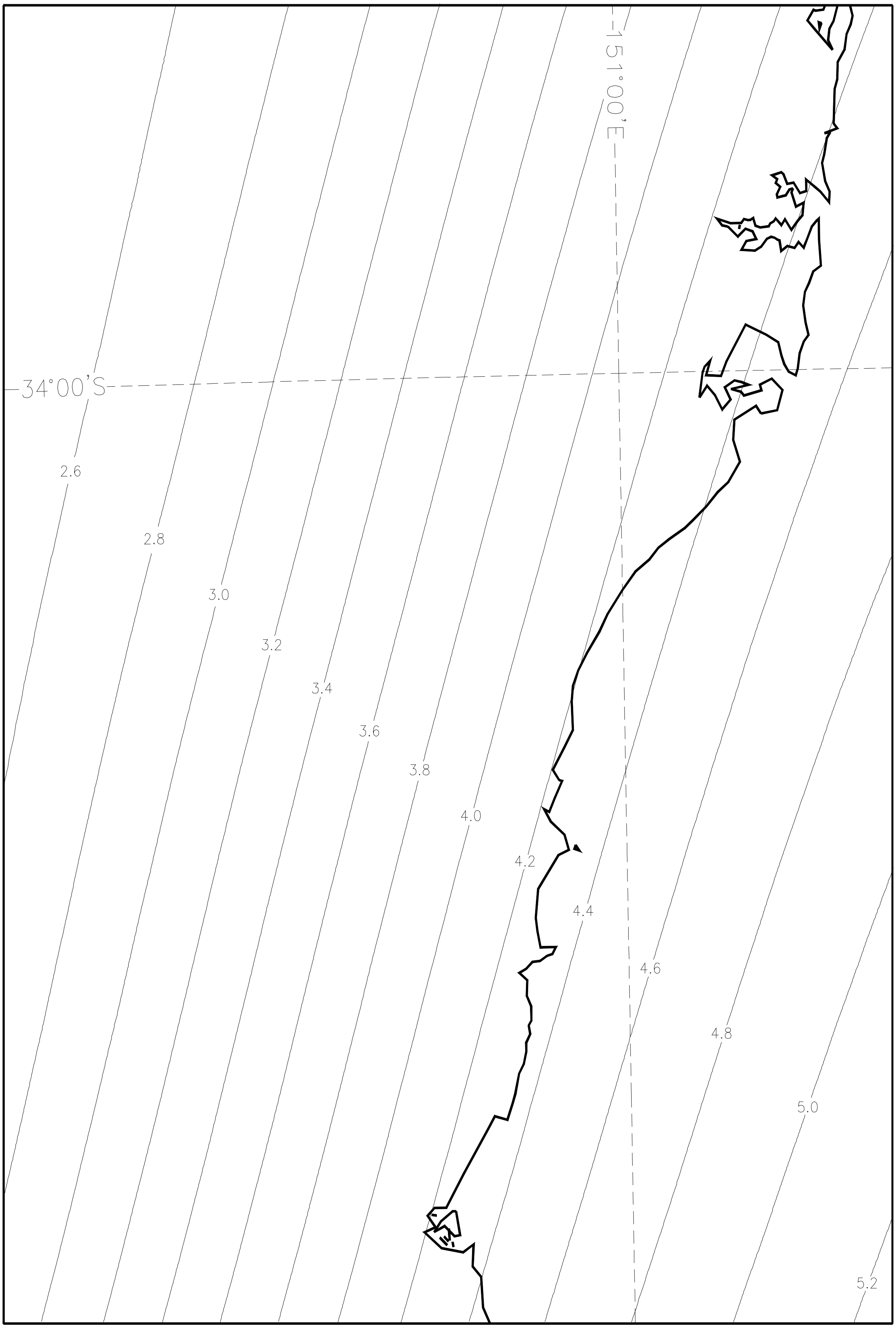

Figure 7: Convergence Component 72-Hour, 50-Year Rainfall Intensities over Central NSW Coast. Isopleths are in mm/hr.

(iii) an Average Recurrence Interval (ARI) of 50 years is about the mean of the range of ARIs for storms of the GSAM storm database.

To test the storm separation technique it was decided to examine the rainfall history of an area which is flat and of a nearby area which has marked topographic features. The only two areas which were suitable for this comparison and which had a sufficiently dense raingauge network were the Sydney and Illawarra areas. The areas selected are shown in Figure 8. The parallelograms are approximately equal in land area; the portions of the parallelograms which are over the sea were ignored in the test.

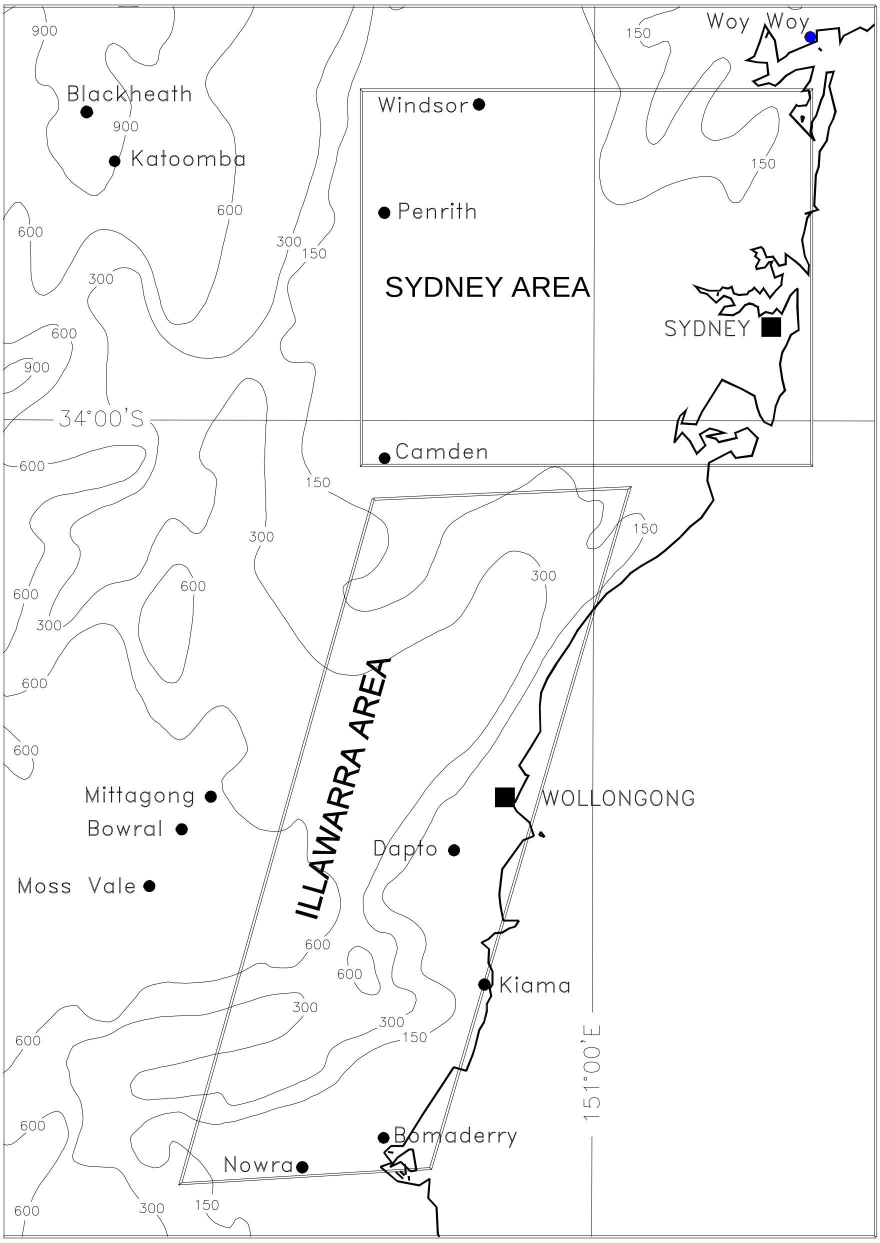

Figure 8: Storm Separation Test Areas. Contours are elevation in metres.

It was assumed that these two areas have had an equal chance of experiencing severe storms during the past 100 years or so for which rainfall data are available. Any major differences in the mean storm rainfall depths are attributed to the differences in the topography of the areas. Using the Bureau of Meteorology archive of daily rainfall records, the ten highest 1-day and the ten highest 4-day storms were selected for each area. The convergence components of the storms were obtained by dividing the storm total by the rainfall intensity ratio at each grid point. Depth-area curves (as defined in 3.1.1.5) were calculated for the total storm and the convergence component of each storm. An example is given in Figure 9 of the total storm and convergence component depth-area curves for a 1-day storm in the Sydney region, while Figure 10 shows an example for the Illawarra region.

