HYDROLOGY REPORT SERIES

HRS Report No. 8

REVISION OF THE GENERALISED TROPICAL STORM METHOD FOR ESTIMATING PROBABLE MAXIMUM PRECIPITATION

Hydrology Unit
Melbourne
August 2003

HYDROLOGY REPORT SERIES

HRS Report No. 8

REVISION OF THE GENERALISED TROPICAL STORM METHOD FOR ESTIMATING PROBABLE MAXIMUM PRECIPITATION

David Walland, Jeanette Meighen, Karin Xuereb,
Catherine Beesley and Tam Hoang

Hydrometeorological Advisory Service
www.bom.gov.au/hydro/has
Hydrology Unit
Melbourne
August 2003

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

Figure **Page**

LIST OF TABLES

1. INTRODUCTION

The World Meteorological Organisation has defined Probable Maximum Precipitation (PMP) 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 can be thought of as a reasonable upper limit on the rainfall that could be anticipated and is a key design rainfall input to the calculation of the Probable Maximum Flood (PMF) and the Probable Maximum Precipitation Design Flood (PMPDF). These quantities are used as design standards for the spillways of large dams. If a spillway is not able to safely release the PMF, breaching of the dam wall or erosion of the abutments due to overtopping can occur. It is also recommended as a defined flood event for use in floodplain management studies (SCARM, 2000).

The PMP concept is based around the hypothesis that the rainfall results from the simultaneous occurrence of a storm of optimal efficiency together with maximum moisture availability (Paulhus and Gilman, 1953; Gibbs, 1958; United States Weather Bureau, 1960; Weisner, 1970; Minty, Meighen and Kennedy, 1996). The hypothesis of maximum moisture availability is approximated by assuming maximum moisture inflow to the storm (and maximising the rainfall for the storm accordingly).

Ascertaining maximum storm efficiency is problematic with Australia having only approximately 100 years of data at best to estimate the biggest storms. However, it is assumed that one of the storms recorded during the period would be operating at, or close to, maximum efficiency. Having a much longer period of data would not necessarily be without problem either as there is no guarantee that the whole period would be representative of the current climate that is most relevant for the life of the dam. However, the limited length of record necessitates some clever use of the data to try and estimate the much rarer storm.

The area of Australia relevant to the current study is depicted in Figure 1. This Generalised Tropical Storm Method (GTSM) zone is the area of Australia affected by tropical storms and includes the majority of the continent with the exception of the south-east. The original generalised method for estimating PMP over regions of Australia affected by tropical storms, the Generalised Tropical Storm Method (GTSM) has been deemed to be in need of revision. The method, developed in the 1970s (Kennedy, 1982; Kennedy and Hart, 1984) was based on work from the US Weather Bureau (United States Weather Bureau, 1965) and only a very limited quantity of data. A review of the study was always envisaged although it has taken some 20 years and a spillway remedial works program in each of the states (affected by tropical storms) as a catalyst for this revision to take place. The GTSM (and the current revision study) estimate PMP derived from large, longer duration storms. The methods are separate from the Generalised Short Duration Method (Bureau of Meteorology, 1985, 1994, amended 1996 and 2003), otherwise known as the Thunderstorm Method, used to derive PMP for durations less than 6 hours.

1.1 HISTORY OF PMP ESTIMATION

Since the 1950s, a number of methods have been employed to estimate the most efficient storm mechanism (Pearce and Kennedy, 1993). Early estimates based on the highest

recorded rainfall at a specific location (in situ maximisation) suffered because of the limited data available and as such, PMP estimates for different locations in the same vicinity differed substantially.

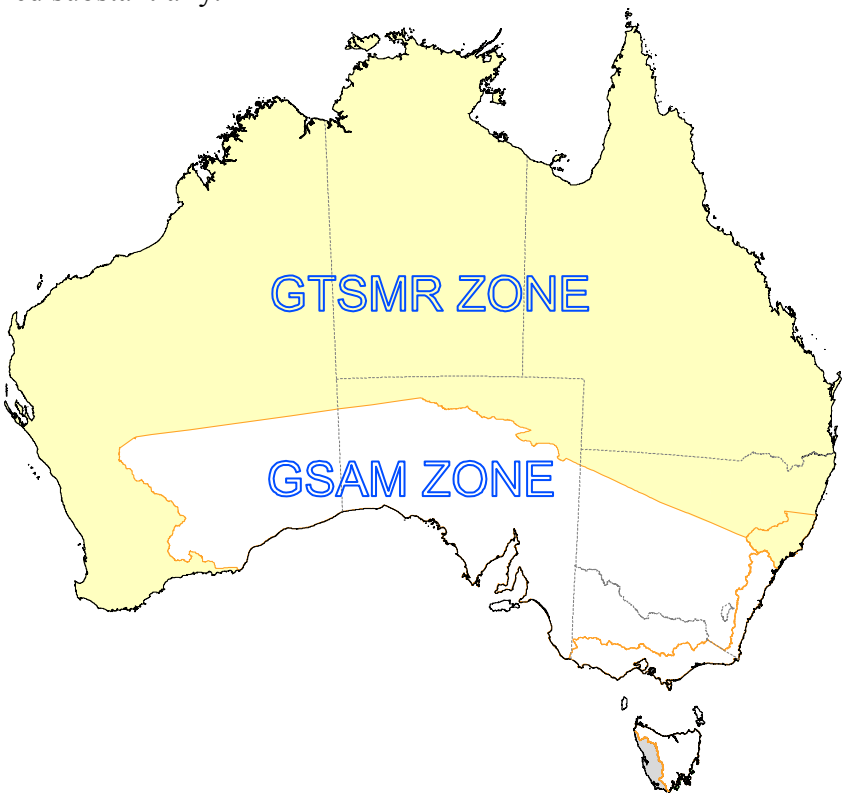

Figure 1: The area of Australia relevant to the GTSM (yellow) and GSAM (white).

Storm transposition methods allowed the displacement of a storm from the location where it had occurred to a target location assuming the storm could just as likely have occurred there. This improved technique generally tended to increase the estimates of PMP due to the greater likelihood of the data including an outlier (i.e., finding at least one storm that is operating near maximum efficiency). However, the degree to which additional storms can be transposed into an area was limited by how similar the neighbouring catchment was considered to be; particularly the topography.

From the mid 1970s, generalised methods have been developed. These allow rainfall from much wider regions to be analysed, which further increases the likelihood of an outlier being included in the dataset compared with the transposition techniques. The difficulty with sampling from a much wider region is that there are site-specific characteristics that influence the rainfall potential of any specific location. In order for direct comparisons to be made between the different locations, these site-specific components of the rainfall must be removed.

Successive revisions of the methodology for estimating PMP have, in turn, brought progressively higher estimates of PMP depths for individual catchments. This is because each revision has utilised a greater amount of data and better techniques to determine estimates of the PMP more accurately. Although, the WMO defines the PMP as the 'the theoretical greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year' (WMO, 1986), it is recognised that limitations in data and understanding of extreme

meteorological conditions means that there is a finite probability, albeit small, of the PMP estimates being exceeded.

In order to take into consideration the inability to accurately estimate the theoretical upper limit of rainfall, the term *operational estimate of the PMP* has been coined (Schaefer, 1994). This represents the best estimate of the PMP depth for a particular location that can currently be made using information obtained from observed large events and the generalised PMP methods. Therefore, the GTSMR PMP estimates that are derived are the *operational* estimates of the PMP as opposed to the *theoretical* PMP. This distinction acknowledges the finite probability of occurrence of the PMP as discussed above

Evaluating the probability of the *operational* GTSMR PMP estimates was not part of the scope of this project. For guidance on assigning an annual exceedance probability (AEP) to the PMP, reference should be made to Laurenson and Kuczera (1999) and Book VI of Australian Rainfall and Runoff (Nathan and Weinmann, 1999). In addition, work that is currently being undertaken on the AEP of the PMP for the GSAM region (Agho, Kuczera, Green, Weinmann and Laurenson 2000) (Green, Weinmann, Laurenson, Nathan and Kuczera, 2002) will eventually be applied to the GTSMR region.

1.2 OUTLINE OF REPORT

This document will record the revision project (referred to as GTSMR) and will refer frequently to its related project, the development of the GSAM (Minty et al. 1996). The report begins by describing the process followed to construct a database of the most efficient storms recorded in the Australian rainfall record. This database of storms will form the basis of the method. The procedure of preparing the data before analysing it and then generalising it in terms of topography, moisture and mechanism decay will be described in some detail. While a method for accounting for the site-specific effect of surface moisture content has been well documented (WMO, 1986), a relatively new technique will be used for the removal of the topographic influence on rainfall based on the Generalised South-east Australia Method (GSAM) (Minty et al. 1996). Further concepts will also be introduced that enable the storms to be successfully generalised such that they may be freely transposed and compared.

When all of the data is put in a form such that a comparison can take place, then the data will be enveloped providing the means by which PMP can be determined. In addition, the process of deriving design temporal and spatial patterns with which to apply the PMP to a specific catchment will be documented before describing in detail the way in which all of this material can be put back together to derive PMP for a catchment.

2. GTSMR STORM DATABASE

There is currently no satisfactory theoretical or modelling approach available at present that allows the estimation of the optimal storm mechanism that will generate the PMP. Consequently, it is necessary that the very low probability design rainfall event be estimated from only one hundred or so years of data. Therefore, central to the development of this generalised method, is a high quality database containing the most significant rainfall events for the region in question. The overall approach of the generalised methods is to collect the most significant rainfall events recorded over the region and then to put them in a form such that they may be transposed anywhere within the region. As such, the database of the most significant rainfall events is critical to the success of the method. In the United States, PMP estimates were drawn from a catalogue of about 800 storms (US National Weather Service, 1988). For GSAM, some 110 storms were used for the area in the southeast of Australia (Meighen and Kennedy, 1995).

Because of the relatively short time available for its development, one of the shortcomings of the previous GTSM was that a rather heuristic method was used to develop a database of the largest storms upon which to build the model and this database was small (only seven events). This set was based on the considerable experience and knowledge of the authors, who had a very good understanding of which were the largest storms in the rainfall record. Inevitably, however, some significant rainfall events may have been missed.

The current method attempts to construct a comprehensive database of large storms in an objective fashion and then present each storm in the database in a form ready for the later steps of generalising this database. The process can be broken down into the following steps:

1. Storm Selection
2. Data Quality Control
3. Storm Analysis and Gridding
4. Depth-Duration-Area Analysis

2.1 STORM SELECTION

2.1.1 Computerised Searches of the Rainfall Archive

Computer software was specifically written for this project, enabling an interrogation of the Bureau of Meteorology's Oracle database of daily rainfall and extraction of data for the largest rainfall totals. The program was designed to interrogate each station history, extract and rank the top ten rainfall totals in the record for durations of 1 – 7 days. The dates of these rainfalls were then grouped into common events by grouping stations with rain on the same date(s) and assuming these to be the same storm. There were instances when this assumption was not correct and there was significant rainfall occurring on the same date from independent events that needed to be distinguished.

The storm data showed the biggest rainfall depths recorded at each station. However, this did not guarantee that the rainfalls were significant. For example, stations with only a short record would still produce ten rainfalls, while stations with a long record may simply not have had any particularly rare storms. Thus, it was a useful exercise to extend this computerised search by calculating for each storm event, the average recurrence interval (ARI) for every rain observation within it, to ascertain how rare the event was. This was

accomplished using the Bureau of Meteorology intensity-frequency-duration (IFD) database on rainfall intensity (IEAust, 1987). The storm events were then ranked, separately for each duration, according to how many one-in-one-hundred-year ARI rainfall observations were recorded. In this manner, the list of large storms was prioritised according to the rarity of each event relative to its own location.

The final stage of the automated sorting was to divide all storm events geographically. It was important for the validity of the method that, in the database, there was representation from all areas, rather than just those that looked, on the face of it, to be the biggest. Thus, Australia was divided into seventeen sub-zones. These consisted of groups of generally two to five Bureau rainfall districts. This subdivision is presented in Figure 2. For every one of the seventeen new sub-zones, a list of storms occurring at this location and ranked according to the rarity of the event was formed. Based on this list, a selection of the highest ranked storms on zone-by-zone basis was then identified for the next stage of the selection process.

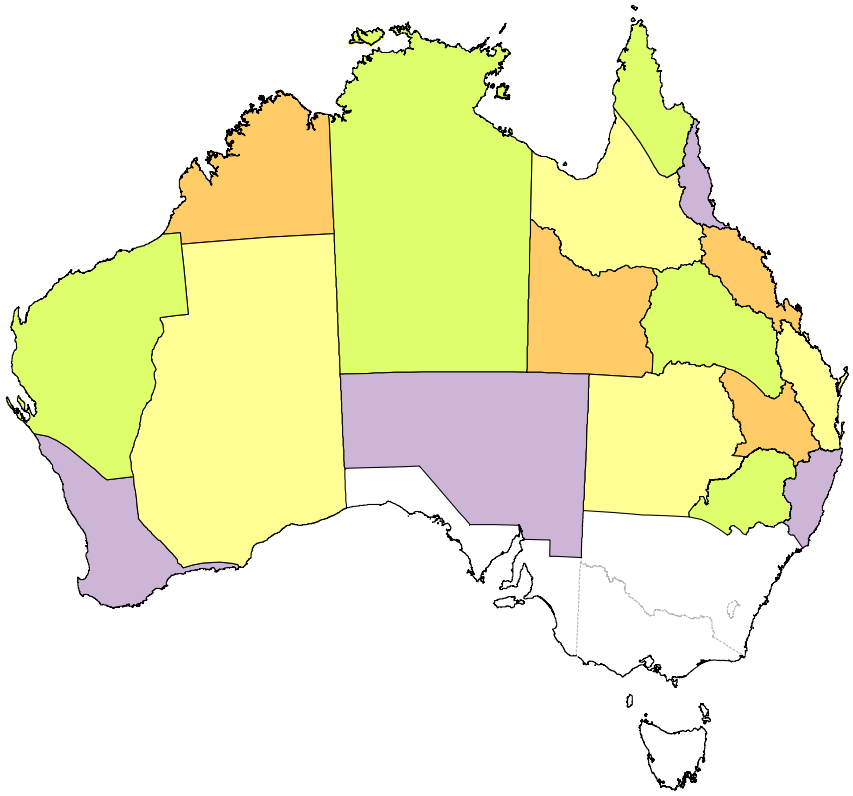

Figure 2: The distribution of the seventeen sub-zones (coloured) used in the storm search. No storm search was conducted for the region in white.

2.1.2 Visual Inspection of Candidate Storms

Despite the automated comparisons and filtering, a great deal of data remained, albeit in a form ranked by rarity. This amount of data was still far too much for detailed analysis and therefore to construct the storm database, further refinement was required. However, the opportunity to remove storms in an automated fashion was past. In order to confidently refine the storm database further, it was necessary to make a visual inspection of the storm rainfall depths. This was done for the highest ranked storms in the lists for each sub-zone. All storms that could potentially have been important based on the rankings were assessed and consequently, in the order of five to ten times the number of storms required for the

final list were examined. This conservative approach enabled higher confidence in the final storm database.

The analysis process was aided by the use of a Geographical Information System (GIS) that enabled the spatial structure and storm magnitude to be visualised easily. On the basis of these examinations, a final set of 122 storms was chosen (see Appendix 1 for details). These storms spanned the range of daily durations from 24 hours through to 168 hours and different spatial extents right through to 150,000 km^2. It was also a requirement that the top storms from each of the 17 geographic basins were chosen, ensuring that the database contained data representative of the whole region. Lastly, it was necessary that data from winter in the southwest of Australia was also included, as this is an important season in terms of flooding for the region. The location of the resultant storms is presented in Figure 3 (note that some storms are co-located or were analysed at multiple durations, so less than 122 storm locations are shown in this figure).

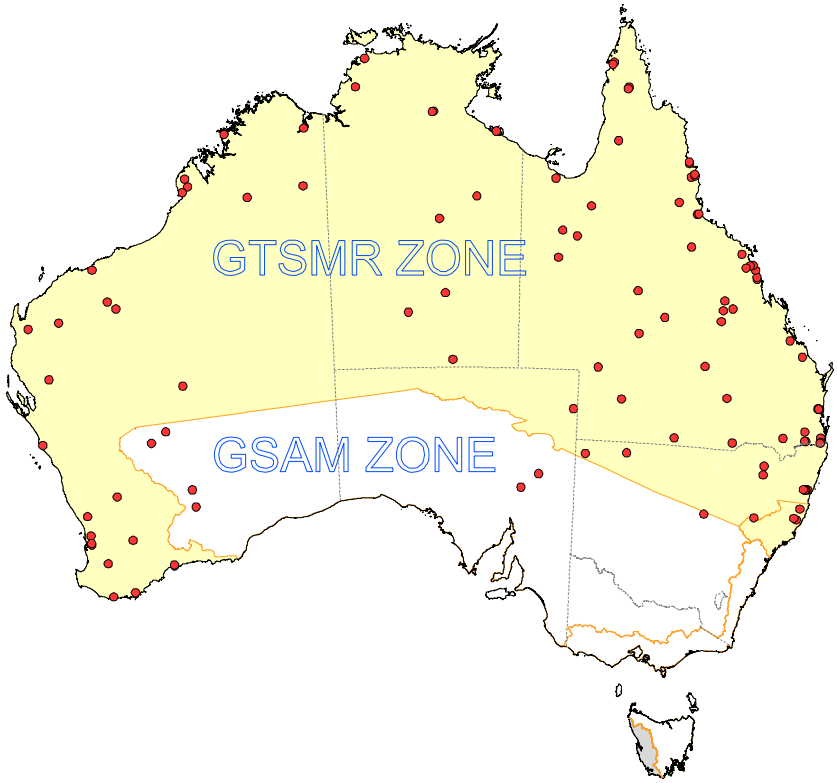

Figure 3: The distribution of storms in the final GTSMR storm database

2.2 DATA QUALITY CONTROL

At this stage of the work, a catalogue of storms had been identified. However, the basis for this identification was rainfall data that had only had a moderate level of quality control. Because the purpose of the study was to identify outliers, an unfortunate side effect is that erroneous data also tends to be picked out. This may include data that have been recorded on the wrong date, accumulated over more than 24 hours, or simply entered incorrectly. In order for the data to be used confidently in the later analysis, it is crucial that corrections be made to the data where possible.

The data quality control involved a rigorous manual search through all the rainfall observations, identifying any outlier information. Once earmarked, the data were checked

against neighbouring stations for consistency. If supported, the data were retained. However, if they were completely contradicted by the neighbouring stations, and no further evidence for their validity could be found, the data were removed from the record. Usually, it was clear where the error originated and thus it was a relatively simple decision on how to fix it. In particular, accumulated observations were often found, particularly for observations at 9am on a Monday. This total would erroneously incorporate the Saturday and Sunday rainfalls. These accumulations may or may not have been flagged in the observations. Often zeroes were recorded for Saturday and Sunday and no flag was set in the Monday record; only its large magnitude relative to neighbouring observations indicating an accumulation. In this instance, the data were disaggregated by comparison with the stations nearby. This quality control was a time-consuming, but essential, component of the construction of the storm database.

2.3 STORM ANALYSIS AND GRIDDING

The resultant, checked rainfall record for each of the 122 storms could now be analysed to prepare the storm rainfall isohyets. The quality-controlled data were imported into a GIS where they were projected onto a Transverse Mercator projection and plotted out at a suitable scale to be overlaid on a topographic map; typically 1:800,000. The storm was then analysed manually by a trained analyst. Observations were the primary source of data for the analysis, but in areas of limited data, use was made of the topography and knowledge of the prevailing flow direction to infer additional information.

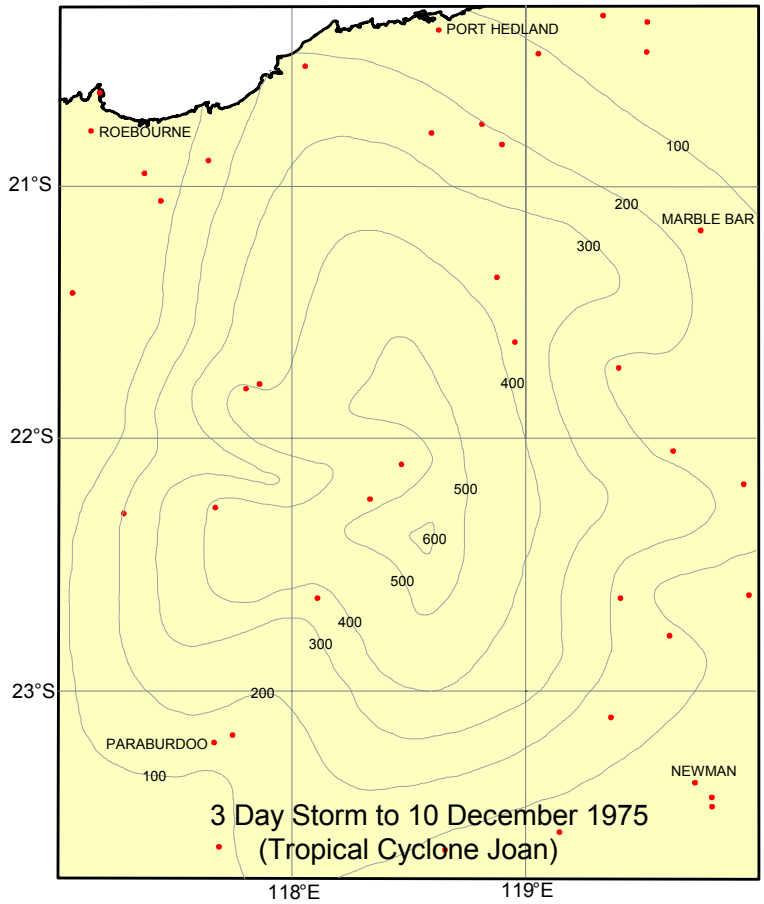

Figure 4: An example of a storm isohyetal analysis (rainfall totals in millimetres)

Once an analysis was complete, the contours of the storm were digitised on a large digitising pad. The strings of latitude and longitude values representing lines of isohyets could then be interpolated to a regular grid using a spline function following the method of Canterford, Hutchinson and Turner (1985). Values over the ocean were masked out and the resultant grid contoured and compared with the original analysis to ensure an acceptable reproduction. If not acceptable, additional contours were added and digitised to constrain the objective analysis further. An example storm with isohyetal contours is presented in Figure 4 to help clarify the process.

2.4 DEPTH-DURATION-AREA ANALYSIS

A convenient way of presenting a storm is in terms of its maximum analysed rainfall depths over standard sized areas and standard durations; a depth-area curve. The method used follows that of the GSAM and differs from the standard method (WMO 1969) in that multi-centred storms are treated as if they were single centred. Minty et al. (1996) report that test comparisons of the two methods found minimal differences in the calculated depth-area relationships when making this assumption. The depth-area curve of each gridded storm is determined by counting the number of grid-points between evenly spaced isohyets, from the maximum to the minimum isohyet; calculating the arithmetic mean rainfall per interval and determining a running average rainfall depth and cumulative area over all intervals. The area calculations can then be based on the number of grid-points counted and the known resolution of the grid. An example depth-area curve is presented in Figure 5.

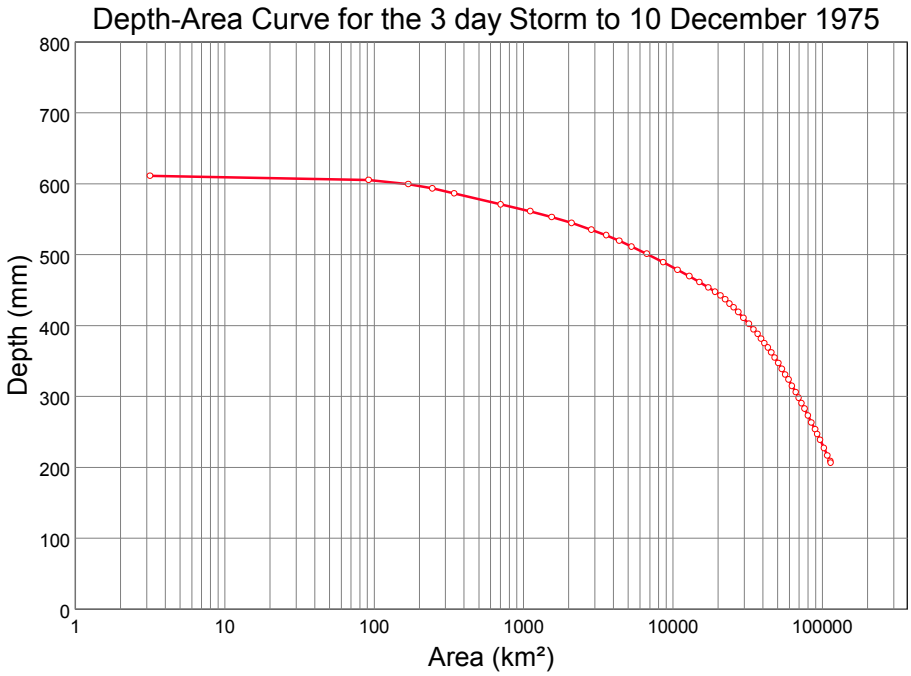

Figure 5: An example of a depth-area curve defining a single storm

2.5 RESTRICTED AND UNRESTRICTED DATA

While much of the Bureau of Meteorology's rainfall database consists of daily totals representing the rainfall between 9:00 am and 9:00 am, this restriction has no physical bearing on real rainfall event duration, which often spans a 9:00 am boundary. Nonetheless, the searching of the Bureau records for the storm database was based on this

'restricted' dataset. However, more information can be gained about the storms in the database by making use of any data available at a higher temporal resolution. Using the 3-hourly rainfall data, the 'unrestricted' rainfall totals at the set durations can be inferred. Unrestricted rainfall totals for 6-, 12-, 24-, 36-hours and the standard longer durations were constructed.

