BUREAU OF METEOROLOGY, AUSTRALIA

HYDROLOGY REPORT SERIES

HRS Report No. 6

RAINFALL ANTECEDENT TO LARGE AND EXTREME RAINFALL BURSTS OVER SOUTHEAST AUSTRALIA

Hydrology Unit
Melbourne
December 1999

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L. J. MINTY AND J. MEIGHEN

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1. INTRODUCTION

1.1 Antecedent Rainfall in Design Flood Estimation

Estimates of large and extreme floods are part of the safe design of major hydraulic works, such as spillways on major dams. These works are designed to pass, or safely contain, a flood with a low probability of exceedance.

In Australia, guidelines for estimating design floods are provided by the Institution of Engineers in *Australian Rainfall and Runoff - A Guide to Flood Estimation* (IEAust, 1987). These guidelines recommend that large and extreme floods be estimated from design rainfalls. A design rainfall is a deterministic or statistical estimate of rainfall, to which is attributed an Annual Exceedance Probability (AEP). The intention of the guidelines is that the design flood and the design rainfall should have the same AEP.

In estimating the flood that results from a large rainfall event, account must be taken of the prevailing catchment wetness. For the same rainfall, a larger flood will result from a saturated catchment than from a dry catchment. For a design flood, an ‘initial loss’ due to prevailing catchment dryness must be assumed. To ensure that the design flood has the same AEP as the design rainfall, a median or a ‘typical’ *initial loss* is specified.

Knowledge of the ‘typical’ initial loss associated with large rainfall events is very limited. Current guidelines for estimating large and extreme floods reflect this limited knowledge, recommending the use of cautiously low values. The hydrological community has expressed concern that the recommended values are too low, and has called for more research (Pilgrim and Robinson, 1988).

In general, the initial losses associated with large rainfall events have not been measured directly, so guidance on initial losses is sought from the examination of the rainfall antecedent to such events. Since design rainfalls represent rainfall bursts, which do not necessarily describe complete storms, the relevant antecedent rainfall to examine is pre-burst: within-storm as well as pre-storm.

1.2 Prior Work on Antecedent Rainfall

Prior work in Australia on antecedent rainfall has mostly dealt with rainfall antecedent to annual maximum rainfall bursts at selected sites:

- Sydney and Griffith (Cordery, 1970; Pilgrim and Cordery, 1975);
- Brisbane and Melbourne (Srikanthan and Kennedy, 1991); and
- Rockhampton and Adelaide (Farnsworth et al, 1996).

The main findings of these various works are that the amount of rain that falls prior to these rainfall bursts:

(i) depends on the climate regime of the rainfall event;
(ii) decreases with increasing burst duration;
(iii) may be correlated with the amount of rainfall in the main burst, but not necessarily; and
(iv) may be higher than the average rainfall for the duration, location and time of year, but not necessarily.

Prior published work in the United States, where rainfall-based flood estimation is also practised, has been primarily concerned with rainfall prior to large and extreme storms, not bursts. Work has been limited in geographic extent to:

- Kentucky, Tennessee, Alabama and North Carolina (US Weather Bureau, 1965; US Weather Bureau 1969; National Weather Service, 1986);
- Oklahoma, Kansas and eastern Colorado (Chin and Vogel,1990; Chin and Vogel, 1995); and
- Washington State (Washington State Department of Ecology, 1989).

The main findings of these works are that *antecedent storms*:

(i) may derive from a variety of meteorological situations;
(ii) may be separated from the main storm by a dry interval of 2-10 days, dependent on the climate regime and the duration of the main storm; and
(iii) are highly variable in duration and rainfall volume, though typically less than 30% of the main storm.

The general conclusion is that antecedent storms may be viewed as independent of the main storm and not significantly different from storms normally experienced at that time of year.

The one US study to have focussed on the rainfall prior to extreme bursts (National Weather Service, 1986) found that rainfall in the two days prior to a 24-hour burst will tend to exceed the average rainfall for the location and time of year, but that this rainfall amounts to less than 15% of the main burst.

The US Weather Bureau has also investigated the occurrence of successive tropical storms over the Mekong River Basin in Southeast Asia (US Weather Bureau, 1970). This study concluded that tropical storms in close succession are:

(i) more common on the Vietnam coast than in North America;
(ii) may be separated by a dry interval of 3-10 days; and
(iii) may have the lesser storm as large as 75% of the main storm.

1.3 The GSAM - Antecedent Rainfall Project

In July 1996 the Bureau of Meteorology was approached by members of the Australian design-flood hydrology community for advice on appropriate values of antecedent rainfall to use in conjunction with large and extreme design rainfalls on catchments in the southeast of Australia. In response, the Hydrometeorology Section initiated an investigation of rainfall antecedent to the largest storms and bursts on record in the region. The investigation made use of an existing catalogue of storms (Meighen and Kennedy, 1995), which had been compiled for a major research project on the development of a generalised method of estimating Probable Maximum Precipitation (PMP) for the region, known as the Generalised Southeast Australia Method (GSAM) (Minty et al, 1996). The investigation of antecedent rainfall was thus named the GSAM-Antecedent Rainfall Project (GSAMARP).

An earlier investigation of a subset of the GSAM storms (Sinclair Knight Merz, 1997) had concluded that the rainfall 1-3 months antecedent to these storms was not significantly different from normal, therefore 15 days was considered a sufficient antecedent period for the present investigation. The GSAMARP also drew on techniques developed in the GSAM project for constructing sequences of areal-average rainfall at daily intervals or, where sub-daily data was available, at a temporal resolution of three hours. The investigation focussed separately on the pre-storm and the pre-burst periods. Pre-storm periods were examined for the frequency of occurrence and magnitude of antecedent storms. Pre-burst rainfalls were examined with the assumption that design pre-burst temporal distributions 'typical' of large and extreme design rainfall bursts could be developed from them. A further assumption was that these design pre-burst temporal distributions could be used in the assessment of the initial losses associated with large and extreme design rainfall bursts, including the PMP.

Design pre-burst temporal distributions were derived by the end of 1998. They were subsequently tested in flood estimation studies on six catchments in northern Victoria (Hill et al, 1999). The revised edition of *Australian Rainfall and Runoff*, Book VI - ARR (Nathan and Weinmann, 1999), recommends the use of these design pre-burst temporal distributions in the estimation of large to extreme floods on catchments in the southeast of Australia.

The purpose of this document is to record the investigations and the outcomes of the GSAM-Antecedent Rainfall Project.

2. THE GSAMARP DATABASE

The GSAMARP investigations were based on an analysis of sequences of areal-average rainfall within and 15 days antecedent to each of the storms in the GSAM Storm Catalogue. This section describes the features of the storm catalogue and the construction of the sequences of areal-average rainfall.

2.1 GSAM Storm Catalogue

The GSAM storm catalogue contains the dates, locations and areal extents of 110 of the largest storms occurring between the years of 1889 and 1990 over southeast Australia. Figure 1 shows the locations of the centre of each these storms: 75 coastal storms are located along the strip from the NSW-Qld border to northern and eastern Tasmania, and 35 inland storms are spread across the interior of NSW, Vic and SA. The classification of each storm as either 'coastal' of 'inland' reflects the notion that between these two 'zones' the mechanisms by which such storms are produced are genuinely different. While the precipitation mechanisms within these storms vary, the storms display an

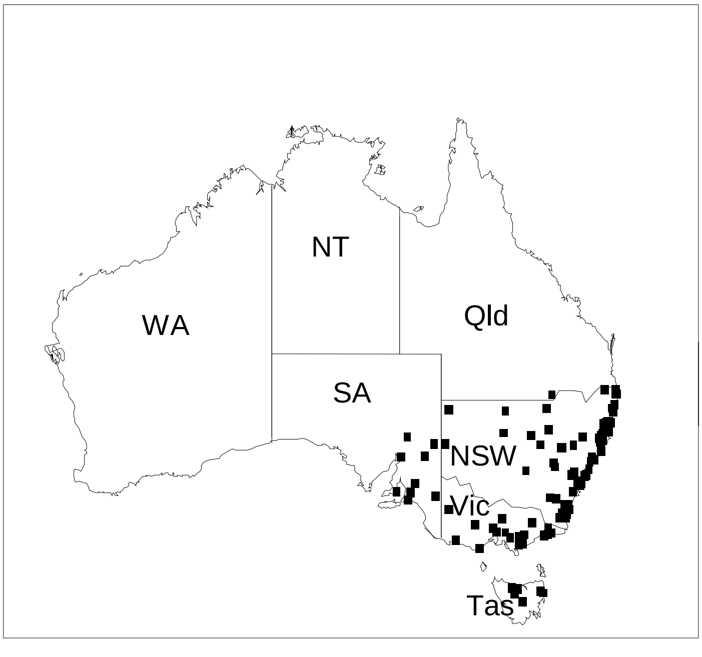

Figure 1: Locations of the Centres of the GSAM Storms

essential common feature of sustained moisture feed from the tropics.

The storms vary in duration from 1-7 days and extend to areas of up to 60,000 km^2. The catalogue of storms covers all seasons but is biassed towards Summer and Autumn. Figure 2 and Table 1 show the number of storms of each duration and season. Appendix A gives a complete list of storm dates, locations and areal extents.