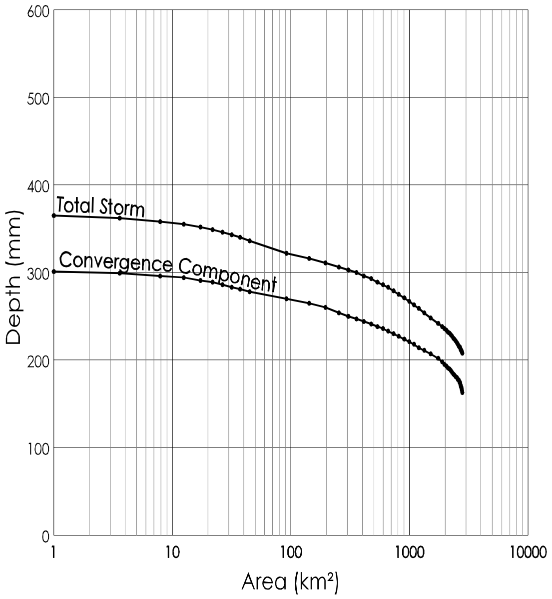

Figure 9: Total Storm and Convergence Component Depth-Area Curves for a Sydney Storm

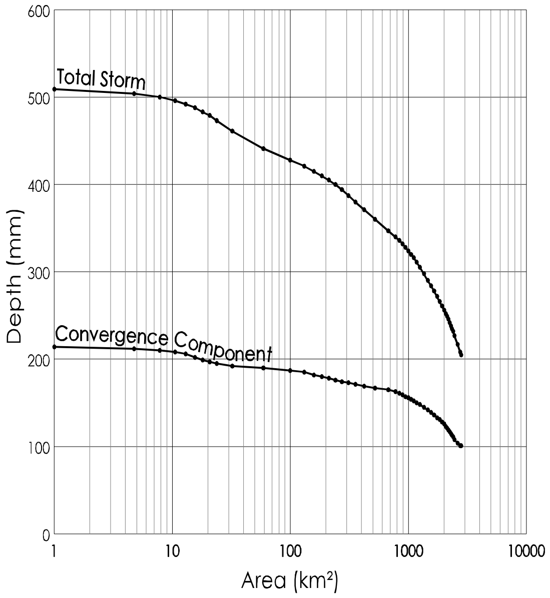

Figure 10: Total Storm and Convergence Component Depth-Area Curves for an Illawarra Storm

A mean storm depth-area curve was calculated for each test area by averaging the ten individual storm depth-area curves. Figure 11 shows the mean 4-day storm depth-area curves for the two test areas. Also shown are the standard deviations about the means. Note that the mean depths for the Illawarra area are about 50% higher than those from the Sydney area.

Similarly a mean convergence component depth-area curve was calculated for each of the test areas and this shown in Figure 12. Note that there is now no significant difference between the curves for the two test areas.

It was further decided to test the significance of the observed differences in the depth-area curves via a statistical technique. The sign test (Pollard, 1968) was used. The test hypothesis was that the Sydney and Illawarra total storm depths came from different populations, but that the convergence component depths came from the same population. The test on the 4-day rainfall depth-area values is outlined in Tables 1(a) and 1(b).

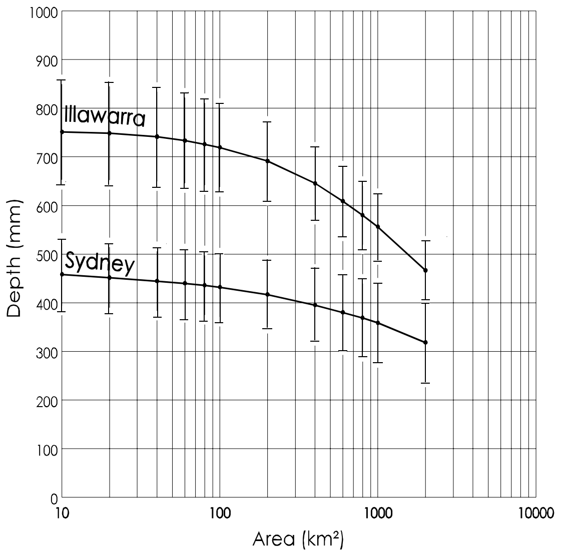

Figure 11: Mean Total Storm Depth-Area Curves and Standard Deviations of the 4-day Storms of the Test

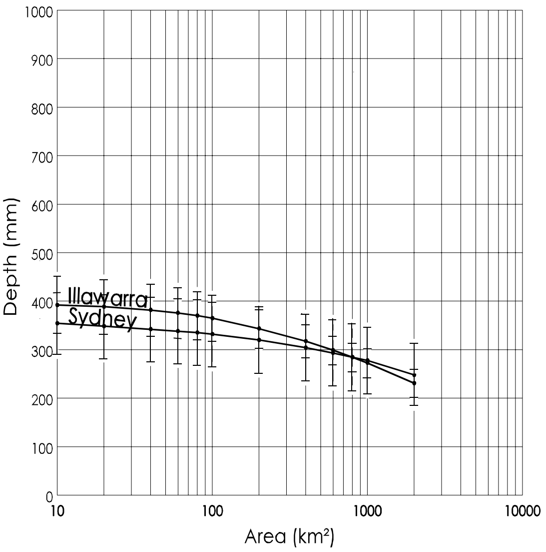

Figure 12: Mean Depth-Area Curves and Standard Deviations of the Convergence Components of the 4-day Storms of the Test

Table 1(a): Sign Test of the Total Storm Depths of the Storm Separation Test Areas

4-day Total Storm Rainfall (mm)

(a) Sydney area sample
565, 281, 408, 347, 379, 358, 323, 298, 314, 311 mm

(b) Illawarra area sample
691, 500, 549, 571, 481, 491, 491, 560, 598, 628 mm

Median of combined samples = (491 + 491)/2 = 491 mm

Contingency Table

Area	<Median	>Median	Total
Sydney	9	1	10
Illawarra	1	9	10
Total	10	10	20

Chi-squared Value

$$\chi^2 = \text{(observed - expected)}^2/\text{expected}$$
$$= (9-5)^2/5 + (1-5)^2/5+(1-5)^2/5+(9-5)^2/5$$
$$= 12.8$$

The probability that the two samples come from the same population is very low.

Table 1(b): Sign Test of the Convergence Component Depths of the Storm Separation Test Areas

4-day Convergence Rainfall (mm)

(a) Sydney area sample
452, 222, 322, 276, 275, 272, 261, 223, 239, 232 mm

(b) Illawarra area sample
343, 257, 283, 271, 262, 226, 257, 273, 281, 273 mm

Median of combined samples = (271 + 272)/2 = 271.5 mm

Contingency Table

Area	<Median	>Median	Total
Sydney	5	5	10
Illawarra	5	5	10
Total	10	10	20

Chi-squared Value

$\chi^2 =$ (observed - expected)^2/expected
= 0

The probability that the two samples come from the same population is very high.

The statistical results for the 1-day storms were similar to those above.

It was thus concluded that the GSAM technique for separating the convergence and topographic components of storm rainfall was satisfactory and generally applicable.

3.1.2.4 Moisture Maximisation and Standardisation

Moisture maximisation is ‘the process of adjusting observed precipitation amounts upwards based upon the hypothesis of increased moisture inflow to the storm’ (WMO, 1986). As described in section 3.1.1.6, the moisture content of a storm is estimated from the **Storm Dewpoint Temperature**. The maximum possible moisture content of a storm is estimated from the extreme 24-hour persisting MSL dewpoint temperature recorded for the storm location and time of year: the **Storm Extreme Dewpoint Temperature**. Extreme 24-hour persisting dewpoint temperatures have previously been analysed, and exist as a set of monthly charts. The location of the storm peak was chosen as the storm location, and the month which provided the maximum extreme dewpoint temperature within ±28 days of the date of the storm commencement was chosen as the time of year. The ratio of the precipitable water values associated with the extreme and prevailing dewpoint temperature conditions is termed the **Maximisation Factor** for the storm.

$$MF = \frac{EPW_{insitu}}{SPW}$$

where EPW_{insitu} is the Extreme Precipitable Water associated with the Storm Extreme Dewpoint Temperature.

and SPW is the Storm Precipitable Water associated with the Storm Dewpoint Temperature.