Pluviograph data collected by the Bureau of Meteorology and other authorities were the primary source of higher resolution temporal data, along with records from the Synoptic Station network. Individual storm studies also provided temporal information that often incorporated details from sources such as farmers and lighthouse keepers. As with the storm analyses, the data used to construct the temporal distributions were checked for temporal and spatial consistency. Such temporal data was not available for all storms. The additional information was incorporated for approximately 70% of the storms in the database.

The temporal distributions were constructed at a number of standard polygon areas surrounding the storm centre. The areas used were the same as for GSAM with the addition of 2 larger areas: 100, 500, 1000, 2500, 5000, 10000, 20000, 40000, 60000, 100000 and 150000 km^2. Analogous with GSAM (Minty et al 1996), no storm temporal patterns were constructed for areas smaller than 100 km^2 since these would usually have to be based on a single station and are unlikely to be representative of the true storm peak. Figure 6 shows an example storm; the polygons of approximately standard areas are positioned around the centre of the storm so as to enclose the area of highest rainfall totals.

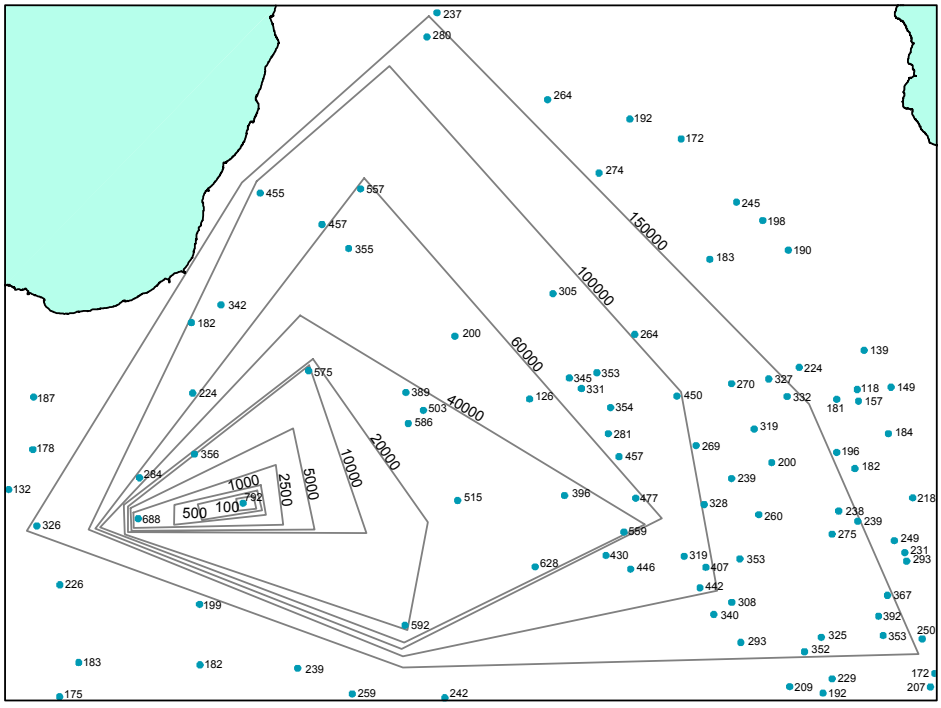

Figure 6: An example of the standard area polygons as applied to the 6-day storm to 23 January 1974.

The daily rainfall observations within each polygon were averaged using an areal weighting technique (Thiessen, 1911). This produced a series of percentages of total storm depth that occurred on each day, for each polygon area. This was then compared with the 3-hourly distribution data from any pluviograph or other data in the vicinity of the

polygon. These 3-hourly data were manually weighted for both their consistency with the daily distributions and the relevance of their location to the polygon. The weighted 3-hourly distribution was then imposed upon the daily polygon-averaged rainfall totals to give 3 hourly rainfall totals for each polygon area. These can then be interpolated to standard areas.

The final step in the construction of the storm temporal distributions was to determine the maximum percentages of total storm depth that fall within the standard durations of 6-, 12-, 24-, 36-, 48-, 72-, 96-, 120-, and 144-hours, that is, the maximum 6 hour burst (percentage), the maximum 12 hour burst and so on. Durations of 168 hours were also analysed although it was usually the case that 100% of the 7-day total had fallen within 5 or 6 days. These maximum bursts were then used for the depth-area curves at standard durations and areas. A detailed description of this technique can be found in (Minty and Meighen, 1999 pages 9-10).

3. GENERALISING THE GTSMR STORM DATABASE

The primary aim of assembling the storms database was to identify rare storm events. By searching over such a large zone as that for GTSMR (see Figure 1), the probability of identifying a very rare event improves. However, not all storms from this large region are directly comparable. There are features specific to a location that will influence the depth of rain that could be expected. These include:

1. Spatial distribution of rainfall
2. Storm type
3. Topographic enhancement of rainfall
4. Local moisture availability
5. Geographic variation in decay of storm mechanism

This section deals with the removal of these site-specific components from the storms in the GTSMR database.

3.1 SPATIAL DISTRIBUTION OF RAINFALL

It is plausible that most locations will have a preferential distribution of rainfall, given a storm mechanism, which influences the size, shape and orientation of isohyets. These are related to various factors including topography, and the preferential direction of flow and therefore moisture inflow. Some catchments will exhibit a stronger preference than others will. However, for the purpose of generalising the storm events so that they can be transposed to another location, this information is no longer relevant. Thus, for each storm, a set of depth-duration-area curves are constructed. This reduces the site-specific spatial distribution of rainfall to a magnitude that can be easily compared with other storms.

3.2 STORM TYPE

For the GTSMR region, there are different types of storm mechanisms that produce significant rainfall events. In order to determine the causative mechanism, for each storm, the surface mean sea level pressure analyses (synoptic charts drawn daily) as well as the upper air charts (if available) were obtained and examined. The meteorological features that gave rise to each event were identified and the storms were broadly classified into four groups:

1) Tropical cyclones
2) Ex-tropical cyclones
3) Monsoon activity
4) Extratropical systems

Events classified as *tropical cyclones* were those that were caused by the proximate passage of a tropical cyclone. An example is shown in Figures 7(a) and (b) which depict severe tropical cyclone ‘Thelma’ that gave rise to heavy rainfall near Darwin in December 1998.

When tropical cyclones drift over the land, their intensity diminishes as they lose the moisture supply from the warm ocean that sustains them. However, there may still be

enough remnant convection in the system to cause heavy rainfall. Such systems are classified as *ex-tropical cyclones*. Figures 8(a) and (b) depict such an event that occurred in January 1990 and resulted in heavy rainfall in southwest Western Australia.

Another common type of system, which brings heavy rainfall in the Australian tropics, is *monsoon activity*, which refers to enhanced convection associated with a monsoon depression over northern Australia. There is as yet no rigorous definition of monsoon depressions in the Australian region, however, the term 'monsoon depression' in the Australian region generally refers to a warm-cored low pressure system situated over the land (Zhao and Mills (1991) and Davidson and Holland (1987)). An example of such an event appears in Figures 9(a) and (b) for January 1991. For the purpose of this project, events classified as arising from monsoon activity also include rainfall events resulting from monsoon depressions, which were undergoing the transition to cold-cored low pressure systems owing to interactions with subtropical systems, and which may not strictly have been warm cored.

The fourth category into which the storms in the database could be classified, is *extratropical systems* which includes cold-cored events of non-tropical origin, such as extratropical cyclones, troughs and frontal systems. Most of the events in this category occurred in the cooler months of the year. Figures 10(a) and (b) show a snapshot of such an event in May 1996 for the area near the Gold Coast that caused heavy rainfall from an east coast low near the surface and a cold upper trough and a strong jet stream in the upper levels. Another example of an extratropical system is shown in Figure 11, which depicts an extratropical cyclone with a frontal system over southwest Western Australia.

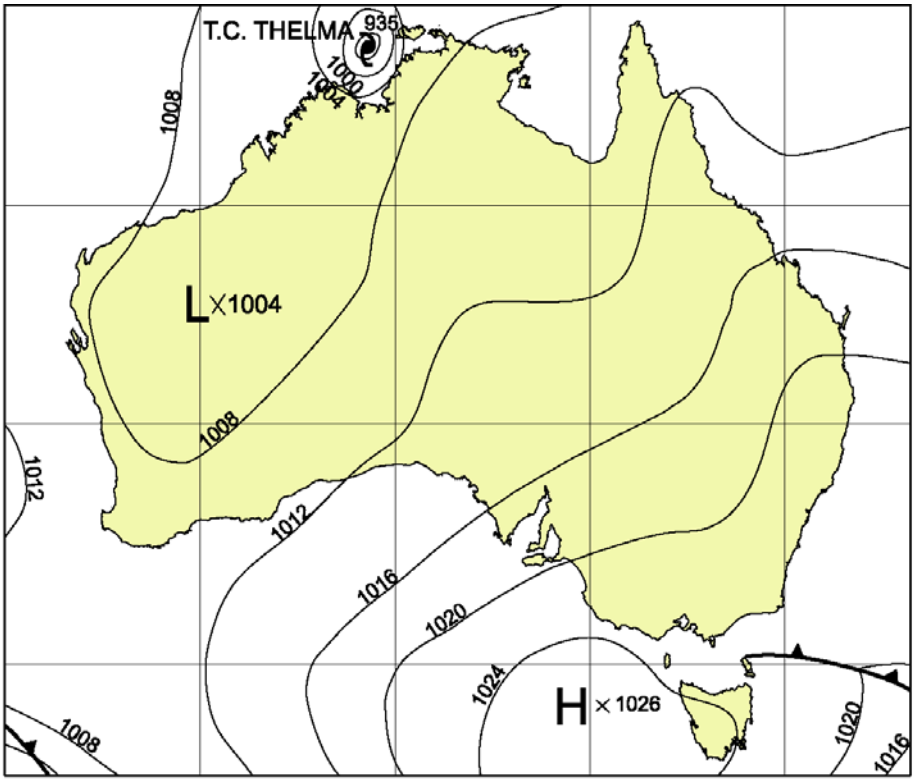

Figure 7(a): Tropical cyclone. 2-day storm ending 10 December 1998 (chart for 9 December 1998 0000 UTC).

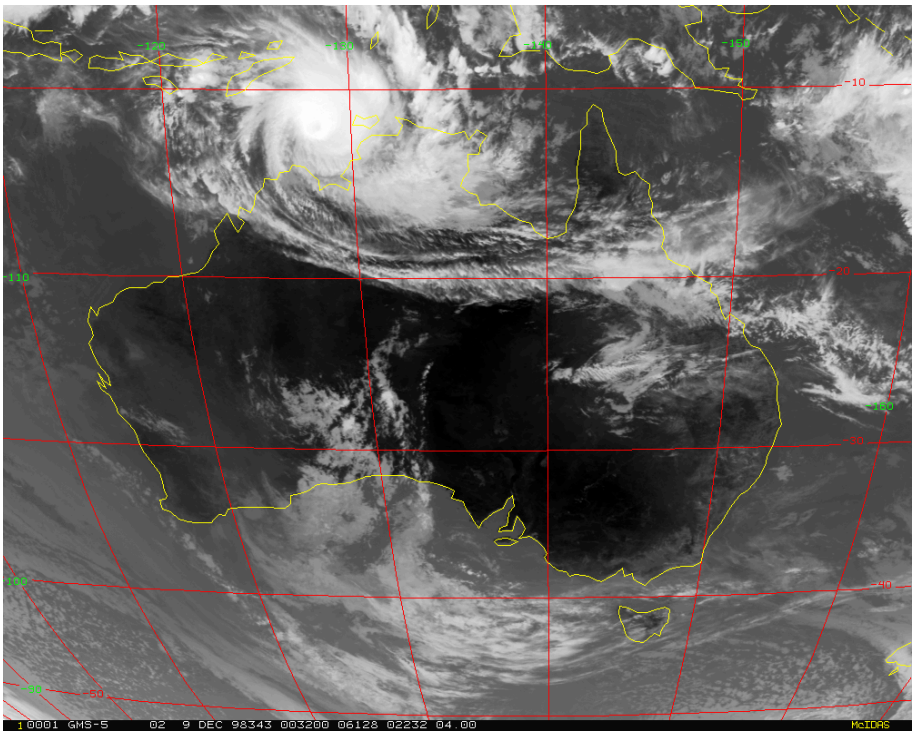

Figure 7(b): Tropical cyclone. 2-day storm ending 10 December 1998 (satellite image for 9 December 1998 0030 UTC).

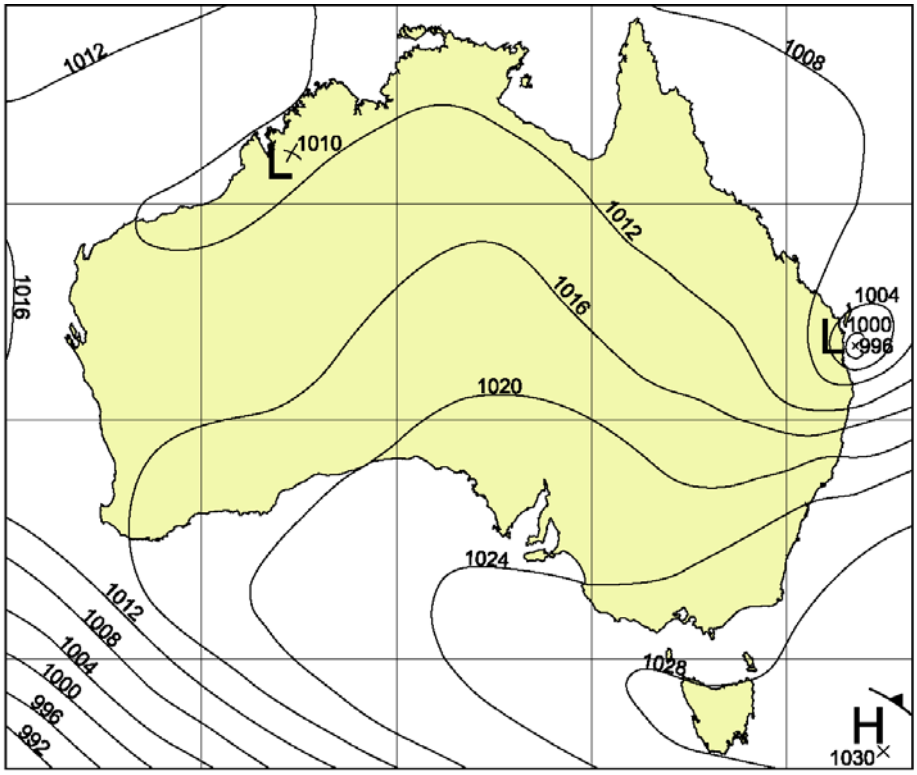

Figure 8(a): Ex-tropical cyclone. 2-day storm ending 29 January 1990 (chart for 28 January 1990 1200 UTC).

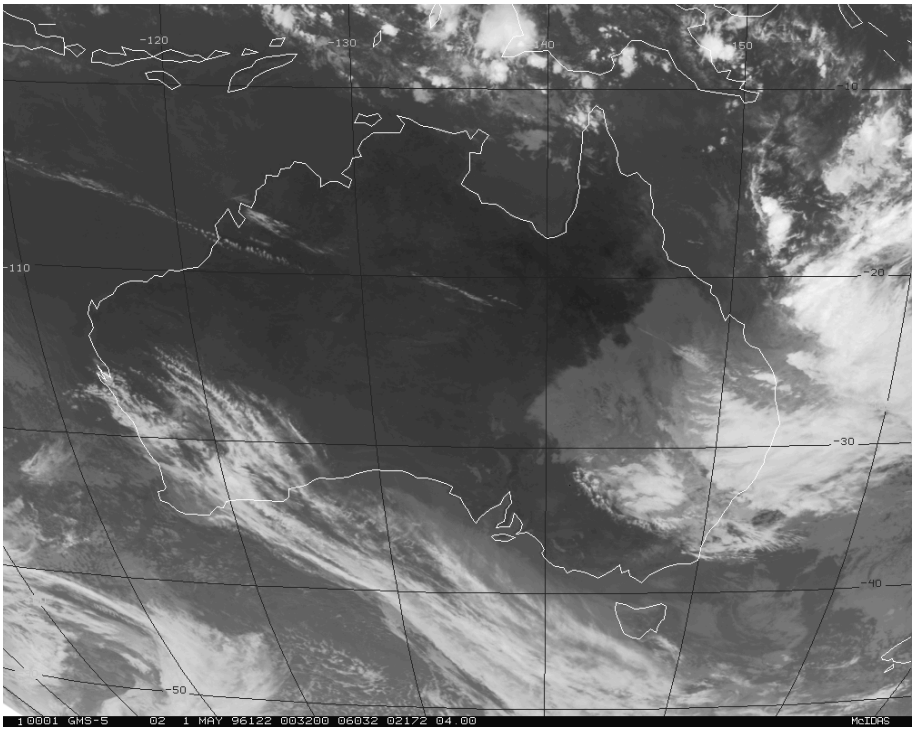

Figure 8(b): Ex-tropical cyclone. 2-day storm ending 29 January 1990 (satellite image for 28 January 1990 1130 UTC).

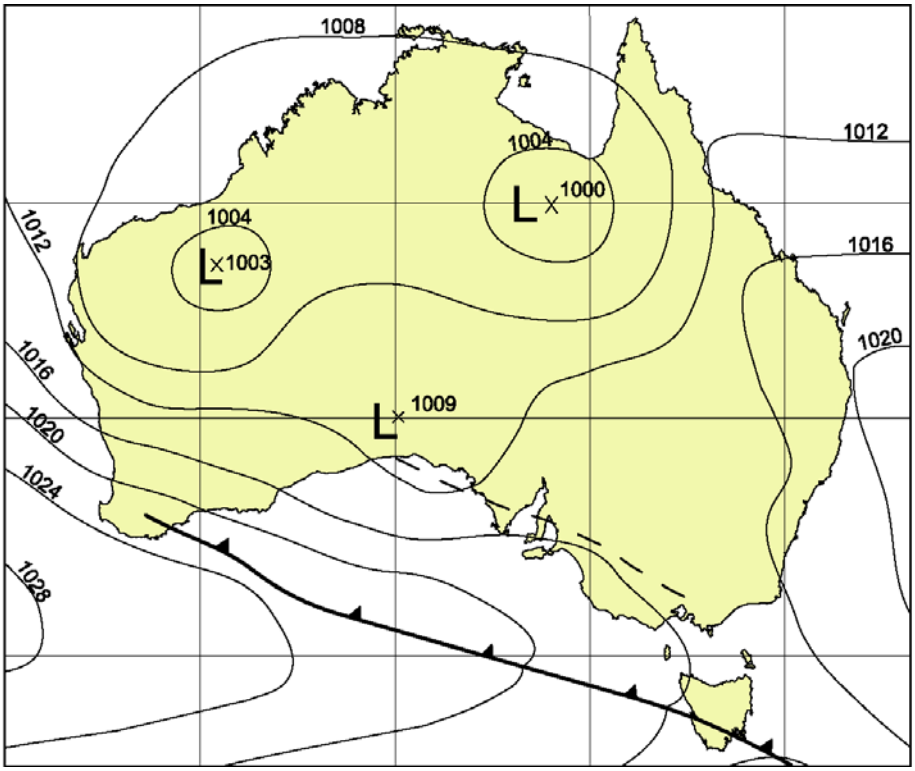

Figure 9(a): Monsoon activity. 1-day storm ending 14 January 1991 (chart for 14 January 1991 0000 UTC).

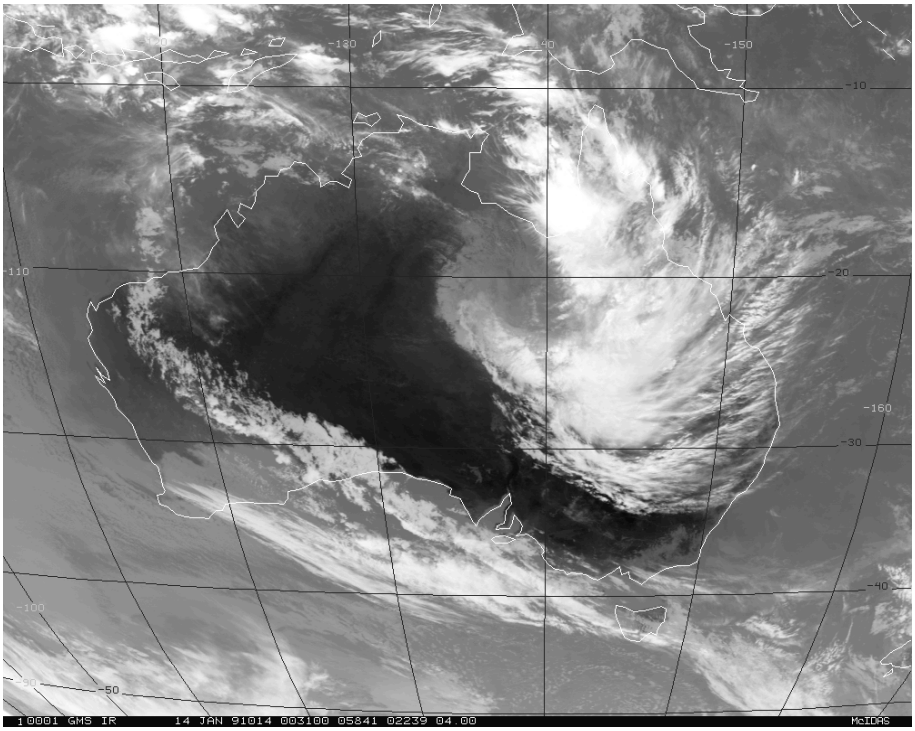

Figure 9(b): Monsoon activity. 1-day storm ending 14 January 1991 (satellite image for 14 January 1991 0030 UTC).

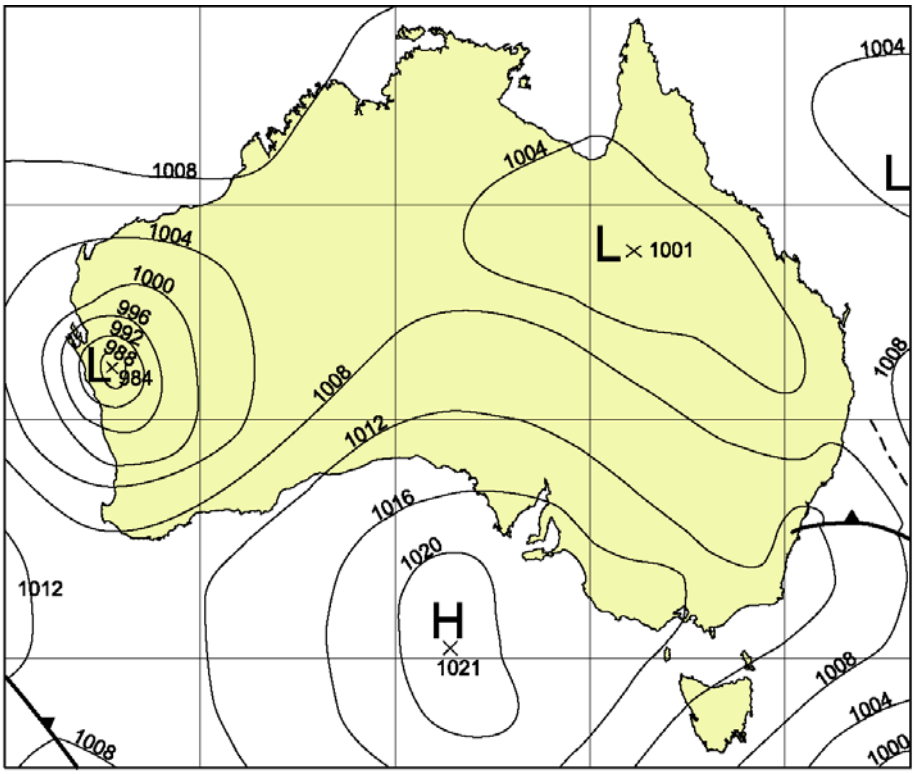

Figure 10(a): Extratropical cyclone. 6-day storm ending 6 May 1996 (chart for 2 May 1996 1200 UTC).

