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The Estimation of Probable Maximum Precipitation in Australia: Generalised Short-Duration Method

HYDROMETEOROLOGICAL ADVISORY SERVICE
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JUNE 2003

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1. INTRODUCTION

Probable Maximum Precipitation (PMP) is defined by the World Meteorological Organization (1986) as ‘*the greatest depth of precipitation for a given duration meteorologically possible for a given size storm area at a particular location at a particular time of year*’.

Hydrologists use a PMP magnitude, together with its spatial and temporal distributions, for the catchment of a dam to calculate the probable maximum flood (PMF). The PMF is one of a range of conceptual flood events used in the design of hydrological structures. In the main, it is used to design a spillway that will minimise the risk of overtopping of the dam. Overtopping of a dam structure can result in damage to the dam wall or abutments through breaching. The risk of loss of life, cost of rebuilding the dam, cost of the additional flood damage downstream and cost to the community due to the loss of a water supply can thus be minimised.

The purpose of this publication is to provide a method that can be used to make consistent and timely estimates of probable maximum precipitation for catchment areas up to 1000 km^2. Estimates are limited to a duration of six hours along the tropical and subtropical coastal areas and three hours in inland and southern Australia. The method allows for two classes of terrain and takes into account the local moisture availability and the mean elevation of the catchment.

The low density of the raingauge networks, particularly the pluviograph network, has resulted in few severe short-duration rainstorms having been recorded or documented in Australia. This is particularly the case in the sparsely populated part of the continent away from the coastal fringe and is a severe limitation on the estimation of short duration probable maximum precipitation in Australia. For this reason, United States data and Australian data have been used in the development of the Generalised Short Duration Method for use in Australia. Areal rainfall data are provided for some major Australian rainstorms in Appendix 3 to support the PMP magnitudes derived.

Design temporal and spatial distributions of PMP based on average storm characteristics are also given. These facilitate the distribution of the PMP depth when used in hydrological models.

This document replaces ‘Bulletin 53: The Estimation of Probable Maximum Precipitation in Australia: Generalised Short Duration Method’ (Bureau of Meteorology, December 1994), and should be used instead. It was considered that a new version was required as, since 1994, a revised method of spatial distribution has been introduced and the moisture factors updated.

2. HISTORY OF THE DEVELOPMENT OF PMP METHODOLOGY IN AUSTRALIA

The early methods used to estimate extreme floods, other than reliance on local knowledge, were statistical. Frequency analysis has been used in most parts of Europe where it is relatively effective due to the homogeneity of the storm population, the long length of records and the availability of historical flood marks. The original spillway designs of some Australian dams, such as the Warragamba Dam, were based on this method. In the tropics and subtropics (e.g. Australia), the lack of homogeneity in the storm population and relatively short length of records cause significant deficiencies in the severe storm rainfall sample available for frequency analysis. This led to the need to develop deterministic methods, which used the sample outliers to estimate the rainfall from the optimum storm mechanism and a maximisation factor to adjust the storm rainfall to that possible with the potential extreme moisture inflow.

The deterministic methods of estimating PMP have developed from '*in situ* maximisation' through 'storm transposition' to the current 'generalised' methods.

2.1 *In Situ* Storm Maximisation Method

Early estimates of PMP in Australia (1950s to 1970s) were based on *in situ* maximisation. Only storms that had occurred over the catchment were considered for maximisation. The rainfall depths from storms covering a range of durations were maximised for moisture and the maximum depth at a specified duration was taken as the PMP for that duration. The maximisation procedure consisted of the adjustment of the rainfall depth measured in a storm by the ratio of the highest observed atmospheric moisture content in the area of the catchment to that observed in the storm. In some cases, the rainfall was also maximised for potential wind speed and direction accompanying the rainfall, but in general there was insufficient information available to make this practical. Wind speed and direction are now considered to be part of the overall storm mechanism. Recorded temporal and spatial distributions of the individual storms were used as design patterns.

The occurrence or lack of occurrence of an outlier in the storm sample, within the length of rainfall records available for different catchments, led to inconsistencies between PMP estimates for catchments in the same general area.

2.2 Storm Transposition Method

During the late 1960s and early 1970s storm transposition was gradually introduced. This procedure increased the size of the sample of significant storms that could be maximised for a catchment. The larger sample improved the consistency of PMP estimates within regions of similar topography, and generally led to higher PMP estimates than those produced using *in situ* maximisation.

The method was limited to the transposition of storms that had occurred near the catchment in regions with similar topographic features to those of the catchment. No guidance was available on how to adjust storm depths for the response of rainfall to differing topography. Consequently, storms that occurred near the subject catchment could not be transposed if they had occurred over a region with different topography. In addition, the individual storm spatial patterns of the transposed storms reflected the topography of the storm area and were not always appropriate for use in the target catchment. The choice of storms for transposition introduced a significant level of subjectivity to the methodology.

A storm transposition method is used for catchments in southwestern Tasmania, as described in ‘Development of the Method of Storm Transposition and Maximisation for the West Coast of Tasmania - HRS 7’ (Xuereb et al., 2001); the extreme lack of data making it impractical to develop a generalised method for this region.

2.3 Generalised Methods

Generalised methods of estimating PMP have gradually been developed for various parts of Australia and were introduced from the mid-1970s onward. This follows the trend in the United States where they were gradually introduced from the early 1960s. Generalised methods differ from the *in situ* and transposition methods in that they use all available data over a large region and include adjustments for moisture availability and differing topographic effects on rainfall depth. These storm data are enveloped by smoothing over a range of areas and durations. Generalised methods also provide design spatial and temporal patterns of PMP for the catchment. These methods require a considerable investment of time to develop, but when completed, estimates for individual catchments can be made more easily and objectively.

The United States generalised methods for areas with minimal topographic enhancement were developed first as an extension of the limited transposition methods. This type of method was suitable for most of the United States east of the Rocky Mountains (United States National Weather Service, 1978). Variations on the basic method were then gradually developed for areas with significant topographic enhancement of the rainfall. The method of dealing with topographic effects varies considerably, reflecting the specific problems posed by the prevailing meteorological regime and the availability of meteorological information (World Meteorological Organization, 1986; United States Weather Bureau, 1961, 1965, 1969; United States National Weather Service 1977, 1984, 1988; Wang, 1986).

The use of generalised methods has tended to increase the PMP estimates for a given catchment, compared with those obtained using the ‘*in situ* maximisation’ and ‘storm transposition’ methods due to the increased chance of the larger sample containing an outlier. This is discussed with respect to the Warragamba Dam Catchment in Pearce (1993). Generalised method estimates have a lower notional Annual Exceedance Probability (AEP). They also have the advantage of providing regionally consistent estimates, although the notional AEP may vary slowly across a large zone or differ between zones. In assessment of both comparative risk and cost-benefit analyses between dams within a region, generalised methods set a more uniform standard than *in situ* or limited transposition methods (where topographic effects made transposition subjective).

The generalised methods currently available in Australia are:

i) The Generalised Short Duration Method (GSDM) described in chapters 3 and 4.

(ii) The Generalised Southeast Australia Method (GSAM), which was finalised in 1992. This method is for use in catchments in southeast Australia and is described by Kennedy et al. (1988), Pearce and Kennedy (1993, 1994) and Minty et al. (1996). Figure 1 shows the two zones for application of the GSAM: inland and coastal. The maximum duration covered by this method ranges from 3 to 5 days

(iii) The revised version of the Generalised Tropical Storm Method (GTSMR), which was finalised in 2003. This method is applicable to those parts of Australia affected by tropical storms and divides the region into 3 parts: the coastal application zone (CAZ), the inland application zone (IAZ) and the southwest Western Australia application zone (SWAZ). Figure 1 shows these zones. The maximum duration covered by this method is 5 days in the coastal zone in summer and 4 days for all other zones and seasons. The method is described in Walland et al. (2003).