Precipitation amounts are adjusted upwards by multiplication by this factor. In the absence of better information, the same maximisation factor is applied to the whole storm area and for the total storm duration.

The concept of moisture maximisation assumes a 1‑to‑1 relationship between increased precipitable water and increased precipitation. The range over which such an assumed relationship is valid has been the subject of much debate; a large increase in moisture inflow could alter the dynamics of the storm. In consequence, ad hoc limits on the size of the maximisation factor have been set in past PMP studies, ranging from values of 1.5 to 2.0. In constructing the GSAM storm database it was originally decided not to impose a limit on the maximisation factor. However, it soon became apparent that the range of maximisation factors was not randomly distributed throughout the year and that the highest values were clustered in the Autumn and Winter periods. An investigation into why this was so revealed that for many storms the assumption of an atmosphere saturated through its depth was invalid; where the moisture inflow to a storm is at mid-levels the surface dewpoint temperatures may not be representative of this rain-producing airmass. Such situations were more common in the non-summer storms of the GSAM database. Because of the potential for large errors in maximisation factors calculated using this technique we decided to set our own limit based on the highest maximisation factors calculated from the summer storms of the database. The moisture maximisation factors for each of the storms in the Coastal Zone database is plotted against month of the year in Figure 13. From this plot an upper limit of 1.8 was chosen. One of the summer storms, in fact, has a maximisation factor exceeding this 1.8 limit. However, closer investigation of the meteorological observations taken at the time of this event revealed great variation in surface dewpoint temperatures recorded in the area, casting doubt upon the assumption of a generally saturated atmosphere in this storm.

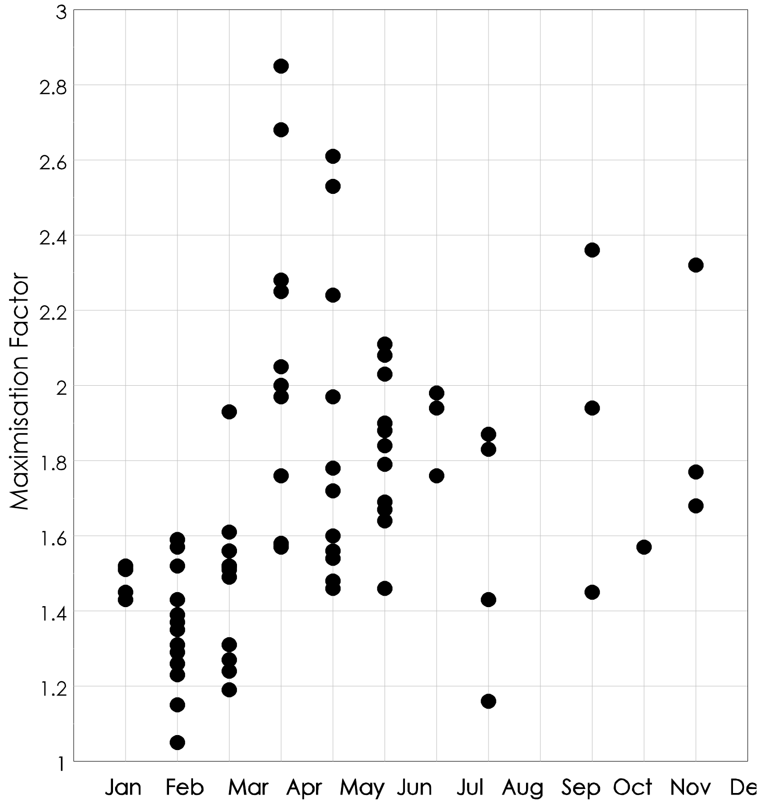

Figure 13: Maximisation Factors for the GSAM Coastal Zone Storms

Moisture maximisation thus removes the 'storm-specific' feature of **moisture content.** To remove the 'site-specific' feature of moisture content requires moisture **Standardisation**: storm moisture content is increased to the level of a **Standard Extreme Dewpoint Temperature** for the zone rather than for the storm location. In essence standardisation is equivalent to transposition of each storm from its original location to a common hypothetical location. Since this is purely a transposition in terms of moisture content, standardisation is only valid for the convergence component of a storm. A **Standardisation Factor** is calculated in an analogous fashion to the maximisation factor: it is the ratio of the precipitable water value at the standard extreme dewpoint temperature to that at the storm extreme dewpoint temperature.

$$SF = \frac{EPW_{std}}{EPW_{insitu}}$$

where EPW_{std} is the Extreme Precipitable Water associated with the Standard Extreme Dewpoint Temperature.

and EPW_{insitu} is the Extreme Precipitable Water associated with the Storm Extreme Dewpoint Temperature.

It is worth noting that the only essential difference between moisture maximisation and standardisation is in the imposition of a limit on the maximisation factor.

Dividing the GSAM region into two zones, Coastal and Inland, effectively limited the transposability of the storms in space. A similar limitation on their transposability in time was also considered necessary; **storm type** is correlated with season as much as with geographical zone. For this reason the storm database was further divided into four **'seasonal' groups**, with four different standard extreme dewpoint temperatures. These four standards were chosen on the basis of the annual variation of the extreme 24-hour persisting dewpoint temperature within the GSAM region. This annual oscillation was approximated by four irregular step functions. The timespan of each step was chosen on the basis of the gradient of the oscillation curve and the desire to minimise the range of associated dewpoint temperatures within each step. The groupings, therefore, are not truly seasonal. This precaution kept the effects of standardisation of the database reasonably consistent from group to group. The values of these 'seasonal' standard extreme dewpoint temperatures are typical of the northern extremities of the GSAM region, so that standardisation factors, in general, are greater than 1.0. The standard steps are shown in Figure 14, with the annual variation in extreme dewpoint temperature at Brisbane for comparison.

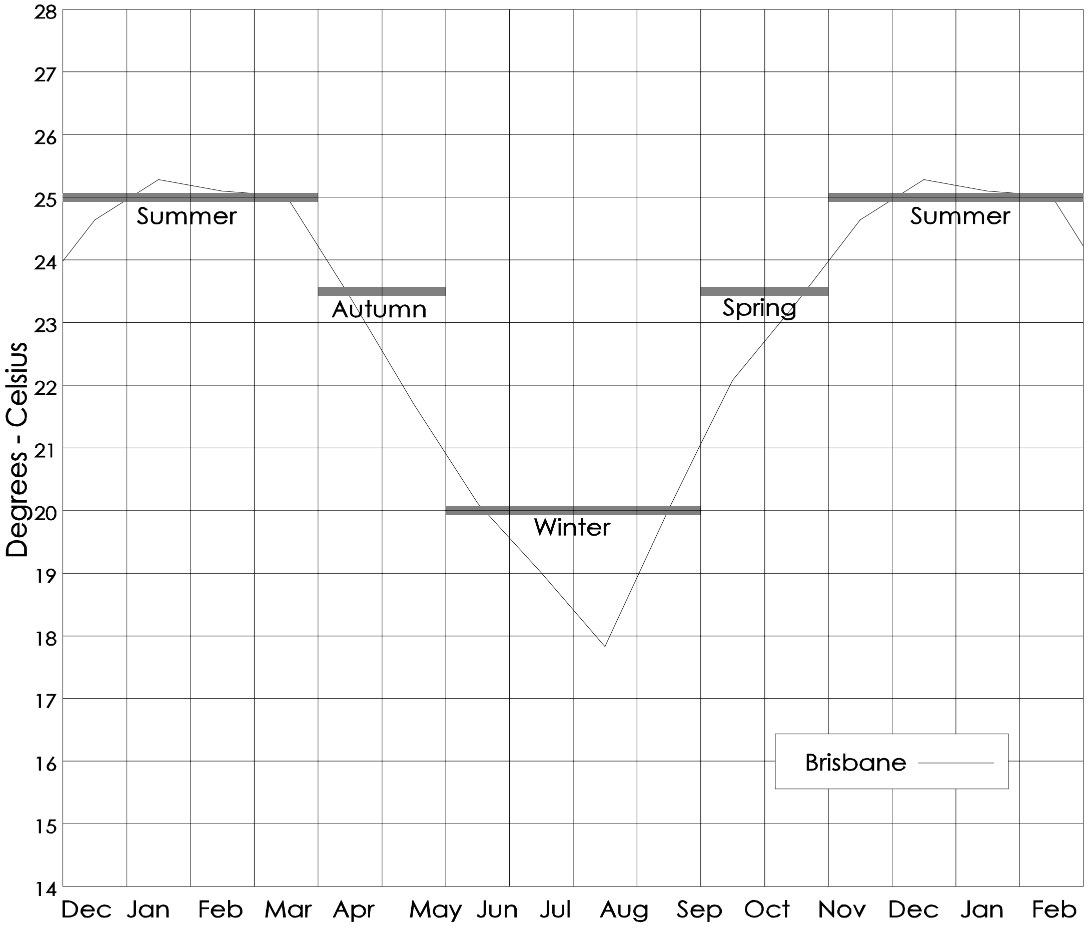

Figure 14: Annual Extreme 24-hour Persisting Dewpoint Temperatures within the GSAM Region, and the Four Standard 'Seasonal' Groups