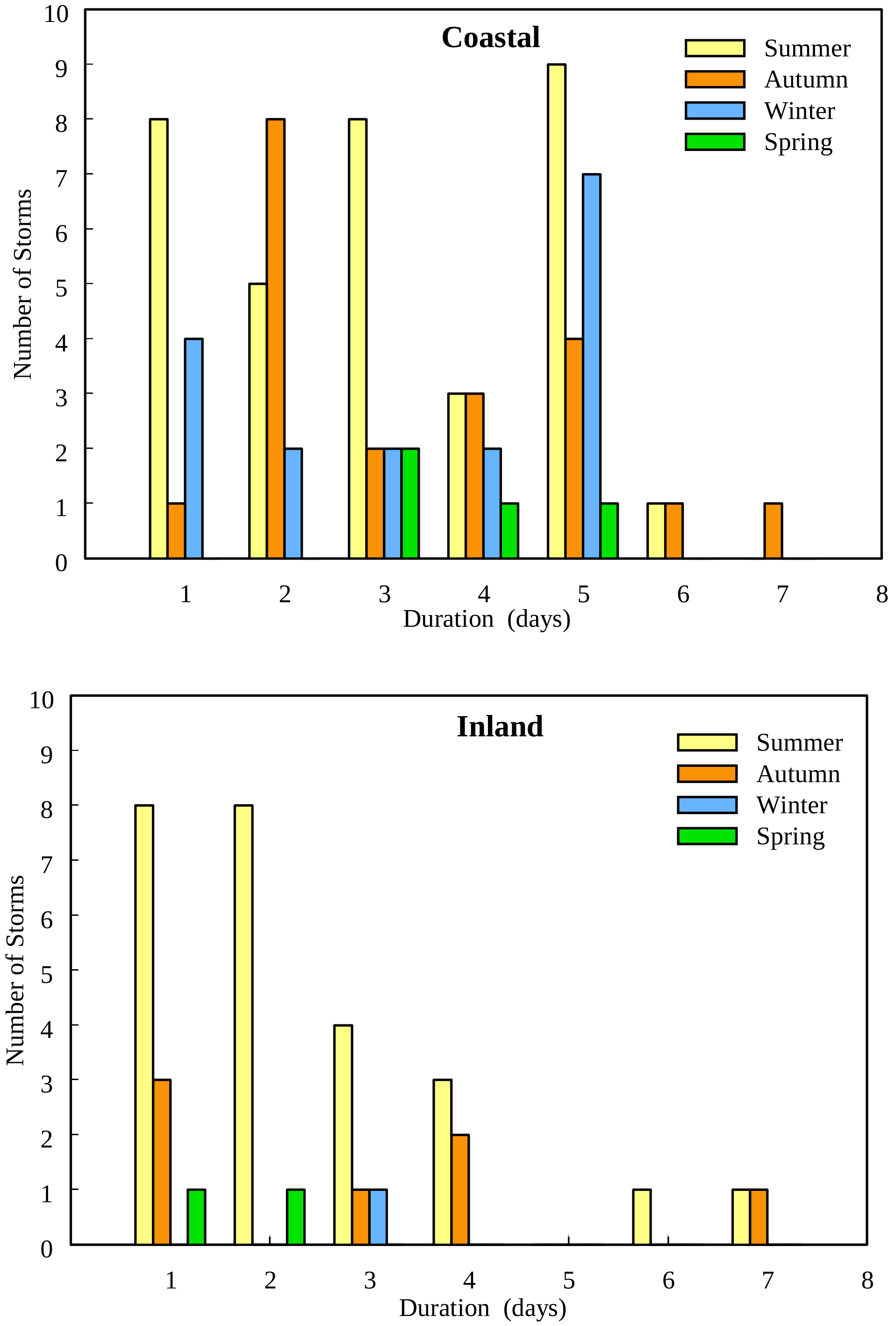

Figure 2: Number of GSAM Storms of Each Duration and Season

Table 1: Number of GSAM Storms of Each Duration and Season

Duration	**Summer**		**Autumn**		**Winter**		**Spring**		**Year**	
(days)	No.	*%*	No.	*%*	No.	*%*	No.	*%*	No.	*%*
Coastal										
1	8	*24*	1	*5*	4	*24*	0	*0*	13	*17*
2	5	*15*	8	*40*	2	*12*	0	*0*	15	*20*
3	8	*24*	2	*10*	2	*12*	2	*50*	14	*19*
4	3	*9*	3	*15*	2	*12*	1	*25*	9	*12*
5	9	*26*	4	*20*	7	*41*	1	*25*	21	*28*
6	1	*3*	1	*5*	0	*0*	0	*0*	2	*3*
7	0	*0*	1	*5*	0	*0*	0	*0*	1	*1*
All	34	*100*	20	*100*	17	*100*	4	*100*	75	*100*
Inland										
1	8	*32*	3	*43*	0	*0*	1	*50*	12	*34*
2	8	*32*	0	*0*	0	*0*	1	*50*	9	*26*
3	4	*16*	1	*14*	1	*100*	0	*0*	6	*17*
4	3	*12*	2	*29*	0	*0*	0	*0*	5	*14*
5	0	*0*	0	*0*	0	*0*	0	*0*	0	*0*
6	1	*4*	0	*0*	0	*0*	0	*0*	1	*3*
7	1	*4*	1	*14*	0	*0*	0	*0*	2	*6*
All	25	*100*	7	*100*	1	*100*	2	*100*	35	*100*

2.2 Sequences of Rainfall Within and Antecedent to GSAM Storms

Sequences of rainfall within, and 15 days antecedent, to the GSAM storms were constructed from station rainfall data held in the Bureau of Meteorology's Australian Data Archive for Meteorology (ADAM). Areal averages of daily rainfalls were calculated for a set of standard-sized, nested areas fixed in space for the duration of the sequence. Where sub-daily rainfall data was available, these areal averages were refined to a 3-hourly resolution.

The following section describes how the sequences of areal-average rainfall were constructed. It includes the following topics:

1. Station Rainfall Data
2. Data Quality Control
3. Areal Averages of Daily Rainfall
4. Areal Averages of 3-Hourly Rainfall

2.2.1 Station Rainfall Data

The construction of the rainfall sequences began with the identification of the Bureau of Meteorology rainfall-recording stations that were in operation at the time and within the areal extent of each storm. The identification included daily-read raingauges and continuously-recording pluviometers. Stations from the synoptic station network, which record 3-hourly observations, and which had provided useful rainfall data to the GSAM project, were also included. Typically a storm event will be defined by rainfall from 100-300 daily-read stations (where a day is 9am-9am) and 0-5 continuously-recording pluviometer stations. Synoptic stations provided supplemental rainfall data to five storm events.

For each identified station the rainfall totals for the days of the storm and the 15 days prior were extracted from the rainfall archive. Though the analysis of subsequent rainfalls was outside the scope of the project, we took the opportunity to extract also the rainfall totals for the 15 days succeeding each storm for the benefit of future research on this topic. The station rainfall data held in ADAM is continuously maintained so the data extracted for this project differed slightly from that extracted for the GSAM project.

2.2.2 Data Quality Control

The extracted daily rainfall totals were subjected to intensive quality control prior to further analysis. To facilitate the quality control process the data for each storm was output as comma- and quote-delimited text so that it could be ingested easily into a spreadsheet utility. The spreadsheet format made identification and correction (or deletion) of erroneous data very simple. As well, a plotting utility was written to facilitate comparison of rainfall totals at nearby stations.

The data quality issues encountered were:

- a. *Accumulated rainfall totals* - If the gauge is not read and emptied every day then the rainfall accumulates in the gauge until the next time it is read, and the amount recorded in the archive is flagged as having been accumulated over a number of days;
- b. *Missing rainfall records* - If the rainfall is not recorded at all for a day then the archive record is flagged as missing;
- c. *Misdated rainfall records* - Often the rainfall is attributed to the wrong date, usually one or two days before or after the correct date. Misdated falls are only obvious when relatively large and when they can be compared with falls at nearby stations;
- d. *Un-flagged accumulated rainfall totals* - Not all accumulated rainfalls are properly flagged as such in the rainfall archive. These, again, are only obvious when relatively large and when they can be compared with falls at nearby stations; and
- e. *Inconsistent/wrong records* - Sometimes the rainfall totals at one station are completely at odds with those of nearby stations. Sometimes a cause for this can be determined, eg the archived station location is incorrect, but mostly no cause is forthcoming. Once again, inconsistent or wrong rainfall totals are only identifiable when they are large.

Table 2 shows an example of the data quality issues *a.*- *d.* for a daily rainfall sequence. In this example, daily station rainfall totals for the 15 days prior and 3 days after a 1-day rainfall event are tabled. The rainfall event is marked by light shading and erroneous data by a darker shading. Flagged accumulated rainfall totals (*a.*) are coded as sequences of “-888 -x”, where “x” denotes the rainfall accumulated in the gauge over the preceding accumulation days. Missing records (*b.*) are coded as “-999". The example sequence of misdated rainfall records (*c.*) shows rainfall totals incorrectly attributed to the day before. Un-flagged accumulated rainfall totals (*d.*) invariably show up as sequences of “0 x”, where “x” denotes the accumulated total.

To assess the incidence of issues *a.* - *e.* for the GSAMARP database, a sample of 12 storms, representative of the geographical and temporal coverage of the GSAM Storm Catalogue, were identified. The data for each of the 12 storms were subjected to intensive quality control and the frequency of occurrence of the issues *a.* - *e.* determined. For this sample of storms, issues *a.* and *b.* each constituted 2.6%, *c.* and *d.* 2.0%, and *e.* 0% of the data. The data quality issues *c.*- *e.* represent issues that were identifiable by virtue of being associated with large rainfall totals. Due to the high variability of rainfall at these spatial and temporal scales, it is virtually impossible to tell whether small rainfall totals ($\leq$15mm) have been misdated, represent un-flagged accumulations, or are just wrong. The incidence of such data errors must, in consequence, be somewhat higher than the 2.0% identified.