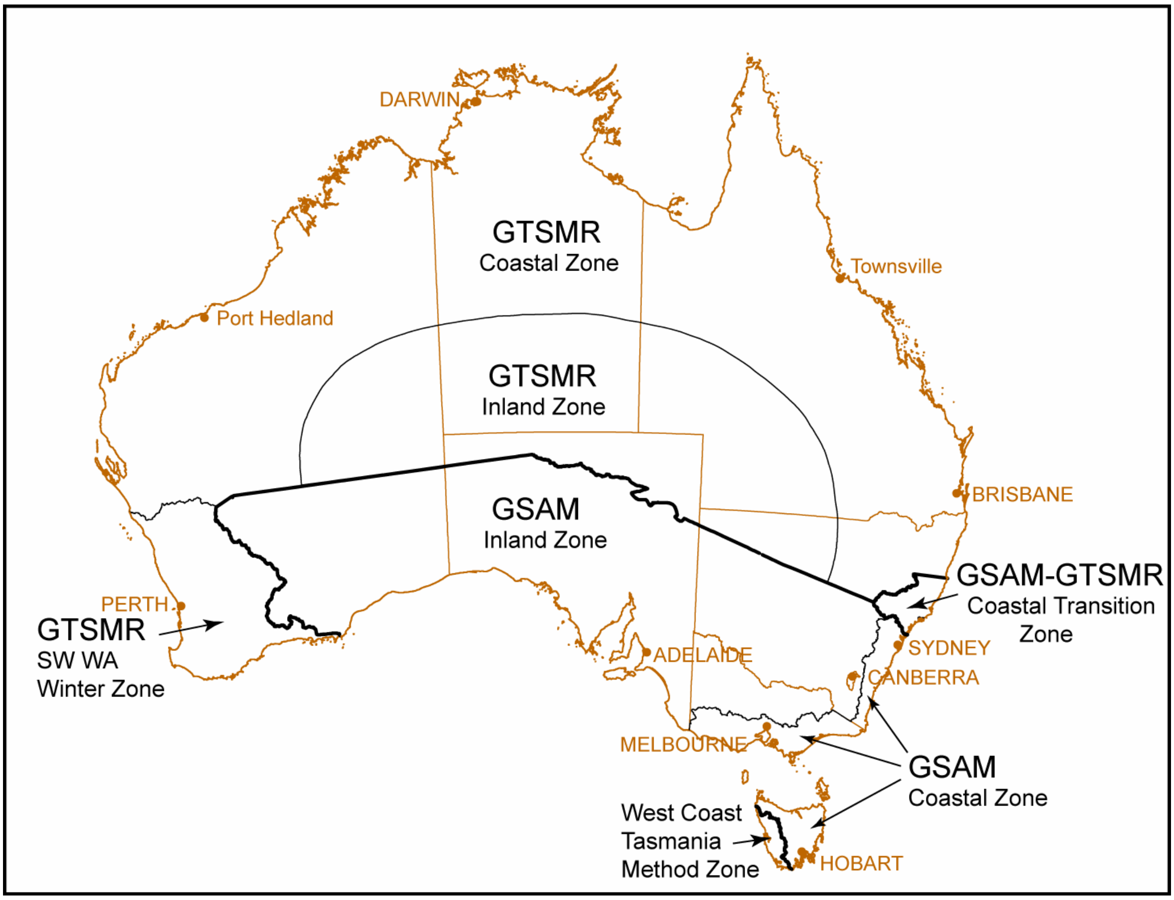

Figure 1: **Generalised Tropical Storm Method and Generalised Southeast Australia Method Zones**

2.4 Limitations and Restrictions on Generalised PMP Estimation Methods used in Australia

The accuracy and reliability of an estimate depends on the amount and quality of the data available for use in the estimating procedure and the maintenance of a balance in the degree of maximisation used in order to obtain realistic estimates. The transposition method was limited to the use of storms that occurred near the catchment in areas with similar topographic features. The generalised methods use a deterministic approach to adjust for topographic and moisture effects and thus increase the usable transposition area. However, even with these adjustments there are meteorological limitations on the transposability of some types of storms. The selection of meteorologically compatible zones in generalised PMP methodology requires that an equivalent optimum storm mechanism could occur anywhere in the transposition area; the frequency of occurrence is not important. The GTSMR, for example, is only applicable to those parts of Australia affected by tropical storms. The frequency of occurrence of the storm mechanisms varies considerably across the zones, but this does not necessarily affect the magnitude of the estimated PMP.

The restrictions on the GSAM and GTSMR PMP estimation methods for short durations are due to the limitations on availability and quality of short duration storm data. The development of these methods relied significantly on daily data in order to make the most effective use of record length and network density for the storm search procedures. These methods therefore need to be used in conjunction with the GSDM where appropriate (i.e. over small catchments where the critical duration is between that covered by the GSDM and the GSAM or GTSMR).

All three of the generalised methods are based on single storm events only, including single storms with multiple peaked temporal distributions. This means that the methods have an upper limit to the effective duration for which they can be applied to the catchment. The joint probability of a design sequence of two or more extreme rainfall events would be much lower than the probability of the generalised PMP event by itself.

None of the methods incorporates long-term climate change, other than climatic variability implicitly contained within the available years of records. However, climatic trends progress slowly so their influence on PMP is small compared to other uncertainties in estimating extreme values. This is consistent with the current practice described in World Meteorological Organization (1986).

3. BACKGROUND TO PMP ESTIMATION FOR SHORT DURATIONS

Methods for estimating PMP for small areas and short durations have been used by the Bureau of Meteorology since 1960. The first depth-duration-area (DDA) values used in Australia were those published by the United States Weather Bureau in 1945 (United States Weather Bureau, 1945).

The original method was known as the ‘Thunderstorm Model’ method because extreme rainfall totals for short durations and small areas are most likely to be produced by large, efficient convective cells. These cells may be either isolated thunderstorms or form part of a mesoscale or synoptic scale storm system. Later, the method became known as the ‘method of adjusted United States data’ (Kennedy, 1982). PMP estimation for short durations and small areas in Australia was based on the maximisation of United States thunderstorm depth-duration-area (DDA) data because of an inadequate supply of Australian short duration rainfall data. The Australian network of daily rainfall gauges has a far greater density and more effective years of record than the pluviograph network.

Initially it was recommended that the method be used to estimate PMP over areas up to 200 mi^2 (520 km^2) and for durations up to 6 hours for catchments in the tropical and subtropical coastal strips of the continent. The method was later extended to cover inland and southern Australia where the limit to the duration was 3 hours. The maximum area for application was also increased to 1000 km^2 for all areas.

In 1978 the DDA curves used by the Bureau of Meteorology were updated using information given in later hydrometeorological reports (United States Weather Bureau, 1960, 1969; United States National Weather Service, 1977, 1978) and by Wiesner (1970). At this time, terrain classifications of ‘rough’ and ‘smooth’ were introduced, with separate sets of DDA curves being provided for each category.

In 1984 a phenomenal storm occurred near Dapto in New South Wales (Shepherd and Colquhoun, 1985). For some areas and durations, the maximised rainfall from this storm exceeded the adjusted United States values. Areal rainfall depths recorded in this storm were added to the United States data when the method was published in 1985 as ‘Bulletin 51: The Estimation of Probable Maximum Precipitation in Australia for Short Durations and Small Areas’ (Bureau of Meteorology, 1985).

With the publication of *Bulletin 51,* the six-hour zone was broadened, especially in northern Australia, and an intermediate zone was introduced between the three and six hour zones. Subsequently, the definitions of ‘rough’ and ‘smooth’ terrain were altered, as described in ‘Australian Rainfall and Runoff’ (The Institution of Engineers, Australia, 1987). This and other adjustments were included in the next edition, published as *Bulletin 53* in 1994. Since then, the method has been referred to as the ‘Generalised Short Duration Method’ (GSDM), in line with the terms used to describe other generalised methods.

The GSDM is suitable for application to small catchments such as those of tailings dams and small reservoirs anywhere in Australia. Chapter 4 explains the GSDM procedure in detail and a worked example is found in Appendix 2. Additionally areal rainfall depths recorded in a number of severe Australian storms are given in Appendix 3.

4. GSDM PROCEDURE

This section describes in detail the steps to be followed in determining GSDM PMP estimates for a catchment. A sample calculation sheet to use with this procedure is given in Appendix 1 and an example covering all the steps is provided in Appendix 2.

4.1 Selection of Duration Limits

The first step is to establish the maximum duration for which the method is applicable to the catchment. Figure 2 shows the areas of Australia subject to the duration limits of three and six hours. There is also an intermediate zone where the maximum duration can be determined by using linear interpolation, setting the boundary values to three and six hours.