The four 'seasonal' groupings are as follows :

		EDP_{std} (°C)	**EPW_{std} (mm)**
'Summer' DEC - MARCH	(inclusive)	25.0	80.80
'Autumn' APRIL - MAY	"	23.5	71.00
'Winter' JUNE - SEPT	"	20.0	52.60
'Spring' OCT - NOV	"	23.5	71.00

Thus storms occurring from December 1st to March 31st were standardised to 25.0°C; those from April 1st to May 31st were standardised to 23.5°C, etc. Storms crossing 'seasonal' steps were included in both 'seasonal' groups and thus had two standardisation factors.

3.1.2.5 Enveloping the Depth-Duration-Area Curves

The final step in generalising the GSAM storm database was to draw an enveloping curve to the maximised, standardised convergence component depth-area curves. Enveloping effectively creates from the database a single hypothetical storm of maximum moisture content and maximum 'efficiency', that is, the standard convergence component of a PMP storm. The enveloping process is depicted in Figure 15.

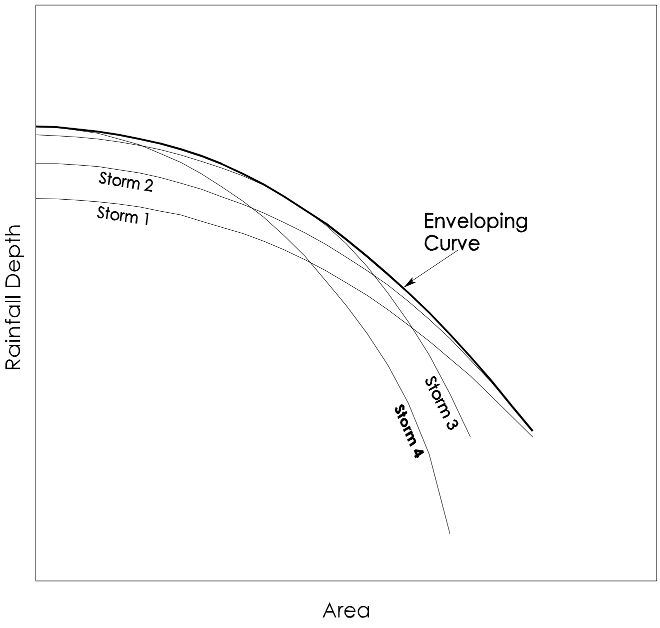

Figure 15: Envelopment of Storm Depth-Area Curves

In examining the depth-area curves of all the storms in the GSAM database, prior to enveloping, it appeared that the curves of the oldest storms and those of the Inland Zone in particular were rather flat for areas less than a few hundred square kilometres. Concerns that this feature was a product of inadequate definition of the storm peak, rather than a characteristic of certain storms, prompted an investigation into the effect of raingauge density on the structure of the depth-area curves. Four storms were reanalysed with a reduced number of rainfall observations and the differences created in their depth-area curves noted.

For the Coastal Zone it appeared that insufficient raingauge density could lead to undercutting of storm maxima by about 15% at 1 km^2, varying to 0% at 1,000 km^2.

For the Inland Zone the shape of storm depth-area curves appeared to be a function of many influences; raingauge density being only one of these. Often one extra observation could increase the maximum depth at 1 km^2 by 30%.

The scale at which storms were analysed influenced the isohyetal interval of the analysis and the size of the maximum isohyet drawn. Coastal Zone storms were invariably analysed at scales of 1:100,000 or 1:250,000 while Inland Zone storms were often analysed at a scale of 1:500,000. It became necessary therefore to make an individual assessment of the possible undercutting of the maxima of each of the storms in the Inland Zone.

A table of small-area adjustments was constructed for the Inland Zone storms and a blanket small-area adjustment used for the Coastal Zone storms. The adopted maximum **small-area adjustments** to the depths of the storms in the GSAM database are given in Table 2.

Table 2: Small-Area Adjustments (%)

Area (km^2)	1	10	100	1,000	10,000
Inland (upper limit of values used)	50.0	37.5	25.0	12.5	0.0
Coastal (values used)	15.0	10.0	5.0	0.0	0.0

Enveloping Curves were drawn to the maximum depths of each ‘season’ and each zone. The curves were drawn smoothly and by hand, with considerable subjectivity. In general the 24-, 48- and 72-hour curves were the most reliable and formed the basis from which decisions about the shapes of the other curves were made. Depth-duration curves were also plotted at the standard areas to assist in the fixing of the depth-area curves at intermediate durations. The hand-drawn depth-area envelopes were then digitised and a Hermite polynomial fitted to the standard area depths. In the course of this enveloping process inconsistencies in the depths at various areas and durations were identified. These depths were adjusted and readjusted, making the enveloping process an iterative one.

In total 57 envelope curves were constructed: 8 durations for each of 4 seasons and 2 zones, except for Inland ‘Spring’ for which there was only 1 storm and therefore 1 curve, at 24 hours. The duration-area limits for this envelope database are presented in Table 3.

Table 3: Duration-Area Limits for the GSAM Envelope Curves

Durations (hrs)	**Areas (km^2)**
6, 12	1,000 to 100,000
24, 36, 48, 72, 96, 120	1 to 100,000

3.2 GSAM PMP ESTIMATION TECHNIQUE

The final stage in the development of the GSAM was in establishing a general technique for estimating PMP from the envelope curves of the generalised storm database. PMP estimates are predominantly required for PMF calculation and are therefore determined for the area of a catchment. To estimate the PMP of a catchment the ‘catchment-specific’ features of the PMP storm must be derived and combined with the standard convergence component of the PMP storm. The ‘catchment-specific’ features of the PMP storm were identified as:

(i) Storm Type
(ii) Topographic Influences
(iii) Moisture Content

Again, the features are interrelated, as are the techniques developed to include them.

Patterns were designed, also, for the spatial and temporal distribution of the PMP storm.

3.2.1 Catchment Area and Location

The standard convergence component of the PMP storm is simply the envelope depth at the area of the catchment. Determining this depth requires an accurate specification of the catchment boundaries and the area within. Catchment outlines were hand-drawn on topographic maps, digitised and gridded. The area of the catchment could then be calculated from the number of gridpoints within the catchment outline and the known resolution of the grid. The envelope depths, from the appropriate zonal database, could then be interpolated between the standard areas to the area of the catchment.

Transposition of the standard PMP convergence rainfall from the standard, hypothetical location to the location of the catchment, required adjustment of the depths for the different moisture potentials of the two locations. A **Moisture Adjustment Factor** was calculated in an analogous fashion to the standardisation factor: it is the ratio of the precipitable water at the **Catchment Extreme Dewpoint Temperature** to that at the **Standard Extreme Dewpoint Temperature**.

$$MAF = \frac{EPW_{catchment}}{EPW_{std}}$$

where $EPW_{catchment}$ is the Extreme Precipitable Water associated with the Catchment Extreme Dewpoint Temperature.

and EPW_{std} is the Extreme Precipitable Water associated with the Standard Extreme Dewpoint Temperature

Since there are four standard extreme dewpoint temperatures, corresponding to the four ‘seasonal’ groups, four catchment extreme dewpoint temperatures were required. The centroid of the catchment was taken as the catchment location, and four seasonal extreme dewpoint temperatures were determined for this latitude and longitude.

The envelope depths, from each ‘seasonal’ group, were then multiplied by these catchment moisture adjustment factors. A **Catchment PMP Convergence Component** was defined as the maximum of these depths across all seasons for each duration.