Table 2: Example of Data Quality Issues for a Daily Rainfall Sequence

Station Name	**Daily Rainfall Totals (mm)**																		
	Days prior to event															Event	Days after event		
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	1	1	2	3
COOLANGATTA	4	0	0	7	104	223	22	16	0	1	1	0	4	11	158	237	3	0	0
FOXLEY	0	0	0	11	24	130	32	18	0	0	0	0	0	0	95	248	0	0	0
CHRISTMAS CRK	0	0	0	5	31	135	28	17	0	3	0	0	0	0	60	155	0	11	2
BRUFF HILL	0	0	10	5	7	181	4	25	0	0	0	0	0	0	8	89	0	0	0
MUNDOOLUN	0	0	4	34	189	65	17 (*c.*)	0	3	0	0	0	0	3	58	126	3	0	0
INNISPLAIN	0	0	0	8	26	155	31	19	0	3	0	0	0	0	26	79	0	5	10
NERANG	0	0	0	6	125	198	40	10	0	9	0	0	0	0	137	0	229 (*d.*)	0	16
NUMINBAH	0	0	0	19	83	231	55	3	0	0	0	0	0	33	163	331	0	9	0
PALEN CREEK	0	0	0	8	58	193	12	15	3	6	0	0	0	4	57	161	0	0	0
RATHDOWNEY P.O.	0	0	0	12	35	159	32	15	0	4	0	0	0	3	25	0	70 (*d.*)	4	0
O'REILLY'S	0	0	1	4	53	136	50	4	5	4	22	11	43	59	397	197	5	8	11
SOUTHPORT	0	0	0	3	164	194	36	21	1	4	0	1	0	5	122	188	0	0	3
SPRINGBROOK	0	0	0	23	137	285	72	38	0	0	15	10	0	0	361	687	0	0	0
GUINEAS CREEK RD	0	0	0	5	138	216	42	0	8	4	0	0	0	29	155	417	3	0	0
MOUNT TAMBORINE	0	0	0	10	99	236	63	12	0	9	3	0	0	16	86	190	9	0	1
PALEN CREEK	-999	-999	-999	-999	-999	-999	-999	-999	-999	-999	-999	-999	-999	-999	-999	-999	-999	-999	-999 (*b.*)
LITTLE NERANG DAM	0	0	0	5	150	260	33	22	8	2	0	0	0	13	163	257	0	0	0
WUNBURRA	0	0	0	16	132	231	49	23	3	25	3	0	0	15	227	247	4	1	8
CAINBABLE	0	0	0	7	18	185	28	8	1	3	0	0	0	0	53	122	0	3	1
NUMINBAH	0	0	1	24	100	250	43	33	3	6	2	1	0	10	156	373	2	1	3
WIDGEE	0	0	0	5	32	154	36	17	0	0	0	0	0	0	180	436	0	0	0
GILSTON SCHOOL	0	0	0	5	144	240	32	12	1	10	0	0	1	14	111	218	3	1	7
MOUNT LINDSAY	0	0	0	14	103	167	17	20	0	7	0	0	0	0	0	300 (*d.*)	0	0	0
ROTTINGTON	1	0	0	12	162	279	59	18	2	5	4	0	2	23	234	308	1	0	12
ALSTONVILLE P.O.	1	0	1	7	0	125 (*d.*)	28	12	0	2	0	0	0	3	101	278	0	0	0
ST FRANCIS PLACE	1	0	3	3	44	155	42	16	-888	-4 (*a.*)	1	0	0	3	100	264	0	0	0
BANGALOW MOTEL	1	0	0	6	88	247	21	5	0	3	0	3	0	5	134	257	0	0	0
BINGEEBEEBRA	0	0	0	5	93	37	31	14	0	0	0	0	0	47	8	0	0	27	17
MISTY MOUNTAIN	3	0	1	9	39	155	27	24	0	3	1	0	0	3	147	254	0	0	0
TENNYSON ST	1	0	0	3	-888	-312 (*a.*)	28	5	0	3	2	0	4	3	155	0	226 (*d.*)	0	0
CAPE BYRON	0	0	0	3	28	155	13	7	2	0	5	0	11	11	86	90	0	0	0
CHILLINGHAM	3	0	0	10	70	194	36	28	0	4	1	0	0	5	146	217	0	0	0

The procedures adopted for error identification and correction of daily rainfall data were entirely manual. Automated procedures were canvassed but found to be unwieldy and inadequate.

No correction of sub-daily rainfall data (pluviometer and synoptic station) was attempted, but daily aggregates of sub-daily data were checked for consistency with nearby daily-read rainfall totals. Where inconsistencies were found no data from the sub-daily station was used.

2.2.3 Areal Averages of Daily Rainfall

Areal averages of quality-controlled station rainfall were calculated for standard-sized areas, for each day of the sequence. The areas were described by a set of nested parallelograms, which were originally defined for the GSAM project and adopted in the GSAMARP. The parallelograms are storm-centred, defined to encompass the highest storm totals, and range from 100 to 60,000km^2. An example set of standard areas, is given in Figure 3.

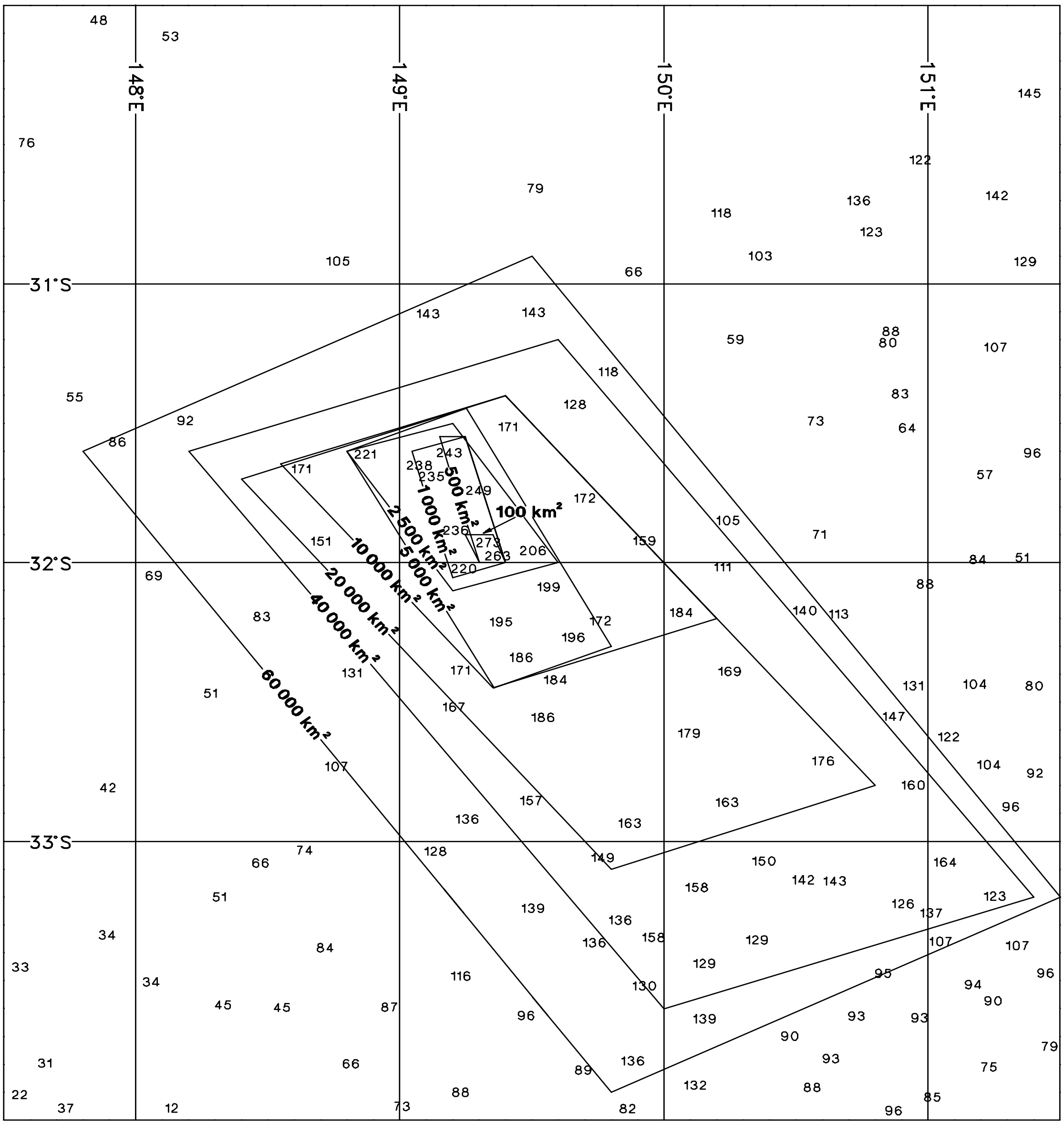

Figure 3: Areal Averaging: Example Set of Nested Parallelograms of Standard Areas

The coordinates describing the parallelograms are fixed for the duration of the storm and the antecedent period. They thus represent an Eulerian sampling of areal rainfall, like catchment-average rainfall.

Areal averages of daily station totals were calculated using the Thiessen polygon method (see Bruce and Clark, 1966). Thiessen station weights were calculated separately for each day of the sequence since the number of station totals available, i.e. not missing, varied from day to day. Station weights for each standard area parallelogram were calculated for each station within the areal extent of the storm. Daily areal-average rainfall was calculated using these weights via the following formula:

$$R_{da} = \frac{\sum_{s=1}^{N_d} W_{sda} \; R_{ds}}{N_d} \tag{1}$$

where R_{da} is the average rainfall on day d for area a
W_{sda} is the station weight for station s on day d for area a $\quad (0 \leq W_{sda} \leq 1; \sum_{s=1}^{N_d} W_{sda} = 1)$
R_{ds} is the station rainfall for station s on day d
N_d is the total number of stations within the areal extent of the storm with non-missing rainfall data on day d

An example sequence of areal averages for a 3-day storm (shaded) and the 15 days prior is given in Table 3. Note that because the parallelograms are fixed throughout the period and centred on the storm totals (in this case 3-day totals), the daily areal averages do not necessarily vary regularly with area-size.

Table 3: Example Sequence of Daily Areal-Average Rainfall (mm)

Standard Area (km^2)	**Days prior to event**															**Event**		
	15	**14**	**13**	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**1**	**2**	**3**
60000	0	0.1	0	0	0	0	0	0.8	4.6	15.6	21.8	8.8	2.4	0.1	2.0	15.7	67.0	77.3
40000	0	0	0	0	0	0	0.1	0.8	3.5	16.3	26.4	11.0	3.5	0.1	2.4	15.8	65.5	87.4
20000	0	0	0	0	0	0	0	0.7	1.8	12.3	30.8	15.2	4.0	0	2.6	15.4	65.9	98.0
10000	0	0	0	0	0	0	0	0.8	1.4	11.9	34.9	21.1	4.4	0	4.4	17.7	64.0	101.3
5000	0	0	0	0	0	0	0	0.7	0.9	15.4	33.0	21.2	2.9	0	4.5	21.2	63.1	98.4
2500	0	0	0	0	0	0	0	0.6	0.8	14.9	30.6	22.2	3.5	0	6.4	21.4	59.6	97.0
1000	0	0	0	0	0	0	0	0.4	0.7	12.4	30.6	24.0	3.6	0	6.9	22.6	55.7	96.3
500	0	0	0	0	0	0	0	0.4	0.6	11.1	30.6	25.0	3.7	0	7.4	23.8	53.0	96.3
100	0	0	0	0	0	0	0	0.4	0.4	6.2	31.7	28.8	4.3	0	8.3	25.8	46.7	95.6

2.2.4 Areal Averages of 3-Hourly Rainfall

For consistency with the design temporal distributions of rainfall within GSAM PMP bursts, the GSAMARP sequences of rainfall were refined, where possible, from daily to 3-hourly resolution. Rainfall data from the identified pluviometer stations were aggregated into 3-hourly totals, giving 8 rainfall totals per day for each day of a sequence. The 3-hourly totals, including those from synoptic stations, were then aggregated into daily (9am - 9am) totals, and the percentage contribution of each 3-hourly total to the daily total calculated. This percentage variation of 3-hourly rainfall within a day was then imposed on the areal averages of daily rainfall to provide areal averages of 3-hourly rainfall.