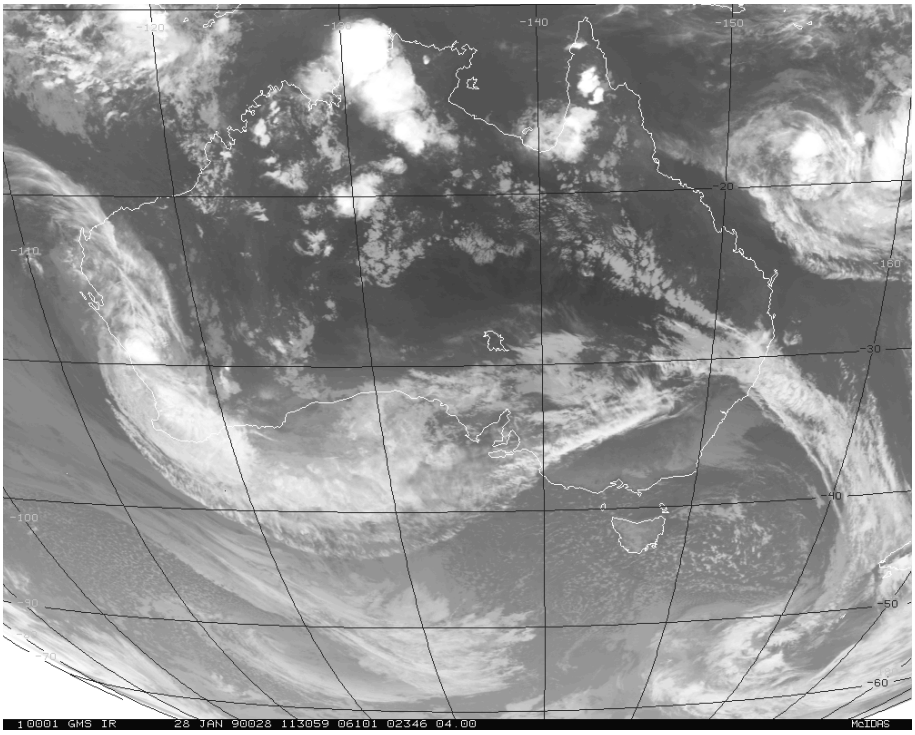

Figure 10(b): Extratropical cyclone. 6-day storm ending 6 May 1996 (satellite image for 1 May 1996 0030 UTC)

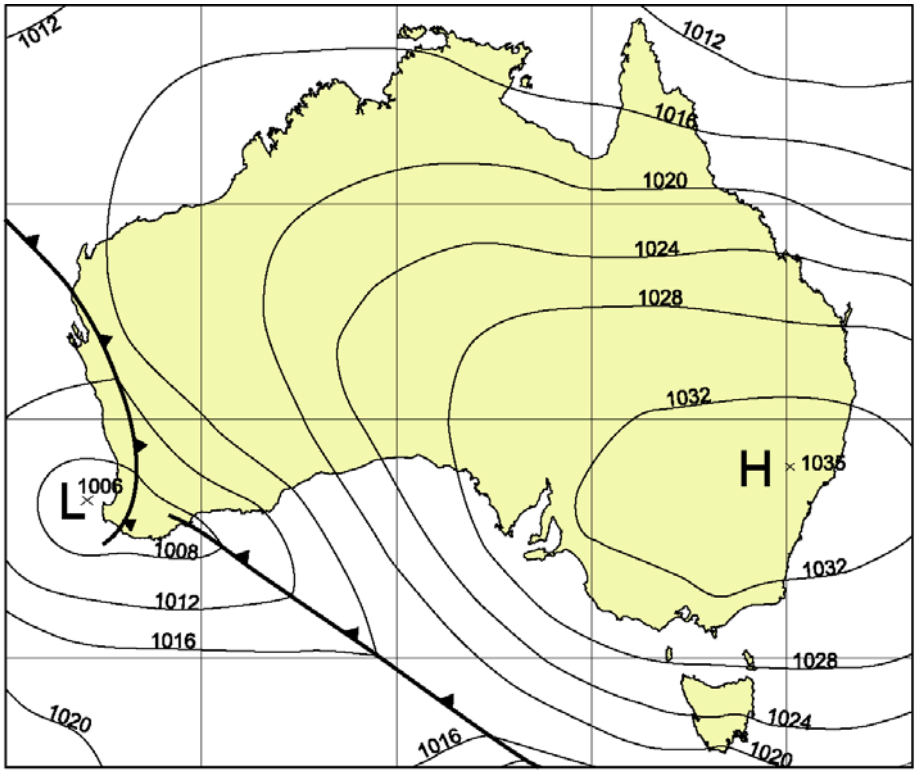

Figure 11: Front over southwest Western Australia. 4-day storm ending 27 June 1988 (chart for 25 June 1988 0000 UTC)

Each of these types of storms can be limited to certain areas and to certain times of the year. Thus, it is possible to create zones showing the limits of where different storm mechanisms are relevant and may be transposed. Accordingly, the GTSMR zone has been divided up into sub-zones to represent the particular type of storm mechanism that would be important. The sub-zones are presented in Figure 12.

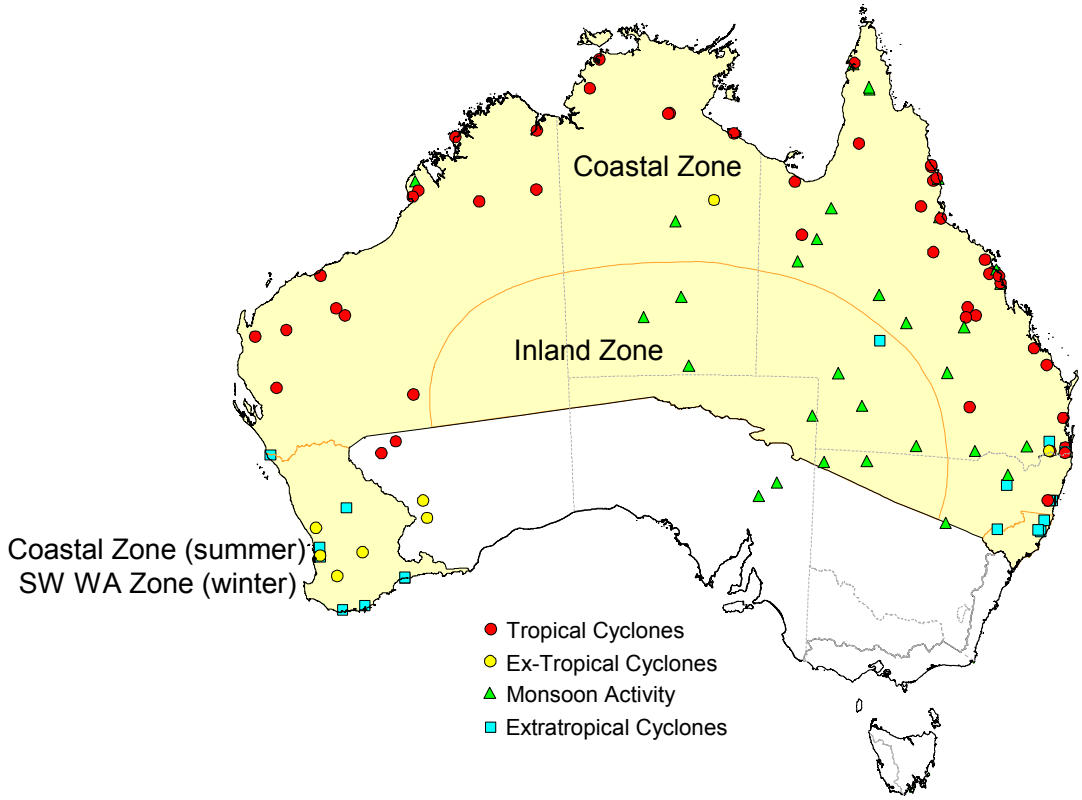

Figure 12: New zones for the GTSMR: Coastal zone, Inland zone and Southwest Western Australia zone.

In the coastal zone, any of the four mechanisms could be the principal influence. However, for the inland zone, only monsoonal lows would be expected to produce extreme rainfall. While the coastal zone gets storms in the 'summer' and 'winter' seasons, the only significant storms for the inland zone are monsoonal lows in summer. An added complication is the southwest Western Australian zone, which indicates an area within the coastal zone relevant only in winter where a different type of storm mechanism (frontal systems as shown in Figure 11) generates the largest rainfall event. It should be noted that this type of event is not really a tropical storm but the zone is included because this area of Western Australia has a significant flood risk in the winter season.

3.3 TOPOGRAPHIC ENHANCEMENT OF RAINFALL

Precipitation results from the convergence and vertical motion of moist air and these motions can be instigated from synoptic-scale atmospheric disturbances, for instance non-geostrophic flow and frontal lifting, or large-scale instability in an airmass (WMO, 1973). These motions can also be brought about or enhanced by topographic influences and this will often lead to an increase in the rainfall. The technique that is used for estimating this topographic element is taken directly from the procedure in the GSAM (Minty et al. 1996). This technique is loosely based 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).

If the topographic element of the rainfall can be estimated, then it can be removed from the total rainfall leaving just the convergence or synoptic component. The methodology of GSAM proposes that rainfall frequency analyses can be used as a measure of the topographic influences operating in an area based on WMO 1986, (p54). *'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'.

Suitable rainfall frequency analyses have already been constructed for the Australian region in Australian Rainfall and Runoff (ARR87) (IEAust, 1987) and are presented in the form of maps of Intensity, Frequency and Duration isopleths. A gridded version of these maps is held by the Bureau of Meteorology. An example of the type of data available is depicted by the solid lines in Figure 13. The spatial variability of rainfall intensity over the area indicates the average variation in topographic influence on rainfall for relatively rare (50 year average recurrence interval), medium duration (72 hour) rainfall events. If a topographic map was overlayed over the intensity plot, in areas of negligible topography, the intensity is that which would represent the convergence component of the rainfall. The rainfall intensities over elevated terrain presumably represent the combined effect of the underlying meteorology (convergence precipitation) and the topographic enhancement. Thus, the ratio of values from areas of significant topography and regions of negligible topography in the same general vicinity would give a rough estimate of the average enhancement of rainfall due to the presence of topography.

In GSAM the following relationship is used:

$$\frac{Total\ Rainfall\ Intensity}{Convergence\ Rainfall\ Intensity} \approx \frac{Total\ Storm\ Depth}{Convergence\ Storm\ Depth} \tag{1}$$

Assuming an exact relationship:

$$Convergence\ Storm\ Depth = Total\ \ Storm\ Depth \times \frac{Convergence\ Rainfall\ \ Intensity}{Total\ \ Rainfall\ \ Intensity} \tag{2}$$

and

$$Topographic\ Storm\ Depth = Total\ Storm\ Depth - Convergence\ Storm\ Depth \tag{3}$$

Minty et al (1996) discuss that while the concept of convergence and topographic precipitation has been used widely, their definition is strictly method-dependant and the GSAM (and therefore GTSMR) definitions differ from those used by others (US Weather Bureau, 1966; US National Weather Service, 1977; US National Weather Service, 1984), and Wang (1986).

In order to obtain the storm convergence depth, which is that part of the storm rainfall due to the underlying meteorology, the total storm depth plus the total and convergence rainfall intensities are required. The total rainfall intensity is well defined in ARR87 as discussed above. The total storm depth is derived from the rainfall observations for individual storms. This leaves the convergence rainfall intensity, which, as described above, is the intensity of the convergence component of the rainfall and is equal to the total intensity in areas of negligible topography. Following the method of GSAM, the convergence component of the 72 hour, 50-year rainfall intensities over the whole GTSMR region was constructed. This was achieved by identifying those areas in the region where rainfall is

unaffected by topography and manually interpolating between these regions to produce the 'flat-land' IFD. Effectively, this represented the intensities for the 72-hour 50-year storm if Australia was flat, or topographic influences on rainfall were zero.

It was decided that the 72-hour 50-year intensities could be used to estimate the topographic enhancement factor for all storms, primarily by the example set from GSAM. Minty et al (1996) reasoned that the 72-hour 50-year rainfall intensities were the most accurate of the six basic rainfall frequency analyses developed for ARR87 (IEAust, 1987). The 72-hour duration represents approximately the middle duration range required for GTSMR and GSAM and an ARI of 50 years is approximately the mean range of ARIs for storms in the database.

Construction of the convergence intensity map was relatively simple over the inland region, however much greater judgement was required over the relatively orographic coast (particularly the east coast of Australia). To demonstrate the differences in structure, Figure 13 presents the total and convergence IFD for a region around Townsville on the Queensland coast.

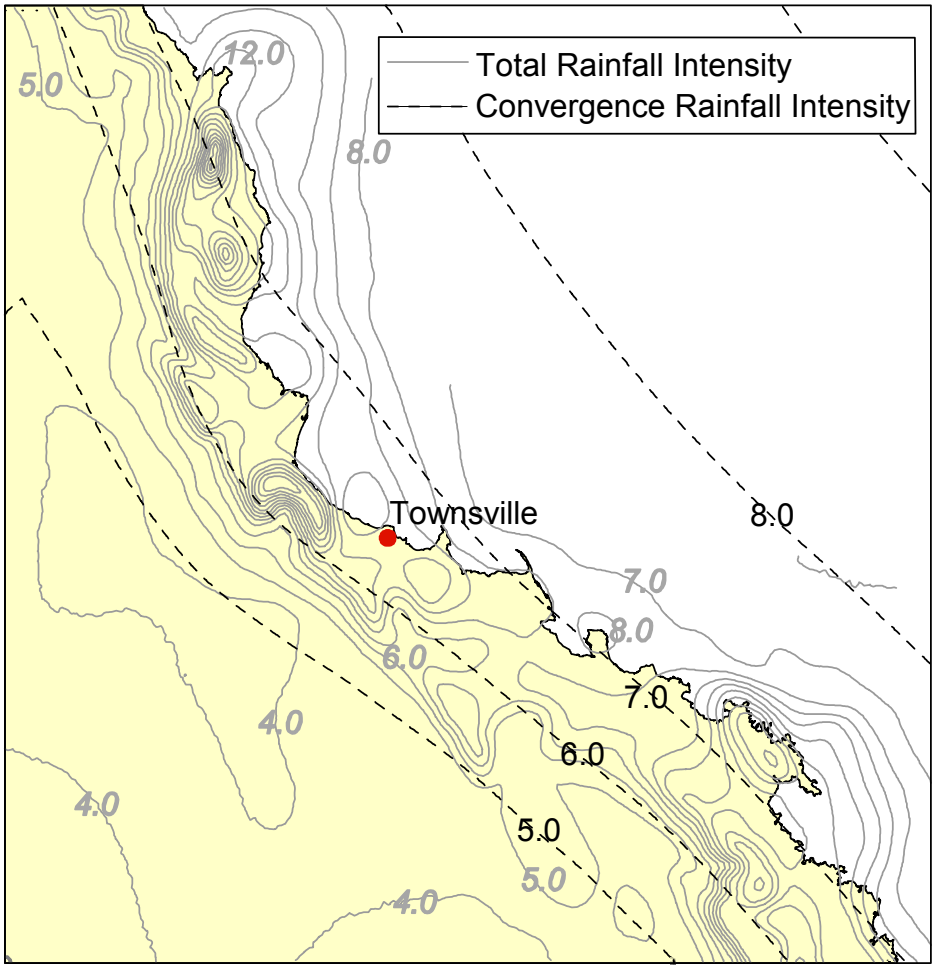

Figure 13: The geographic variation in expected rainfall intensity for a 72-hour duration storm with ARI of 1 in 50 years (solid line) and estimated intensity of the same assuming flat topography (dashed line).

The flat-land intensity data for Australia were also digitised and gridded to the specifications of the ARR87 intensities. A grid of the ratio of intensities as per Equation 2

above can then be simply constructed and this ratio can be multiplied by the spatial map of storm depth on a point-by-point basis to produce a spatial map of convergence rainfall depth. This rainfall depth represents the component of the total storm rainfall due to the underlying meteorology and excludes that component of the total storm rainfall that was due to topographic enhancement.

The technique was tested for applicability using two regions; the southern Queensland coast and an area near Perth. This test, described in Appendix 2, indicated relatively clearly that the method discussed above was successful in separating the topographic and convergence components of a storm.

3.4 LOCAL MOISTURE AVAILABILITY

While topography is one of the critical elements that vary with location, it is not the only one. Local moisture availability will also vary with location and impact heavily on the potential rain that a storm mechanism can produce. The technique applied in GSAM and prescribed in WMO (1986) is moisture maximisation for the storms in the database.

3.4.1 Moisture Maximisation

Moisture maximisation is 'the process of adjusting observed precipitation amounts upward based upon the hypothesis of increased moisture inflow to the storm' (WMO, 1986). The maximised storm rainfall is the rainfall that would have occurred if maximum moisture inflow for a particular location at a particular time of year had been available to the storm.

The technique of moisture maximisation requires knowledge of two quantities: the maximum or extreme moisture that could possibly occur at a particular location and time of year, and the moisture content that was actually available to the observed storm. An indicator of moisture is the dewpoint temperature, which is derived from surface synoptic (climate station) observations and radiosonde observations.

Extreme persisting dewpoint temperatures are obtained using long-term climatological data. The method for estimating extreme persisting dewpoint temperatures involves plotting and enveloping the maximum 24-hour persisting dewpoint temperatures for each month of the year for each suitable site as outlined in WMO (1986), Section 2.2.5. Extreme persisting dewpoint temperatures for Australia been updated and the revised values have been in use since 2001. As an example, the annual maximum, extreme persisting dewpoint temperatures from this new analysis are presented in Figure 14.

The technique of moisture maximisation involves representing the moisture content available to the observed storm by the storm dewpoint temperature, which is most accurately determined using temperature and humidity soundings from radiosonde observations. Unfortunately, these are usually not available for notable storms due to the sparseness of the radiosonde observational network. However, in extreme storms, the atmosphere is usually saturated throughout a considerable depth and therefore estimates of storm dewpoint temperatures can be derived from surface synoptic observations, which are available at three-hourly intervals for recent storms. In general, the availability of dewpoint temperature was very good.

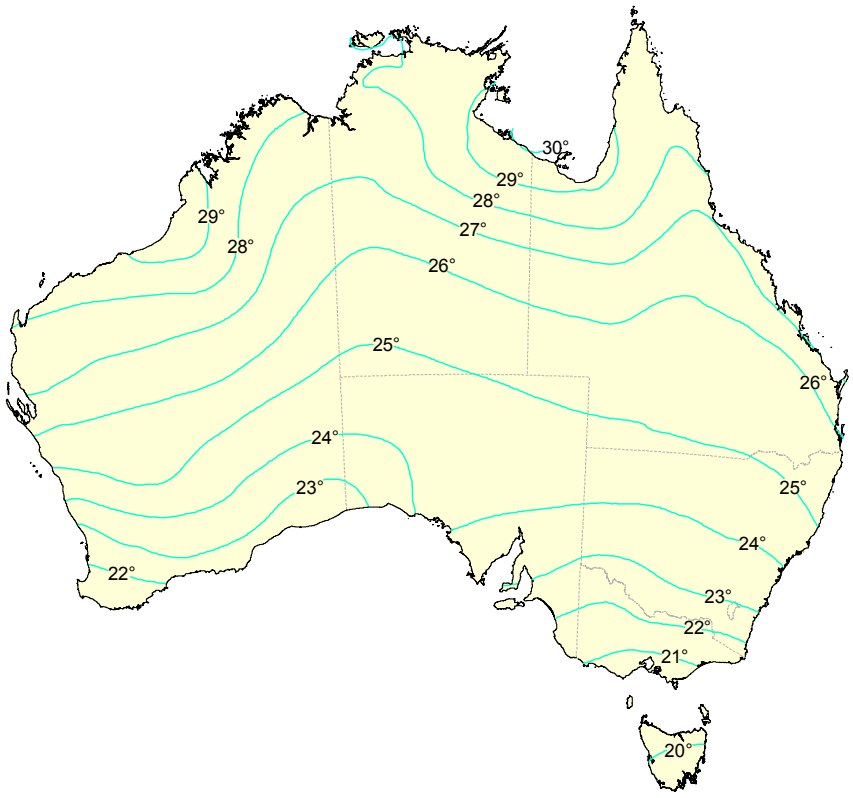

Figure 14: Annual maxima of monthly extreme 24-hour persisting dewpoint over Australia.

For each storm, time series of surface dewpoint temperature, as well as other meteorological data, were prepared using several sites near the main storm area. The data were extracted from the Australian Region Mean Sea Level charts, observers logbooks obtained from National Archives of Australia, and the Bureau of Meteorology National Climate Centre database. The dewpoint temperatures of suitable sites along the inflow path, recording high dewpoints over a period of 6 to 24 hours prior to the storm, were reduced pseudo-adiabatically to 1000 hPa values (United States Weather Bureau, 1951), if station elevations exceeded 100 metres, and averaged. Care was taken to ensure that the surface dewpoints were not contaminated by rain, otherwise estimates of storm dewpoints could be too high due to local evaporation.

The estimation of a dewpoint temperature to represent the moisture inflow into the storm from a number of surface observations, which are varying over time, involves a great deal of judgement. Various factors need to be assessed such as the influences of local topography on dewpoint temperature observations, the quality of the observations, whether any have been rain-contaminated, the onset of rainfall, the inflow path, and the representativeness of the surface dewpoint temperatures of the layer in which the rainfall is forming. Radiosonde data were used whenever they were available and were assessed along with surface observations. Minty et al. (1996) (page 10), while discussing storm dewpoint estimation for the Generalised Southeast Australia Method (GSAM), state that despite taking all due care, no more accuracy than about 2^{o} C could be achieved.

Storm and extreme persisting dewpoint temperatures can be related to precipitable water values with the use of look-up tables (e.g. WMO, 1986). The moisture maximisation factor is defined as the ratio of the extreme precipitable water corresponding to the extreme

dewpoint temperature, to the storm precipitable water corresponding to the storm dewpoint temperature. Thus,

$$MF = \frac{EPW}{SPW} \tag{4}$$

where MF is the moisture maximisation factor,
EPW is the Extreme Precipitable Water corresponding to the extreme dewpoint temperature, and
SPW is the Storm Precipitable Water corresponding to the storm dewpoint temperature.

The highest extreme dewpoint temperature for the same location as the storm dewpoint temperature, within +/- 28 days of the date of the storm commencement was chosen. Storm convergence precipitation was maximised by multiplying by the maximisation factors.

If a storm was analysed at more than one duration, the same storm dewpoint temperature was used for all durations. If storm dewpoint temperatures were to be estimated for, say, every 24-hour period, then the appropriate extreme dewpoint temperatures would also alter to reflect the different atmospheric conditions. This would result in only minor variations in maximisation factors for the sub-durations, which do not render the extra effort entailed worthwhile (WMO, 1986). Therefore, in line with general practice, the same storm dewpoint temperatures apply for all periods within the storms.

The concept of moisture maximisation assumes that the relationship between increased moisture and increased precipitation is linear at least with relatively small increases in moisture. The extent to which storm efficiency could be altered by changes in moisture is not known, however it is reasonable to assume that small changes in moisture inflow would have a minimal impact on storm efficiency while large changes in moisture inflow may well affect storm efficiency significantly. Excessively large moisture maximisation factors are therefore to be avoided as they may alter the storm dynamics. It is common practice to set a limit on the maximisation factor. In the past, this limit has ranged from 1.5 to 2.0. For the GSAM, the limit imposed was 1.8. Figure 15 depicts maximisation factors for the GTSMR storms. Only 5 storms have maximisation factors in excess of 1.8. The highest maximisation factor of 2.33 is associated with a storm that occurred in the cooler months, when the assumption of a saturated pseudo-adiabatic lapse rate is more likely to be violated than in the warmer months. The next highest maximisation of 1.96 occurred with a warm season storm, which was caused by a tropical cyclone. This maximisation factor was determined both from surface and radiosonde observations, therefore there was a certain degree of confidence in the estimate. Hence, a limit of 2.0 was chosen for the maximisation factor, which affects only one storm. For the GSAM, there were many more storms affected (Minty et al, 1996, pp, 20-21). The reason for this is that the GTSMR database contains many more tropical rainfall events where the assumption of a saturated pseudo-adiabatic lapse rate is more often satisfied.