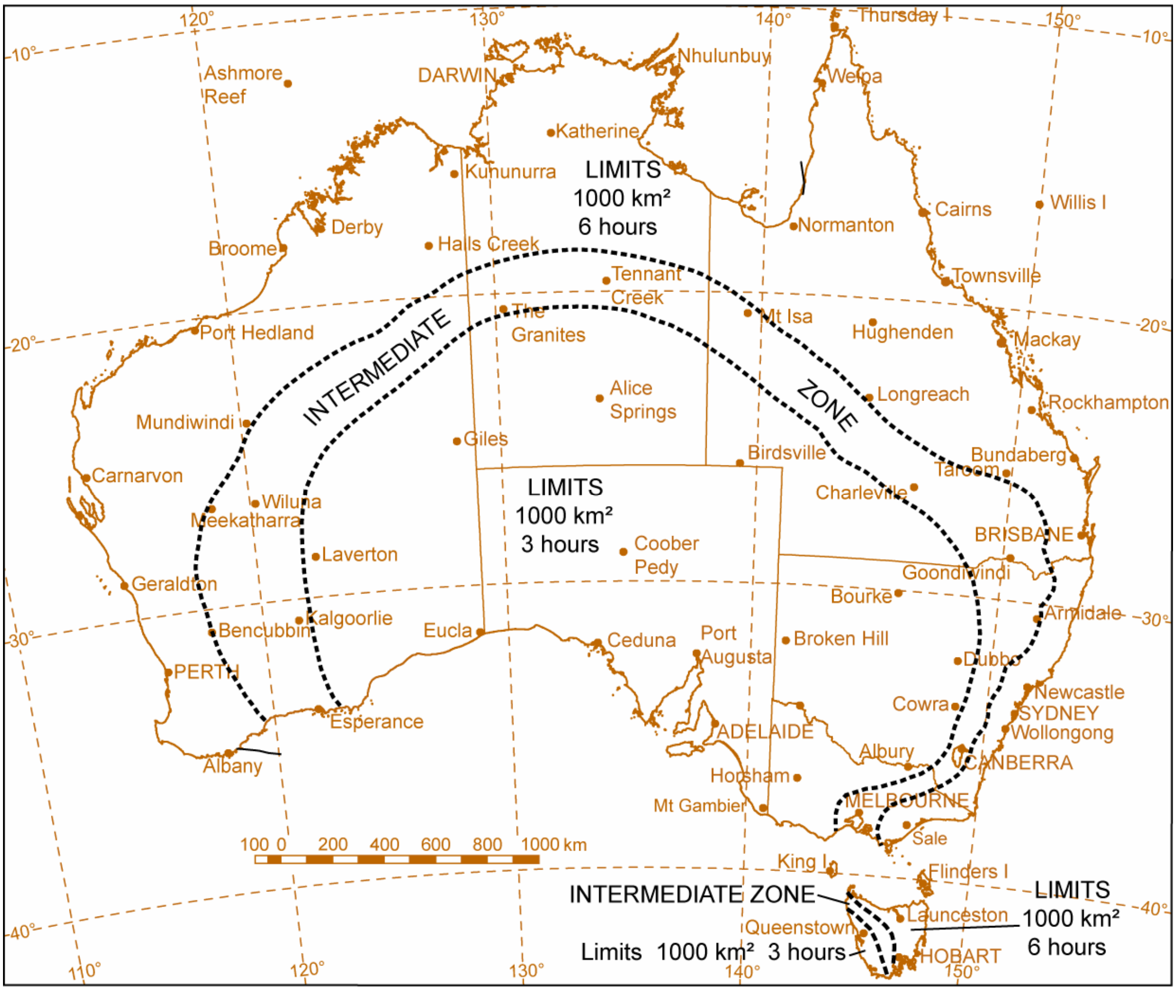

Figure 2: Generalised Short-Duration Method zones.

4.2 Selection of Terrain Category

Rainfall from single, short duration thunderstorm events is not significantly affected by the terrain. Therefore, it is not necessary to classify the terrain of the catchment for durations of an hour or less.

If durations longer than one hour are required, the next step is to establish the terrain category of the catchment and to calculate the percentages of the catchment that are ‘rough’ and ‘smooth’. ‘Rough’ terrain is classified as that in which elevation changes of 50 m or more within horizontal distances of 400 m are common. ‘Rough’ terrain induces areas of low level convergence which can contribute to the development and redevelopment of storms, thereby increasing rainfall in the area over longer durations.

Terrain that is within 20 km of generally ‘rough’ terrain should also be classified as ‘rough’. If there is ‘smooth’ terrain within the catchment that is further than 20 km from generally ‘rough’ terrain, an areally weighted factor of ‘rough’ (**R**) and ‘smooth’ (**S**) terrain should be calculated such that **R** plus **S** equals one. If a catchment proves difficult to classify under these guidelines then the whole catchment should be classified as ‘rough’.

4.3 Adjustment for Catchment Elevation

The next step is calculation of the Elevation Adjustment Factor (**EAF**). The mean elevation of the catchment should be estimated from a topographic map. If this value is less than or equal to 1500 m the EAF is equal to one. For elevations exceeding 1500 m the EAF should be reduced by 0.05 for every 300 m by which the mean catchment elevation exceeds 1500 m. For most catchments in Australia the EAF will be equal to one.

4.4 Adjustment for Moisture

The moisture index used in PMP work is the precipitable water value corresponding to the 24-hour persisting dewpoint. By assuming a saturated atmosphere with a pseudo-adiabatic lapse rate during storm conditions, the precipitable water value can be estimated from the surface dew point temperature, a commonly measured quantity. The ratio of the extreme moisture index for a storm location to the moisture index at the time of the storm was used in the maximisation process.

The rainfall Depth-Duration-Area (DDA) curves in Figure 4 have been standardised to a moisture index equivalent to a surface dew point temperature of 28°C. An adjustment is required to allow for the potential moisture availability at the catchment. A map has been constructed based on the percentage adjustment for any locality and is given in Figure 3. The Moisture Adjustment Factor (**MAF**) for a catchment can be read from this map.

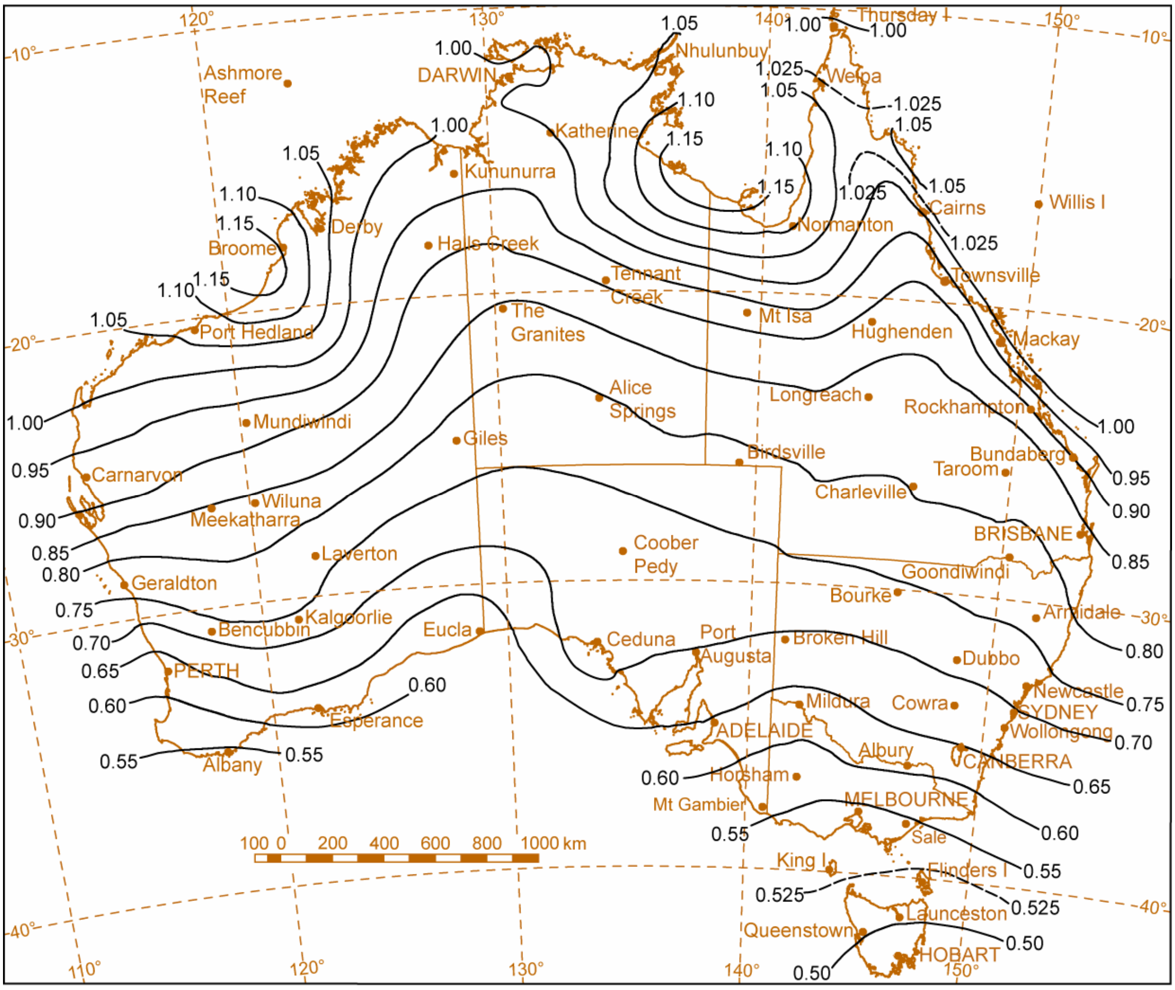

Figure 3: Moisture Adjustment Factor

4.5 Calculation of PMP Estimates

The DDA curves, given in Figure 4, were produced by drawing enveloping curves to the highest recorded United States and Australian rainfall depths, which had been adjusted to correspond to a common moisture index.

Also given in Figure 4 are PMP values applicable to a point, based on those given by Wiesner (1970). If a PMP value is required for an area smaller than 1 km^2 the value can be estimated by using linear interpolation between the 1 km^2 and the point values.

The initial rainfall depth for the ‘smooth’ (**D_S**) and/or ‘rough’ (**D_R**) terrain categories are read from the DDA curves for the required catchment area and storm duration. To obtain rainfall values for intermediate durations a plot of rainfall (log) versus duration (linear) can be used. The value for the specified duration can then be interpolated.

The PMP estimates for the catchment are calculated from:

PMP Value = $(S \times D_S + R \times D_R) \times MAF \times EAF$

This value should then be rounded to the nearest 10 mm.