To assess the appropriateness of imposing a 3-hourly rainfall variation at a station on the rainfall average over an area, the daily variation of the two data types were compared. Figures 4 and 5 show the daily variation in areal-average rainfall and pluviometer station rainfall respectively, for a 2-day storm and the 15 days before and after. The plots are schematic, with each being scaled to the largest daily total of its sequence. Gaps in the plots of Figure 5 indicate missing data.

The relevance of a sub-daily station's daily rainfall variation was also verified with a plot showing the location of each with respect to the standard area parallelograms. Figure 6 shows this plot for the pluviometer and synoptic stations of Figure 5.

The example shown is unusual in that it has a large number of sub-daily stations but it demonstrates one of the typical difficulties of this technique; a lack of spatially appropriate sub-daily stations.

Where there were more than one sub-daily station showing a good match with the areal averages, a weighting was assigned to each, with the weights of all summing to 1. Due to the sparsity and heterogeneous distribution of sub-daily stations, as well as the subjective assessment of their match with the areal averages, weights were assigned manually. Unique weights were assigned to each station for each day and each standard area. Weights were held constant for each 3-hourly interval within a day.

Areal averages of 3-hourly rainfall were calculated using these weights via the following formula:

$$R_{ida} = R_{da} \sum_{s=1}^{N} W_{sda} \; r_{sid} \qquad (2)$$

where R_{ida} is the average rainfall in the 3-hour interval i on day d for area a (in mm)

R_{da} is the average rainfall on day d for area a (in mm)

W_{sda} is the weight assigned to sub-daily station s on day d for area a ($0 \leq W_{sda} \leq 1$)

r_{sid} is the fraction of daily rainfall for sub-daily station s in the 3-hour interval i on day d ($0 \leq r_{sid} \leq 1$)

N is the total number of sub-daily stations s contributing non-missing fractions to area a on day d

Due to the general lack of sub-daily rainfall data, areal averages of 3-hourly rainfall could only be determined for 59 of the 110 storms in the GSAM Storm Catalogue.

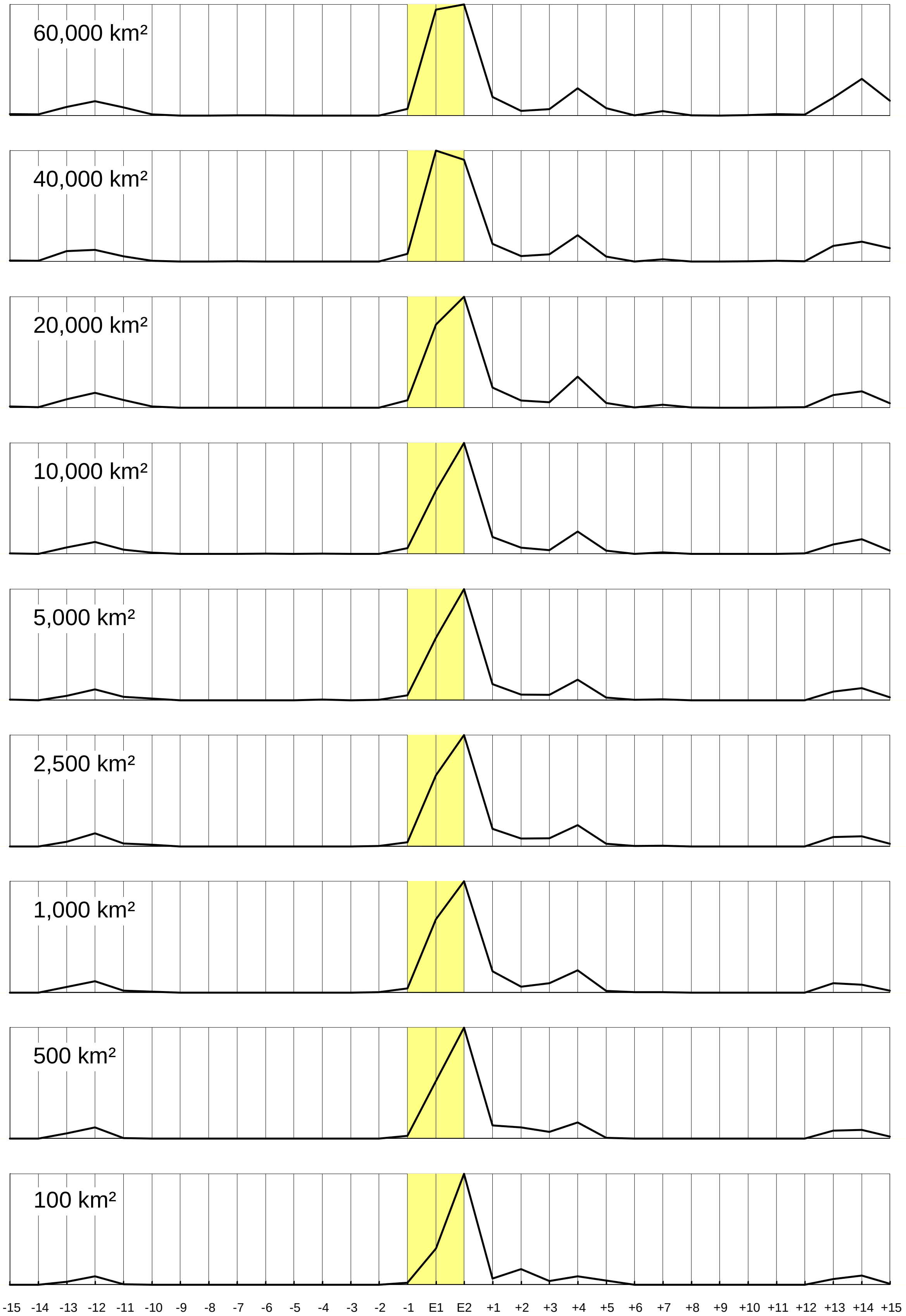

Figure 4: Example Daily Areal-Average Rainfall Sequence at Each Standard Area, for a 2-day Storm (shaded). Each plot is scaled to the largest daily total of its sequence.

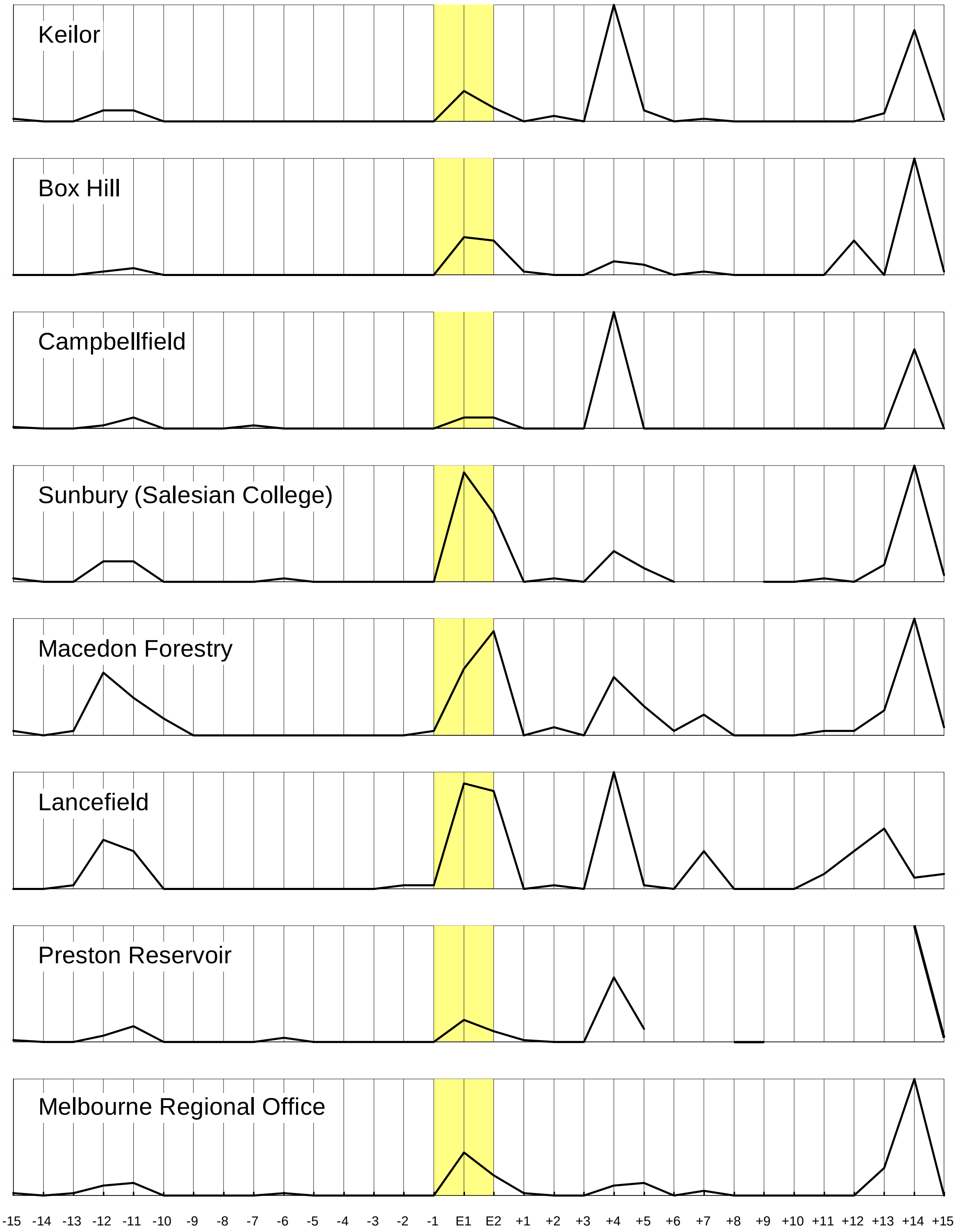

Figure 5: Example Sequences of Daily Aggregates of Sub-Daily Rainfall Totals at Various Stations, for the 2-day Storm (shaded) of Figure 4. Each plot is scaled to the largest daily total of its sequence. Gaps in the plots indicate missing data.