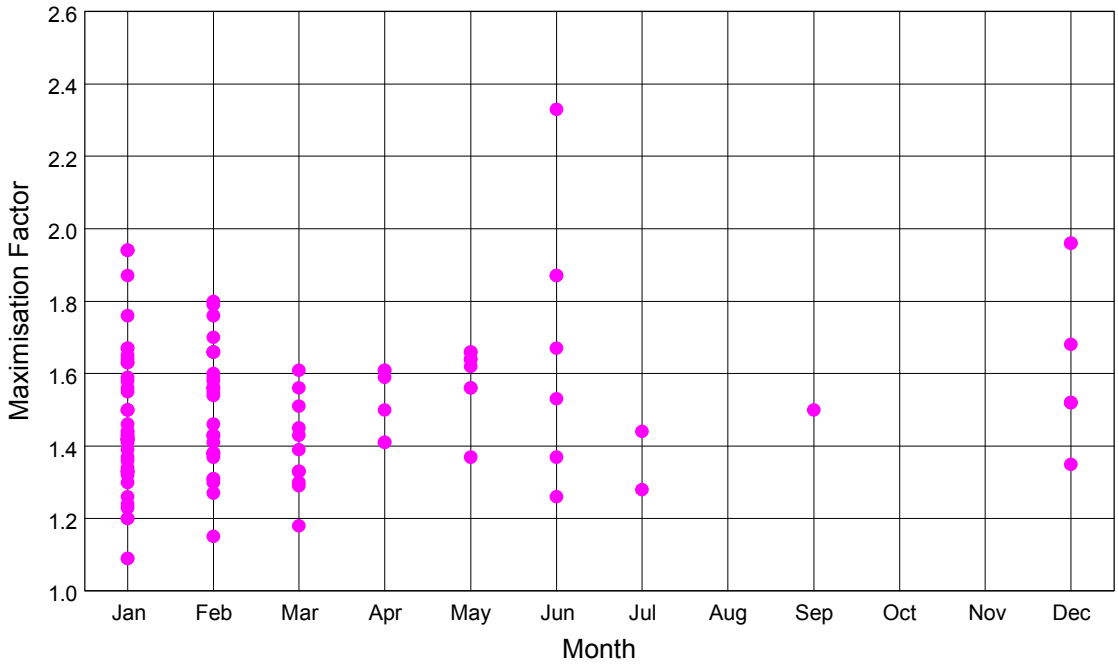

Figure 15: Maximisation factors for the GTSMR storms

3.4.2 Standardisation

The process of standardisation subjects all storms to a common moisture inflow, removing the location-specific effect of moisture inflow, by effectively transposing the storms to one location. The location chosen is not crucial. Broome Airport was chosen as the reference site, because it has a reasonably long record and it has close to the highest maximum persisting monthly dewpoints in Australia.

There are limitations on the transposability of storms with season. For example, a winter storm cannot be transposed to summer because this would alter the storm dynamics. The storms were therefore grouped into seasons. The majority of the storms were caused by tropical cyclones or monsoon activity. The May storms were all caused by extra-tropical cyclones, which are typical of winter events. All but one of the events caused by cool-season extra-tropical cyclones occurred in the months of May, June and July. Two seasons were defined: *summer season* (October – April) and *winter season* (May – September). October was assigned to the *summer season* because it would be unrealistic to transpose the late autumn/early winter storms to spring since these storms typically occur due to intensification of extra-tropical cyclones from the south as they encounter remnant warm air over the continental land mass. In early spring, the atmosphere over the continent is more stable and relatively cold, which explains why there was only one storm occurred in spring.

The maximum summer and winter season extreme persisting dewpoints for Broome were used to standardise summer and winter season storms. Table 1 shows extreme persisting dewpoints and the corresponding extreme precipitable water values for the *winter* and s*ummer* seasons. Note that the *summer* season extreme persisting dewpoint will be the annual extreme persisting dewpoint. Figure 16 depicts Broome's extreme 24-hour

persisting dewpoint temperatures for each month of the year and the standard extreme persisting dewpoint temperatures adopted for the *winter* and *summer* seasons.

Seasons	EDP_{std} (°C)	EPW_{std} (mm)
Summer (October – April)	29.6	120.0
Winter (May – September)	25.2	82.3

Table 1: Standard extreme dewpoint temperatures (EDP_{std}) and standard extreme precipitable water (EPW_{std}) for the summer and winter seasons

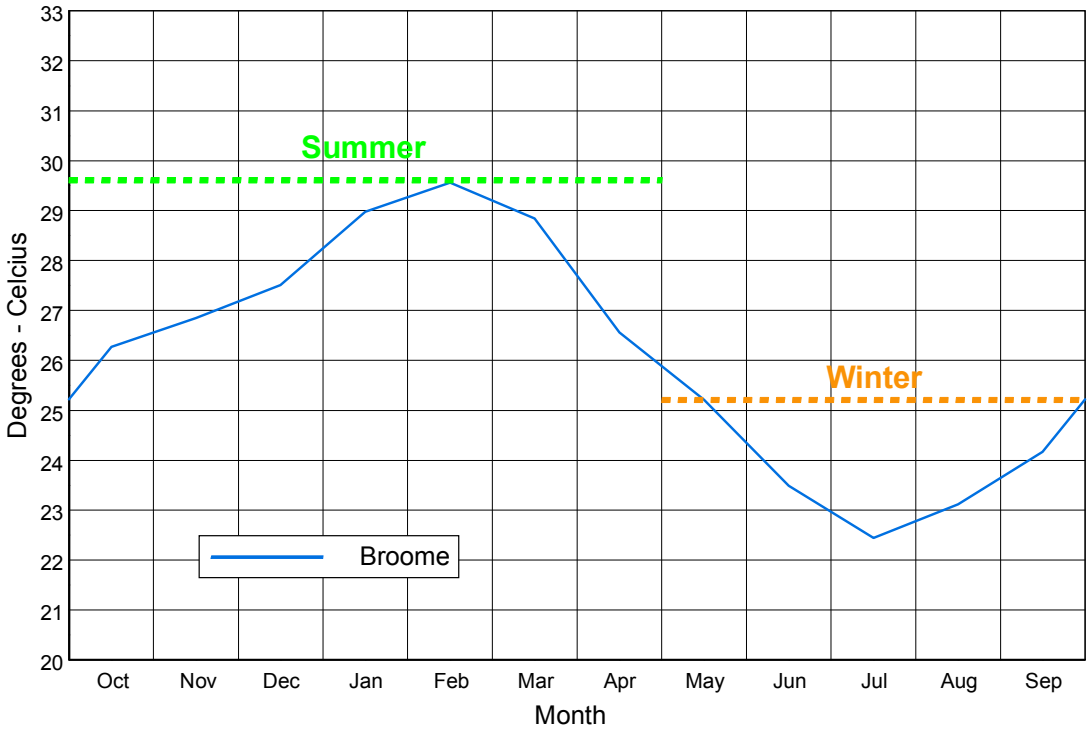

Figure 16: Extreme monthly 24-hour persisting dewpoint temperatures for Broome and the standard extreme persisting dewpoint temperatures for the GTSMR summer and winter seasons.

The standardisation factor is defined as the ratio of the extreme precipitable water corresponding with the extreme dewpoint temperature to the extreme precipitable water corresponding with the storm extreme dewpoint temperature. Thus,

$$SF = \frac{EPW_{std}}{EPW_{insitu}} \tag{5}$$

where SF is the standardisation factor
EPW_{std} is the Extreme Precipitable Water associated with the Standard Extreme Dewpoint Temperature (Broome),
and EPW_{insitu} is the Extreme Precipitable Water associated with the Storm Extreme Dewpoint Temperature.

The maximised convergence depths were multiplied by the standardisation factor, giving the maximum storm convergence depths that could hypothetically occur at the standard location, which in this case is Broome.

3.5 GEOGRAPHIC VARIATION IN DECAY OF STORM MECHANISM

Removal of the effects of topography and moisture maximisation and standardisation was sufficient in the case of the GSAM to generalise the storms such that they could be transposed within the zone. However, the GTSM zone is much bigger and the type of storms that generate extreme rainfall scenarios, particularly in the coastal zone, are tropical cyclones. These storms have some peculiarities that need to be considered, in particular, tropical cyclones, which originate over warm sea-surface temperatures (SSTs) in the tropics. They can then propagate to remote locations. However, the form in which the tropical cyclones reach that location is loosely a function of the environment that they traversed to get there. For example, should the tropical cyclone have moved south from the tropical genesis region, it might pass over cooler SSTs, thereby starving the mechanism of the source of energy it requires to be sustained and so it will reach the point of interest in a decayed form. In general, it is true that tropical storms have a greater energy source to draw on over the warm moist ocean and so the further they are located from this source of energy, the more reduced in magnitude they will be. In order for the storm mechanisms to be able to be transposed within the zone, this additional geographic variation needs to be considered.

The residual variation of storm strength is clear once the geographic distribution of standardised depths from the storm database is plotted. It would be anticipated that if the storms in the database were generalised completely following separation of the storm topographic component and moisture adjustments, then what would remain would be a random distribution of ranked depths over the zone. The only variable that should remain would be the AEP of each event in the storm database. An examination of such plots (see Figure 19(a)) indicate that there remains significant residual structure in the data, such that the biggest values all reside near the coastal band and tend to be in the north of the country. This confirms, as suspected, that some remaining geographic information exists and needs to be accounted for.

A useful way of quantifying this is to take the IFD information from ARR87 (IEAust, 1987) as the basis for the geographic variation of rainfall intensity over the country: it being the best information currently available for this purpose. The IFD data, however, represents rainfall variability due to topography and moisture as well as the residual variability that needs to be captured. The component of the rainfall contributed by moisture and by topography must be removed from the IFD data so as not to double-count it. The convergence intensity data (Section 3.3), which present rainfall intensity assuming Australia is flat, serves to remove the effect of topography on rainfall. The existing information on maximum persisting dewpoints can be used to help remove the effect of moisture based on the following hypothesis:

$$R_a \approx SmoothIFD_a \times \left(\frac{EPW_{Australia}}{EPW_a} \right) \qquad (6)$$

where R_a is the residual IFD value at point a

$SmoothIFD_a$	is the flatland IFD value at point a
$EPW_{Australia}$	is the depth of precipitable water equivalent to the extreme 24-hour persisting dewpoint for Australia (the extreme 24-hour persisting dewpoint at Broome being chosen as it has the highest dewpoints in Australia at a reliable Climate station. 29.5°C ⇔ 118.9mm)
EPW_a	is the depth of precipitable water equivalent to the extreme 24-hour persisting dewpoint at point a

Having standardised the IFD information for topography and moisture, what remains is any residual geographic variation due to other effects such as distance from the coast, latitude, and the effect of barriers to preferential flow, along with any other more subtle variations.

To get the residual IFD data in to a form that is useable, it is scaled into an amplitude factor based on supporting data (SST and observed events). The distribution of amplitude is also smoothed to remove noise. Figure 17 shows the resulting amplitude distribution.

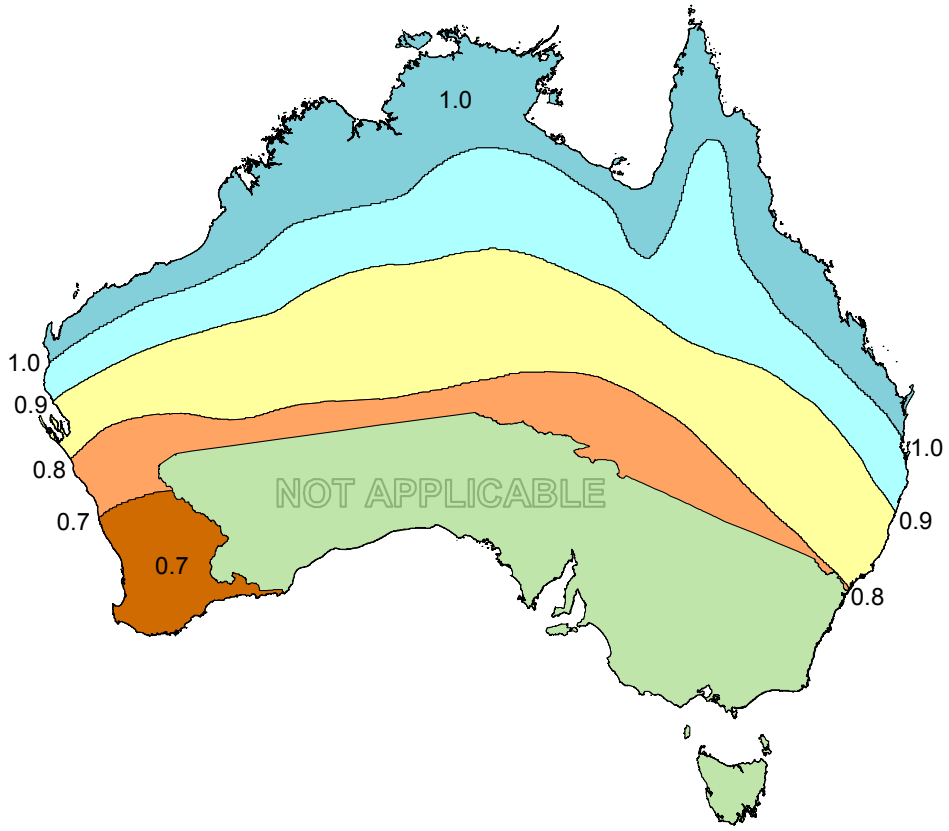

Figure 17: The distribution of amplitude factors defining the degree of mechanism decay expected over the GTSMR zone

An important aspect of the process of scaling and smoothing the data was to choose where the new 1.0 contour should intersect the coast. The choice of where to position the southern-most latitudes for unmodified storms (and their coastal intersections) was made partly on the basis of SST information (Figure 18). While it is a complex relationship (De Maria and Kaplan 1994), it is reasonable to make the conservative assumption (McBride,

Shay; personal communications) that the 25-26 degree isotherm in SST is approximately the ocean temperature at which a tropical cyclone can remain over and maintain its full potential. The latitude of this isotherm thus gives a good indication of where the southern extent of unmodified storm strength should lie.

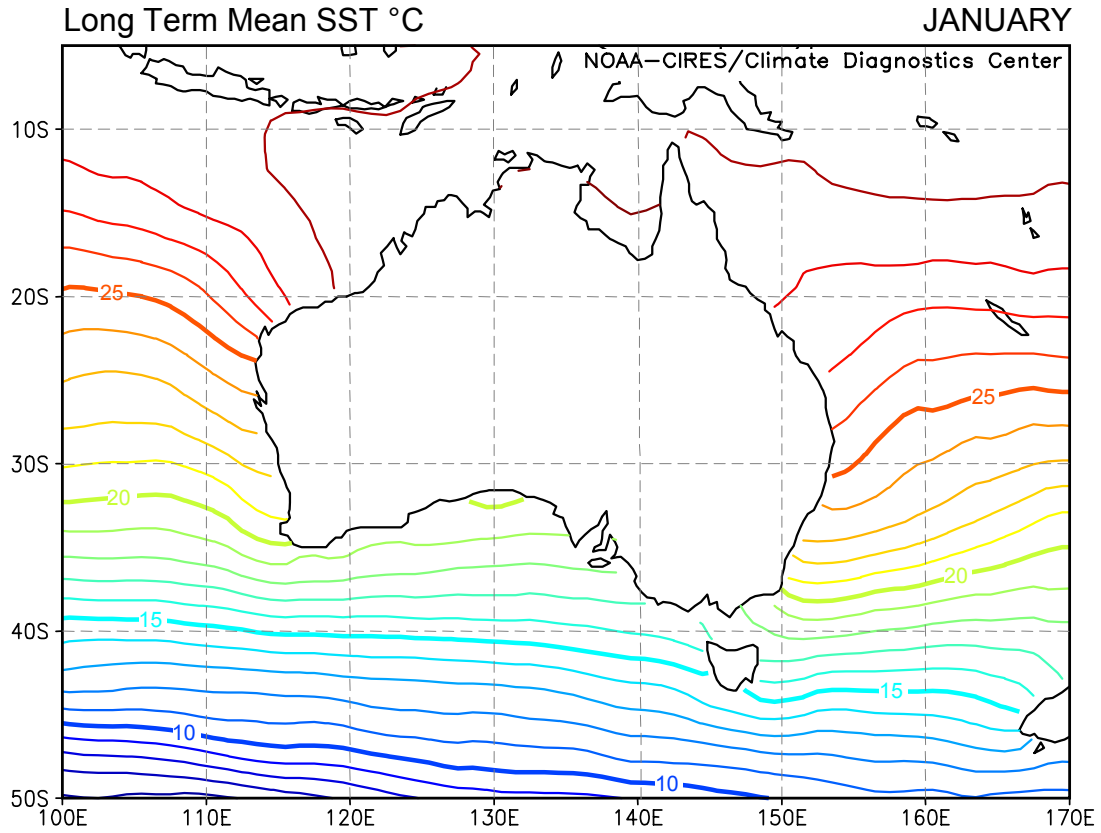

Figure 18: Climatological sea-surface temperatures (derived from image of Reynolds SST data provided by NOAA-CIRES Climate Diagnostic Center, Boulder, Colorado, USA, at http://www.cdc.noaa.gov/)

Also considered was the location of some of the larger tropical cyclones that have reached higher latitudes. The Crohamhurst 1893 storm affected Brisbane on the east coast and it is one of the more important storms in the storms database. This latitude coincided reasonably well with the southern extent of the 1.0 decay amplitude region as estimated from SST data. On the west coast, Tropical cyclone Vance, which occurred in 1999, was a category 5 cyclone that crossed land near Exmouth. While it did not produce very significant rainfall compared with other events, it was nonetheless a very intense cyclone and should be considered as within the region of zero decay. As a result, the latitude of the 1.0 amplitude contour was shifted slightly south as part of the smoothing process.

In general, the SST distribution (where it intersects the coast) aligns well with the smoothed amplitude structure (an approximate level of 1 degree Celsius corresponding with a reduction in amplitude by 0.1). The basic asymmetry between the east and west coast in terms of the amplitude is replicated in the SST data. Such a pattern is consistent with the theory that where a storm that has to travel south over cooler SST, it loses some of its intensity. As a consequence of the much shallower SST gradient on the east coast of Australia compared with the west coast, this decay process is much slower on the east coast and thus the gradient in amplitude is smaller.

To highlight what effect the application of the amplitude has to the distribution of storm depths (compare with Figure 19(a) for the altered set), see Figure 19(b). It indicates the change in rank of storm depths across the GTSMR zone. Negative values indicate that the rank of the storm has dropped (become less significant) and positive numbers indicate the opposite. A clear distinction is present between storms in the north and coastal areas, particularly in the northeast, and those in the south and inland, particularly in the west. This implies that application of the factor will try to address the bias that is present in the storm database rainfalls due to the decay in storm mechanism.

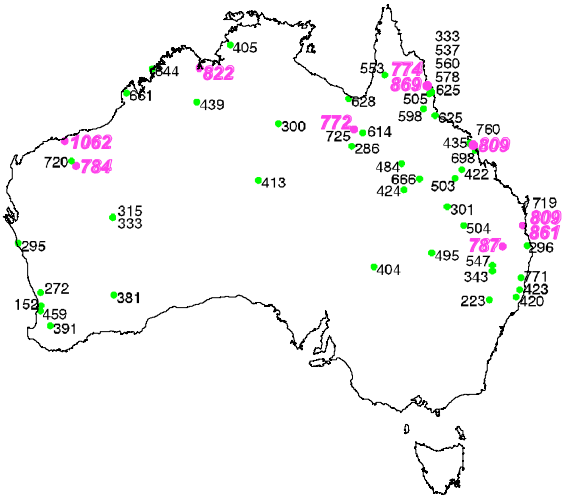

Figure 19(a): Moisture maximised and standardised convergence depths at 24 hours and 1000 km² demonstrating the coastal and northerly bias of the top 10 values.

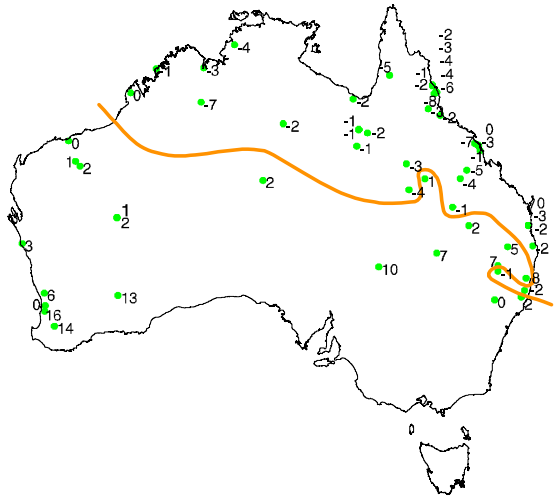

Figure 19(b): The change in rank of the depth values plotted in Figure 19(a) after application of the decay amplitude. It shows that storms inland and in southwestern WA have had their rank enhanced.

3.6 ENVELOPING THE DEPTH-DURATION-AREA CURVES

The five site-specific factors have been outlined particularly, the effects of the three factors (topography, local moisture availability and decay of storm mechanism) that need to be identified and accounted for from the storm rainfall before it can be freely transposed within the zone. When these standardisation processes have been completed, the storms may be compared and subsequently enveloped. Enveloping creates, from the database, a single hypothetical standard convergence component of the PMP storm that has maximum moisture content and maximum efficiency. The envelopment process can be best depicted visually (see Figure 20).

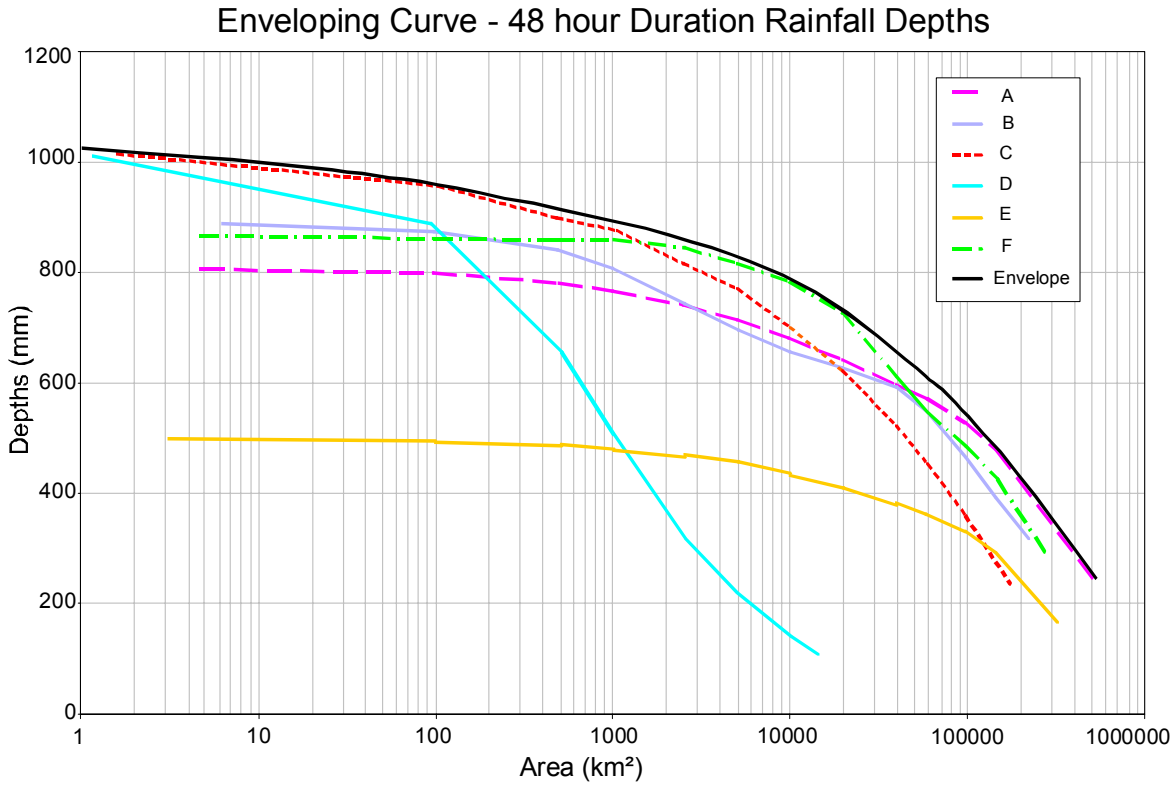

Figure 20: An example of the enveloping process for a set of storms (A-F) defined by their depth-area curves.

In Section 3.2, the GTSMR area has been broken into three zones based on the types of storm mechanisms that are relevant in these locations and the season in which they occurred. It follows that in the procedure of enveloping, only generalised storms with mechanisms that could reasonably expected to have occurred in a particular zone are transposed. The location where the mechanism did occur is irrelevant. Depth-area curves were created to cover the four combinations of season and zone to which the GTSMR might be applied. For the inland application zone (IAZ), this comprises only monsoonal lows (Figure 9). For the coastal application zone in the summer-season (CAZ-S), *all* summer-season storms are used and, similarly, for the coastal application zone in the winter-season (CAZ-W) *all* winter-season storms are used. In the southwest of Western Australia (SWAZ-W), only winter extra-tropical and frontal systems are relevant.

As depicted in Figure 20, all relevant storms for a specified duration in the zone are plotted together for comparison. The drawing of the theoretical envelope is done quite conservatively, in that attempts are made always to pass through the real storm data values

at the standard areas. However, the envelope is drawn through greater values than the real storm data when it appears that only a lack of data is responsible for the shape of an odd-looking curve. The envelope is also drawn through greater values than the storm data in order to maintain a reasonably smooth curvature (see below). A level of smoothness would be expected for design estimates (WMO, 1986) and the fact that this might not be present in the real data, is assumed to reflect sampling inadequacy.