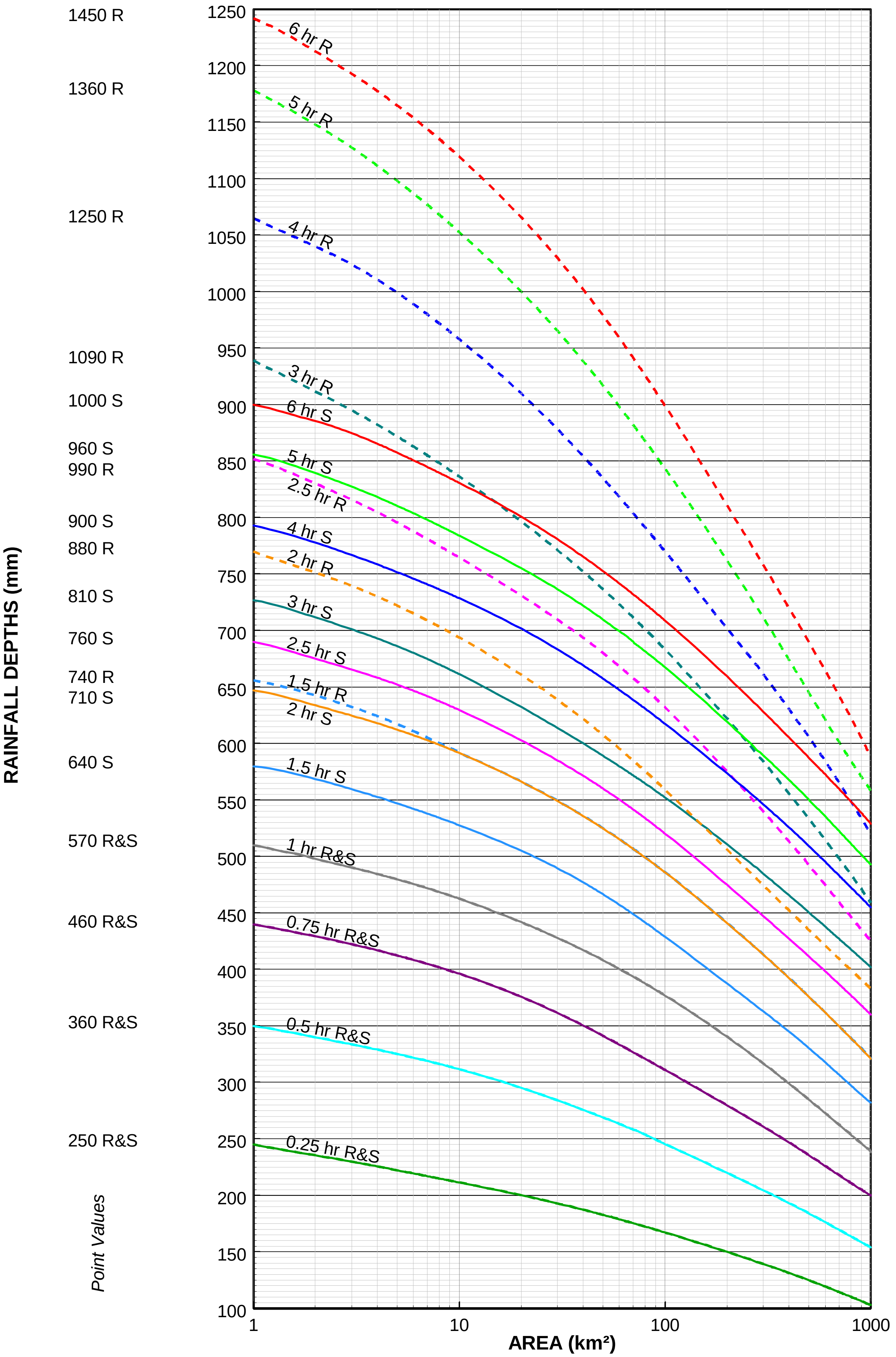

Figure 4: **Depth-Duration-Area Curves of Short Duration Rainfall**

5. DESIGN TEMPORAL DISTRIBUTION OF PMP

A design temporal distribution was derived using pluviograph traces recorded in major Australian storms. This pattern is shown in Table 1 with figures rounded to 1% and presented as a mass curve in Figure 9.

Table 1: Design Temporal Distribution of Short Duration PMP

% of time	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
% of PMP	0	4	10	18	25	32	39	46	52	59	64	70	75	80	85	89	92	95	97	99	100

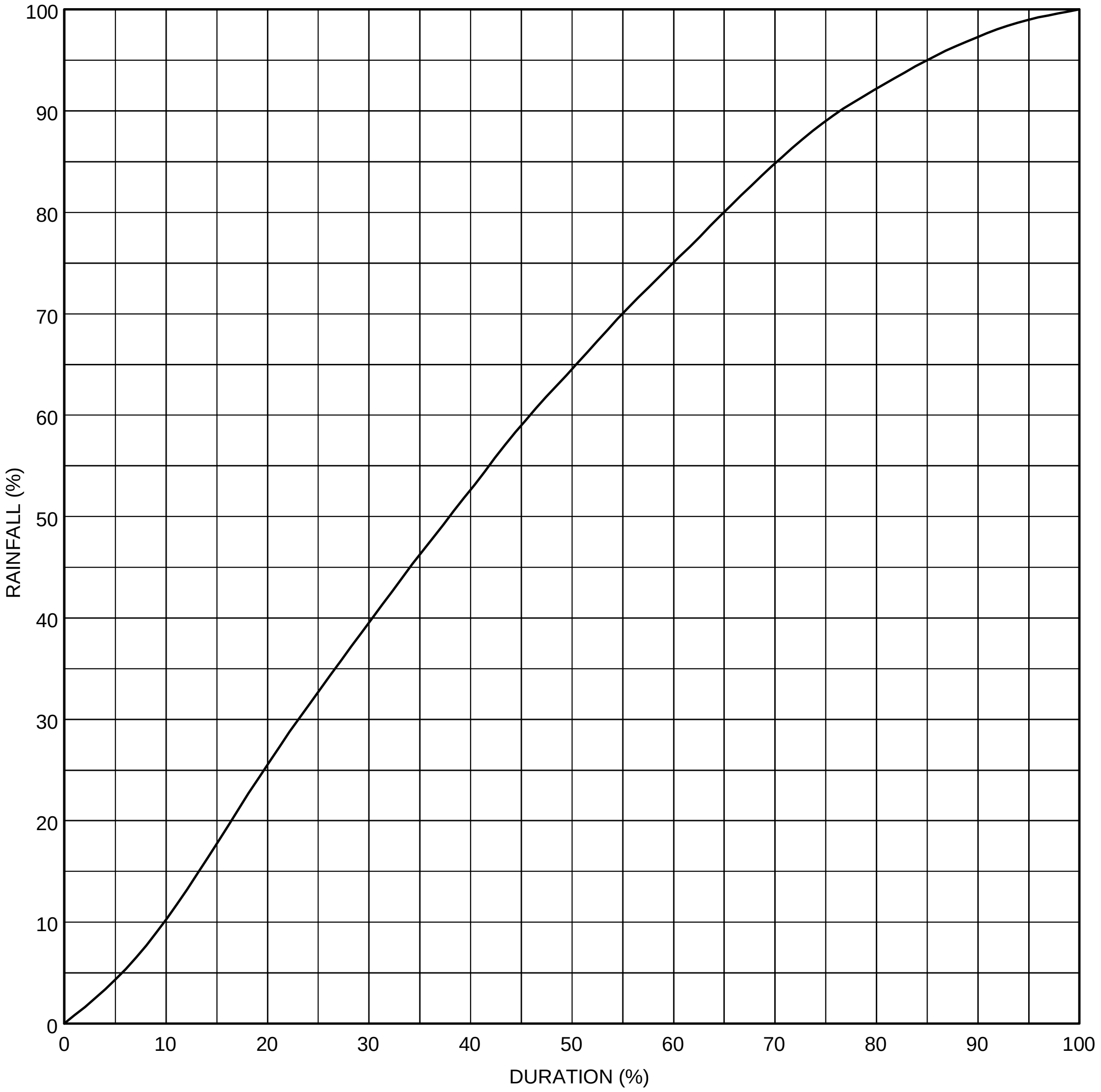

Figure 5: Generalised Short Duration Method Temporal Distribution

6. DESIGN SPATIAL DISTRIBUTION OF PMP

The design spatial distribution for convective storm PMP is given in Figure 6. It is based on the distribution provided by the United States Weather Bureau (1966) and the World Meteorological Organization (1986) but has been modified in light of Australian experience. It assumes a virtually stationary storm and can be oriented in any direction with respect to the catchment. Instructions for the application of the spatial distribution are given below and an example is given in Appendix 2.2.

For simplicity and consistency of application, it is recommended that PMP depth be distributed using a step-function approach. This means having a constant value at all points in the interval between consecutive ellipses (or within the central ellipse), and stepping to a new constant value at each new ellipse. This constant value between ellipses is the mean rainfall depth for that interval and is derived by the procedure described below. Further information on the rationale behind this method may be found in Taylor et al. (1998).

Instructions for the use of the spatial distribution diagram

Step 1 Positioning the spatial distribution diagram

Enlarge or reduce the size of the spatial distribution diagram (Figure 6) to match the scale of the catchment outline map. Overlay the spatial distribution diagram on the catchment outline and move it to obtain the best fit by the smallest possible ellipse. This ellipse is now the outermost ellipse of the distribution.

Step 2 Areas of catchment between successive ellipses

Determine the area of the catchment lying *between* successive ellipses ($CBtn_i$, where the i^{th} ellipse is one of the ellipses A to J).

Where the catchment completely fills both ellipses, this is just the difference between the areas enclosed by each ellipse as given in Table 2.3:

$$CBtn_i = Area_i - Area_{i-1}$$

Where the catchment only partially fills the interval between ellipses, use planimetering or a similar method to determine this area.

Step 3 Area of catchment enclosed by each ellipse

Determine the area of the catchment *enclosed by* each ellipse ($CEnc_i$):

$$CEnc_i = \sum_{k=A}^{i} CBtn_k$$

The area of the catchment enclosed by the outermost ellipse will be equal to the total area of the catchment.