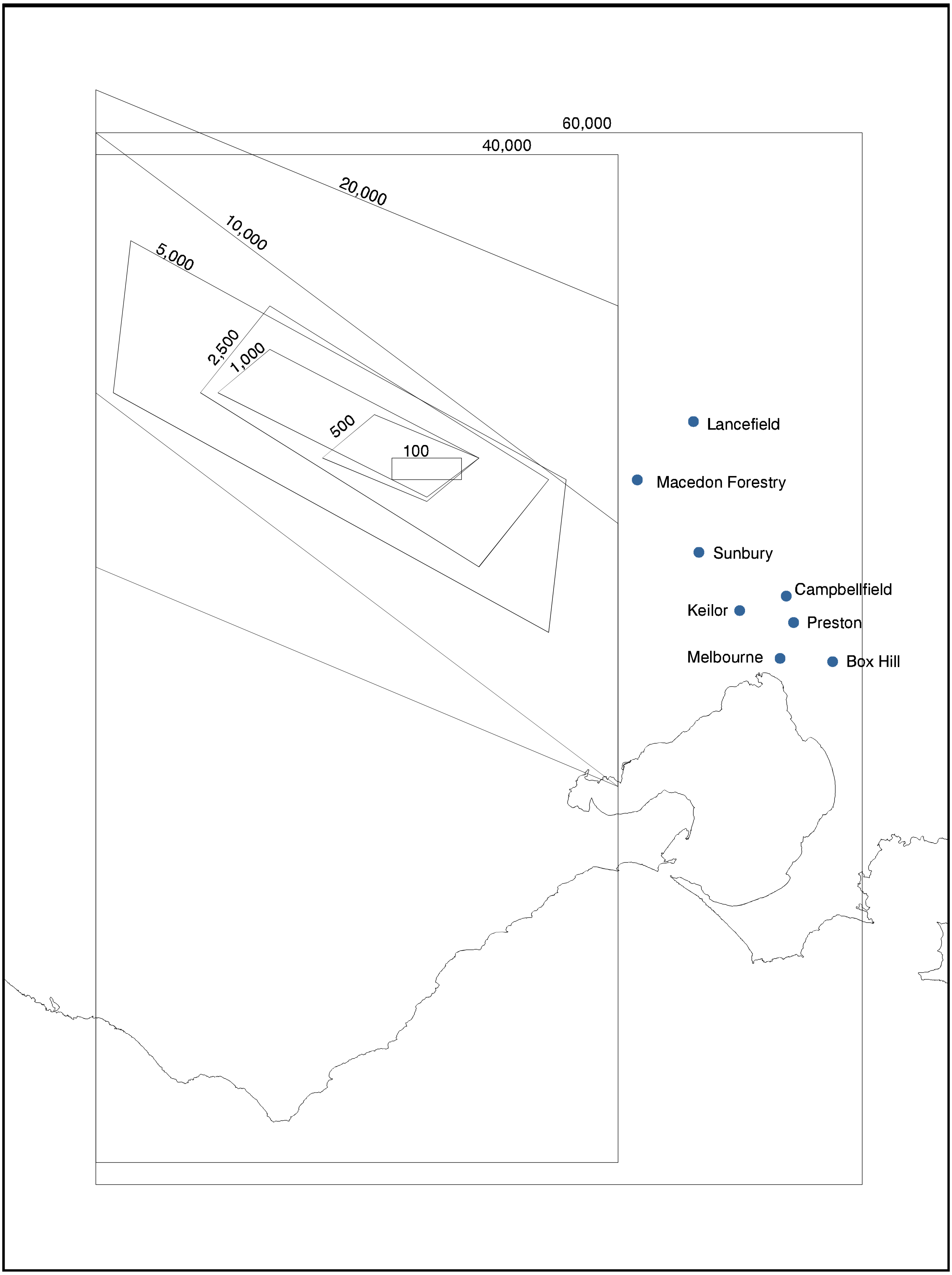

Figure 6: Location of Sub-Daily Rainfall Stations of Figure 5 with respect to the Standard Area Parallelograms (km^2) over which the Areal Rainfalls of Figure 4 were calculated.

3. ANALYSIS OF ANTECEDENT RAINFALL

The GSAMARP investigations began with an attempt to describe the ‘typical’ characteristics of the daily sequences of areal-average rainfall. Simple plots of the individual sequences showed the full array of possible scenarios: no antecedent rainfall at all; small antecedent rainfalls well-separated from the main storm; large antecedent rainfalls immediately prior to the main storm; and moderate antecedent rainfalls contiguous with the main storm. From comparison of individual plots it was difficult to determine any general characteristics of these sequences. Subsequent analysis therefore attempted to provide some simple statistical parameters to describe the sequences. To facilitate this statistical approach the analysis was divided into two parts:

1. Pre-Storm - an examination of the rainfall prior to each storm; and
2. Pre-Burst - an examination of the rainfall prior to all bursts within each storm.

This section describes the analysis and identified pre-storm and pre-burst characteristics of the daily sequences of areal-average rainfall.

3.1 Pre-Storm Rainfall

In the analysis of pre-storm rainfall, the areal averages of daily rainfall at 100km^2 only were examined in detail for the occurrence of antecedent rainfall, and ‘antecedent storms’ in particular.

3.1.1 Pre-Storm Antecedent Rainfall

Because the GSAM storm dates were chosen to encompass the most significant daily rainfall totals, they do not, in all cases, describe the start and end of the storm rainfall. To distinguish main storm rainfall from pre-storm rainfall, therefore, the start and end dates of the main storm were redefined, to encompass days contiguous with the highest total with $\geq$10mm of rainfall. In general this redefinition made the main storms longer, but in cases where the Storm Catalogue dates included small totals it made the main storm shorter. Pre-storm rainfall was thus defined as rainfall within the 15-day antecedent period but separated from the main storm by at least one ‘dry’ day of <10mm. Defining this intervening ‘dry’ day as <10mm is somewhat arbitrary but reasonable for a 100km^2 average.

Of the sample of 110 sequences of daily areal-average rainfall, 73 (66%) exhibited pre-storm antecedent rainfall of >10mm in a unbroken block within the antecedent period.

3.1.2 Antecedent Storms

Pre-storm antecedent rainfall was more specifically defined as an ‘antecedent storm’ if it was separated from the main storm, and if (a) there was more than 20mm of rain on any one day, or (b) the pre-storm rainfall (in an unbroken block of rainfall) totalled more than 5% of the main storm.

Of the sample of 110 sequences, 46 (42%) exhibited antecedent storms at some time within the 15-day antecedent period. For each of these 46, the depth and duration of the main storm, the antecedent storm and of the ‘dry’ period between the two were determined.

The variation in the duration of the antecedent storm, across the sample of 46 sequences, is shown in Figure 7. Note the dominance of 1-day storms (52% of the sample). These 1-day storms were found to be well spread throughout the 15-day antecedent period, suggesting temporal independence from the main storm.

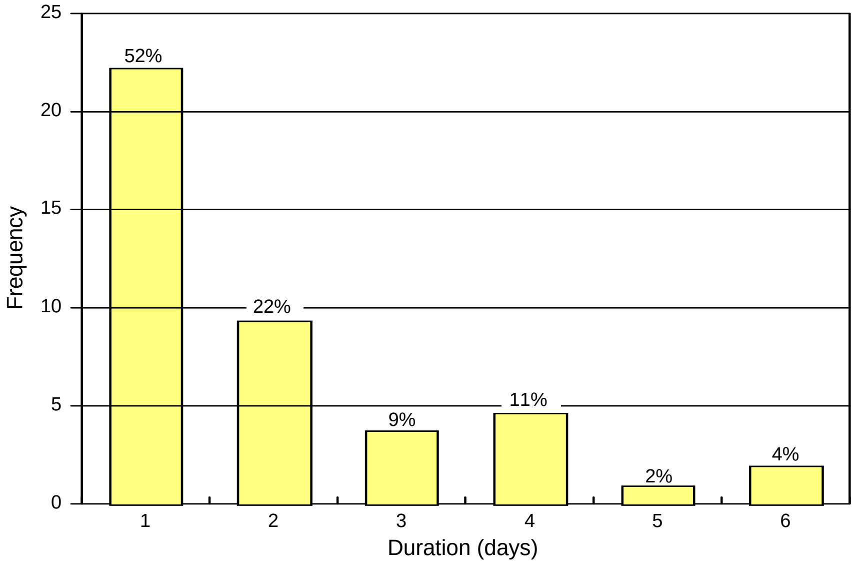

Figure 7: Frequency of Antecedent Storms of Various Durations

3.1.3 Intervening Dry Period

The variation in the duration of the intervening dry period, across the sample of 46 sequences, is shown in Figure 9. The peak in this figure at a duration of 1 day is most likely an artifact of using a simple rainfall cutoff value to detect the start of the main storm and not a representation of the expected frequency at this duration. The peak at 14 days is difficult to interpret in any physically meaningful way without knowing the pattern of variation beyond the analysed antecedent period. The peak at 8-9 days, however, is consistent with the time of passage of ordinary ‘synoptic’ scale events in the region. It also parallels the findings of the Washington State Department of Ecology (1989), in their analysis of rainfalls antecedent to extreme 24-hour storms in Washington State. Their study found that the average number of dry days between the main storm and the antecedent storm varied from 7 to 10 days.