3.6.1 Smoothing Process

The enveloping curves were drawn over the depth-area information to represent the theoretical maximum depth for each of the three zones and their relevant season across the range of standard durations. The next step was to combine all the depth-area curves for a particular zone onto a single plot. The curves were smoothed to remove inconsistencies or unlikely scenarios such as having a lower rainfall depth at a longer duration. These situations arise from the fact that there is only limited initial information from which to construct the envelopes with the result that some of the enveloped curves are more representative of the theoretical maximum at a specific duration than others, depending on the make-up of the storms database. Generally, the 24- 48- and 72-hour curves are the most reliable as they are based on the largest quantity of data and these were used to form the basis from which decisions on the shape of other curves were made.

To further aid in the smoothing process, the rainfall depths for each duration were also plotted against area, creating a set of depth-duration curves for each of the standard areas. As in the previous step, the curves were smoothed to remove inconsistencies. This ensures consistency at any specific area; this is important, as in the application stage, the design depths are extracted at various durations for a specific catchment area.

The enveloping process was designed to remove inconsistencies in depth and it was an iterative process. The design envelopes, which define the PMP Convergence Component at all durations for each of the four GTSMR application zones, are presented in Appendix 3.

3.7 DESIGN SPATIAL DISTRIBUTION OF PMP STORM

As discussed in Section 3.1, it is plausible that locations may have a preferential distribution of rainfall, based on the structure of the catchment. Some catchments will exhibit a stronger preference than others will and this will be related to the topography, the preferential direction of flow of storms (e.g., onshore flow) and the associated moisture inflow. In the storm comparison and enveloping process, the storms were represented as depth-area curves. In order to apply the rainfall depth to a specific catchment it is necessary to describe the spatial distribution of the storm rainfall.

The spatial pattern to apply the GTSMR PMP depth will be defined in the same way as the GSAM (Minty et al., 1996). With little prior knowledge about the spatial distribution of the convergence component of the rainfall within the storm, we can really only infer the most probable distribution of the topographic component of rainfall within the catchment. The best estimate we have for this distribution is one based on the distribution of the IFD ratio (see section 3.3 for discussion) Thus, the design spatial distribution for the PMP storm is simply given by the field of modified topographic enhancement factors over the catchment. A sample spatial pattern is presented in Figure 21. While there is no certainty as to the spatial distribution of rainfall in a PMP event, the assumption we have made is that the spatial pattern determined in this manner is considered the most probable.

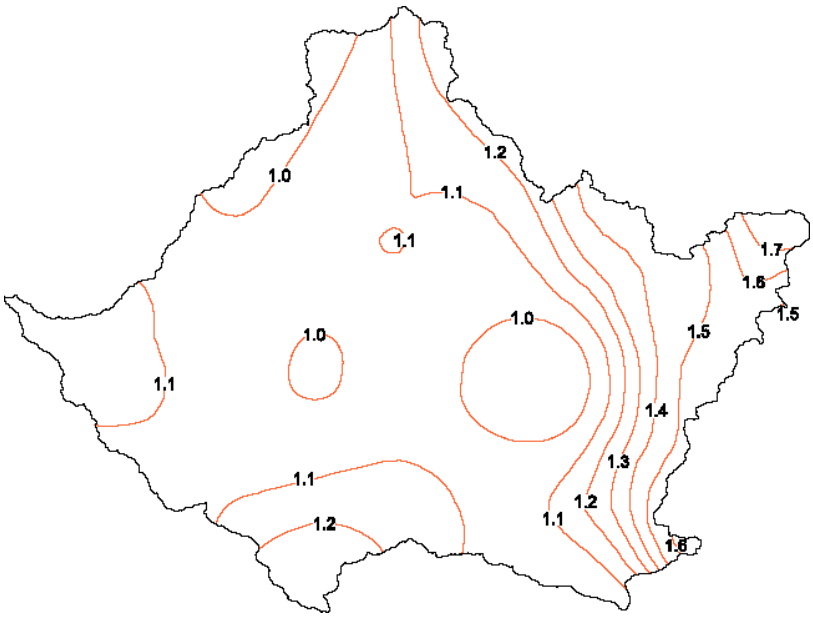

Figure 21: The spatial pattern with which the PMP design rainfall can be applied for a sample catchment. This depicts the relative weighting with which the PMP rainfall is distributed over the catchment.

3.8 DESIGN TEMPORAL DISTRIBUTION OF PMP STORM

Rainfall based estimates of design floods require a design temporal distribution of the rainfall total. Since a PMP event has not been observed, the derivation of an appropriate design temporal distribution for use with the GTSMR PMP depths can only be inferred from the sample of observed storms used in deriving those depths. As discussed in Section 1.1, the current Australian design flood guidelines emphasise the need for design flood estimation to adopt an AEP-neutral approach where 'the objective is to derive a flood with an AEP equivalent to its causative design rainfall' (Book VI in Australian Rainfall and Runoff – A Guide to Flood Estimation) (Nathan and Weinmann, 1999). For the GSAM, the Average Variability Method (AVM) (Pilgrim, Cordery and French, 1969) was used, in conjunction with smoothing (Nathan, 1992), to derive an appropriate pattern. As it was decided that the GTSMR project would be based on the GSAM method, the AVM was chosen as the starting point for deriving the design temporal distribution for the GTSMR.

In applying the AVM to the GTSMR database, the following factors were considered and examined:

- the number of storms and their representativeness of the extreme processes being considered.
- the degree of smoothing to be applied to the temporal patterns of the selected storms.
- temporal patterns adopted with PMP in other countries.

In the first instance, the AVM was derived for each duration/area/zone from all relevant storms within the GTSMR database (the *all-storms* patterns). However, as the GTSMR database is very large and because of the requirement to include storms over a range of durations and extents from all geographic areas, many of the storms in the database may not be representative of the extreme processes assumed in a PMP event. This means that the derived AVM patterns based on all GTSMR storms may not be representative. This view is consistent with the findings of Pilgrim et al. (1969), Milston (1979) and Nathan (1992) that the temporal distributions of the heavier rainfall events are characteristically smoother than rainfall of less intensity.

An alternative approach for deriving design temporal patterns for use in the GTSMR therefore, was to only choose the top ten events (ranked by storm depth) for each duration/area/zone combination for use in the AVM (the *top-10* storms). To rank the events, some normalisation was necessary and generalising for topography and location was essential in order to rank the events on an equal basis. Thus the standardised, decay amplitude modified, convergence components of the *unmaximised* storm depths magnitude were chosen to rank the events. Unmaximised storm depths were used because *maximising* these events could have significantly altered their temporal patterns and given too much weight to patterns from the smaller events.

A further consideration in the selection of storms for the AVM was the need to ensure consistency of patterns between durations. Because the temporal patterns are to be used to define the temporal structure of a PMP, it is important to ensure that the pattern still prescribes realistic rainfall rates. A situation can occur for a longer duration PMP where a burst (a period of heavy rainfall within the storm) defined by the temporal pattern results in that burst having a depth greater than the depth for a PMP of the same duration as the burst. Given the higher level of confidence that exists for the PMP depths, it is not reasonable to allow the temporal patterns to dictate such a situation and thus the temporal

patterns for the longer duration events were adjusted to remove this possibility. The adjustment consists of lowering the rainfall within the burst to a level that is possible given the PMP burst information and then redistributing this rainfall linearly within the remainder of the storm. For the small number of events where a large redistribution was required, the temporal pattern was deemed not to be typical of a PMP for that duration and the event removed from the list and the next event down for that duration brought into the set of contributing storms.

A fundamental assumption underpinning the adoption of the AVM for determining design temporal patterns was that it preserved AEP-neutrality. Published papers justifying this assumption were limited; however, Nathan, Weinmann and Hill (ANCOLD, 2002) adopted a Monte Carlo approach for testing the preservation of AEP-neutrality in estimating the PMPDF. Although it must be recognised that the validity of the outcomes of a Monte Carlo simulation are dependent on the degree to which the inputs are representative of the extreme range of each of the variables that is of interest, it was considered that this is currently the most appropriate method to adopt.

Therefore, a Monte Carlo simulation study was undertaken to test the AEP-neutrality properties of a range of temporal patterns for sample catchments of varying sizes in Western Australia, New South Wales and Queensland; SinclairKnightMerz (2003). In summary, a comparison was made between the flood frequency curves derived from a Monte Carlo simulation using historic temporal patterns from which the AVM patterns were derived and those frequency curves derived deterministically using the AVM temporal pattern (*top 10* and *all-storms* based) and, for comparison, various single design patterns used in previous PMP methods both in Australia and overseas. The study showed that, in general, the temporal pattern which produced flood frequency curves which best fit the Monte Carlo derived curve (and therefore was assumed to maintain AEP-neutrality) across all storm durations and areas was the unsmoothed AVM temporal pattern based on the top-ten storms. This temporal pattern is therefore recommended as the single design temporal distribution to use in estimating the PMPDF (Green, Walland, Nandakumar, and Nathan, 2003).

There may also be instances when the temporal distributions of the individual observed storms used in deriving the AVM are also required to assess the impacts of different temporal distributions on the flood estimates such as in the estimation of the Probable Maximum Flood (Nathan and Weinmann, 1999). The individual temporal patterns can also be used if a more rigorous analysis e.g., joint probability analysis is required as discussed in Book VI. Figure 22 shows the top ten temporal distributions for the 48-hour duration, 5000 km^2 storm for the coastal zone in summer along with the derived smoothed AVM design distribution to demonstrate the patterns that could be made available. It should be noted, however, that the use of a single historic pattern or any combination other than the design distribution recommended above, may or may not maintain AEP-neutrality, and users will need to make their own judgement about the validity of using other design temporal patterns and the resulting PMPDF.

It is important to make some acknowledgement of the uncertainties involved in constructing these temporal distributions and the limitations to using a single design distribution. There can be no certainty of the nature of the temporal structure because there is no observational record of a PMP event. What is available is a less than perfect set of observed large to extreme rainfall events that must be used to construct the best estimate of

the temporal distributions. Events from the late 1800s and early 1900s have little temporal data as there were few pluviograph records until the 1950s, however, because of the limited data set, these events must be included, particularly when they are the most extreme events recorded. Similarly, there is the assumption that the temporal variability seen in the largest observed events does represent what would occur in a PMP. So, while these are the best data we have and such an assumption is plausible, it is nevertheless an assumption and must be remembered as such.

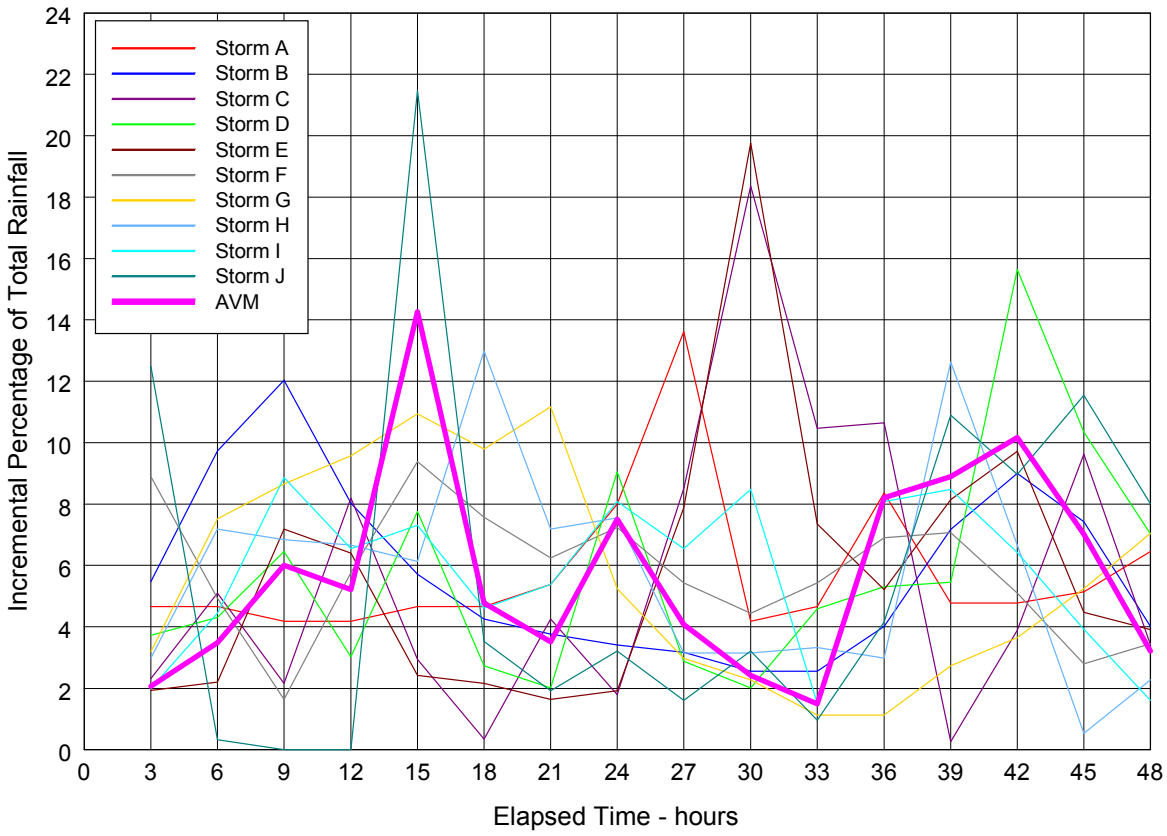

Figure 22: Top ten temporal patterns for a storm of 48 hours duration, 5000 km^2 spatial extent in the coastal zone in the summer season

4. PMP ESTIMATION TECHNIQUE

PMP estimates are required for the PMF and PMPDF calculations and are thus determined on a specific catchment basis. The process of estimating PMP for any catchment is to begin with the convergence components of the PMP storm derived from the set of design curves constructed in Section 3.6 and then adjust that storm by reconstructing the site-specific features of that catchment.

These site-specific factors include:
- Storm Type
- Topographic Influence
- Local Moisture Availability
- Mechanism decay
- Spatial distribution

These features are somewhat interrelated, as are the techniques for reconstructing them.

4.1 CATCHMENT AREA AND LOCATION

From the set of theoretical curves for the zone in which the catchment is located, the convergence component of the PMP storm depth for the area of the required catchment is extracted. Generally, the catchment boundary outline is prepared and displayed within a GIS from which an accurate area and zone location are obtained. It is then a matter of reading off the convergence component of the PMP storm depth at that area from theoretical curves for the appropriate zone, for the various standard durations. These area-specific values have then to be adjusted to account for location-specific factors: moisture potential (MAF) and storm mechanism decay (DAF) according to Equation 7.

$$Catchment\ PMP\ Convergence\ Component = PMP\ Convergence\ Component \times MAF \times DAF \quad (7)$$

where *MAF = Moisture Adjustment Factor* &
DAF=Decay Amplitude Factor

4.1.1 Moisture Adjustment Factor

In order to transpose the convergence component of the PMP depth from the hypothetical location to the actual location of the catchment, it is necessary to adjust the depth for the difference in moisture potential at the two locations. The moisture adjustment factor (MAF) is calculated in an analogous fashion to the standardisation factor, i.e., it is the ratio of the precipitable water at the catchment extreme dewpoint temperature to the standard extreme dewpoint temperature (Equation 8).

$$MAF = \frac{EPW_{catchment}}{EPW_{standard}} \quad (8)$$

where $EPW_{catchment}$ is the Extreme Precipitable Water associated with the catchment Extreme Dewpoint Temperature.
and $EPW_{standard}$ is the Extreme Precipitable Water associated with the Standard Extreme Dewpoint Temperature (Broome).

As discussed in Section 3.4.2, the standardisation of moisture is done on a seasonal basis (summer and winter seasons) and so the reconstruction of the local moisture must also be done on a seasonal basis. Catchment extreme dewpoints are constructed by a linear areal average over the catchment for each of the two seasons. The summer season moisture data being identical to the annual values. The envelope depths for the different seasons (as appropriate for zone) are then multiplied by the catchment moisture adjustment factors.

4.1.2 Decay Amplitude

Before the storm is transposed account must also be taken of the degree to which the hypothetical storm mechanism would be decayed given the geographic location of the catchment (Section 3.5). From Figure 17, a catchment average estimate of the decay amplitude factor (DAF) is estimated that can then be used to adjust further the convergence component of PMP using Equation 7.

This defines the catchment PMP Convergence Component. It reconstructs the catchment moisture potential, the expected degree to which a storm mechanism would decay by the time it reached the catchment, and the type of storm is also defined on the basis of the zone in which the catchment is located (therefore which set of enveloping curves were used to estimate the standard PMP convergence rainfall). In addition, the PMP quantity has been estimated for both summer and winter seasons (where appropriate).

4.2 ESTIMATING THE TOPOGRAPHIC COMPONENT OF THE PMP STORM

The remaining adjustment that needs to be made in order to progress from the catchment PMP Convergence Component to the catchment PMP depth is to reconstruct the topographic component of the PMP storm at the catchment. The method for doing this is analogous to that for removing the same component for the GTSMR storms in the database (Section 3.3) and involves modifying the catchment PMP Convergence Component by the topographic adjustment factor (TAF).

$$Catchment\ PMP\ Depth = Catchment\ PMP\ Convergence\ Depth \times TAF \tag{9}$$

$$\text{where}\quad TAF = \frac{Total\ Rainfall\ Intensity}{Convergence\ Rainfall\ Intensity} \tag{10}$$

However, because it was considered that the PMP event would have a greater convergence component than orographic component compared with storms in the database with typical average recurrence interval of 50-100 years (see Klemes, 1993; Minty et al 1996), some adjustment to the original TAF (Section 3.3) was considered necessary. This was based on evidence comparing extreme rainfall over high and low topography in the GSAM database as well as evidence of truly extreme rainfall over the globe. As a result, a function modified topographic enhancement for PMP storms was used and this was replicated from the GSAM study. The details are presented in Table 2 and Figure 23.

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

Table 2: Modified topographic adjustment factors (Minty et al., 1996)

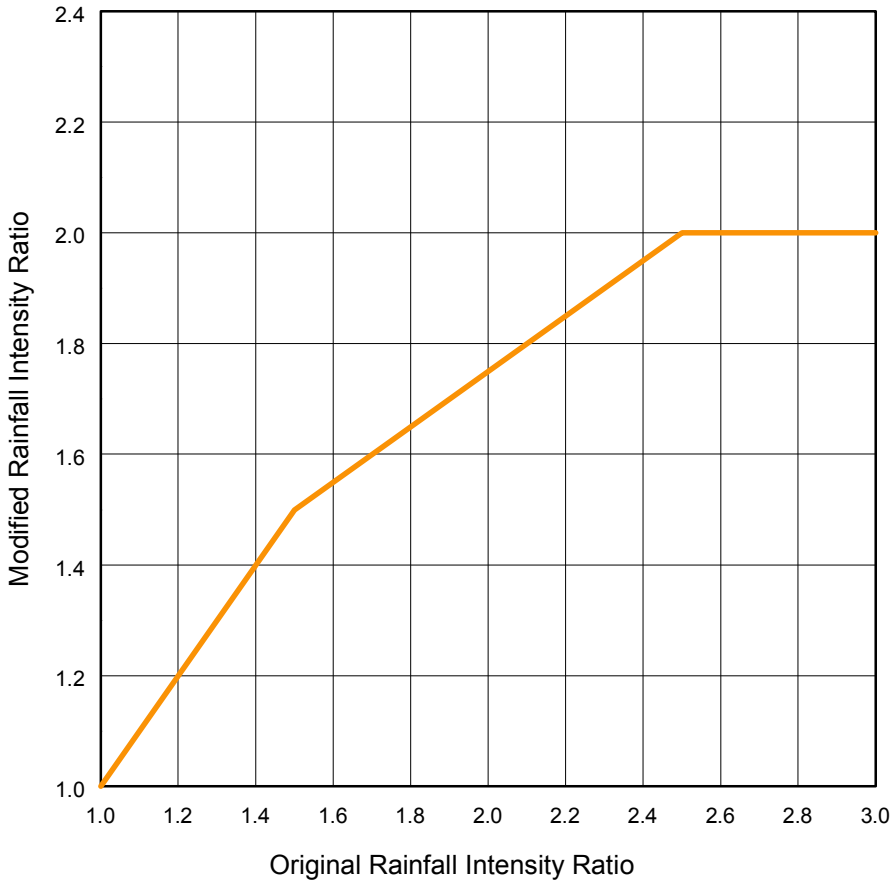

Figure 23: The function that defines the modified topographic adjustment factors (Minty et al., 1996)

The modified topographic enhancement factors, as calculated for each point on the Australia-wide grid (Figure 17), were then averaged over the catchment area to produce a catchment PMP Topographic Adjustment Factor (TAF).

4.3 CATCHMENT PMP ESTIMATES

The procedure described in the previous two sections produces a set of catchment PMP depths for an area equal to that of the catchment, for each of the standard durations. This set of depths is then itself enveloped as shown in Figure 24. The rationale for this final enveloping of the PMP estimates is:

1. The GTSMR database is only a sample of all possible storms and so cannot be expected to define fully the PMP design storm for all of the standard durations.
2. PMP estimates for the different durations may be derived from different seasons; no attempt has been made to envelope the database on a seasonal basis.

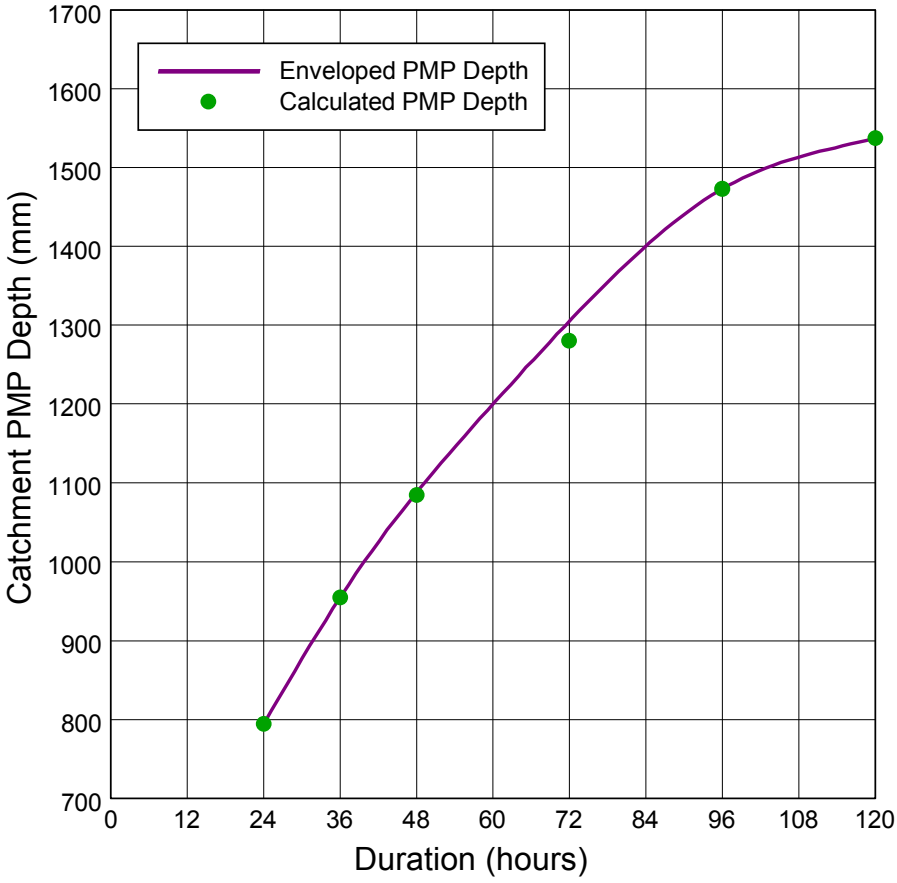

Figure 24: Enveloping process to define PMP depth across a range of durations for a specific area.

4.4 DESIGN SPATIAL DISTRIBUTION OF THE PMP STORM

As discussed in Section 3.7, the process of using the PMP in any hydrological analysis requires a spatial distribution. The catchment PMP depth (Section 4.3) is an average depth of rainfall across the catchment; however, rain does not fall uniformly across a catchment. It is assumed that there will be preferential distributions of rainfall and this distribution is normally presented using a spatial pattern of the type shown in Figure 21.

The depth of rain to be placed in the catchment is that equivalent to the catchment PMP depth applied uniformly over the catchment. The total volume of rainfall over the catchment after distribution must be the same as the uniform volume before distribution, thus some normalisation is required in the use of the spatial pattern. The distribution of the PMP depth over any sub-catchment for any duration follows the process used for the GSAM and can be defined as follows:

$$PMP_i = PMP\ for\ Catchment \times \frac{Average\ ratio_i}{\sum_{i=1}^{n} \left(Average\ ratio_i \times PA_i \right)} \qquad (11)$$

where

i is the individual sub-catchment, 1 to n

$Average\ ratio_i$ is the average value of the function-modified ratios of the 72-hour 50-year IFD to flat-land IFD over the catchment for an individual sub- catchment i

PA_i is the proportion of the area of an individual sub-catchment, i, to the total area of the catchment.