Step 4 Initial mean rainfall depth enclosed by each ellipse

Obtain the x-hour initial mean rainfall depths ($IMRD_i$) for each of the areas enclosed by successive ellipses ($CEnc_i$) (Step 3).

Where the catchment completely fills an ellipse ($CEnc_i=Area_i$), determine the x-hour initial mean rainfall depth for this area from Table 2.3. Where the catchment only partially fills an ellipse ($CEnc_i < Area_i$), determine the x-hour initial mean rainfall depth for that area from the appropriate Depth-Duration-Area (DDA) curves (Figure 4).

Table 2: Initial Mean Rainfall Depths Enclosed by Ellipses A-H in Figure 6

Ellipse label	*Area Enclosed ((km^2)*	*Area between (km^2)*	*Initial Mean Rainfall Depth (mm)*										
			Duration (hours)										
			0.25	*0.5*	*0.75*	*1*	*1.5*	*2*	*2.5*	*3*	*4*	*5*	*6*
SMOOTH													
A	2.6	2.6	232	336	425	493	563	628	669	705	771	832	879
B	16	13.4	204	301	383	449	513	575	612	642	711	765	811
C	65	49	177	260	330	397	453	511	546	576	643	695	737
D	153	88	157	230	292	355	404	459	493	527	591	639	679
E	280	127	141	207	264	321	367	418	452	490	551	594	634
F	433	153	129	190	243	294	340	387	422	460	520	562	599
G	635	202	118	174	223	269	314	357	394	434	491	531	568
H	847	212	108	161	208	250	293	335	373	414	468	506	544
ROUGH													
A	2.6	2.6	232	336	425	493	636	744	821	901	1030	1135	1200
B	16	13.4	204	301	383	449	575	672	742	810	926	1018	1084
C	65	49	177	260	330	397	511	590	663	717	811	890	950
D	153	88	157	230	292	355	459	527	598	647	728	794	845
E	280	127	141	207	264	321	418	480	546	590	669	720	767
F	433	153	129	190	243	294	387	446	506	548	621	664	709
G	635	202	118	174	223	269	357	417	469	509	578	613	656
H	847	212	108	161	208	250	335	395	441	477	541	578	614

Note that no initial mean rainfall depths are required for ellipses I and J because the areas of these ellipses are greater than 1,000 km^2 which is the areal limit of the DDA curves.

Step 5 Adjusted mean rainfall depth enclosed by each ellipse

Adjust the initial mean rainfall depths for moisture and elevation using the adjustment factors and procedure described in Section 4:

$$AMRD_i = IMRD_i \times MAF \times EAF$$

The adjusted mean rainfall depth (AMRD) for the area enclosed by the outermost ellipse will be equal to the (unrounded) PMP for the whole catchment (Section 4.5).

Step 6 Volume of rain enclosed by each oval

Multiply the area of the catchment enclosed by each ellipse ($CEnc_i$) (Step 3) by the corresponding adjusted mean rainfall depth for that area ($AMRD_i$) (Step 5) to obtain the volume of rainfall over the catchment and within each ellipse ($VEnc_i$):

$$VEnc_i = AMRD_i \times CEnc_i$$

Step 7 Volume of rainfall between successive ellipses

Obtain the volume of rainfall over the catchment and between successive ellipses ($VBtn_i$) by subtracting the consecutive enclosed volumes ($VEnc_i$) (Step 6):

$$VBtn_i = VEnc_i - VEnc_{i-1}$$

The volume of rainfall within the central ellipse has already been obtained in Step 6.

Step 8 Mean rainfall depth between successive ellipses

Obtain the mean rainfall depth over the catchment and between successive ellipses (MRD_i) by dividing the volume of rainfall between the ellipses ($VBtn_i$) (Step 7) by the catchment area between them ($CBtn_i$) (Step 2):

$$MRD_i = \frac{VBtn_i\,(Step 7)}{CBtn_i\,(Step 2)}$$

Step 9 Other PMP Durations

Repeat steps 1 to 8 for other durations.

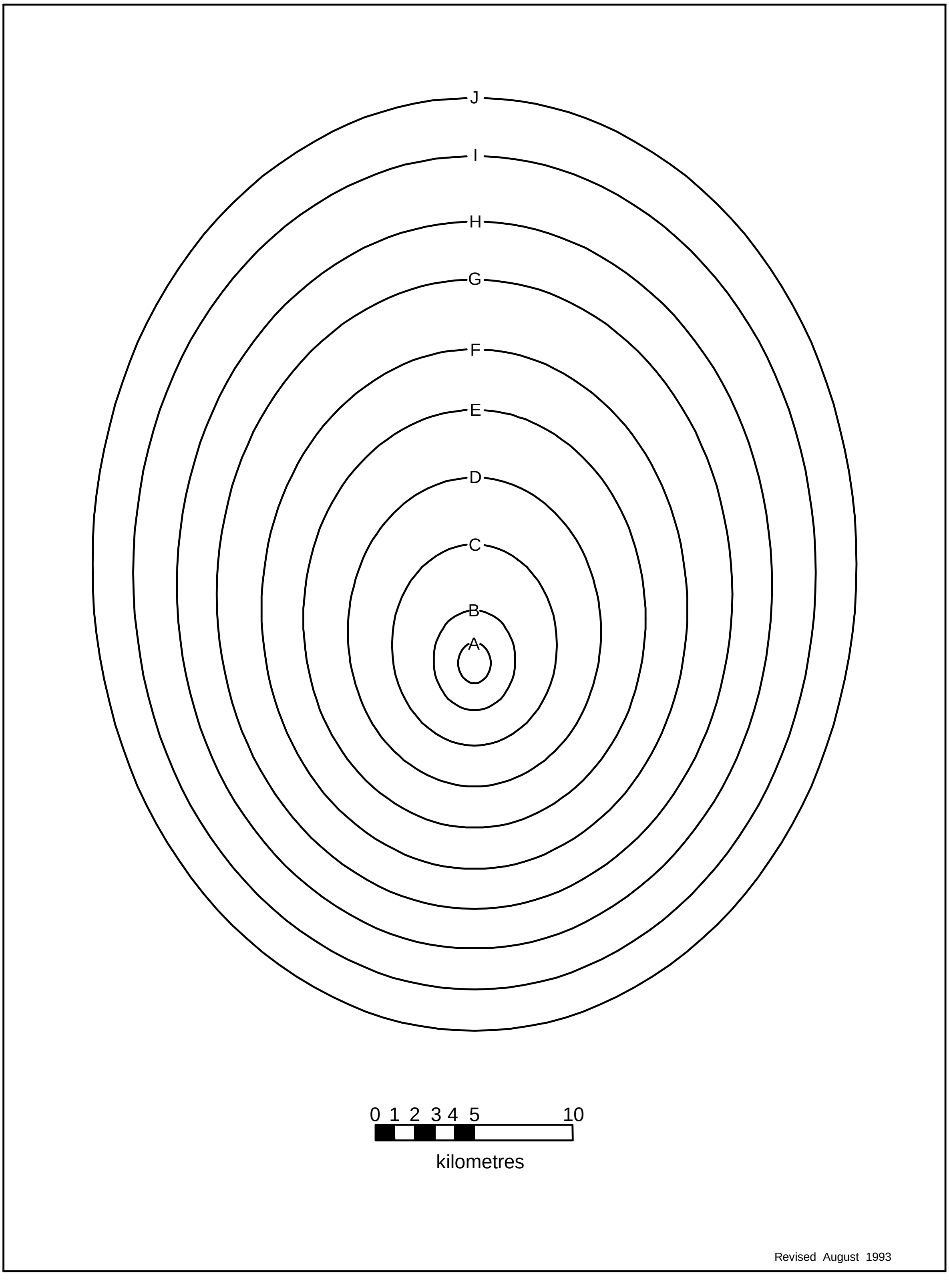

Figure 6: **Generalised Short Duration Method Spatial Distribution**

7. SEASONAL VARIATION OF PMP

The meteorological events associated with short duration, limited area PMP are most likely to be summer or early autumn convective storms. They may be isolated ‘supercells’, or they may consist of numerous convective cells embedded in a larger storm system. However, other seasonal factors, such as high antecedent rainfall, may cause greater floods to occur at other times of the year.

In some regions summers are mostly dry so very large catchment loss rates may be assumed in the calculation of the probable maximum summer flood. If the winters are wet, winter PMP values with low losses may produce a higher flood. This is sometimes the case in southwestern Australia.

The areal limit for short duration winter PMP estimates is taken as 500 km^2. It is reasonable to transpose smaller scale convective storms between seasons, as their basic structure is not considered to vary significantly with season. However, seasonal transposition of synoptic-scale storms to estimate PMP over large areas is not considered realistic.

For Australian catchments south of 30°S, Figure 7 can be used to convert the annual PMP to the PMP for a specific month. The monthly percentage moisture adjustment has been derived for a number of locations in southern Australia by calculating the extreme moisture index for each month as a percentage of the extreme annual moisture index. The highest monthly values are given in Figure 7. It is a straightforward procedure to calculate the annual PMP and convert it to a monthly PMP by multiplying by the appropriate percentage given in Figure 7.