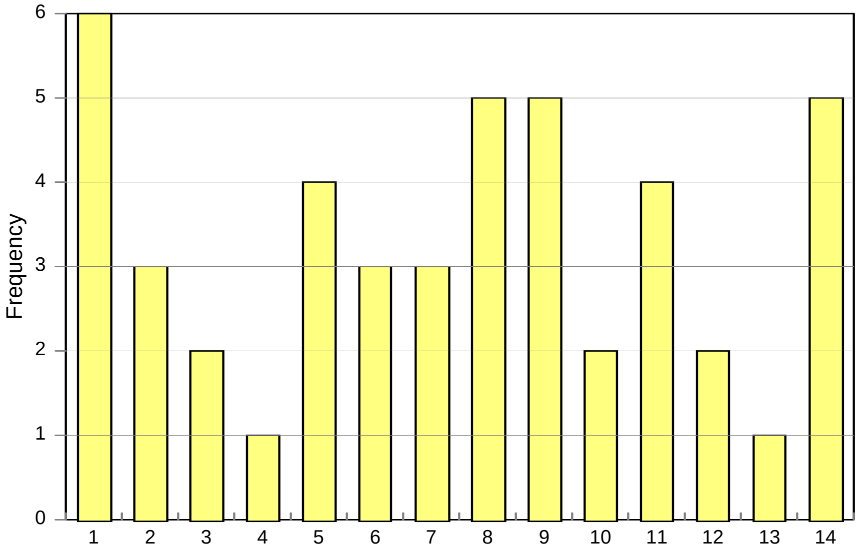

Figure 8: Frequency of Intervening Dry Periods of Various Durations

Various studies of pre-storm rainfall for the Tennessee Valley (US Weather Bureau, 1965; US Weather Bureau, 1969; National Weather Service, 1986) find that an intervening dry period of 3-4 days is a reasonable design scenario for that region. Chin and Vogel (1995), in their study of pre-storm rainfall in the central US, also find that an intervening dry period of 3-4 days is typical of large storms. Figure 8, however, suggests that 3-4 days is fairly atypical for large storms in the southeast of Australia.

Chin and Vogel also find an apparent negative correlation between the duration of the main storm and the duration of the intervening dry period. Such a correlation is also consistent with the notion of a standard 'synoptic' timing for these storms. The Bureau of Meteorology also found a negative correlation between the durations of these two periods, but the correlation is only weakly negative and not significant.

3.1.4 Size of Pre-Storm Events

The frequency of pre-storm rainfall totals of various sizes is shown separately for coastal and inland GSAM storms in Figure 9. This histogram shows the percentage of all storms in the catalogue which are preceded by rainfall totals of various sizes, where the size of the pre-storm rainfall has been expressed as a percentage of the main storm. It includes antecedent storms as well as occasions where contiguous pre-storm rainfall amounted to less than 5% of the main storm.

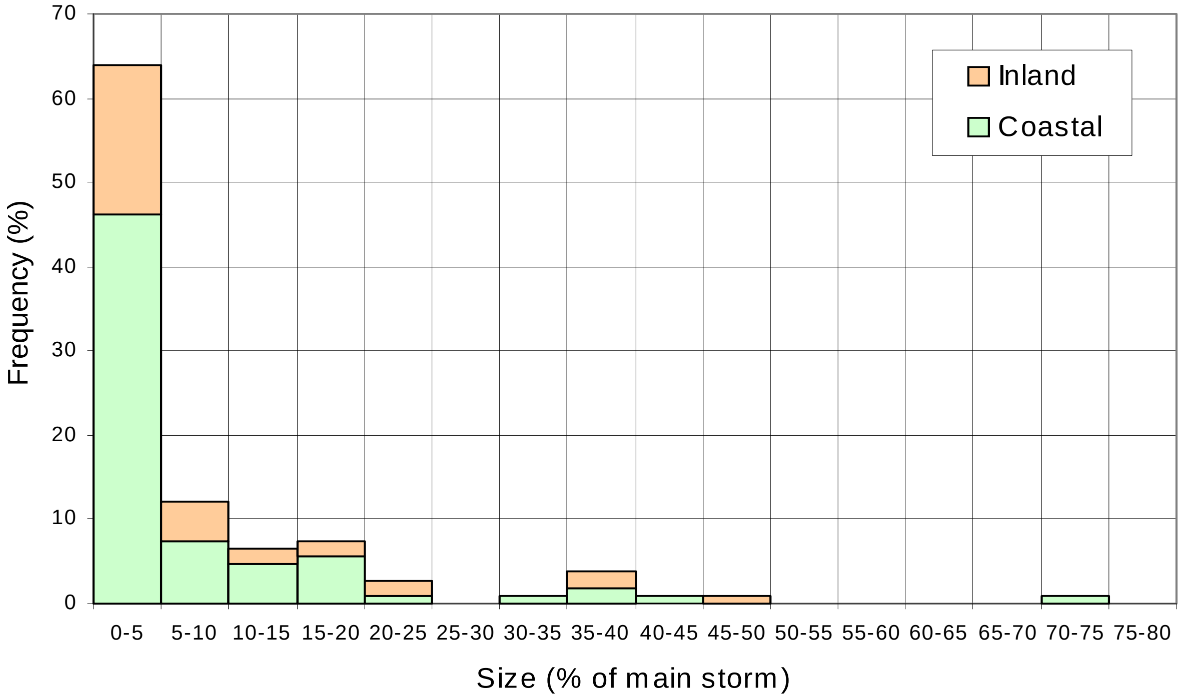

Figure 9: Frequency of Pre-Storm Rainfall Totals of Various Sizes. Size is expressed as a percentage of the main storm. Note the appearance of two different populations of antecedent storms.

From this histogram it appears, firstly that *significant* pre-storm rainfall is rare: 64% of GSAM storms are preceded by rainfalls totalling less than 5% of the main storm, and secondly that occasions of significant pre-storm rainfall, when they do occur, appear to derive from two different event populations. Most antecedent storms (38 out of 46) are <25% of the main storm: consistent with identification over southeast Australia as common frontal events. A small number (8 out of 46) are between 30 and 75% of the main storm. This smaller group might be identified, speculatively, as similar in character to the main storm.

The finding that storms prior to large and extreme storms over southeast Australia are typically less than 30% of the main storm agrees with the findings of the previously cited US studies.

The geographic location of the main storm (coastal or inland) does not appear, from Figure 9, to have any bearing on the frequency of occurrence of pre-storm rainfall of various sizes.

An investigation for possible seasonal bias did reveal a disproportionately high representation of Autumn sequences with significant pre-storm rainfall: Autumn sequences represent 25% of the GSAMARP database, and 39% of sequences with antecedent storms greater than the median antecedent storm.

3.1.5 Typical Antecedent Storm Scenarios

Table 4 shows the average and the median values of the depth and duration of the main storm, the antecedent storm and of the 'dry' period between the two, for the sample of 46 sequences with antecedent storms.

Table 4: 'Typical' Antecedent Storm Scenarios

	Average	**Median**
Depth of main storm (% of main storm)	100	100
Duration of main storm (days)	3.9	3
Depth of intervening 'dry' period (% of main storm)	3.6	2.5
Duration of intervening 'dry' period (days)	7.3	8
Depth of antecedent storm (% of main storm)	16.3	11.7
Duration of antecedent storm (days)	2.0	1

A schematic of the average scenario is also given in Figure 10. The horizontal proportions of this figure are scaled to the durations (days) and the vertical proportions are scaled to the percentage of the main storm (100%).

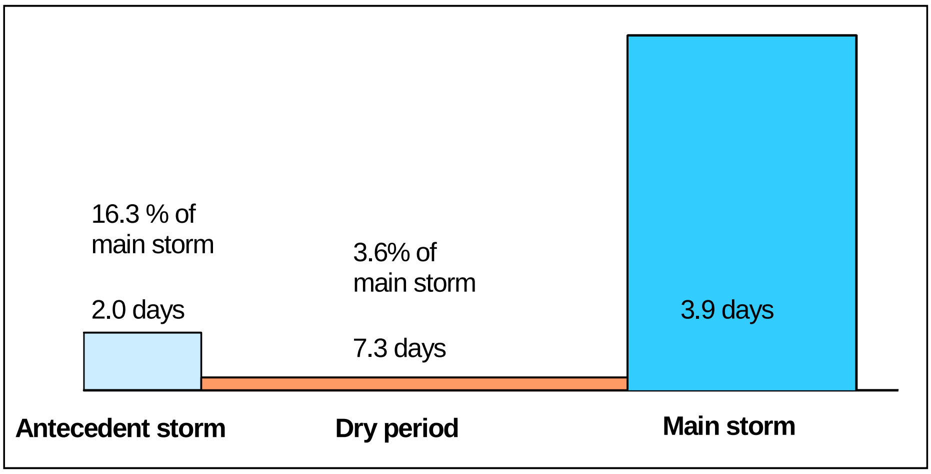

Figure 10: Schematic of Average Antecedent Storm Scenario

3.1.6 Summary

In 93% of the GSAM sample of the largest storms on record over southeast Australia, pre-storm rainfall amounts to less than 25% of the main storm. In 64% of the sample, pre-storm rainfall amounts to less than 5% of the main storm. In 34% of the sample, rainfall in the 15 days prior amounts to less than 10mm. Thus significant pre-storm rainfall appears to be rare for large and extreme storms over southeast Australia. When it does occur, it is typically short in duration and separated from the main storm by a standard synoptic period of 7 days. This profile of pre-storm rainfall is consistent with its identification, in this part of Australia, as common frontal rain. The above lends support to the general conclusion that pre-storm rainfall may be viewed as independent from the main storm and not significantly different from the rainfall normally experienced at that time of year.

3.2 Pre-Burst Rainfall

In the analysis of pre-burst rainfall, areal averages of daily rainfall at all standard areas were examined; pre-burst rainfall being defined as all rainfall before the burst, both within storm and pre-storm. The largest bursts of rainfall within each rainfall sequence were identified, and the rainfall prior to each burst isolated. Pre-burst rainfalls, for each burst duration and standard area, were then analysed to determine the proportions in which the rainfall is ‘typically’ distributed throughout the antecedent period.