The computed grid of PMP depths across the catchment must then be checked to ensure that within the catchment there are no sub-areas where the prescribed PMP exceeds the design PMP depth for that area. This could only potentially happen when there is extreme orographic enhancement in one sub-area of the catchment such that when the average depth is distributed according to this pattern, it is raised too high in this location. In this instance, the Average Ratio would be capped at lower values, which would effectively smooth out the spatial pattern.

4.5 DESIGN TEMPORAL DISTRIBUTION OF THE PMP STORM

In order to apply the catchment PMP depth with a spatial distribution as discussed in the previous section, an appropriate temporal distribution is also required. The manner in which these temporal distributions are derived is discussed in Section 3.8.

When assigning a design temporal distribution to apply to a catchment PMP depth, temporal patterns are provided only for catchments of standard area. The distribution for the standard area closest to the area of the catchment should be used; there is *no* interpolation between areas. This is done for each standard duration. An example design temporal distribution, as derived from the AVM of the *top-10* storms, is shown in Figure 25. In addition, the temporal patterns from the top ten real storms, relevant at this area, are provided (in a PMP catchment study) should any additional analysis be required.

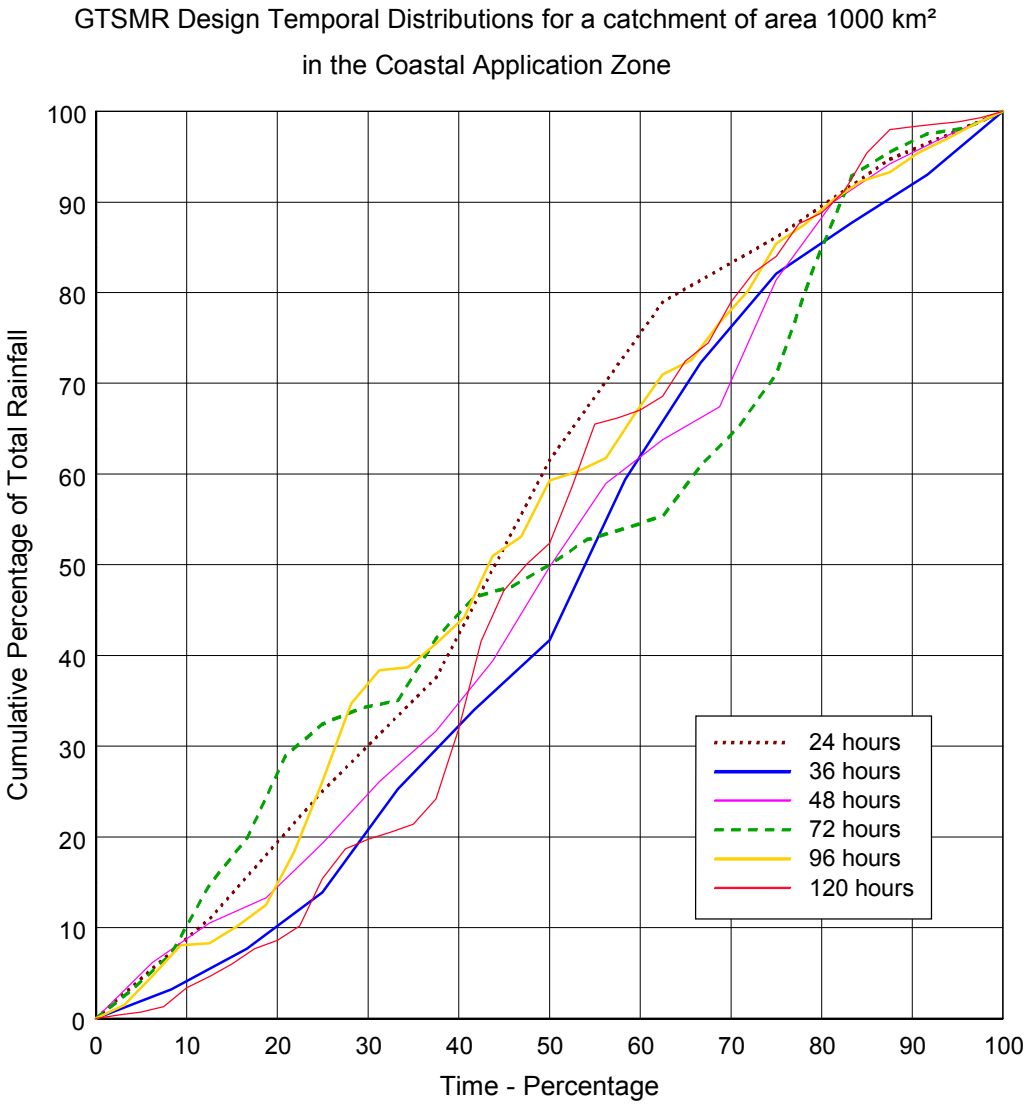

Figure 25: Example of a GTSMR design temporal distribution derived from the AVM

5. LIMITATIONS OF APPLICATION

5.1 DURATION AND AREA LIMITS

Application of the GTSMR will allow for the provision of PMP estimates for catchments in the GTSM zone ranging from 1 - 150,000 km^2 in size and durations of 24-, 36-, 48-, 72-, 96-, 120-, and 144-hours. For catchments with an area less 1000 km², estimates up to 6-hours are derived using the Generalised Short Duration Method (GSDM) (Bureau of Meteorology (1985, 1994, amendments 1996 and 2003)). The 12-hour value is generally interpolated between the 6- and 24-hour values.

5.2 ZONES

There are two primary zones in the GTSMR; a coastal and an inland zone, with a secondary zone in the southwest of Australia, which is relevant only for the winter season. The zones correspond to regions where a specific storm mechanism would cause the PMP event. These zones were presented in Section 3.2, and are displayed in Figure 26.

The inland zone defines a region where a monsoonal low is the mechanism that causes the extreme rainfall and where a tropical cyclone (or ex-tropical cyclone) will not be the mechanism that causes the extreme storm event. When selecting the storms to use in creating the envelope of depth-area curves for this zone (Section 3.6), only those generated by monsoonal lows were used. As monsoonal lows only occur in the summer season, there is no set of enveloping curves for the inland region in the winter season.

For the coastal zone, however, any of the summer season mechanisms can produce the extreme event. Therefore, rainfall from all storms is considered in the enveloping process for this region. The coastal zone, however, is divided again in the winter season. The southwest of Western Australia is a special case in winter when the region is affected by frontal systems, often interacting with deep troughs. This is a particularly important time of the year from a flood risk point of view; accordingly, the southwest of Western Australia has been examined separately in winter.

In summary, there are three zones: the inland zone, the coastal zone and the southwest of Western Australia zone. The inland zone is considered only for the summer season, the coastal zone is assessed in both the summer and winter seasons and the southwest zone is considered for winter (northern dry season) but in summer (northern wet season) it is incorporated into the general coastal zone.

Zone	Summer Season (Oct – Apr)	Winter Season (May – Sep)
Inland	✓	
Coastal	✓	✓
Southwest WA		✓

Table 3: Summary of seasons investigated for each zone.

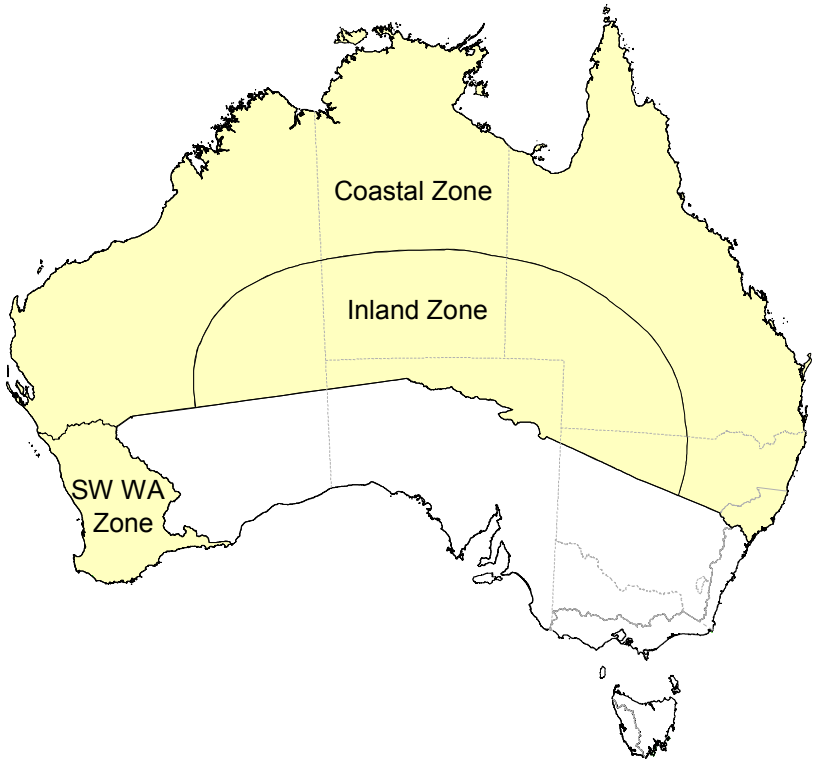

Figure 26: Location of the zones in the GTSMR region.

5.3 TRANSITION ZONES

The boundary between the GSAM and GTSM models must be examined because there are two different models generating PMP estimates, creating the potential for a discontinuity. If an estimate of PMP is made for a catchment on one side of the boundary, a substantially different result may be obtained when estimating PMP for a similar catchment on the other side; a result that is both undesirable and physically unrealistic. This issue is particularly important for the region of the GTSM – GSAM border in the populated areas of New South Wales but less important in other regions as there is very little in the way of the development that would necessitate knowledge of the PMP.

The GSAM introduced a transition zone between the GSAM and existing GTSM in coastal NSW (Minty et al 1996). Estimates from both methods were made for catchments in this zone and then a distance-weighted average (from GSAM/GTSM borders) used. This transition zone will be maintained following this review of the GTSM, although rather than a distance-weighted average estimate, it is recommended that both GSAM and GTSMR coastal zone PMP estimates be provided for the flood estimation. The decision on which to use will reside with the user, taking into consideration the mechanism that has produced observed large events as well as the risks of adopting each of the resultant floods.

There are two transition zones for the GTSMR: The current one on the NSW coast remains the same and a second is introduced which incorporates that part of Western Australia, east of the GTSMR boundary to the South Australian border. It is envisaged that both GSAM and GTSMR inland zone PMP estimates will be provided for this second zone. The transition zones are presented in Figure 27.

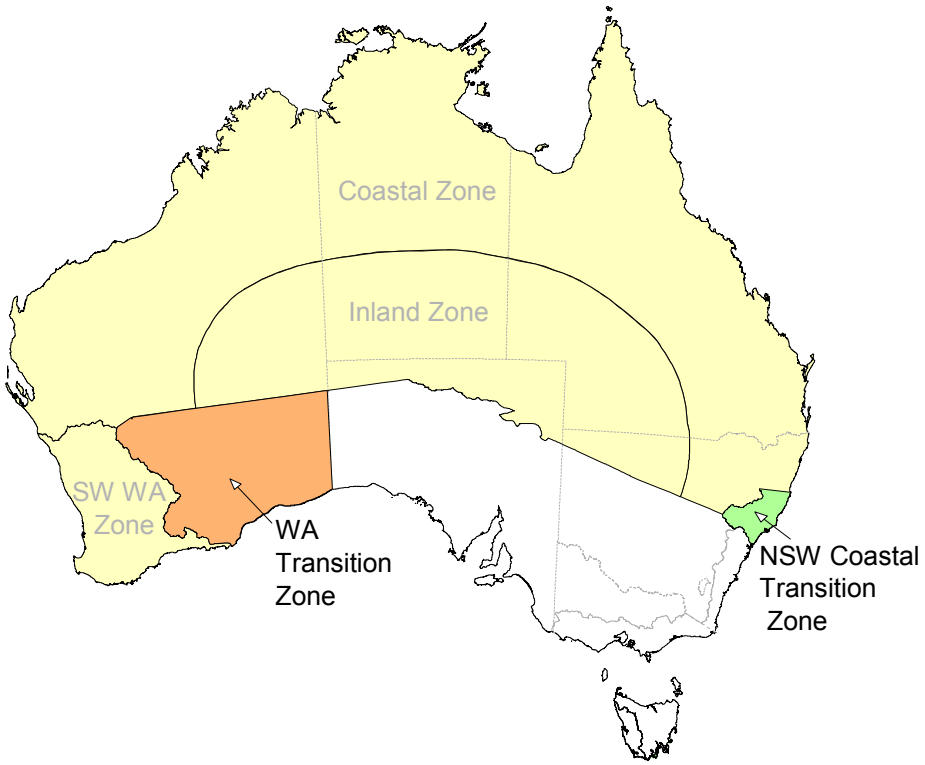

Figure 27: Transition zones highlighted relative to the main zones for the GTSMR region.

In the unlikely event that a PMP is required in the remaining region along the border between GSAM and GTSMR, then a similar approach would be implemented. PMP estimates using both methods would be made and then a decision on which estimate was preferred would reside with the user as discussed above.

A similar situation exists for any catchments abutting or falling across a zone boundary within GTSMR. Once again, PMP estimates should be made using the procedures that apply either side of the zone border and the user of the PMP decides on which estimate to use after consideration of their particular requirements at the time.

6. ACKNOWLEDGEMENTS

The authors thank the agencies that have funded this major project. These include the Water Corporation in Western Australia, the Department of Natural Resources and Mines in Queensland, the Department of Land and Water Conservation and the Hunter Water Corporation in New South Wales. They would especially like to acknowledge the tireless efforts of the Technical Advisory Committee drawn from these agencies (Janice Green, John Ruprecht and John Ruffini); they were a part of all decisions made in the project and provided a significant contribution reviewing this document.

They also acknowledge the commitment from the Bureau of Meteorology, in particular, their fellow members of the Hydrology Unit: Jim Elliot, Brian Taylor, Max Monahan and Helen Campbell.

7. REFERENCES

Agho, K., Kuczera, G., Green, J.H., Weinmann, P.E. and Laurenson, E. (2000). Estimation of Extreme Rainfall Exceedance Probabilities: Nondimensional Stochastic Storm Transposition. Presented at Hydrology and Water Resources Symposium, Perth, WA, November 2000.

Bureau of Meteorology (1985). The Estimation of Probable Maximum Precipitation in Australia for Short Durations and Small Areas. Bulletin 51, August 1984, AGPS, Canberra.

Bureau of Meteorology (1994). The Estimation of Probable Maximum Precipitation in Australia: Generalised Short-Duration Method. Bulletin 53, December 1994, AGPS, Canberra. Amendments issued December 1996 and January 2003.

Canterford, R. P., Hutchinson, M. F. and Turner, L. H. (1985). The Use of Laplacian Smoothing Spline Surfaces for the Analysis of Design Rainfalls. Hydrology and Water Resources Symposium, Institution of Engineers, Aust., 14-16 May, Sydney.

Davidson and Holland (1987). A Diagnostic Analysis of Two Intense Monsoon Depressions over Australia. Monthly Weather Review, Vol. 115, pp. 380-392.

De Maria, M. and Kaplan, J. (1994). Sea Surface Temperature and the Maximum Intensity of Atlantic Tropical Cyclones. J. Climate, Vol. 7, pp. 1324-1334.

Gibbs, W. J. (1958). The Rain Process. Proc. Conf. Extreme Precipitation, Melbourne. Bureau of Meteorology, Melbourne, pp. 10-56.

Green, J.H., Weinmann, P.E., Laurenson, E., Nathan, R. and Kuczera, G. (2002). Estimation of Storm Arrival Probabilities in the GSAM Inland Zone. Proceedings, Hydrology and Water Resources Symposium, Melbourne, May 2002.

Green, J.H., Walland, D.J., Nandakumar, N. and Nathan R.J. (2003). The Impact of Temporal Patterns on the Derivation of PMPDF and PMF Estimates in the GTSM Region of Australia. Presented at Hydrology and Water Resources Symposium, Wollongong, NSW, November 2003.

Institution of Engineers, Australia (1987). Australian Rainfall and Runoff - A Guide to Flood Estimation, Revised Edition.

Kennedy, M. R. (1982). The Estimation of Probable Maximum Precipitation in Australia - Past and Current Practice. Proc. Workshop on Spillway Design, Melbourne, 1981. AWRC Conf. Ser. No. 6. AGPS, Canberra, pp. 26-52.

Kennedy, M. R. and Hart, T. L. (1984). The Estimation of Probable Maximum Precipitation in Australia. Civ. Engng Trans. Instn Engrs Aust., Vol.CE26, No.1, pp.29-36.

Klemeš, V. (1993). Probability of Extreme Hydrometeorological Events – A Different Approach. Extreme Hydrological Events: Precipitation Floods and Droughts (Proceedings of the Yokohama Symposium, July 1993) IAHS Publ. No. 213, pp. 167-176.

Laurenson, E.M. and Kuczera, G.A. (1999). Annual Exceedance Probability of Probable Maximum Precipitation. Australian Journal of Water Resources Volume 3(2), pp. 167-176.

Meighen, J. and Kennedy, M. R. (1995). Catalogue of Significant Rainfall Occurrences over Southeast Australia. Hydrology Report Series No. 3, Hydrometeorological Advisory Service, Bureau of Meteorology.

Milston, A.K. (1979). The Influence of Temporal Patterns of Design Rainfall on Peak Flood Discharge. Thesis, (M.Eng.Sci.), The University of NSW, Sydney.

Minty, L.J., Meighen, J. and Kennedy, M.R., (1996). Development of the Generalised Southeast Australia Method for Estimating Probable Maximum Precipitation. HRS Report No. 4, Hydrometeorological Advisory Service, Bureau of Meteorology.

Minty, L.J. and Meighen, J. (1999). Rainfall Antecedent to Large and Extreme Rainfall Bursts over Southeast Australia. HRS Report No. 6, Hydrometeorological Advisory Service, Bureau of Meteorology.

Nathan, R. J. (1992). The Derivation of Design Temporal Patterns for Use with the Generalised Estimates of Probable Maximum Precipitation. Civ. Engng Trans. Instn Engrs Aust., Vol. CE34, No. 2, pp. 139-150.

Nathan, R.J. and Weinmann, P.E. (1999). Estimation of Large to Extreme Floods. Book VI in Australian Rainfall and Runoff - A Guide to Flood Estimation, The Institution of Engineers, Australia.

Nathan, R.J., Weinmann, P.E. and Hill, P.I. (2002). Use of a Monte Carlo Framework to Characterize Hydrologic Risk. ANCOLD 2002 Conference on Dams, 21-22 October, Adelaide.

Paulhus, H. L. H. and Gilman, C. S. (1953). Evaluation of Probable Maximum Precipitation. Trans. Am. geophys. Un., Vol. 34.

Pearce, H. J. and Kennedy, M. R (1993). Generalised Probable Maximum Precipitation Estimation Techniques for Australia. Hydrology and Water Resources Symposium, Newcastle, June 30-July 2, 1993. Instn Engrs, Aust., Natl Conf Pub. No. 93/14.

Pilgrim, D. H., Cordery, I. and French, R. (1969). Temporal Patterns of Design Rainfall for Sydney. Civ. Engng Trans. Instn Engrs Aust., Vol. CE11, No. 1, pp. 9-14.

Schaefer M.G. (1994). PMP and Other Extreme Storms: Concepts and Probabilities. Proceedings, Association of State Dam Safety Officials National Conference, Baltimore, Maryland, September 1994.

SinclairKnightMerz (2003). GTSM-R Probable Maximum Precipitation Method: Assessment of Temporal Patterns on Flood Frequency Curves for Eight Dams, Draft B. February 2003.

Standing Committee on Agricultural and Resource Management (SCARM), (2000). Floodplain Management in Australia: Best Practice Principals and Guidelines. SCARM Report 73, CSIRO Publishing.

Thiessen, A. H. (1911). Precipitation Averages for Large Areas. Monthly Weather Review, Vol 39, pp. 1082-1084.

United States National Weather Service (1977). Probable Maximum Precipitation Estimates, Colorado River and Great Basin Drainage. Hydromet. Report No. 49.

United States National Weather Service (1984). Probable Maximum Precipitation for the Upper Deerfield Drainage Massachusetts/Vermont. NOAA Tech. Memo. NWS HYDRO 39.

United States National Weather Service (1988). Probable Maximum Precipitation Estimates, United States between the Continental Divide and the 103rd Meridian. Hydromet. Report No. 55A.

United States Weather Bureau (1951). Tables of Precipitable Water and Other Factors for a Saturated Pseudo-Adiabatic Atmosphere. Tech. Paper No. 14.

United States Weather Bureau (1960). Generalised Estimates of Probable Maximum Precipitation for the Unites States for the West of the 105th Meridian. Tech. Paper No. 38.

United States Weather Bureau (1965). Probable Maximum and TVA Precipitation over the Tennessee River Basin above Chattanooga. Hydromet. Rep. No. 41.

United States Weather Bureau (1966). Probable Maximum Precipitation, Northwest States. Hydromet. Report No. 43, ESSA, US Department of Commerce, Washington DC

Wang, B. H. (1986). Probable Maximum Flood and its Application. Harza Engineering Company.

Wiesner, C. J. (1970). Hydrometeorology. Chapman and Hall, London.

World Meteorological Organisation (1969). Manual for Depth-Area-Duration Analysis of Storm Precipitation. WMO No. 237, TP 129, Geneva.

World Meteorological Organisation (1973). Manual for Estimation of Probable Maximum Precipitation. Operational Hydrology Report No. 1, WMO - No. 332, Geneva.

World Meteorological Organisation (1986). Manual for Estimation of Probable Maximum Precipitation. Second Edition. Operational Hydrology Report No. 1, WMO - No. 332, Geneva.

Zhao and Mills (1991). A Study of a Monsoon Depression Bringing Record Rainfall over Australia. Part ii: Synoptic-Diagnostic Description. Monthly Weather Review, Vol. 119, pp. 2074-2094.

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.

ARR87 – Australian Rainfall and Runoff (IEAust, 1987)

AVM – Average Variability Method. Technique for estimating design temporal pattern of average variability to ensure AEP Neutrality in transition from **PMP** to PMP design flood.

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 depth - 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.

CAZ-W – Coastal Application Zone (Winter). The set of design depth-area curves to be applied to catchments within the GTSMR coastal zone in winter.

CAZ-S – Coastal Application Zone (Summer). The set of design depth-area curves to be applied to catchments within the GTSMR coastal zone in summer.

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.

cold-cored low - a low pressure system which has its coldest temperatures near the centre, and warmer temperatures near the periphery.

Convergence Component -

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

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

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

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.

DAF – Decay Amplitude Factor. Factor to account for the decay in a storm mechanism as it propagates to remote locations.

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

depression – an area with low pressure near the centre.

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.

EPW – Extreme precipitable water associated with extreme **persisting dewpoint**.

Extratropical Cyclone - A low pressure frontal system not of tropical origin found in the **middle** and **high latitudes**.

Ex-tropical cyclone - A low pressure system which was previously categorised as a **tropical cyclone** but which does not satisfy the criteria for a tropical cyclone any more, and is undergoing the transition from a **warm-cored** to a **cold-cored** low pressure system.

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.

GIS – Geographical Information System. A useful proprietary software tool for visualisation of data

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.

GTSMR – Revision of the **GTSM**. (Current study)

GTSMR Storm Catalogue (Database) – A catalogue of the 122 storms selected for the GTSMR database, their dates and locations, DDA values, and storm dewpoint temperatures.

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

HAS – Hydrometeorological Advisory Service

High Latitudes - Regions located approximately 60 to 90 degrees latitude North and South.

HRS – Hydrometeorological Report Series

IEAust - The Institution of Engineers, Australia.

IAZ – Inland Application Zone. The set of design depth-area curves to be applied to catchments within the GTSMR inland zone.

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 (MF) - The factor by which storm rainfall amounts are multiplied to simulate maximised storm moisture content, defined as:

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

Middle Latitudes - Regions located approximately between 35 and 65 degrees latitude North and South.

Moisture Adjustment Factor (MAF) - 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:

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

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 that 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.

NSW Transition Zone – Region reflecting boundary between **GTSMR** and **GSAM** on the NSW coast indicating some ambiguity over the appropriateness of which method to use.

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).

PMFDF - Probable Maximum Precipitation Design Flood. The flood associated with the PMP using a temporal structure for the rainfall that maintains AEP between the PMP and the flood.

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.

severe tropical cyclone - A **tropical cyclone** with maximum sustained winds equalling or exceeding 65 knots (1 knot = 1 nautical mile per hour).

SPW – Storm precipitable water associated with storm **persisting dewpoint**.

SST – Sea surface 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 (SF) - The factor by which storm convergence component rainfalls are multiplied to simulate transposition to a standard location, defined as:

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

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.

subtropical - The regions adjacent to the **tropics,** up to approximately 40 degrees North and South latitude.

SWAZ-W – South West Application Zone (Winter). The set of design depth-area curves to be applied to catchments within the GTSMR southwest Western Australia zone in winter.