Thus the ‘catchment-specific’ feature of **storm type** was included, by virtue of the zone in which the catchment was located, and by virtue of the season which provided the greatest convergence depths at the area and location of the catchment, for a given duration. And **moisture content** was included by virtue of the moisture adjustment factors for the catchment location.

3.2.2 Estimating the Topographic Component of the PMP Storm

The topographic component of the PMP storm was estimated using the 72-hour 50-year rainfall intensity field in the same manner as the topographic component of the GSAM storms. It was felt, however, that there would be less scope for topographic enhancement of rainfall in a PMP storm than there is in a storm with an average recurrence interval of about 50 years, as are the storms of the GSAM database. To test this hypothesis a number of investigations were made into the **topographic influences** on record rainfall events. These included:

A. Record 1-4 day Rainfalls

In this investigation the highest 1-4 day rainfall totals for each station within the Coastal Zone were plotted on the same scale as the 72-hour 50-year rainfall intensities. The high topography and low topography values for the two plots were then compared. It was found that the highest rainfall totals over flat terrain were 50 to 100% greater than the 50-year values over the same area, and in mountainous areas they were 25 to 50% greater. These results suggested that the amount of topographic enhancement experienced by these record rainfalls was considerably less than that experienced on average by 50-year rainfall events. Clearly these record rainfalls have average recurrence intervals much longer than 50 years.

On the plot of the station highest rainfall totals, spot values at high and low topography locations were also compared. A set of 'rainfall ratios', ratios of high topography rainfall totals to low topography rainfall totals, were calculated. At coincident locations on the rainfall intensity plot 'rainfall intensity ratios', ratios of high topography rainfall intensities to low topography rainfall intensities, were also calculated. The 'rainfall ratios' were then plotted against their co-located 'rainfall intensity ratios' to compare the magnitude of topographic enhancement experienced by each rainfall field. A selection of these co-located ratios is plotted in Figure 16.

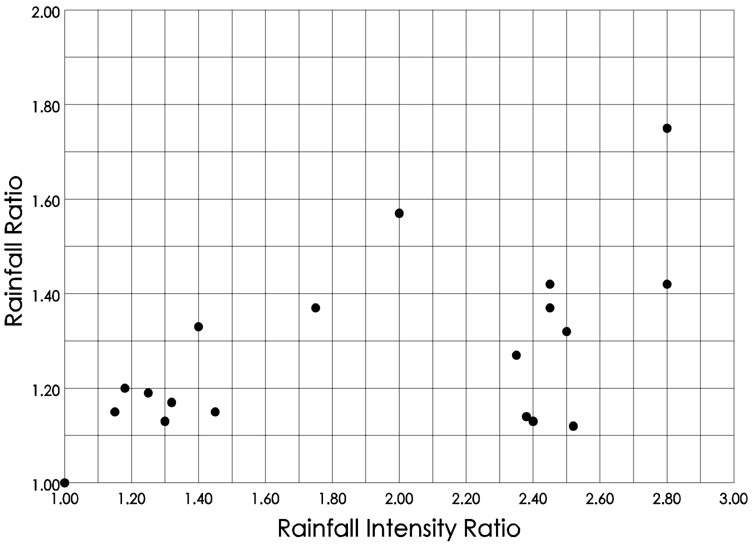

Figure 16: Ratios of High Topography Rainfall and Low Topography Rainfall

Clearly the relationship between the ratios of the two fields is not one to one, and the record rainfall values exhibit much less topographic enhancement than the coincident 50-year rainfall intensities. The highest topographic enhancement factor for the record rainfall events in this investigation was less than 1.8.

B. GSAM Storm Maxima

In this investigation the analysed point maxima of the Coastal Zone storms of the GSAM database were tabulated against their calculated topographic enhancement factor. The ratio of highest rainfall values from high and low topography areas were again calculated for each duration. The highest 'rainfall ratio' obtained in this investigation was 1.7.

C. Record 24-hour Rainfalls

In this investigation world record rainfalls from high and low topography locations were compared. The highest recorded 24-hour rainfall, 1825mm, occurred at an elevation of 2200m on the side of a very steep volcano on the island of La Reunion (WMO, 1986, pg.258). The highest flat-terrain 24-hour rainfall recorded in the United States, 983mm, occurred at Yankeetown in Florida (WMO, 1986, pg.261). The ratio of these two numbers is 1.9.

In Australia the record 24-hour rainfall, 960mm, occurred at Bellendon Ker in Queensland (Bureau of Meteorology, 1994). The highest flat-terrain 24-hour rainfall, 747mm, was recorded at Whim Creek in Western Australia (Bureau of Meteorology, 1994). The ratio of these two numbers is only 1.3.

Although this series of investigations was far from conclusive, an upper limit to the possible topographic enhancement of large storms was suggested. Within the region of the GSAM, topographic enhancement factors range from 0.8 to 3.4. A subjective decision was made, in the absence of more conclusive evidence, to **modify the topographic enhancement factors** for PMP storms in the manner set out in Table 4.

Table 4: Topographic Enhancement Factors

Original	Modified
$x \leq 1.0$	$x = 1.0$
$1.0 < x \leq 1.5$	$x = x$
$1.5 < x < 2.5$	$x = 0.5x + 0.75$
$x > 2.5$	$x = 2.0$

This modification is expressed graphically in Figure 17.

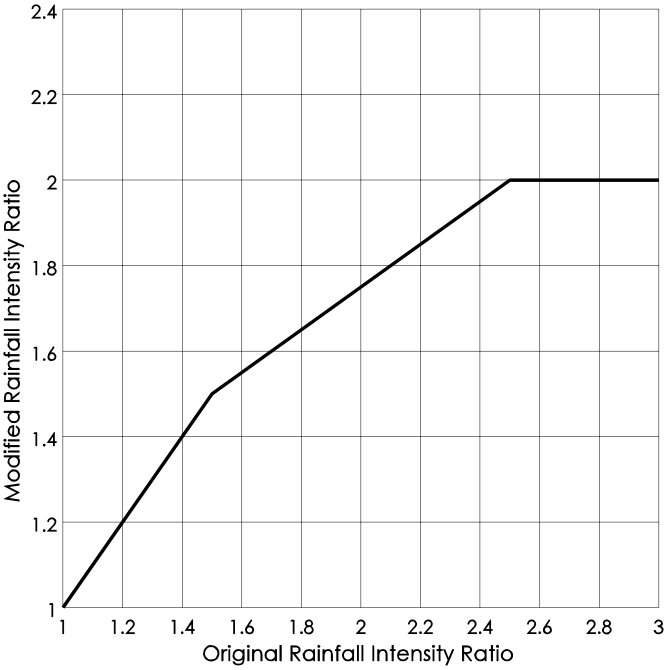

Figure 17: Modification of Topographic Enhancement Factor for PMP Storms

Modified topographic enhancement factors were then calculated at each gridpoint within the catchment. The average of these provided the **Catchment PMP Topographic Enhancement Factor**.

3.2.3 Catchment PMP Estimates

Finally, total PMP depths were calculated, for each duration, from the multiplication of the catchment PMP convergence components by the catchment PMP topographic enhancement factor. These depths were then plotted against duration and a final envelope drawn to these. Catchment PMP estimates are taken from this final envelope. An example is given in Figure 18.

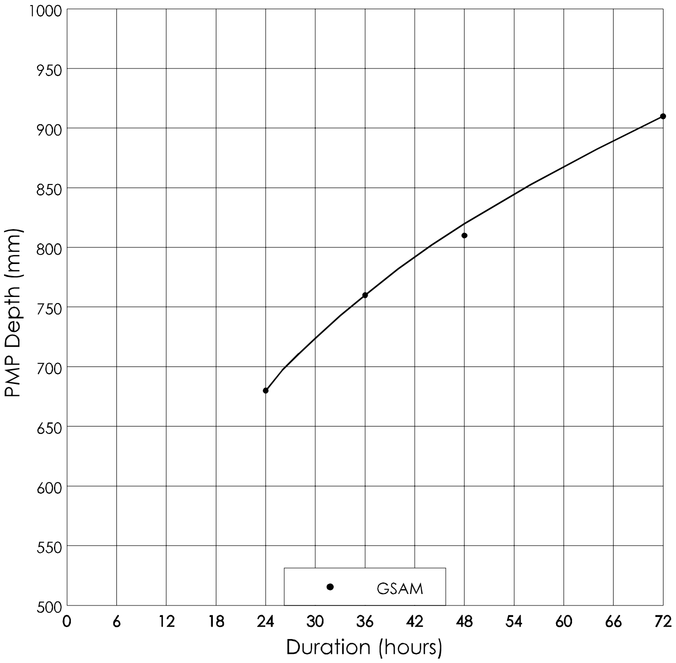

Figure 18: Enveloping PMP Depths

The rationale for the final enveloping of the PMP estimates is that:

(i) the GSAM storm database is necessarily incomplete and cannot of itself provide the form of the PMP design storm in total

(ii) different duration PMP estimates may derive from different seasons and there has been no attempt to envelope the database across season.