3.2.1 Identifying Rainfall Bursts

Because the main aim of the GSAMARP is to provide advice on the appropriate values of antecedent rainfall to use in conjunction with GSAM PMP estimates, it was important that GSAMARP rainfall bursts be identified using the same criteria as used in the GSAM project. Essentially this means selecting the highest rainfall bursts within the window defined by the GSAM storm start and end dates, as given in the GSAM Storm Catalogue.

The highest 1-, 2-, 3-, 4- and 5-day bursts, where a day is from 9 am to 9 am, were identified at each standard area within each storm. These bursts constitute the largest, daily-resolved rainfall bursts on record for southeast Australia.

3.2.2 Daily Distribution of Pre-Burst Rainfall

To determine the proportions in which pre-burst rainfall is 'typically' distributed through the antecedent period, two statistics were computed: first, the frequency with which rainfall occurs on any given day within the pre-burst sequence; and second, given rain, the average amount to expect. In this analysis a rainday is any day with a non-zero rainfall average.

Frequency of Pre-Burst Rainfall

Figure 11 shows, for the 100km^2 standard area, the percentage of 1-, 2-, 3-, 4- and 5-day bursts that were accompanied by rain on any one of the 10 days prior to the burst.

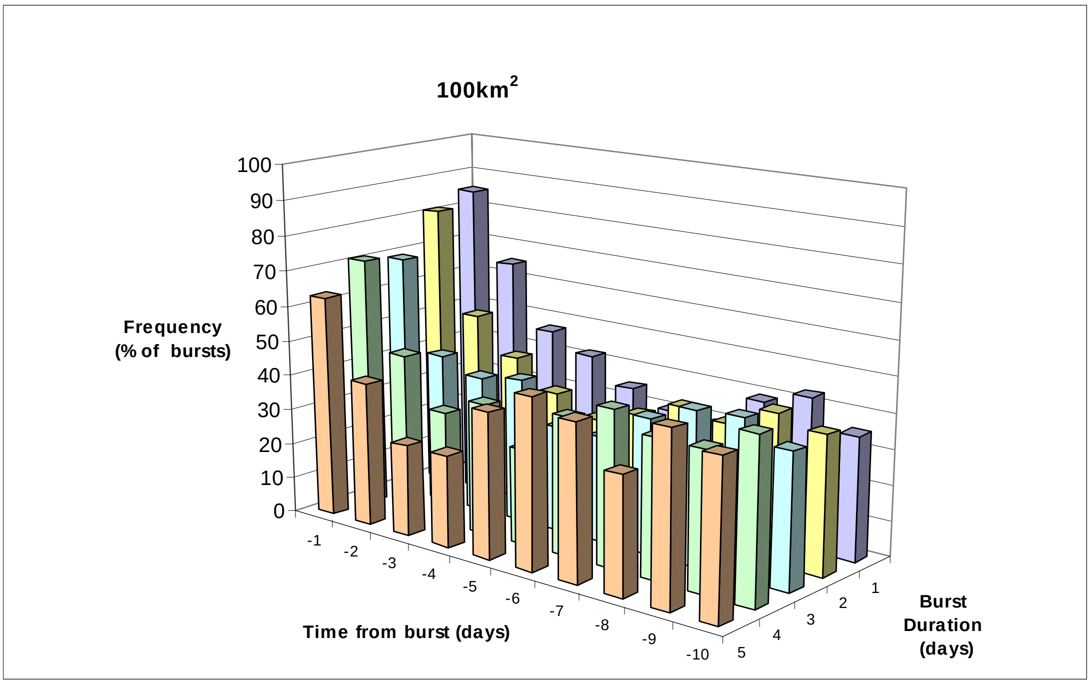

Figure 11: Frequency of Rainfall Within the 100km^2 Pre-Burst Sequence

The figure shows that on any day in the preceding 10-day period there is a 26% chance or greater of recording rain within an area of 100km^2. While there is roughly the same chance of rain throughout this period, the chance of rain is greatest in the days immediately prior to the burst. That there is a greater chance of rain 1 day prior to the burst than at any other time is not unexpected since all daily rainfalls are 9am-9am totals and it is extremely unlikely that bursts of daily resolution will be entirely contained within these 9am-9am periods. That there is a greater chance of rain 2 days prior to a 1-day burst (65% of the time) than there is of rain 2 days prior to a 5-day burst (41% of the time) is also to be expected. This is because for these storms a 1-day burst is more likely than a 5-day burst to be embedded within a longer storm. This is truer of the coastal storms in the GSAM Storm Catalogue than of the inland storms (see number of storms of each duration in Table 1).

For standard areas larger than 100km^2 (not shown), the percentage of bursts accompanied by rain on any one of the 10 days prior generally increases with area-size, as the chance of rain occurring somewhere within the area increases. At the 10,000km^2 standard area, for example, there is a 42% chance or greater of recording rain on any one day in the 10-day period preceding the largest bursts.

The finding that there is a greater chance of rain immediately prior to a 1-day burst than at any other time in a 10-day antecedent period is consistent with the findings of Chin and Vogel (1995). However, probably because their analysis is based on point rather than areal rainfalls, their frequency percentages are lower than those of Figure 11.

To ascertain whether rainfall in the 10 days prior to the largest bursts on record was more frequent or less frequent than 'normal', an analysis of the frequency of daily rainfall at 12 selected stations across the GSAM region was undertaken. The stations were selected on the basis of geographic representation and length of record. Not surprisingly, the frequency of daily rainfall was found to vary considerably across the region and through the year. In fact the frequency of daily rainfall is a fairly classic indicator of climate regime. Averaged across all 12 stations, however, the frequency of point daily rainfall was consistently between 20 and 30% on all days of the year.

An equivalent analysis of the frequency of areal daily rainfall proved problematic, since the record overlap for 2 or more stations is generally not large: individual stations with over 50 years of record, for example, might only have recorded simultaneously for 10. Nonetheless we expect that the frequency of rainfall over an area would be greater than at a point. Thus it appears from Figure 11 that it is only in the 1-3 days immediately prior to these bursts that the occurrence of rainfall is more frequent than 'normal' for the region.

Average Non-Zero Pre-Burst Rainfall

To compute a meaningful average of the rainfall on any given day in the pre-burst sequence, it was necessary to normalise each sequence. This was done by dividing the rainfall, on each day in the antecedent period, by the average daily burst depth, i.e. daily rainfalls prior to the 5-day burst were divided by 1/5th of the 5-day burst depth.

Figure 12 shows, for the 100km^2 standard area, the average depth of non-zero rainfall on each of the 10 days prior to 1-, 2-, 3-, 4- and 5-day bursts, expressed as a percentage of the average daily burst depth. Note that to improve the clarity of this figure, the 'Burst Duration' axis is the reverse of that in Figure 11.

Figure 12 shows that the average depths within the antecedent period vary greatly from one day to the next, but are largest in the 1-3 days immediately prior to the burst. In general, the plot concords with the lengthy dry period between rainfall events that was determined in the pre-storm investigation. It also indicates something of the structure of the storms from which these bursts derive. For 1-day bursts in particular the 29% average depth 3 days prior to the burst, which derives from only 26% of bursts, indicates that where 1-day events are embedded in longer events those longer events are generally double-peaked.

No systematic variation in pre-burst rainfall depth with increasing area-size was observed. In fact, similar patterns to those in Figure 12 were obtained at all area-sizes. This is understandable since the standard area parallelograms, over which areal-average rainfalls were calculated, are fixed in space and centred on the heaviest storm rainfalls, not the heaviest daily pre-burst rainfalls.

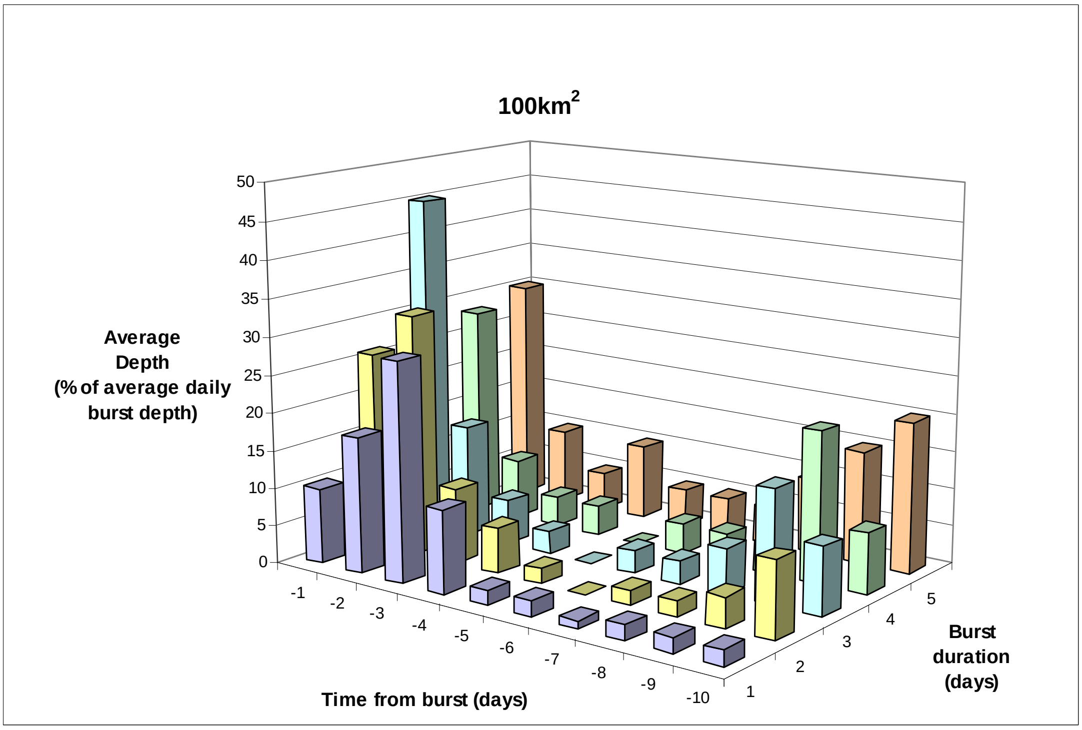

Figure 12: Average Depth of Non-Zero Rainfall Within the $100km^2$ Pre-Burst Sequence

Because the rainfalls in Figure 12 are expressed as percentages of the burst depth, it is not possible to make a meaningful comparison between these and a climatic average daily rainfall for the region. Comparison of pre-burst daily rainfall in individual sequences (expressed in mm) with climatic averages for the same location is also unrewarding due to the great variability in temporal structure from one sequence to the next. It was thus not possible to determine with confidence whether the daily rainfall in the 10 days prior to the largest bursts on record was generally greater or lesser than is 'normal' for the region.