SW WA – Southwest Western Australia

synoptic scale - The scale of meteorological phenomena that can be detected on synoptic weather maps, i.e. 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 Adjustment Factor (TAF) -

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

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

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 along the border of the GSAM and the GTSM, in which application of both methods of estimating PMP is required. The existence of the zone reflects the uncertainty about which method to apply in this part of the Australia.

Tropical cyclones are non-frontal, synoptic scale, cyclonic rotational low pressure systems of tropical origin with maximum sustained winds between 34 and 64 knots (1 knot = 1 nautical mile per hour).

Tropics – Regions between the Tropic of Cancer (23.5 degrees latitude North) and the Tropic of Capricorn (23.5 degrees latitude South).

warm-cored low – a low pressure system which has its warmest temperatures near the centre, and cooler temperatures near the periphery.

WA Transition Zone – Region reflecting boundary between **GTSMR** and **GSAM** in southern Western Australia indicating some ambiguity over the appropriateness of which method to use.

WMO - World Meteorological Organisation.

APPENDIX 1:
Catalogue of GTSMR Storms

Key to Table A.1: Catalogue of GTSMR Storms

Storm:
The code used to identify uniquely each extreme rainfall event. The year, month, end date and duration are given in that order.

End Date:
The last day of the storm. The rainfall totals are to 9:00 am on this date.

Duration:
The number of days of accumulated rainfall, with each day being the 24 hours from 9:00 am to 9:00 am.

Classification:
A brief description of the synoptic situation at the time of the extreme rainfall event.

State:
The state of Australia where the centre of the event was located.

Centre:
The approximate latitude and longitude of the centre of the storm. This was derived from the centre of the enclosing polygons described in Section 2.1.5.

Zone/Season:
The set of design depth-area curves to which the storm contributed (Section 3.6). These depth-area curves are named according to their zone of application (Figure 26).

CAZ-S	Coastal Zone in summer
CAZ-W	Coastal Zone in winter
IAZ	Inland Zone
SWAZ-W	SW WA Zone in winter

Table A.1: Catalogue of GTSMR Storms

Storm Name	End Date	Duration	Classification	State	Centre		Zone/Season
					°E	°S	
1893FEB03-1	2/2/1893	1	Tropical Cyclone	Qld	152.91	-26.78	CAZ-S
1893FEB03-2	2/2/1893	2	Tropical Cyclone	Qld	152.93	-26.79	CAZ-S
1893FEB04-3	3/2/1893	3	Tropical Cyclone	Qld	152.90	-26.79	CAZ-S
1893FEB06-7	5/2/1893	7	Tropical Cyclone	Qld	152.92	-26.79	CAZ-S
1898APR03-2	3/4/1898	2	Tropical Cyclone	WA	117.85	-20.83	CAZ-S
1910JAN15-5	15/1/1910	5	Extratropical (Easterly Dip / Trough)	NSW	150.59	-29.90	CAZ-S
1911JAN08-1	8/1/1911	1	Tropical Cyclone	Qld	139.97	-20.00	CAZ-S
1911JAN09-5	9/1/1911	5	Tropical Cyclone	Qld	139.98	-20.01	CAZ-S
1911APR02-2	2/4/1911	2	Tropical Cyclone	Qld	145.61	-16.74	CAZ-S
1911APR03-5	3/4/1911	5	Tropical Cyclone	Qld	145.60	-16.79	CAZ-S
1913JAN18-4	18/1/1913	4	Tropical Cyclone	Qld	151.79	-24.66	CAZ-S
1916DEC28-1	28/12/1916	1	Tropical Cyclone	Qld	147.81	-22.61	CAZ-S
1916DEC29-2	29/12/1916	2	Tropical Cyclone	Qld	147.77	-23.03	CAZ-S
1917JAN07-4	7/1/1917	4	Tropical Cyclone	WA	122.41	-17.94	CAZ-S
1918JAN22-1	22/1/1918	1	Tropical Cyclone	Qld	149.11	-21.15	CAZ-S
1918JAN24-3	24/1/1918	3	Tropical Cyclone	Qld	149.10	-21.15	CAZ-S
1918JAN25-5	25/1/1918	5	Tropical Cyclone	Qld	149.23	-21.52	CAZ-S
1920JUL03-6	3/7/1920	6	Extratropical (Trough)	NSW	150.35	-31.81	CAZ-W
1922JAN31-1	31/1/1922	1	Monsoon Low	Qld	143.63	-22.46	CAZ-S IAZ
1922FEB02-3	2/2/1922	3	Monsoon Low	Qld	145.02	-23.54	CAZ-S IAZ
1923JAN17-1	17/1/1923	1	Tropical Cyclone	WA	115.10	-25.27	CAZ-S
1927SEP21-3	21/9/1927	3	Extratropical (Cut-off Low)	WA	117.96	-34.92	SWAZ-W
1929FEB12-7	12/2/1929	7	Extratropical (East Coast Low)	NSW	152.39	-31.62	CAZ-S
1930MAR04-6	4/3/1930	6	Monsoon Low	NT	134.21	-19.58	CAZ-S IAZ
1930JUN19-3	19/6/1930	3	Extratropical (East Coast Low)	NSW	152.52	-31.66	CAZ-W

Storm Name	End Date	Duration	Classification	State	Centre		Zone/Season
					°E	°S	
1934MAR09-1	9/3/1934	1	Ex-Tropical Cyclone	WA	116.00	-31.36	CAZ-S SWAZ-S
1942FEB17-3	17/2/1942	3	Tropical Cyclone	Qld	142.34	-16.01	CAZ-S
1945JUN13-4	13/6/1945	4	Extratropical (Fronts with Lows)	WA	116.06	-32.19	SWAZ-W
1945JUN25-10	25/6/1945	10	Extratropical (Fronts with Lows)	WA	116.00	-32.68	SWAZ-W
1946MAR03-1	3/3/1946	1	Tropical Cyclone	Qld	146.23	-18.95	CAZ-S
1947JAN26-3	26/1/1947	3	Tropical Cyclone	Qld/NSW	152.48	-28.25	CAZ-S
1947FEB12-1	12/2/1947	1	Tropical Cyclone	Qld	151.11	-24.01	CAZ-S
1948FEB23-1	23/2/1948	1	Ex-Tropical Cyclone	WA	121.61	-31.51	CAZ-S SWAZ-S
1948FEB23-2	23/2/1948	2	Ex-Tropical Cyclone	WA	121.50	-30.76	CAZ-S SWAZ-S
1950JUN24-1	24/6/1950	1	Extratropical (East Coast Low)	NSW	152.79	-30.35	CAZ-W
1950JUN25-7	25/6/1950	7	Extratropical (East Coast Low)	NSW	152.80	-30.34	CAZ-W
1951JAN14-6	14/01/1951	6	Monsoon Low	Qld	149.20	-21.45	CAZ-S IAZ
1954FEB21-1	21/2/1954	1	Tropical Cyclone	NSW	152.75	-30.36	CAZ-S
1954FEB21-2	21/2/1954	2	Tropical Cyclone	NSW	152.68	-30.35	CAZ-S
1955FEB17-1	17/2/1955	1	Ex-Tropical Cyclone	WA	116.02	-32.55	CAZ-S SWAZ-S
1955FEB18-4	18/2/1955	4	Ex-Tropical Cyclone	WA	116.02	-32.55	CAZ-S SWAZ-S
1955FEB25-2	25/2/1955	2	Monsoon Low	NSW	147.77	-31.86	CAZ-S IAZ
1956JAN22-2	22/1/1956	2	Monsoon Low	Qld	151.35	-28.25	CAZ-S IAZ
1956MAR07-1	7/3/1956	1	Tropical Cyclone	Qld	145.29	-18.50	CAZ-S
1958FEB18-1	18/02/1958	1	Tropical Cyclone	Qld	148.64	-21.10	CAZ-S
1958FEB22-3	22/2/1958	3	Tropical Cyclone	Qld	146.00	-20.42	CAZ-S
1959FEB17-1	17/2/1959	1	Tropical Cyclone	Qld	148.23	-22.91	CAZ-S
1959FEB18-1	18/2/1959	1	Ex-Tropical Cyclone	Qld/NSW	152.45	-28.25	CAZ-S
1959APR06-1	6/4/1959	1	Tropical Cyclone	WA	128.14	-15.48	CAZ-S
1963APR15-1	15/4/1963	1	Tropical Cyclone	NT	133.92	-14.93	CAZ-S
1963APR16-4	16/4/1963	4	Tropical Cyclone	NT	133.98	-14.90	CAZ-S
1964JAN14-1	14/1/1964	1	Monsoon Low	Qld	145.93	-28.69	CAZ-S IAZ

Storm Name	End Date	Duration	Classification	State	Centre		Zone/Season
					°E	°S	
1966JAN20-4	20/1/1966	4	Tropical Cyclone	WA	127.96	-18.00	CAZ-S
1967JAN22-2	22/1/1967	2	Tropical Cyclone	WA	114.45	-22.98	CAZ-S
1968JAN13-2	13/1/1968	2	Extratropical (Easterly Dip / Trough)	NSW	152.64	-31.17	CAZ-S
1970JAN19-1	19/1/1970	1	Tropical Cyclone	Qld	148.39	-20.52	CAZ-S
1970DEC05-1	5/12/1970	1	Tropical Cyclone	WA	122.69	-17.68	CAZ-S
1971JAN26-1	26/1/1971	1	Tropical Cyclone	WA	115.94	-22.91	CAZ-S
1971DEC27-1	27/12/1971	1	Tropical Cyclone	Qld	148.37	-26.80	CAZ-S
1972JAN12-5	12/1/1972	5	Monsoon Low	Qld	146.19	-18.97	CAZ-S IAZ
1973JAN24-1	24/1/1973	1	Tropical Cyclone	WA	121.54	-26.25	CAZ-S
1973JAN24-2	24/1/1973	2	Tropical Cyclone	WA	121.54	-26.26	CAZ-S
1973JUL10-6	10/7/1973	6	Extratropical (East Coast Low)	NSW	152.79	-30.32	CAZ-W
1974JAN08-1	8/1/1974	1	Monsoon Low	Qld	148.86	-28.68	CAZ-S IAZ
1974JAN09-4	9/1/1974	4	Monsoon Low	Qld	143.16	-27.18	CAZ-S IAZ
1974JAN09-3	9/1/1974	3	Monsoon Low	Qld	148.85	-28.68	CAZ-S IAZ
1974JAN14-5	14/1/1974	5	Monsoon Low	NSW	141.51	-29.62	CAZ-S IAZ
1974JAN23-6	23/01/1974	6	Monsoon Low	Qld	141.22	-18.87	CAZ-S IAZ
1974JAN27-9	27/1/1974	9	Monsoon Low	NT	134.45	-22.81	CAZ-S IAZ
1974JAN27-2	27/1/1974	2	Tropical Cyclone	Qld	153.23	-28.03	CAZ-S
1974JAN28-4	28/1/1974	4	Tropical Cyclone	Qld	153.21	-28.03	CAZ-S
1974FEB01-5	1/2/1974	5	Monsoon Low	SA	140.83	-27.69	CAZ-S IAZ
1974MAR13-4	13/3/1974	4	Tropical Cyclone	Qld/NSW	153.22	-28.23	CAZ-S
1975FEB25-6	25/2/1975	6	Tropical Cyclone	WA	120.46	-28.16	CAZ-S SWAZ-S
1975DEC10-2	10/12/1975	2	Tropical Cyclone	WA	118.72	-22.62	CAZ-S
1975DEC10-3	10/12/1975	3	Tropical Cyclone	WA	118.37	-22.29	CAZ-S
1976FEB06-3	6/2/1976	3	Ex-Tropical Cyclone	NT	135.95	-18.61	CAZ-S
1976FEB09-2	9/2/1976	2	Monsoon Low	NT	134.81	-25.70	CAZ-S IAZ
1976FEB10-1	10/2/1976	1	Monsoon Low	NSW	143.60	-29.48	CAZ-S IAZ

Storm Name	End Date	Duration	Classification	State	Centre		Zone/Season
					°E	°S	
1976FEB11-1	11/2/1976	1	Monsoon Low	NSW	150.59	-29.53	CAZ-S IAZ
1977FEB20-2	20/2/1977	2	Monsoon Low	Qld	141.94	-25.85	CAZ-S IAZ
1977MAY19-3	19/5/1977	3	Extratropical (East Coast Low)	NSW	152.92	-30.32	CAZ-W
1977MAY19-5	19/5/1977	5	Extratropical (East Coast Low)	NSW	152.92	-30.32	CAZ-W
1978JAN30-5	30/1/1978	5	Monsoon Low	WA	122.57	-17.32	CAZ-S IAZ
1978FEB02-2	2/2/1978	2	Monsoon Low	Qld	147.73	-23.51	CAZ-S IAZ
1979JAN05-1	5/1/1979	1	Tropical Cyclone	Qld	145.88	-17.28	CAZ-S
1979JAN06-4	6/1/1979	4	Tropical Cyclone	Qld	145.90	-17.26	CAZ-S
1979JAN06-5	6/1/1979	5	Tropical Cyclone	Qld	145.90	-17.26	CAZ-S
1979JAN06-2	6/1/1979	2	Tropical Cyclone	Qld	145.88	-17.27	CAZ-S
1979JAN06-3	6/1/1979	3	Tropical Cyclone	Qld	145.90	-17.28	CAZ-S
1979JAN07-7	7/1/1979	7	Tropical Cyclone	Qld	145.88	-17.26	CAZ-S
1979FEB06-1	6/2/1979	1	Monsoon Low	Qld	148.97	-20.96	CAZ-S IAZ
1981JAN13-7	13/1/1981	7	Monsoon Low	Qld	145.90	-17.30	CAZ-S IAZ
1982JAN20-5	20/1/1982	5	Tropical Cyclone	WA	124.53	-15.53	CAZ-S
1982JAN22-2	22/1/1982	2	Ex-Tropical Cyclone	WA	116.75	-33.51	CAZ-S SWAZ-S
1982JAN31-7	31/1/1982	7	Monsoon Low	Qld	141.91	-12.64	CAZ-S IAZ
1985JAN16-4	16/1/1985	4	Monsoon Low	Qld	142.67	-13.64	CAZ-S IAZ
1985JAN16-1	16/1/1985	1	Monsoon Low	Qld	142.65	-13.68	CAZ-S IAZ
1985MAR28-5	28/3/1985	5	Tropical Cyclone	NT	136.79	-15.75	CAZ-S
1986JAN24-5	24/1/1986	5	Tropical Cyclone	WA	125.35	-18.34	CAZ-S
1988MAR31-1	31/3/1988	1	Monsoon Low	NT	132.69	-23.64	CAZ-S IAZ
1988MAY02-2	2/5/1988	2	Extratropical (Cut-off Low)	WA	120.18	-33.95	SWAZ-W
1988MAY04-4	4/5/1988	4	Extratropical (Cut-off Low)	WA	120.17	-33.92	SWAZ-W
1988JUN27-4	27/06/1988	4	Extratropical (Front / Cut-off Low)	WA	116.79	-34.98	SWAZ-W
1989MAR14-1	14/3/1989	1	Monsoon Low	SA	138.32	-31.18	CAZ-S IAZ

Storm Name	End Date	Duration	Classification	State	Centre		Zone/Season
					°E	°S	
1989MAR14-2	14/3/1989	2	Monsoon Low	SA	139.19	-30.57	CAZ-S IAZ
1989MAY10-1	10/5/1989	1	Extratropical (Easterly Dip / Upper Trough)	Qld	143.82	-24.31	CAZ-W
1989JUN14-1	14/6/1989	1	Extratropical (Cut-off Low)	WA	117.64	-30.70	SWAZ-W
1990JAN29-2	29/1/1990	2	Ex-tropical Cyclone	WA	118.17	-32.64	CAZ-S SWAZ-S
1991JAN01-7	1/1/1991	7	Tropical Cyclone	Qld	148.82	-20.99	CAZ-S
1991JAN14-1	14/1/1991	1	Monsoon Low	Qld	140.66	-20.24	CAZ-S IAZ
1995FEB28-4	28/2/1995	4	Tropical Cyclone	WA	119.70	-28.58	CAZ-S SWAZ-S
1996MAR10-7	10/3/1996	7	Tropical Cyclone	Qld	141.96	-12.55	CAZ-S
1996MAY06-6	6/5/1996	6	Extratropical (East Coast Low)	Qld	152.38	-27.85	CAZ-W
1996MAY07-7	7/5/1996	7	Extratropical (East Coast Low)	Qld/NSW	153.25	-28.19	CAZ-W
1997FEB03-7	3/2/1997	7	Monsoon Low	Qld	147.13	-25.52	CAZ-S IAZ
1997MAR06-7	6/3/1997	7	Monsoon Low	Qld	139.82	-21.20	CAZ-S IAZ
1998JAN29-4	29/1/1998	4	Tropical Cyclone	NT	130.51	-13.74	CAZ-S
1998MAR05-7	5/3/1998	7	Tropical Cyclone	Qld	139.57	-17.76	CAZ-S
1998DEC10-2	10/12/1998	2	Tropical Cyclone	NT	130.97	-12.50	CAZ-S
1999FEB13-2	13/2/1999	2	Tropical Cyclone	Qld	145.75	-17.38	CAZ-S
1999MAY28-3	28/05/1999	3	Extratropical (Cut-off Low)	WA	114.30	-28.04	SWAZ-W

APPENDIX 2:
Testing Applicability of the GSAM Technique for Estimating Convergence Component

The best evidence for the applicability of the technique used for estimating the convergence component of the storm depth is the success of both the GSAM test (Minty et al 1996) and the GSAM application in general. However, it remains important to test whether the same basic approach may be applied in a different meteorological zone with different storm mechanisms generating the significant rainfall events. As such, a test was constructed for a region in the GTSM zone using exactly the same approach as GSAM. The area tested was the region between Brisbane and Fraser Island (Figure A2.1). To test the technique for separating the storm components, the rainfall history of an area that is flat and that of an adjacent area that has marked topography was examined. In the Brisbane example, significant topography exists in the south (Region 1), yet there is a relatively flat area (of the same size) to the north (Region 2). In theory, this is a simple exercise, yet in practice it becomes complicated. In the example shown, the flat region still has some significant topography, yet was chosen this way to encompass a reasonable number of significant storms and still be the same size as the zone with significant topography in the south. Finding an appropriate region of flat and significant topography is quite difficult.

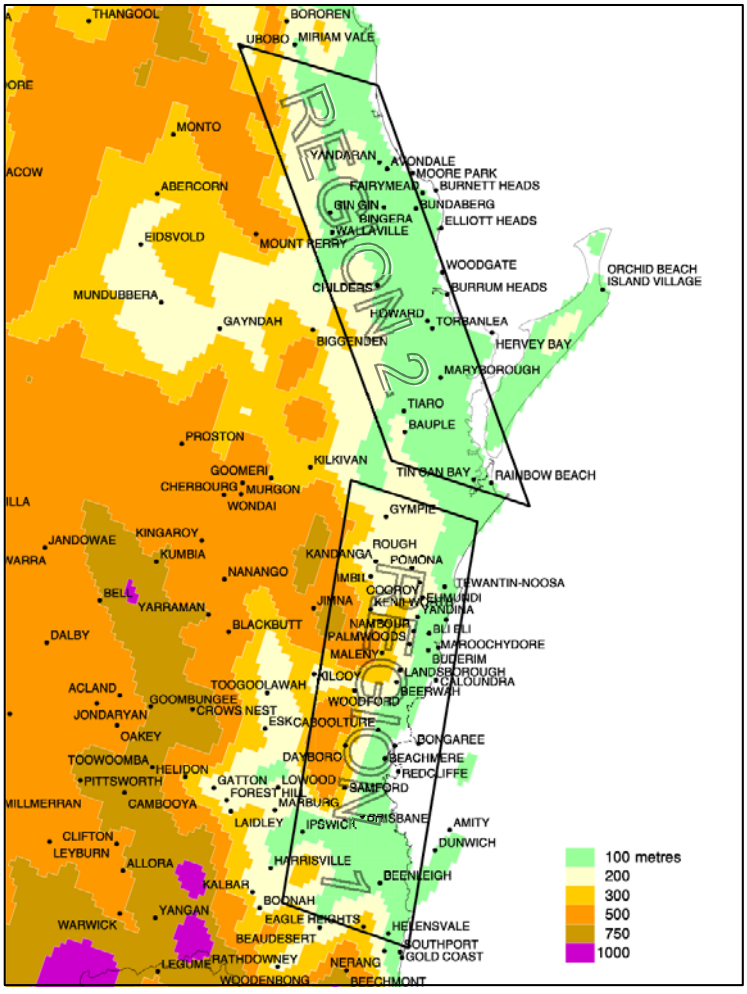

Figure A2.1: The area on the Queensland coast that was used to test the GSAM/GTSMR methodology for topography. Region 1 defines the area of significant topography. Region 2 defines the region with relatively little topography.

It was assumed that the two areas have an equal chance of experiencing severe storms during the period of record (approximately 100 years). With similar meteorology, any substantial differences in rainfall depths recorded for the storms in each area can be attributed to the differences in topography. Based on the Bureau of Meteorology rainfall archives, the ten highest 1-day and 3-day storms were selected for each area. The convergence components of each storm were obtained by multiplying the total storm depth by the rainfall intensity ratio on a point-by-point basis as follows:

$$Convergence\ Storm\ Depth = Total\ \ Storm\ Depth \times \frac{Convergence\ Rainfall\ \ Intensity}{Total\ Rainfall\ \ Intensity} \quad \text{(A2.1)}$$

This gave a spatial map of convergence rainfall depth over the storm. For ease of comparison, the depth-area curve is a convenient way of representing the storm. Such curves were constructed for each storm for both the total storm depth and the convergence depth. These curves are presented for a sample storm over each of Region 1 and Region 2 in Figures A2.2 (a) and (b).

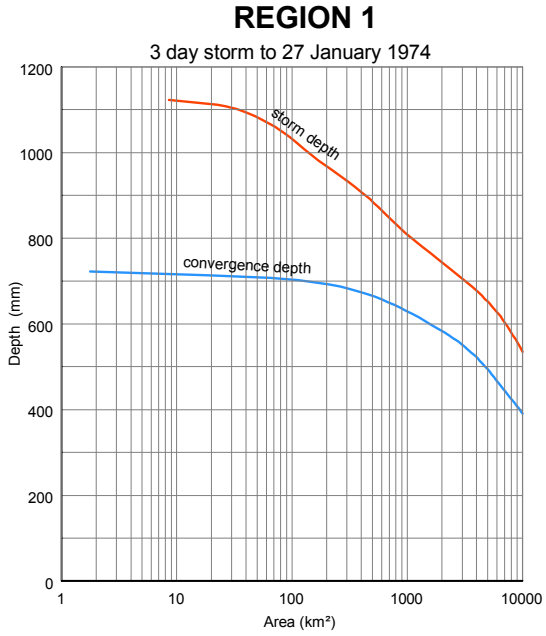

Figure A2.2 (a): Depth-area curves for total storm depth and convergence storm depth in Region 1

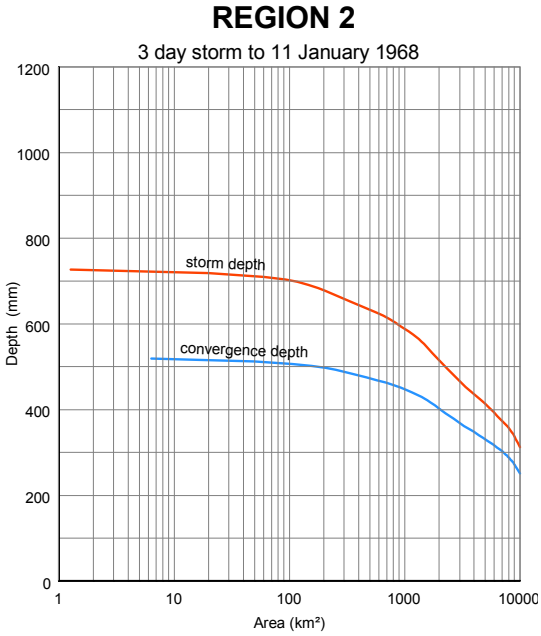

Figure A2.2 (b): Depth-area curves for total storm depth and convergence storm depth in Region 2

An average depth-area for the top ten storms in each area can be calculated. Figure A2.3 (a) shows the average 3-day total storm depth-area curves for both. It is reasonably clear that there is a systematic difference in the depths at all areas. The depths over the Region 1 show depths some 250 mm in excess of the flat region at small areas. Even at very large areas, the differences are still 100 mm. This is not surprising given that it might be anticipated that there will be significant topographic enhancement of the rainfall over Region 1.