3.2.4 Design Spatial Distribution of the PMP Storm

The design spatial distribution for the PMP storm is simply given by the field of modified topographic enhancement factors over the catchment.
An example is given in Figure 19.

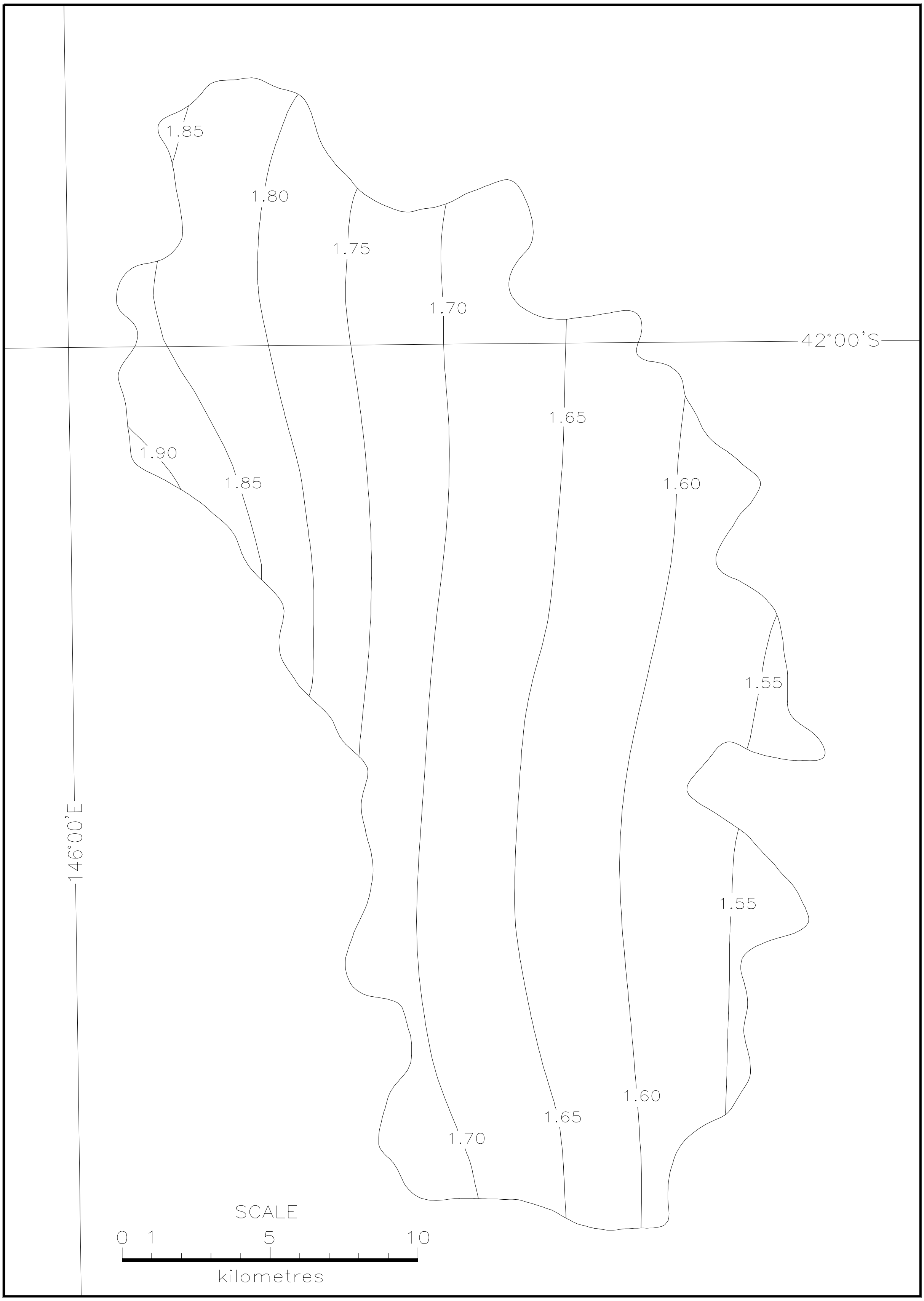

Figure 19: Example of a GSAM Design Spatial Distribution

3.2.5 Design Temporal Distribution of the PMP Storm

Design temporal distributions were developed in a cooperative effort between the Bureau of Meteorology and the Rural Water Commission of Victoria. The work is extensively documented in Nathan (1992).

For each standard area and duration, and separately for each zone, the average variability method of Pilgrim, Cordery and French (1969) was applied to the storm temporal distributions to derive design temporal distributions for the PMP storm.

It was considered that the temporal distribution of rainfall in a PMP storm would be smoother than that of an average storm in the GSAM database. Accordingly the temporal distribution derived by the average variability method were smoothed using the method described by Nathan (1992).

In assigning a design temporal distribution to a catchment PMP depth, the distribution for the standard area closest to the area of the catchment is used. This is done for each standard duration. Examples of design temporal distributions are given in Figure 20.