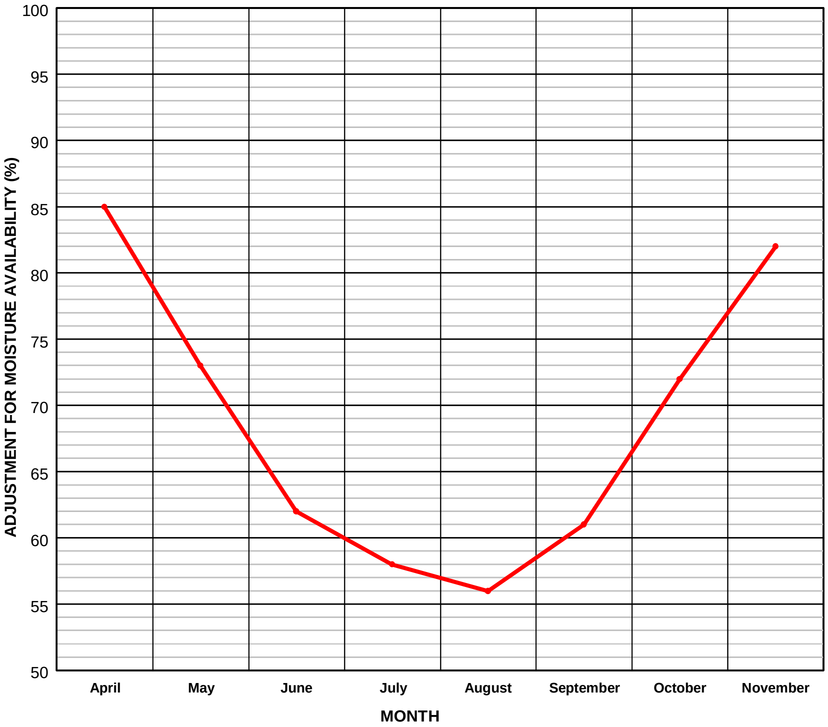

Figure 7: Monthly Percentage Moisture Adjustment for Southern Australia (south of 30°S) Note: The areal limit for winter is 500km^2

8. NOTIONAL AEP OF PMP DEPTHS DERIVED USING THE GSDM

In theory, the PMP concept, as defined in section 2, implies zero probability of exceedance. However, the estimates made by the various PMP methods have a non-zero probability of exceedance. For example, the ‘*in situ* maximisation’ method PMP estimates for the Fortescue River catchment in Western Australia were exceeded by rainfall from Tropical Cyclone Joan in 1975 (Kennedy, 1982). The maximised storm depths from the Dapto 1984 storm (Shepherd and Colquhoun, 1985) near Wollongong in NSW exceeded the ‘method of adjusted United States data’ PMP estimates used at the time. Notional probabilities of exceedance can therefore be associated with the application of the method (i.e. the methodology plus the limitations of available data) used to estimate the PMP, but not with the concept of PMP itself.

Using deterministic methods of estimating PMP rather than statistical methods, means that the assignment of Annual Exceedance Probabilities (AEPs) to the PMP estimates is not straightforward. The uncertainties associated with any estimate of the exceedance probability of a PMP depth are very large. However, by using the same assumptions to estimate AEPs for each of the PMP methods, the results can provide useful guidance in a comparative sense (Pearce, 1994).

Estimates of PMP depth have been made using a variety of methods for some catchments (e.g. *in situ*, limited transposition, generalised), but the associated notional probabilities vary considerably. Generalised methods of PMP estimation, applicable to different meteorological regions, can also have different exceedance probabilities. Probabilities of variables such as temporal patterns, spatial patterns, antecedent rainfall, losses, reservoir levels, flood model assumptions etc. assumed in converting rainfall to floods will also affect the notional exceedance probability of the PMF with respect to that of the PMP estimates. However, as discussed above for the PMP, if similar assumptions and flood models are used in transforming the PMP to PMF, the resultant design flood can provide useful guidance in comparing safety between various dams.

Kennedy and Hart (1984) used notional AEPs for various PMP methods as a means of indicating the different security levels provided by the different methods. Laurenson and Kuczera (1999) issued interim estimates of the AEP which included a modification of Kennedy and Hart’s (1984) figures. They recommended an AEP of 10^{-7} for areas of 100 km^2 and below, rising to 10^{-6} for an area of 1000 km^2. On the subject of confidence limits, they added:

- Recommended AEP values plus or minus two orders of magnitude of AEP be regarded as notional upper and lower limits for true AEPs;
- Recommended AEP values plus or minus one order of magnitude of AEP be regarded as confidence limits with about 75% subjective probability that the true AEP lies within the limits; and
- The recommended AEP values be regarded as the current best estimates of the AEPs.

9. CONCLUSION

The Generalised Short Duration Method of estimating Probable Maximum Precipitation described here enables design engineers to make estimates of PMP for small areas and short durations for any site in Australia. The method is based partly on United States data as only a few severe short duration rainstorms have been adequately documented in Australia. It should be noted, however, that the highest rainfall depths at some durations for the ‘rough’ terrain category were derived from depths recorded in a storm that occurred near Dapto, New South Wales in 1984.

This document included both the revised method of spatial distribution of GSDM depth estimates introduced in 1996 and the updated moisture data used by the Hydrometeorology Section of the Bureau of Meteorology since 2001. It supersedes ‘Bulletin 53: The Estimation of Probable Maximum Precipitation in Australia: Generalised Short Duration Method’ (Bureau of Meteorology, 1994), and should be used instead.

The notional AEP of the GSDM estimates is approximately 10^{-7} for an area of 100 km^2 rising to 10^{-6} for an area of 1000 km^2 for all durations covered by the method (Laurenson and Kuczera, 1999). The uncertainty attached to these estimates is discussed in Section 8.

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Appendix 1

GSDM CALCULATION SHEET

LOCATION INFORMATION

Catchment .... Area .... km²

State .... Duration Limit .... hrs

Latitude ....°...............’ S Longitude.....................°................’ E

Portion of Area Considered:

Smooth , **S** = ... (0.0 - 1.0) Rough , **R** = ... (0.0 - 1.0)

ELEVATION ADJUSTMENT FACTOR (EAF)

Mean Elevation ....m

Adjustment for Elevation (-0.05 per 300m above 1500m) ....

EAF = ... (0.85 - 1.00)

MOISTURE ADJUSTMENT FACTOR (MAF)

MAF = ... (0.40 - 1.00)

PMP VALUES (mm)

Duration (hours)	**Initial Depth - Smooth (D_S)**	**Initial Depth - Rough (D_R)**	**PMP Estimate = ($D_S \times S + D_R \times R$) $\times$ MAF $\times$ EAF**	**Rounded PMP Estimate (nearest 10 mm)**
0.25				
0.50				
0.75				
1.0				
1.5				
2.0				
2.5				
3.0				
4.0				
5.0				
6.0				

Prepared by .... Date ..../.........../..........

Checked by .... Date ..../.........../..........

Appendix 2

EXAMPLE OF THE APPLICATION OF THE GSDM

A2.1 PMP Estimates for the Example Catchment

All calculations and relevant information are recorded on the GSDM Calculation Sheet, Table A2.1.

(i) Estimates of short duration PMP are required for a hypothetical catchment in New South Wales, centred around the coordinates 36°25’ S 148°15’ E. The catchment area is 110 km².

(ii) From Figure 2 it is determined that the catchment lies within the intermediate zone. Linear interpolation across the zone indicated a maximum duration of 5 hours.

(iii) From a suitably contoured map of the area, it was found that 10% of the catchment was considered ‘smooth’ and the remaining 90% ‘rough’. ‘Rough’ terrain is that in which elevation changes of 50 m or more within horizontal distances of 400 m are common. Terrain that was within 20 km of ‘rough’ terrain was classified as ‘rough’. ‘Smooth’ terrain within the catchment but further than 20 km from ‘rough’ terrain was classified as ‘smooth’.

$S = 0.1$ and $R = 0.9$

(iv) From Figure 4, the initial depths for both the ‘smooth’, D_S, and ‘rough’, D_R, categories were read, for a catchment area of 110 km^2 for each duration up to 5 hours.

(v) The average elevation of the catchment was found to be 1750 m.

Adjustment for Elevation = - 0.05 per 300 m above 1500m
= $-((1750-1500)/300) \times (0.05)$
= -0.04

$EAF = 1.0 - 0.04 = 0.96$

(vi) From Figure 3, the moisture adjustment factor was found to be 0.60.

$MAF = 0.60$

(vii) PMP depth

$$\text{PMP depth} = (S \times D_S + R \times D_R) \times EAF \times MAF$$
$$= (0.1 \times D_S + 0.9 \times D_R) \times 0.96 \times 0.60$$

The estimates were then rounded to the nearest 10 mm.

Table A2.1: Example GSDM Calculation Sheet

LOCATION INFORMATION

Catchment .....EXAMPLE.....

Area .....110..... km²

State .....N.S.W.......

Duration Limit .....5..... hrs

Latitude .....36..° .....25..’ S

Longitude ....148..°....15..’ E

Portion of Area Considered:

Smooth , **S** = ...0.1 ..... (0.0 - 1.0)

Rough , **R** = ... 0.9..... (0.0 - 1.0)

ELEVATION ADJUSTMENT FACTOR (EAF)

Mean Elevation ..... 1750..... m

Adjustment for Elevation (-0.05 per 300m above 1500m) ....-0.04.....