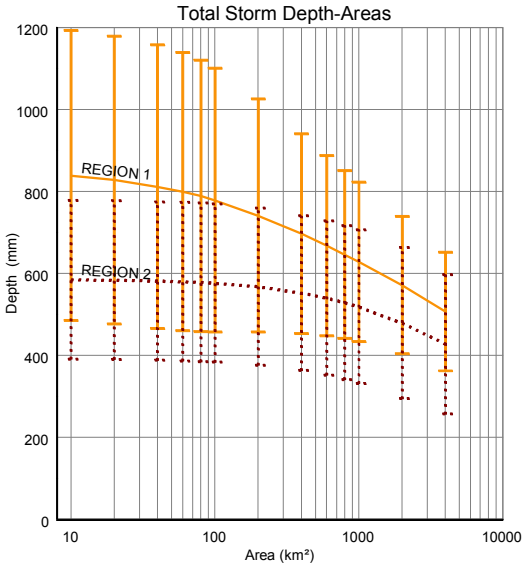

Figure A2.3 (a): Depth-area curves for total storm depth for Region 1 and Region 2. Also marked is the range of 1 standard deviation

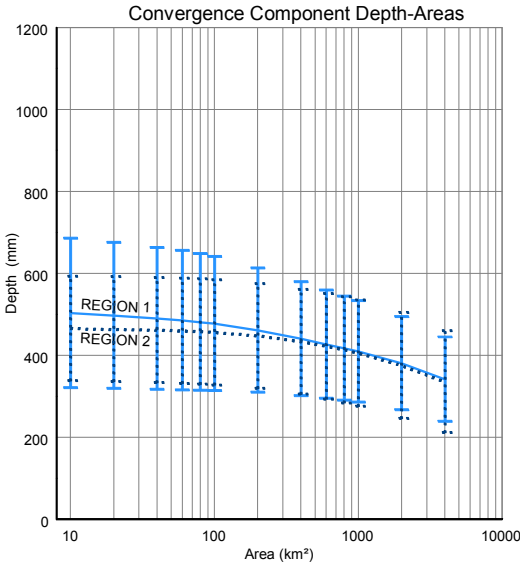

Figure A2.3 (b): Depth-area curves for convergence component of storm depth for Region 1 and Region 2. Also marked is the range of 1 standard deviation

The storm can now be divided into its component rainfalls using the techniques described and Figure A2.3 (b) shows the Convergence component of the rainfall over both regions. The depth has been lowered over both areas (topographic enhancement is present in both), but not surprisingly, there has been much greater change to Region 1 where there were significant topographic landmarks. Encouragingly, within the range of signal versus noise, there is no significant difference between the two locations now. This is as would be hoped given the close proximity of the two locations and their exposure to the same meteorology. It appears that the separation of the storm components using this IFD ratio technique is successful.

A second test was completed for another part of the GTSM zone. The second location was near Perth (see Figure A2.4).

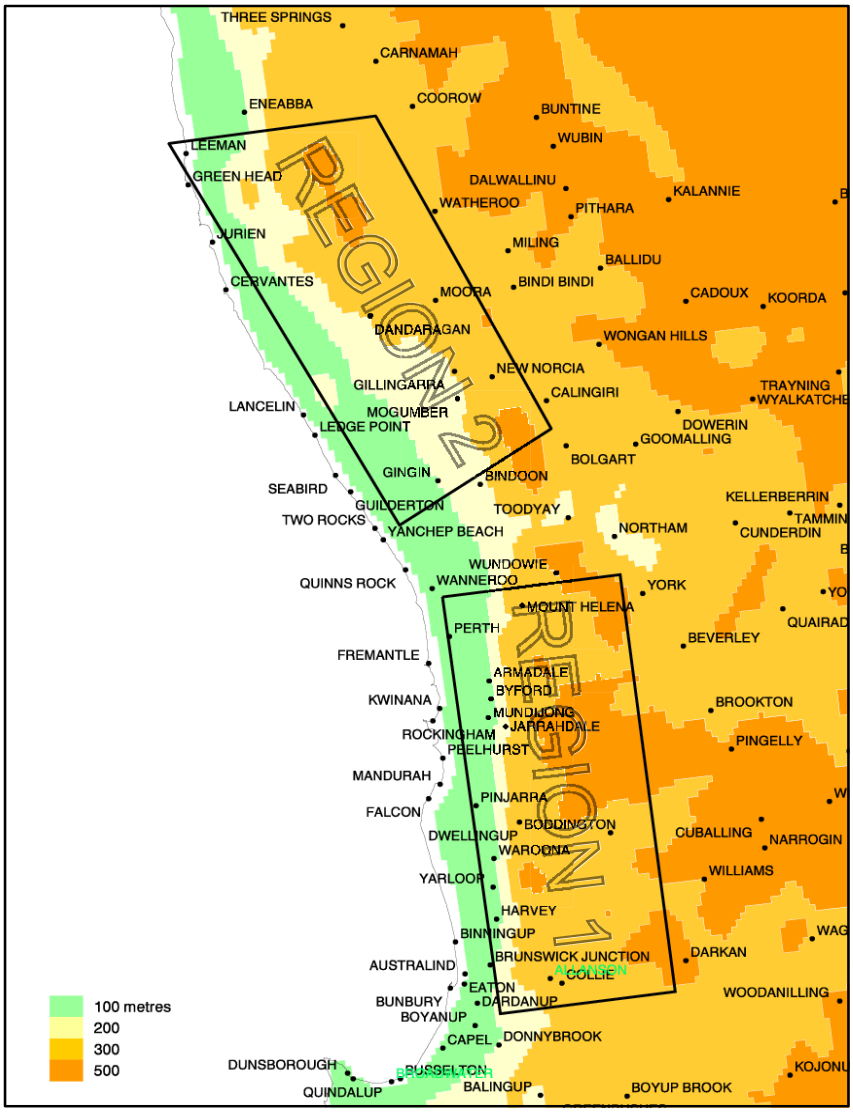

Figure A2.4: The area on the Western Australian coast that was used to test the GSAM/GTSMR methodology for topography. Region 1 defines the area of significant topography. Region 2 defines the region with relatively little topography.

A similar test was applied extracting the top ten storms and constructing average depth-area curves for the total storm rain depth and for the convergence component. However, the southwest of Western Australia provides some interesting problems. The rare, very large event in southwest Western Australia is a decaying tropical cyclone. However, it is a very rare event. In the 100-odd year record in Western Australia, there are not ten of these extreme events and the remainder are padded out with frontal type events that are nearly always systematically lower. When interpreting the results for this region, it is useful to recognise the differences between the winter and summer seasons. The total and convergence depth curves for the two regions, for 72-hour storms, are presented in Figure A2.5 (a) and (b). While the differences between the flat region and that with significant topography are not as great as for Queensland (small topography) we still find that the systematic difference is well captured and removed for the convergence component.

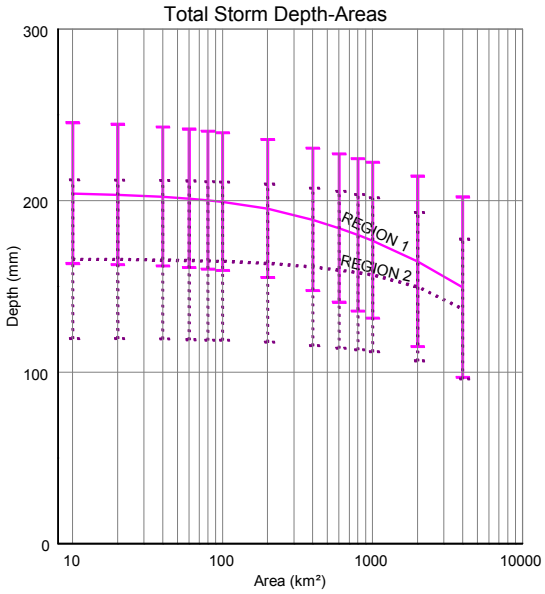

Figure A2.5 (a): Depth-area curves for total storm depth for Region 1 and Region 2

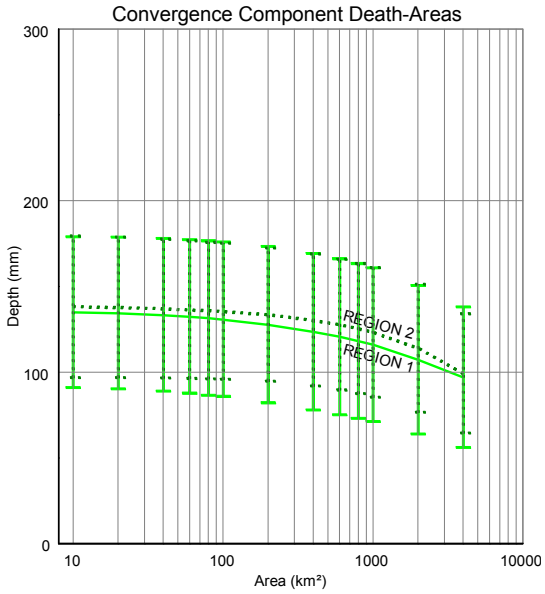

Figure A2.5 (b): Depth-area curves for convergence component of storm depth for Region 1 and Region 2.

The results for southwest Western Australia indicate that while not quite as clear as for Queensland (probably due to the lesser orographic influence and the different storm types in the sample), the storm-separation procedure using the technique of GSAM is successful.

APPENDIX 3: Design Depth-Area Curves for all Zones

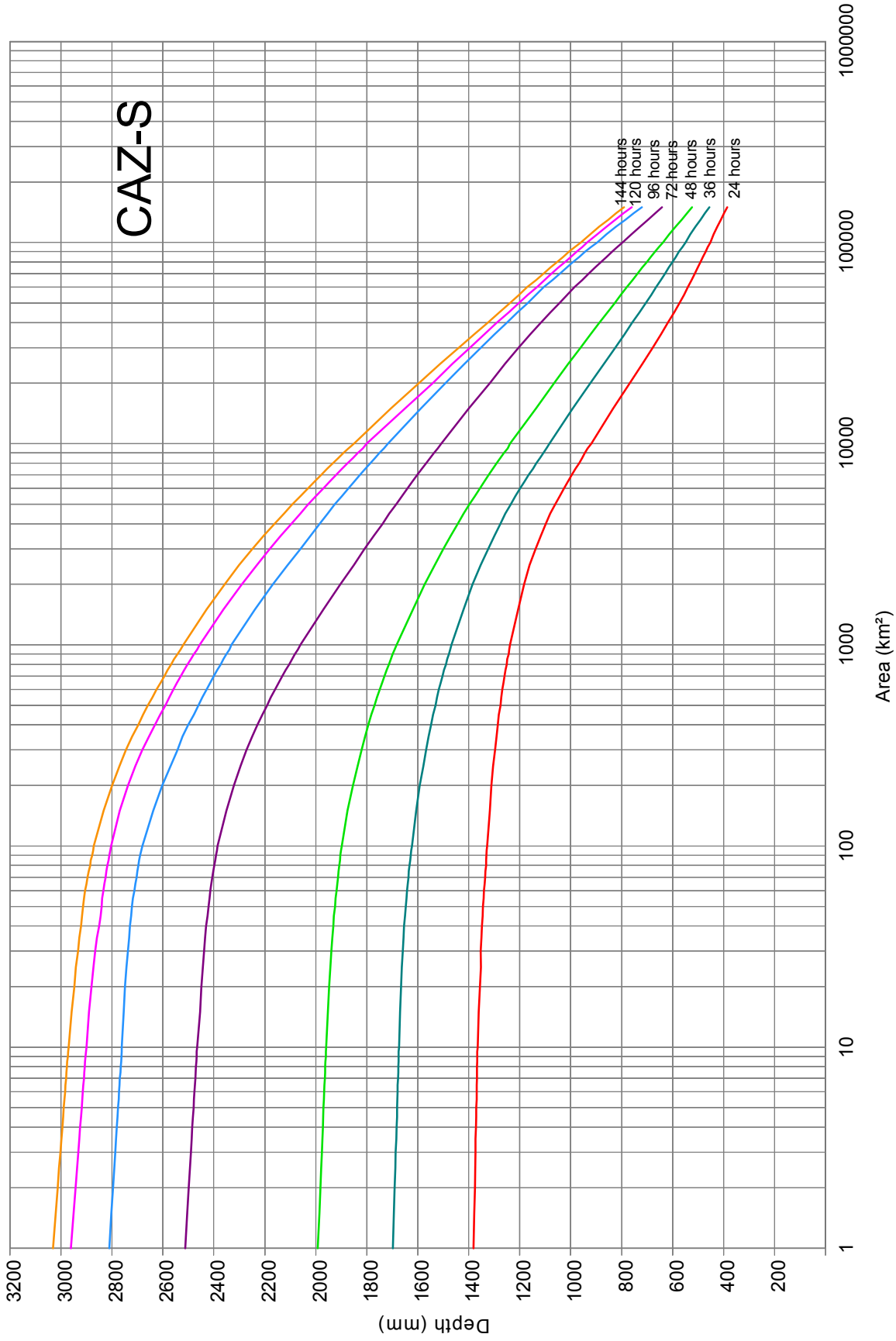

Figure A3.1: Design depth-area curves for use with catchments in the coastal application zone during summer (CAZ-S)

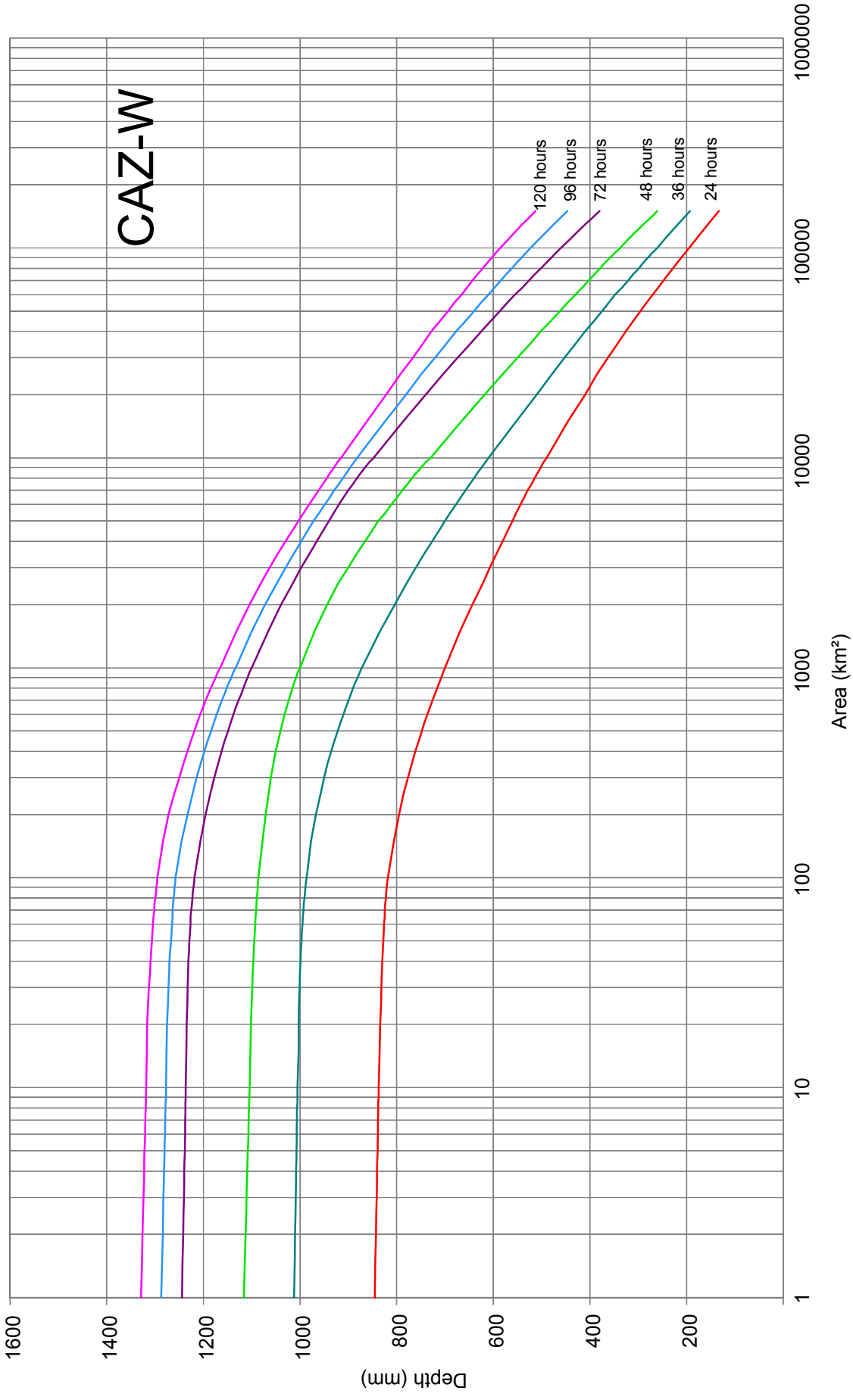

Figure A3.2: Design depth-area curves for use with catchments in the coastal application zone during winter (CAZ-W)

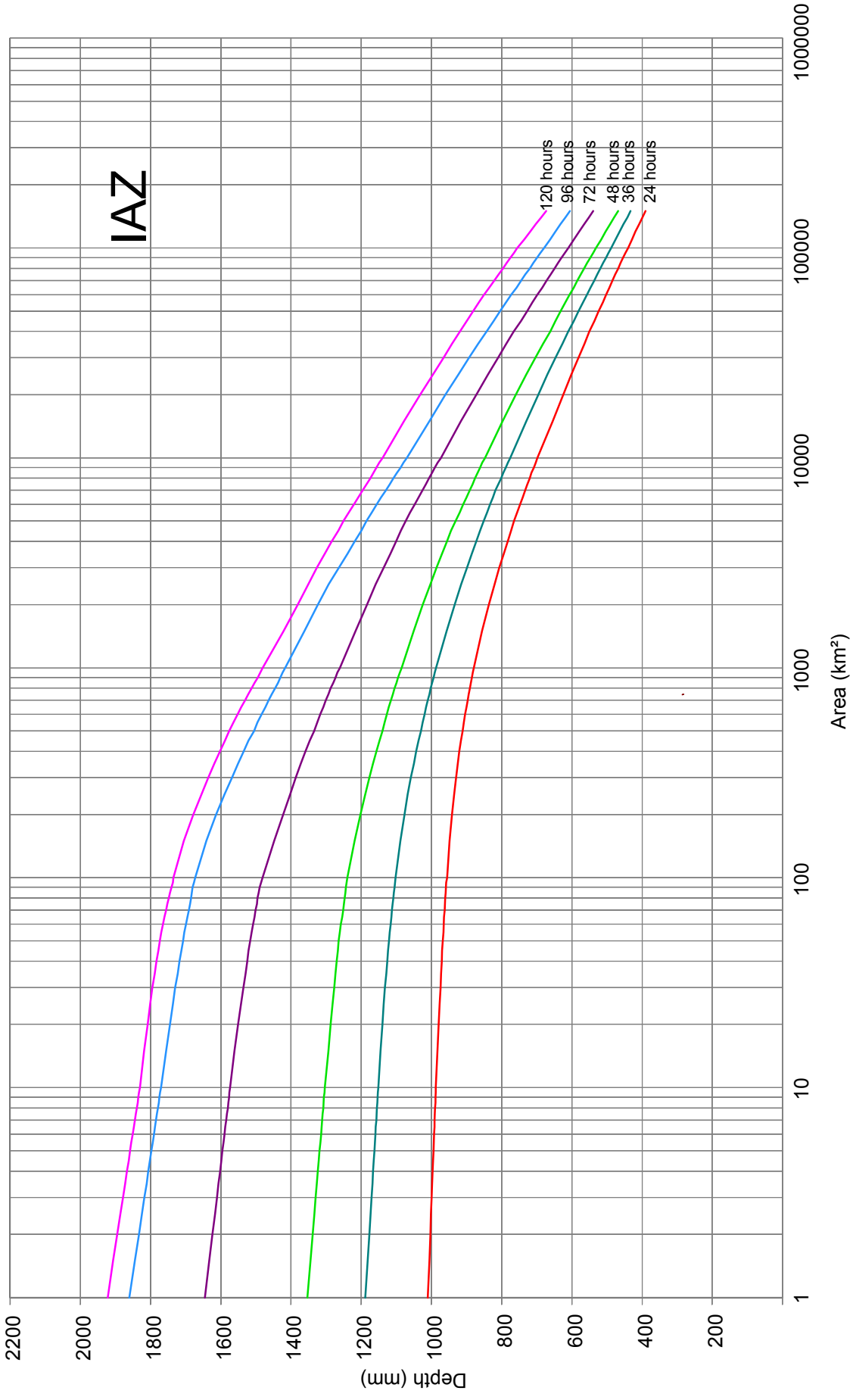

Figure A3.3: Design depth-area curves for use with catchments in the inland application zone (IAZ)

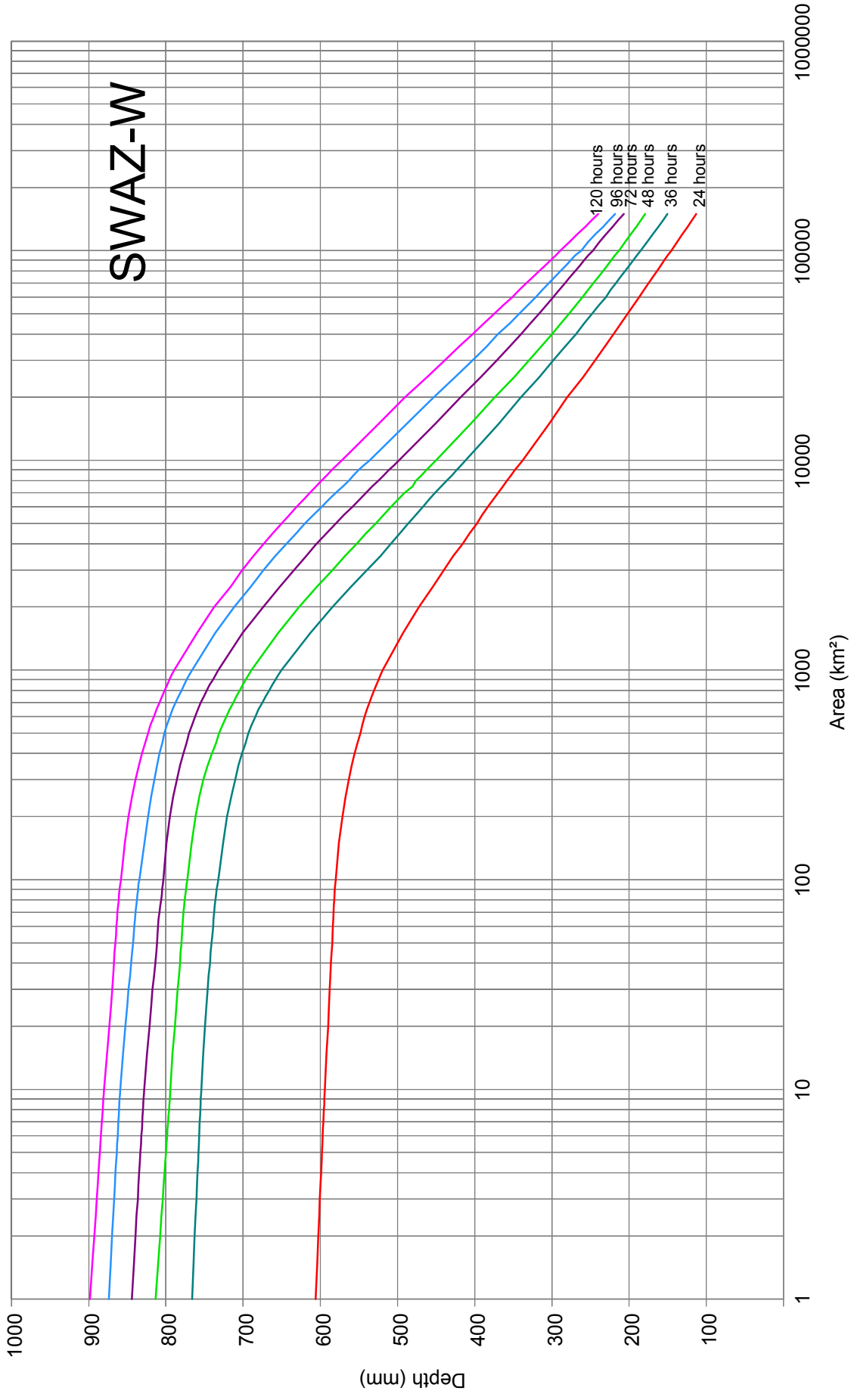

Figure A3.4: Design depth-area curves for use with catchments in the southwest application zone (SWAZ-W)

HYDROLOGY REPORT SERIES

HRS1	Temporal Distributions Within Rainfall Bursts	September 1991
HRS2	Analysis of Australian Rainfall and Rainday Data with Respect to Climatic Variability and Change	February 1992
HRS3	Catalogue of Significant Rainfall Occurrences Over Southeast Australia	October 1995
HRS4	Development of the Generalised Southeast Australia Method for Estimating Probable Maximum Precipitation	August 1996
HRS5	Temporal Distributions of Large and Extreme Design Rainfall Bursts over Southeast Australia	December 1998
HRS6	Rainfall Antecedent to Large and Extreme Rainfall Bursts over Southeast Australia	December 1999
HRS7	Development of the Method of Storm Transposition and Maximisation for the West Coast of Tasmania	January 2001
HRS8	Revision of the Generalised Tropical Storm Method for Estimating Probable Maximum Precipitation	August 2003