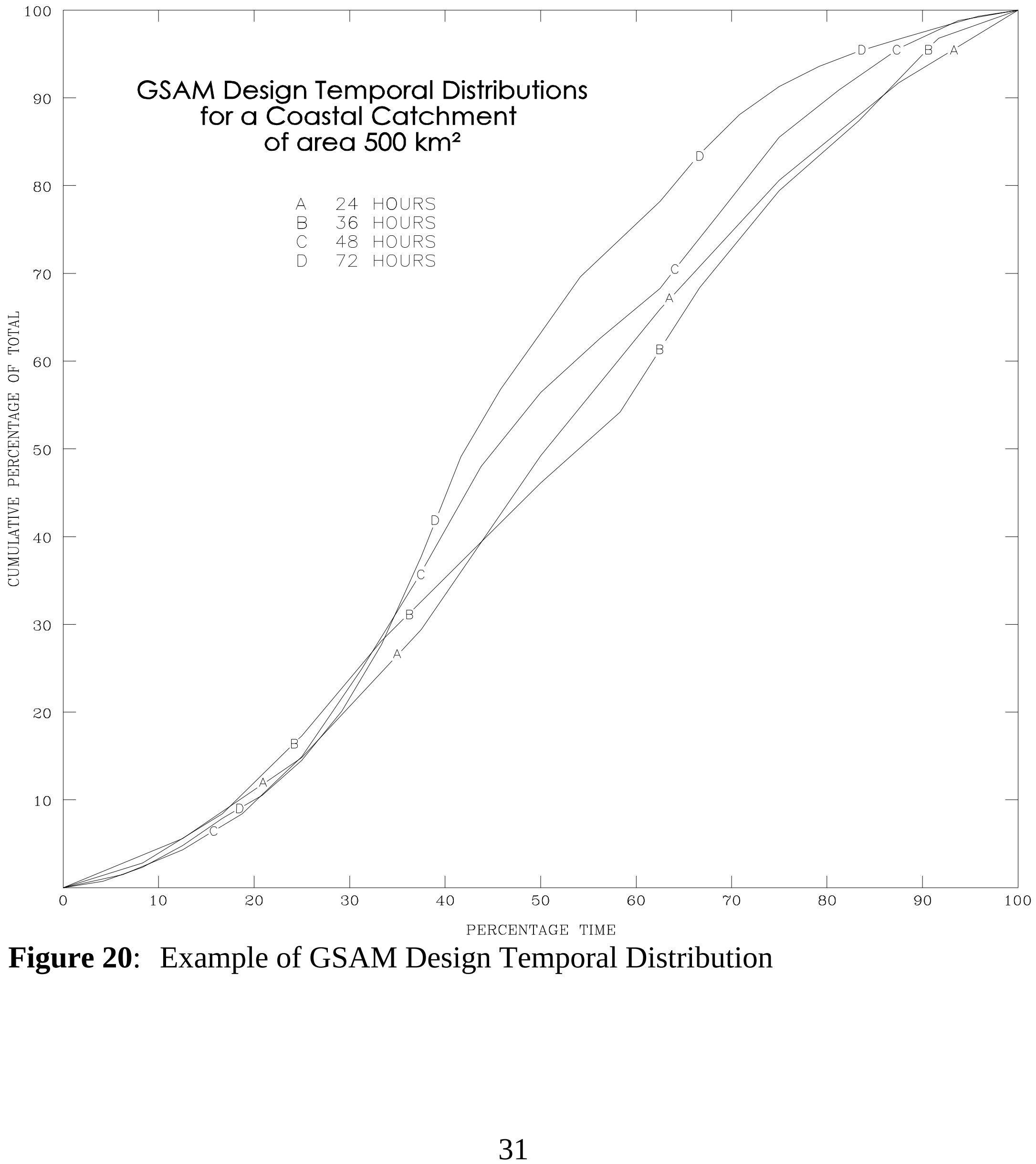

Figure 20: Example of GSAM Design Temporal Distribution

4. LIMITATIONS AND TRANSITIONS

4.1 DURATION AND AREA LIMITS

PMP estimates can be provided using the GSAM for areas between 5 and 100,000 km^2 , at the standard durations of 12-, 24-, 36-, 48-, 72-, 96- and 120-hours. The longer duration estimates derive primarily from storms from the Northern portion of New South Wales. In Victoria and Tasmania the upper level northwesterly to westerly winds are both stronger and more frequent. These winds steer the rain producing low pressure systems towards the east and southeast. For this reason an upper limit of 72 hours was set to the duration of PMP estimates provided by the GSAM for Victoria and Tasmania.

Although estimates can be derived for the 12 hour duration, these estimates are based on a much smaller storm sample: those for which 3 hourly temporal information was available. For this reason less confidence can be vested in these estimates. For areas smaller than 1,000 km^2 , 12 hour estimates are best interpolated between the short duration estimates provided by the GSDM (Bureau of Meteorology, 1994) and the 24 hour estimate provided by the GSAM.

A summary of these duration and area limits is provided in Table 5.

4.2 TRANSITIONS BETWEEN ZONES AND PMP METHODS

For catchments located close to the boundary between the Inland and Coastal Zones of the GSAM the significance of a zonal distinction is blurred. These zones are defined in terms of the storm types included in their respective databases. The boundary, however, is a drainage boundary, not a meteorological boundary. For this reason a **Coastal-Inland Overlap** has been included. PMP estimates for inland catchments with a boundary adjacent to the zonal boundary are calculated as the average of the PMP estimates from both the Coastal and the Inland databases.

For catchments located close to the boundary between the GTSM and the GSAM there is a measure of uncertainty associated with which method to apply. Both methods have their strengths and weaknesses: the GSAM lacks storms of tropical origin, and the GTSM has a rudimentary treatment of topographic effects which may be important at these locations. A **GSAM-GTSM Transition Zone** has therefore been defined between the two methods. This Transition Zone is depicted in Figure 5. PMP estimates for catchments within this Transition Zone are calculated as the distance-weighted average of the PMP estimates from both the GTSM and the GSAM.

Design temporal and spatial distributions from one method or the other may be used in conjunction with these Transition Zone PMP estimates, but not a mixture of the two.

Table 5: GSAM Duration, Area Limits

A.	**Catchment Area (A km^2)**		**5≤ A ≤1000 km^2**
	Zone	**State**	**Duration (D hrs)**
	Inland	SA	24 ≤ D ≤72
	Inland	Victoria	24 ≤ D ≤72
	Inland	NSW	24 ≤ D ≤96 (120(a))
	Coastal	Tasmania	24 ≤ D ≤72
	Coastal	Victoria	24 ≤ D ≤72 (96(a))
	Coastal	NSW	24 ≤ D ≤96 (120(a))
	Both	All	D <24(b)
B.	**Catchment Area (A km^2)**		**1000≤ A ≤40,000 km^2**
	Zone	**State**	**Duration (D hrs)**
	Inland	SA	(12(d)) 24 ≤ D ≤72(96(c))
	Inland	Victoria	(12(d)) 24 ≤ D ≤72(96(c))
	Inland	NSW	(12(d)) 24 ≤ D ≤96 (120(a))
	Coastal	Tasmania	(12(d)) 24 ≤ D ≤72
	Coastal	Victoria	(12(d)) 24 ≤ D ≤72 (96(a))
	Coastal	NSW	(12(d)) 24 ≤ D ≤96 (120(a))
	Both	All	D <12(e)
C.	**Catchment Area (A km^2)**		**40,000≤ A ≤100,000 km^2**
	At these areas the rainfall data are extremely dubious and the maximisation process may not be valid. The GSAM should be used with discretion at these areas with duration limits as in B above.		

Notes:

(a) Estimates supplied for this duration only if specifically requested

(b) The data for these durations are interpolated between GSDM estimates and the 24-hour GSAM value

(c) Estimates supplied for this duration only if A>>1000 km^2

(d) Estimates are supplied for this duration only if specifically requested. The 24-hour design temporal distribution is used with these estimates.

(e) These estimates are not available from the GSAM

5. PROBABILITY OF GSAM PMP ESTIMATES

The PMP concept, as defined in the introduction, effectively involves zero probability of exceedance. However, estimates made by the various PMP methodologies have a non-zero probability of exceedance. For example, '*in situ* maximisation' method PMP estimates for the Fortesque River catchment in Western Australia were exceeded by rainfall from Tropical Cyclone Joan in 1975 (Kennedy, 1982). The maximised rainfall from the Dapto 1984 storm (Shepherd and Colquhoun, 1985) near Wollongong in NSW exceeded the 'method of adjusted US data' PMP estimates used at the time. Probabilities of exceedance can therefore be associated with the methodology used to estimate the PMP, not the concept of PMP itself.

For some catchments estimates of PMP depth have been made using a variety of methods, but the associated probabilities may vary considerably. The generalised methods of PMP estimation applicable to different meteorological regions can also have variation in their associated probabilities. Using deterministic meteorological methods of estimating PMP rather than statistical methods means that the assignment of Annual Exceedance Probabilities (AEPs) to the PMP estimates is not straightforward. However, guidance can be given on the comparative probabilities of exceedance of PMP depths estimated by the different deterministic methods.

The uncertainties associated with any estimate of the exceedance probability of a PMP depth are very large, but by using the same assumptions for each of the PMP methods the results can provide useful guidance in a comparative sense (Pearce, 1994). For the AEP of the PMP to be assigned to the PMF, a significant number of major causative variables are neglected. Probabilities of exceedance of variables such as temporal distributions, spatial distributions, antecedent rainfall, losses, reservoir levels, flood model assumptions etc. assumed in converting rainfall to floods also contribute to changing the notional exceedance probability of the PMF with respect to that of the PMP estimates. However, as discussed above for the PMP, if similar assumptions and flood models are used in transforming the PMP to PMF the results can provide useful guidance in comparing the degrees of safety between various dams.

Kennedy and Hart (1984) used notional AEPs for various PMP methods as a means of indicating the different security levels provided by the different methods and to show why generalised estimates such as those derived by the GSDM for up to 6 hours could, in some cases, exceed the *in situ* maximisation method estimates for 24 hours for some catchments. The notional AEPs for the GSAM and GTSM PMP estimation methods are reviewed by Pearce (1994) and an AEP for the Coastal Zone of the GSAM is estimated at approximately 10^{-6}, while that for the Inland Zone is about 10^{-7}.

Chapter 13 of *Australian Rainfall and Runoff* (IEAust, 1987) states that *"it is not possible to derive rigorously 'correct' or 'true' procedures for estimating floods within the range of very low probabilities (Office of Water Data Coordination, 1986). Despite this the National Committee on Hydrology and Water Resources of the Institution of Engineers, Australia, ANCOLD and NAASRA consider that consistent procedures should be adopted throughout the country"*. Section 13.5 describes a method which standardises the estimation of intermediate AEPs of extreme events and recommends this method for application to either PMP or PMF, though the results will differ slightly.

6. ACKNOWLEDGEMENTS

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8. GLOSSARY

airmass - Body of air possessing similar characteristics over an extensive area.

AEP - Annual Exceedance Probability. The probability that a given rainfall total accumulated over a given duration will be exceeded in any one year.

ANCOLD - Australian National Committee on Large Dams.

ARI - Average Recurrence Interval. The average, or expected, value of the periods between exceedances of a given rainfall total accumulated over a given duration.