EAF = ...0.96..... (0.85 - 1.00)

MOISTURE ADJUSTMENT FACTOR (MAF)

MAF = ... 0.60 ..... (0.40 - 1.00)

PMP VALUES (mm)

Duration (hours)	**Initial Depth - Smooth (D_S)**	**Initial Depth - Rough (D_R)**	**PMP Estimate = ($D_S \times S + D_R \times R$) × MAF × EAF**	**Rounded PMP Estimate (nearest 10 mm)**
0.25	164	164	94	90
0.50	242	242	139	140
0.75	306	306	176	180
1.0	372	372	214	210
1.5	423	480	273	270
2.0	480	552	314	310
2.5	514	624	353	350
3.0	546	675	381	380
4.0	611	760	429	430
5.0	661	832	469	470
6.0	-	-	-	-

Prepared by ....N.Smith...................................... Date ....1..../...06......./.....03.....

Checked by ....P. Citizen..................................... Date ....3..../.....06......./.....03.......

A2.2 Spatial distribution over the example catchment

In this example, the distribution of only the three-hour PMP will be derived. Results are given in columns a-h of Table A2.2.

Step 1 Positioning the spatial distribution diagram

The scale of the spatial distribution diagram was altered to match that of the catchment outline map. The spatial distribution diagram was placed over the catchment outline to obtain the best fit by the smallest possible ellipse. Ellipse E encloses the catchment as shown in Figure A2.1.

Step 2 Areas of catchment between successive ellipses

The catchment areas *between* successive ellipses ($CBtn_i$) were determined. The results are listed in column b.

e.g. between ellipses A and B, $CBtn_B = 13.4$ km^2 (from Table 2)
between ellipses B and C, $CBtn_C = 37.7$ km^2 (by planimetering)

Step 3 Area of catchment enclosed by each ellipse

The catchment area *enclosed by* each ellipse ($CEnc_i$) (column c) was calculated by progressively accumulating the catchment areas between ellipses (column b).

e.g. for ellipse C, $CEnc_C = 2.6 + 13.4 + 37.7 = 53.7$ km^2

As a check, the area enclosed by the outermost ellipse, ellipse E, which is 110 km^2, should equal the area of the catchment.

Step 4 Initial mean rainfall depth enclosed by each ellipse

Since the catchment completely fills ellipses A and B, the 3-hour initial mean rainfall depths ($IMRD_i$) at these areas may be determined from Table 2, weighting and summing the ‘smooth’ and ‘rough’ depths according to the proportions of ‘smooth’ and ‘rough’ terrain (Section A2.1).

i.e., 3 hr, ellipse A, ‘smooth’ = 705 mm
3 hr, ellipse A, ‘rough’ = 901 mm
$IMRD_A = (0.1 \times 705 + 0.9 \times 901) = 881$ mm

For ellipses C, D and E, the initial mean rainfall depths were determined from the 3-hour DDA curves in Figure 4.

e.g. for ellipse C, 3 hr, 53.7 km^2, ‘smooth’ = 585 mm
3 hr, 53.7 km^2, ‘rough’ = 731 mm
$IMRD_C = (0.1 \times 585 + 0.9 \times 731) = 716$ mm

The initial mean rainfall depths are listed in column d.

Step 5 Adjusted mean rainfall depth enclosed by each ellipse

The initial mean rainfall depths (column d) were adjusted for moisture and elevation (column e) by multiplying by the moisture and elevation adjustment factors (Section A2.1).

e.g. for ellipse C, $AMRD_C = 716 \times 0.60 \times 0.96 = 412$ mm

As a check, the adjusted mean rainfall depth for the area enclosed by the outermost ellipse, ellipse E, which is 382 mm, should approximately equal the 3-hour (unrounded) PMP for the catchment (Section A2.1).

Step 6 Volume of rainfall enclosed by each ellipse

The adjusted mean rainfall depths (column e) were multiplied by the areas of the catchment enclosed by each ellipse (column c) to give values for the volume of rainfall enclosed by each ellipse ($VEnc_i$) (column f).

e.g. for ellipse C, $VEnc_C = 412 \text{ x } 53.7 = 22{,}124 \text{ mm.km}^2$

Step 7 Volume of rainfall between successive ellipses

Consecutive enclosed rainfall volumes (column f) were subtracted to obtain the rainfall volume between ellipses ($VBtn_i$) (column g).

e.g. between ellipses B and C, $VBtn_C = 22{,}124 - 7{,}312 = 14{,}812 \text{ mm.km}^2$

Step 8 Mean rainfall depth between successive ellipses

The mean rainfall depths between successive ellipses (MRD_i) (column h) were obtained by dividing the rainfall volume between ellipses (column g) by the area between ellipses (column b).

e.g. between ellipses B and C, $MRD_C = 14{,}812 / 37.7 = 393$ mm

Step 9 Other PMP Durations

Repeat the above steps for other durations for which the spatial distribution of PMP is required.

Table A2.2: Calculation of the Spatial Distribution of 3-hour PMP over the Example Catchment

a	b	c	d	e	f	g	h
	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8
Ellipse	Catchment area between ellipses (km^2)	Catchment area enclosed by ellipse (km^2)	Initial mean rainfall depth (mm)	Adjusted mean rainfall depth (mm)	Rainfall volume enclosed by ellipse (mm.km^2)	Rainfall volume between ellipses (mm.km^2)	Mean rainfall depth between ellipses (mm)
A	2.6	2.6	881	507	1,318	1,318	507
B	13.4	16	793	457	7,312	5,994	447
C	37.7	53.7	716	412	22,124	14,812	393
D	42.6	96.3	673	388	37,364	15,240	358
E	13.7	**110**	663	**382**	42,020	4,656	340

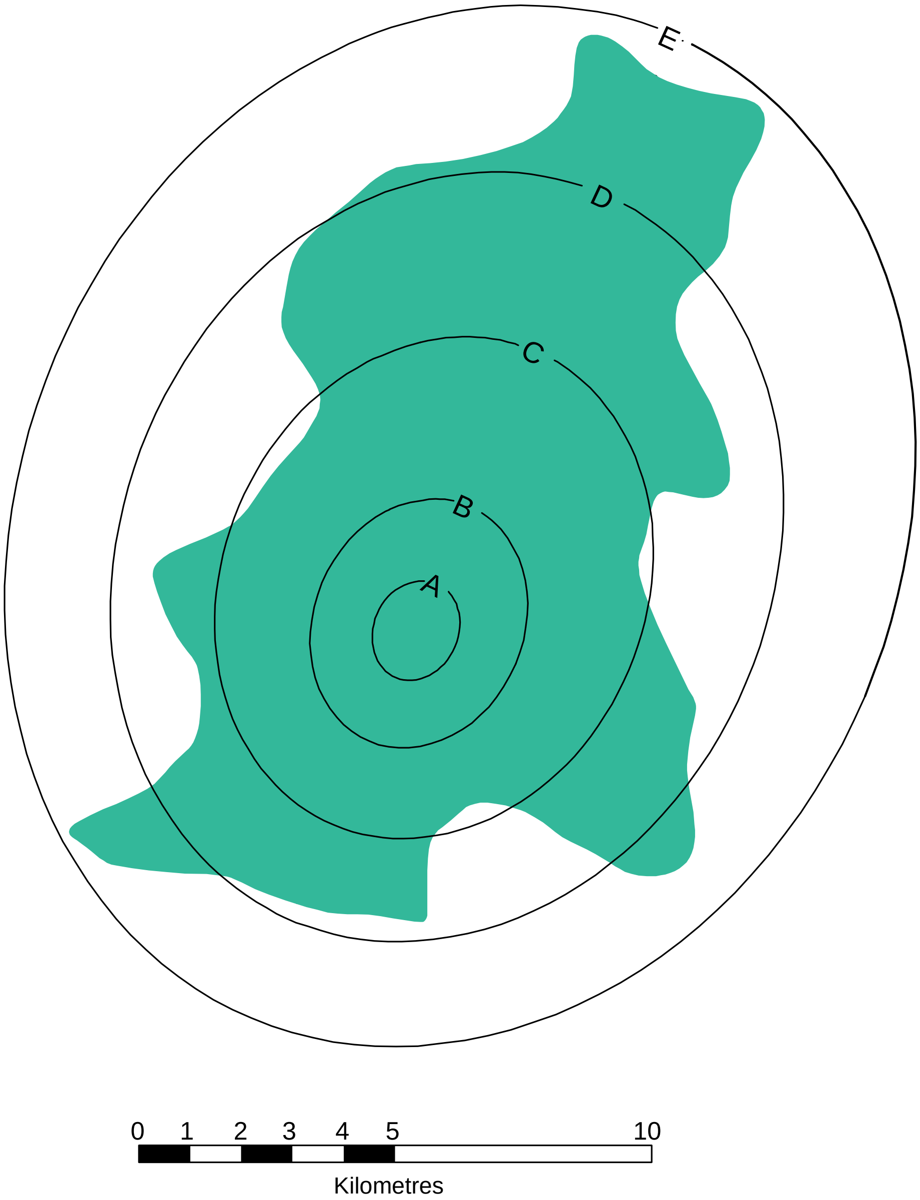

Figure A2.1: Spatial Distribution over Example Catchment

Appendix 3

NOTABLE SHORT DURATION AREAL RAINFALL EVENTS RECORDED IN INLAND AND SOUTHERN AUSTRALIA

A3.1 The Molong Storm of 20 March 1900

On 20 March 1900 a series of thunderstorms formed over a strip of country about 75 km wide extending from near Hungerford to the southeast near Moss Vale in New South Wales. The heaviest rainfall occurred in the Orange-Molong area. The information given by Russell (1901) indicates that the storm lasted for about three hours. The storm dew point temperature was estimated as 19°C. The recorded storm rainfall and the rainfall normalised for the moisture content corresponding to an extreme dew point temperature of 23.5°C are compared with the PMP estimates in Table A4.1.

Table A3.1: Depth-Area Data for the Molong Storm

Area (km²)	Recorded Storm Rainfall (mm)	Storm Rainfall Adjusted to 23.5°C (mm)	3-hour PMP Estimate (mm)
10	205	300	450
50	195	290	400
100	190	280	380
500	180	260	310
1000	170	250	270

A3.2 The St Albans Storm of 8 January 1970

On 8 January 1970 between 1400 and 1730 EST an intense thunderstorm was located in the St Albans area about 15 km west-northwest of Melbourne. Near the centre of the storm rainfall totals exceeding 120 mm were recorded. The storm was studied by Finocchiaro (1970). Radar observations and information obtained from private raingauge readers indicate that about 90 per cent of the total rainfall fell within a period of 1.5 hours. The storm dew point was assessed to have been 13°C and the extreme dew point for the storm area for January is 20.4°C. The storm data are compared with the PMP estimates in Table A3.2.

Table A3.2: Depth-Area Data for the St Albans Storm

Area (km²)	Recorded Storm Rainfall (mm)	Storm Rainfall Adjusted to 20.4°C (mm)	1.5-hour PMP Estimate (mm)
1	111	210	300
10	88	170	280
20	80	150	260
30	72	140	260
50	63	120	240

A3.3 The Woden Valley Storm of 26 January 1971

During the evening of 26 January 1971 extremely heavy rainfall associated with an almost stationary thunderstorm complex fell over the Canberra suburbs of Farrer and Torrens for about 90 minutes (Bureau of Meteorology, 1972). The resulting flood in the Woden Valley claimed several lives. The storm dew point temperature was assessed as 14°C and the extreme dew point is 22.8°C. The storm data are compared with the PMP estimates in Table A3.3.

Table A3.3: Depth-Area Data for the Woden Valley Storm

Area (km²)	Recorded Storm Rainfall (mm)	Storm Rainfall Adjusted to 22.8°C (mm)	1.5-hour PMP Estimate (mm)
1	102	220	370
10	99	210	340
50	87	190	300
100	78	170	270
250	62	130	240

A3.4 The Melbourne Storm of 17 February 1972

On the afternoon of 17 February 1972 an intense thunderstorm developed over the city of Melbourne and the suburbs immediately north of the city. The storm was observed by radar and three pluviograph traces were obtained from sites near the centre of the storm. This storm lasted for about 60 minutes and produced severe local flooding. Rainfall depths for this storm are given by Pierrehumbert and Kennedy (1982). The storm dew point was estimated as 12°C and the extreme dew point is 20.9°C. The storm depth-area values are compared with the PMP estimates in Table A3.4.

Table A3.4: Depth-Area Data for the Melbourne Storm

Area (km²)	Recorded Storm Rainfall (mm)	Storm Rainfall Adjusted to 20.9°C (mm)	1-hour PMP Estimate (mm)
2	83	180	270
20	73	160	240
50	68	150	220
100	60	130	200
250	49	110	180

A3.5 The Laverton Storm of 7 April 1977

A storm lasting for about 12 hours brought exceptionally heavy rain to areas to the west and north of Melbourne on 7 April 1977. The heaviest burst in the storm lasted for about 3 hours and affected areas from Laverton to Sunbury. The Melbourne and Metropolitan Board of Works (1979) gives details of the rainfall recorded over the entire storm area. The representative storm dew point temperature was 10°C and the extreme dew point is 20.1°C. The recorded and maximised storm depth-area data are compared with the PMP estimates in Table A3.5.

Table A3.5: Depth-Area Data for the Laverton Storm

Area (km²)	Recorded Storm Rainfall (mm)	Storm Rainfall Adjusted to 20.1°C (mm)	3-hour PMP Estimate (mm)
10	121	310	340
100	96	240	280
400	73	180	240
600	60	150	220
800	53	130	210
1000	51	130	200

A3.6 The Buckleboo Storm of 26 January 1981

On the afternoon of 26 January 1981 an intense and almost stationary thunderstorm produced some of the highest short-duration rainfalls ever recorded in South Australia. While the only quantitative data are daily totals, it is reliably reported that virtually all the rain fell in a period of about three hours. The representative storm dew point was estimated to have been 19°C. The recorded values were adjusted for a moisture content corresponding to a surface dew point temperature of 23.5°C for comparison with the PMP estimates in Table A3.6.

Table A3.6: Depth-Area Data for the Buckleboo Storm

Area (km²)	Recorded Storm Rainfall (mm)	Storm Rainfall Adjusted to 23.5°C (mm)	3-hour PMP Estimate (mm)
10	187	270	450
50	169	250	400
100	154	230	380
500	106	160	310
1000	77	110	270

A3.7 The Barossa Valley Storm of 2 March 1983

During the evening of 2 March 1983 numerous thunderstorm cells produced very heavy rainfall over the Adelaide Plains and the eastern part of the Mt Lofty Ranges. Nearly all the rain fell in a period of about three hours. The thunderstorms occurred in a moist airmass of tropical origin which was fed into the area from the northeast. The storm is described by Burrows (1983).

The rainfall produced severe flash flooding and extensive property damage, particularly in the Barossa Valley and around Dutton. An unofficial gauge on a farm 1 km north of Dutton recorded 330 mm during the storm. Several unofficial gauges recorded totals in excess of 200 mm, whereas the highest value recorded by an official gauge was 103 mm at Angaston. This illustrates the problem of detecting severe local storms with the sparse network of official gauges.

The representative storm dew point temperature was estimated as 20°C and the extreme dew point is 22.2°C. The storm rainfalls are compared with the PMP estimates for a duration of three hours in Table A3.7.

Table A3.7: Depth-Area Data for the Barossa Valley Storm

Area (km^2)	Recorded Storm Rainfall (mm)	Storm Rainfall Adjusted to 22.2°C (mm)	3-hour PMP Estimate (mm)
1	300	360	440
10	222	270	400
50	190	230	350
100	173	210	340
500	129	150	270
1000	110	130	240

A3.8 The Dapto Storm of 18 February 1984

An extraordinary heavy rainfall event occurred near Dapto in New South Wales on 18 February 1984, as described by Shepherd and Colquhoun (1985). The rainfall was particularly heavy on and near the Illawarra escarpment. While rain fell for more than 24 hours most of the rain fell in a period of about 6 hours. For durations of around 6 hours and areas up to about 200 km^2 the normalised rainfall values exceed the adjusted United States data. The maximised rainfall values from the Dapto storm were used in deriving the `rough' terrain category DDA curves in Figure 2 in the first edition of *Bulletin 51* by the Bureau of Meteorology (1985). The storm dew point temperature was estimated to be 19°C. The extreme dew point temperature for February is 23.3°C. The 6-hour rainfall values for this storm are given in Table A3.8 where they are compared with the PMP estimates.

Table A3.8: Depth-Area Data for the Dapto Storm

Area (km²)	Recorded Storm Rainfall (mm)	Storm Rainfall Adjusted to 23.3°C (mm)	6-hour PMP Estimate (mm)
10	520	750	750
50	450	650	650
100	410	590	600
500	250	360	460
1000	160	230	390

A3.9 The Sydney Storm of 4-7 August 1986

A low pressure centre which moved southwards close to the coast brought very heavy rainfall to the Sydney metropolitan area, the Blue Mountains and the Illawarra region, causing extensive local flooding. Six fatalities resulted from the storm. The Sydney rainfall for the 24 hours to 9 am on 6 August 1986 was a record 328 mm. There was a particularly heavy period of rain on the afternoon of 5 August 1986. Pluviograph data have been used to extract maximum 6 hour depths for that part of the storm which occurred over the metropolitan area. The storm dew point was 10°C and the extreme dew point is 16.7°C. The storm is described by the Bureau of Meteorology (1987). The depth-area rainfall values for the storm are compared with the PMP estimates in Table A3.9.

Table A3.9: Depth-Area Data for the Sydney Storm

Area (km²)	Recorded Storm Rainfall (mm)	Storm Rainfall Adjusted to 16.6°C (mm)	6-hour PMP Estimate (mm)
50	133	250	320
200	124	230	270
500	112	210	240
1000	103	190	200

A3.10 The St Kilda Storm of 7 February 1989

On the afternoon of 7 February 1989, a severe thunderstorm brought torrential rainfall to the inner southern and southeastern suburbs of Melbourne (Board of Works, 1989). The storm was centred over the St Kilda area and caused flash flooding. The heavy rainfall part of the storm lasted for about one hour. The representative storm dew point temperature was estimated to have been 14°C and the extreme dew point for February is 20.9°C. The depth-area rainfall values for the storm are compared with PMP estimates in Table A3.10.

Table A3.10: Depth-Area Data for the St. Kilda Storm

Area (km²)	Recorded Storm Rainfall (mm)	Storm Rainfall Adjusted to 20.9°C (mm)	1-hour PMP Estimate (mm)
5	91	160	260
10	85	150	250
20	75	140	240
40	62	110	230
60	53	100	220
80	49	90	210

A3.11 References for Appendix 3

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