Catchment Extreme Dewpoint Temperature - Extreme 24-hour persisting dewpoint temperature for the location at the centre of the catchment.

Catchment PMP Convergence Component - The maximum of all the seasonal, moisture-adjusted, envelope depths for a duration.

Catchment PMP estimates - The PMP depths from the final catchment depth-duration envelope.

Catchment PMP Topographic Enhancement Factor - The average of the modified topographic enhancement factors calculated at each grid point within the catchment.

CDIRS - Computerised Design IFD Rainfall System. A gridded dataset of the IFD design rainfall published in *Australian Rainfall and Runoff* (IEAust, 1987) and an automated procedure for the construction of IFD curves.

Convergence Component -

of GSAM PMP - The portion of rainfall within a PMP storm that is convergence precipitation, defined as the envelope of the generalised GSAM storm database.

of GSAM storm - The portion of rainfall within a storm that is convergence precipitation, defined as:

$$\text{Total (Storm) Depth} \times \frac{\text{Convergence Component of 72-hr, 50-yr Rainfall Intensity}}{\text{Total 72-hr, 50-yr Rainfall Intensity}}$$

of the 72-hr, 50-yr Rainfall Intensity - The portion of the 72-hr, 50-yr rainfall intensity that is convergence precipitation, defined as the value expected from interpolation between intensities unaffected by topographic influences.

convergence precipitation - Precipitation due to any atmospheric process unaffected by terrain.

DDA - Depth-Duration-Area curves. A set of depth-area curves at standard durations and standard areas.

depth-area curve - Curve showing, for a given duration, the relation of maximum average depth to size of area within a storm or storms.

dewpoint temperature - The temperature at which saturation is attained when air is cooled at constant pressure without the addition or subtraction of water vapour.

envelope - The curve constructed via the procedure of estimating the maximum values of an element by fitting a smooth curve to the highest data points plotted on a graph or map. Other considerations than the data points themselves may influence the shape of the curve between data points.

generalised methods of PMP estimation - Methods which utilise the rainfalls recorded over a large region by separating the portion of rainfall arising from ‘site-specific’ influences from that portion arising from regional influences. Such methods provide regional consistency of PMP estimation.

GSAM - Generalised Southeast Australia Method of PMP estimation. A generalised method for estimating longer-duration PMP in southeast Australia.

GSAM Storm Catalogue - A catalogue of the 110 storms selected for the GSAM database, their dates and locations, DDA values, and storm dewpoint temperatures.

GSDM - Generalised Short Duration Method of PMP estimation. A generalised method for estimating small-area, short-duration PMP in Australia.

GTSM - Generalised Tropical Storm Method of PMP estimation. A generalised method for estimating longer-duration PMP in those parts of Australia affected by tropical storms.

hectopascal (hPa) - Unit of atmospheric pressure, standard atmospheric pressure being 1013.2 hPa.

IEAust - The Institution of Engineers, Australia.

IFD - Intensity-Frequency-Duration of rainfall. Frequency analyses of rainfall expressed as rainfall intensities (in mm/hr) maintained over a specified duration (in hr), and recurring on average once every n-years (an ARI of n-years).

isohyet - Line of equal depth of precipitation.

Maximisation Factor - The factor by which storm rainfall amounts are multiplied to simulate maximised storm moisture content, defined as:

$$\frac{\text{Extreme Precipitable Water (at storm location and time of year)}}{\text{Storm Precipitable Water}}$$

Moisture Adjustment Factor - The factor by which the standard convergence PMP is multiplied to simulate the transposition of this component from a standard location of standard moisture potential to the location of the catchment and its specific moisture potential. It is defined as:

$$\frac{\text{Extreme Precipitable Water at catchment location}}{\text{Extreme Precipitable Water at standard location}}$$

Moisture Maximisation - *'the process of adjusting observed precipitation amounts upwards based upon the hypothesis of increased moisture inflow to the storm'* (WMO, 1986). The increase is generally to theoretical values which could be reached if the moisture content of the air had been at the maximum recorded for that location and season, but the other meteorological conditions affecting the storm had remained unchanged.

NAASRA - National Association of Australian Road Authorities, now AUSROAD.

NCC - National Climate Centre. The section of the Bureau of Meteorology, Australia, responsible for the collection, quality control and archive of Australian climate data.

orographic precipitation - Precipitation which is caused entirely or mostly, by the forced uplift of moist air over high ground. (Also topographic precipitation).

persisting n-hour dewpoint temperature - The dewpoint temperature at a station that has been equalled or exceeded throughout a period of n consecutive hours. Commonly durations of 12 or 24 h are used, though other durations may be used at times. *Extreme 24-hour persisting dewpoint temperature* is the analysed maximum value of 24-hour persisting dewpoint temperature at a given location and time of year.

PMF - Probable Maximum Flood. The flood produced when runoff from the PMP is routed through the catchment.

PMP - Probable Maximum Precipitation is *'the greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends.'* (WMO, 1986).

PMP design storm spatial distribution - The hypothetical size, shape and orientation of the isohyets of the PMP storm, with shape and orientation given by the field of modified topographic enhancement factors, and size given by the Catchment PMP estimates.

PMP design storm temporal distribution - The hypothetical time order in which incremental amounts of the PMP storm fall.

precipitable water - Total water vapour contained in an atmospheric column of unit cross-section, expressed in terms of the depth of an equivalent mass of liquid water of the same cross-section.

pseudo-adiabat - Line on thermodynamic diagram showing the pressure and temperature changes undergone by saturated air rising in the atmosphere, without ice-crystal formation and without exchange of heat with its environment other than that involved in assuming that the liquid water, formed by condensation, drops out. It is the heat exchange associated with condensation that forces the term *pseudo*.

saturation - Upper limit of water-vapour content of an airmass, which is solely a function of temperature.

Standard Extreme Dewpoint Temperature - The extreme 24-hour persisting dewpoint temperature at the standard, hypothetical location.

Standardisation - The process of adjusting precipitation amounts based upon the hypothesis of transposition to some standard location and therefore standard moisture content.

Standardisation Factor - The factor by which storm convergence component rainfalls are multiplied to simulate transposition to a standard location, defined as:

$$\frac{\text{Extreme Precipitable Water at standard location}}{\text{Extreme Precipitable Water at storm location}}$$

storm - As used within the GSAM, it is a meteorological phenomenon significant only for the amount and extent of the rainfall it produces. Not to be confused with thunderstorms.

storm analysis - The manually drawn spatial distribution of isohyets of storm rainfall.

Storm Dewpoint Temperature - The 1000hPa dewpoint temperature that is representative of the rain-producing airmass of the storm.

Storm Extreme Dewpoint Temperature - The extreme 24-hour persisting dewpoint temperature at the location of the storm peak and within ±28 days of the storm commencement.

storm spatial distribution - The size, shape and orientation of the isohyets of the storm analysis.

storm temporal distribution - In general, the variation in rainfall with time as a percentage of the total storm rainfall. Specifically within the GSAM, *the maximum percentages of the total storm rainfall that fell within the standard durations and the standard areas*.

storm transposition - Moving characteristics of a storm from its place of occurrence to another location under study to represent a possible future storm.

synoptic scale - The scale of meteorological phenomena that can be detected on synoptic weather maps, ie not local.

synoptic station network - The network of Australian meteorological observing stations that record observations at 3-hourly intervals.

Topographic Component (of GSAM storm or PMP) - The portion of rainfall within a storm that is topographic precipitation, defined as:

Total (Storm) Depth - Convergence Component (of Storm) Depth

Topographic Enhancement Factor -

of GSAM PMP - The average enhancement of PMP rainfall due to the presence of topography, defined as for GSAM storms but *modified* to reflect the hypothesis of less scope for topographic enhancement than was possible for storms with ARIs of about 50 years.

of GSAM storm - The average enhancement of storm rainfall due to the presence of topography, defined as:

$$\frac{\text{Total 72-hr, 50-yr Rainfall Intensity}}{\text{Convergence Component of the 72-hr, 50-yr Rainfall Intensity}}$$

topographic precipitation - Precipitation which is caused by the interaction of a moist airflow with an orographic feature, either through continued uplift or triggering of unstable air. (Also orographic precipitation).

Transition Zone - A zone within the region of the GSAM which borders the East Coast Tropical Zone of the GTSM, in which application of both methods of estimating PMP, the GTSM and the GSAM, is required. The existence of the zone reflects the uncertainty about which method to apply in this part of the Australia.

WMO - World Meteorological Organisation.

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