3.2.3 Summary

The above analysis tells us that pre-burst rainfall is more frequent than 'normal' only in the 1-3 days immediately prior to the burst. It also tells us that this same immediate period is when the greatest pre-burst depths are expected. From these results we conclude that significant pre-burst rainfall for large and extreme bursts over southeast Australia is 'typically' contiguous with the burst and most likely part of the same storm event.

4. DEVELOPING DESIGN PRE-BURST TEMPORAL DISTRIBUTIONS

The major objective of the GSAMARP was to determine design estimates of rainfall antecedent to design rainfall bursts in the GSAM region, including the PMP. The GSAMARP investigations, described in Section 3, along with an earlier investigation (Sinclair Knight Merz, 1997) had suggested that rainfall in the days and months antecedent to GSAM storms was not significantly different from ‘normal’. Thus ***any design estimate of antecedent rainfall need only cover the within-storm pre-burst period.*** To this end design pre-burst temporal distributions were developed from the GSAMARP sequences of 3-hourly areal-average rainfall. Three-hourly sequences were chosen instead of daily sequences, as the basis of the design distributions, for consistency with the GSAM temporal distributions of design rainfall bursts (Meighen and Minty, 1998). It was thus intended that the burst and the pre-burst temporal distributions would together describe the temporal variation of the complete design storm.

This section describes the development of design pre-burst temporal distributions for the GSAM region from the GSAMARP sequences of 3-hourly, areal-average rainfall, via the following steps:

1. Identify the largest rainfall bursts;
2. Define the storm beginning and thus the pre-burst period;
3. Normalise the pre-burst sequences;
4. Define a standard-length pre-burst period;
5. Combine the normalised, standard-length sequences; and
6. Check and scale the combined sequences for consistency with PMP

4.1 Identifying Rainfall Bursts

The first task in the development of the design pre-burst temporal distributions was to identify, within the sequences of 3-hourly areal-average rainfall, the largest rainfall bursts. Because the pre-burst distributions are intended to be used in conjunction with design rainfall bursts, including GSAM PMP estimates, it was important that the burst durations and the criteria by which the bursts were selected be identical to those used in the GSAM project. Accordingly, the largest rainfall bursts of 12, 24, 36, 48, 72, 96 and 120 hours duration were selected, at each standard area of each storm, from within the window defined by the GSAM storm start and end dates, as given in the GSAM Storm Catalogue. These bursts constitute the largest 3-hourly-resolved rainfall bursts on record for southeast Australia. Table 5 shows the number of rainfall bursts, and therefore pre-burst sequences, identified at each burst duration and standard area.

Table 5: Number of Rainfall Bursts at Each Duration and Area

Duration (hours)	**Area (km^2)**								
	100	**500**	**1,000**	**2,500**	**5,000**	**10,000**	**20,000**	**40,000**	**60,000**
Coastal									
12	41	41	41	41	41	40	27	13	7
24	41	41	41	41	41	40	27	13	7
36	31	31	31	31	31	30	24	11	6
48	31	31	31	31	31	30	24	11	6
72	21	21	21	21	21	21	17	7	4
96	14	14	14	14	14	14	12	3	1
120	8	8	8	8	8	8	7	3	1
Inland									
12	16	16	16	16	16	16	14	12	11
24	16	16	16	16	16	16	14	12	11
36	12	12	12	12	12	12	11	10	9
48	12	12	12	12	12	12	11	10	9
72	8	8	8	8	8	8	7	7	6
96	4	4	4	4	4	4	4	4	4
120	3	3	3	3	3	3	3	3	3

4.2 Defining the Storm Beginning

As with the analysis of pre-storm rainfall, it was necessary to redefine the start date of the main storm to encompass small rainfalls contiguous with the bursts, which could reasonably be identified as part of the main storm, and which might be significant as antecedent rainfall. Because bursts were selected from within the window defined by the GSAM start and end dates, this particular redefinition of the storm beginning only sought to push the start date back in time, where necessary.

The approach adopted for redefining the storm beginning was a blend of objective and subjective decision-making as follows:

- use the daily areal averages of rainfall as the primary basis for decision-making; refine with the 3-hourly areal averages
- make 9am on the GSAM start date the default storm beginning and then check for daily rainfall totals >10mm on the days prior to and contiguous with this date
- proceed backwards in time from 1 day prior until a daily total of ≤10mm is encountered; the day following will be the *daily-resolved* storm beginning
- examine the 3-hourly rainfall totals just prior to the daily-resolved storm beginning in overlapping 6-hourly blocks, checking for 6-hourly rainfall totals >5mm
- proceed backwards in time from 6 hours prior to the daily-resolved storm beginning until a 6-hourly rainfall of ≤5mm is encountered; the 6-hourly block following will be the *6-hourly-resolved* storm beginning
- examine the 3-hourly rainfall totals within the first 6-hourly block of the 6-hourly-resolved storm beginning, checking the distribution of rainfall within this 6-hourly block
- if the rainfall within this first 6-hourly block is ‘back-loaded’ then the 3-hourly period beginning in the second half of the 6 hours becomes the *3-hourly-resolved* storm beginning.

As decision-triggers, 10mm-in-1day and 5mm-in-6hours, are somewhat arbitrary numbers, but consistent with the amounts of rainfall observed within single large storms in the region.

With the above approach, 12 of the sample of 59 storms with sub-daily rainfall data had their storm beginnings redefined. There was no apparent need to determine different storm beginnings for each standard area within each storm: a characteristic stationarity in the GSAM storms provides for near-simultaneous start and end times for rainfall over a wide area.

An example of a redefined storm beginning is shown in Figure 13. In this figure the storm beginning has been redefined, on the basis of daily areal averages of rainfall, as 1 full day earlier than the GSAM start date.

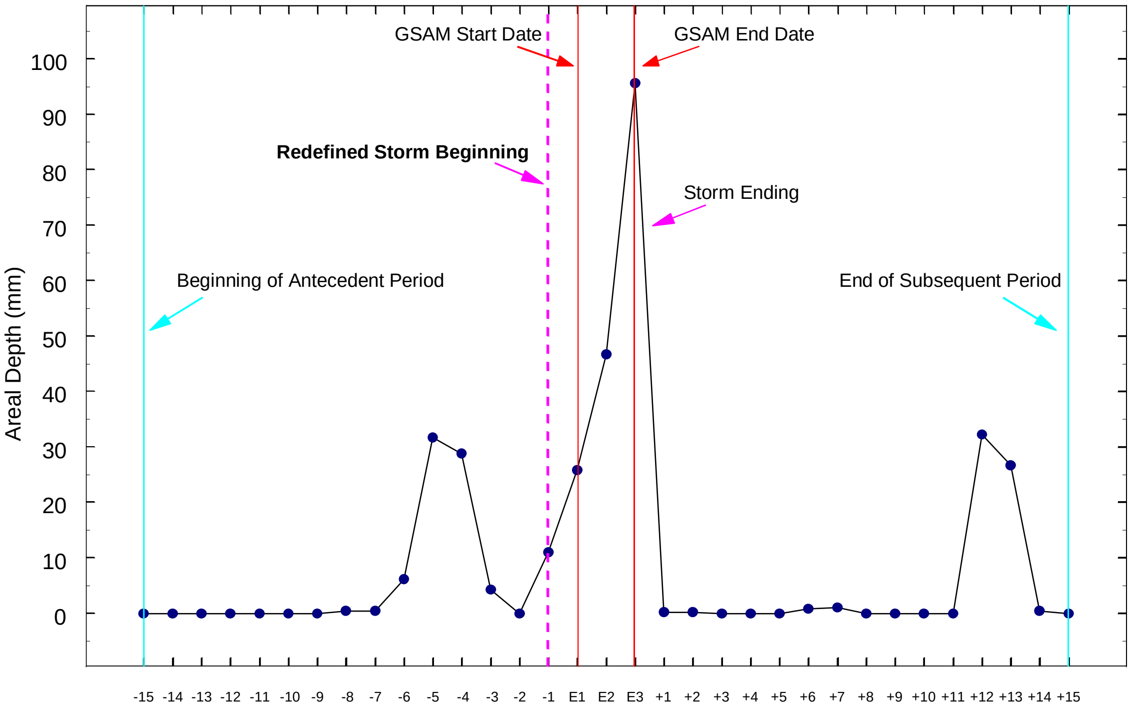

Figure 13: Example of Redefining the Storm Beginning

The storm beginning and ending markers in Figure 13 serve to delineate a single ‘synoptic’ event. They imply a physical relation between the rainfall totals at each interval between the markers. Equally they imply a reduced physical relation between the event and the rainfall totals outside the markers.

Defining the storm beginning also defines, by default, the relevant period of pre-burst rainfall: the period of rainfall within-storm but prior to the largest rainfall burst.

4.3 Normalising Sequences

To determine a ‘typical’ pre-burst rainfall distribution from the sample of pre-burst sequences, it was also necessary to normalise the pre-burst rainfalls. This was achieved by dividing each 3-

hourly rainfall in the pre-burst period by the burst depth. Normalisation ensured that sample sequences from storms in the far south of the region would be on equal footing with those from the far north. It also means that converting a pre-burst distribution back into a sequence of rainfall totals is a simple matter of multiplying by the burst depth.

Expressing pre-burst rainfalls as a fraction of the burst implies a strong physical relation between the burst and the pre-burst period. Restricting the normalisation to the within-storm, pre-burst period is consistent with this implied physical relation.

4.4 Defining a 'Typical' Pre-Burst Period

To combine the normalised pre-burst sequences of individual storms into a single 'typical' sequence, a standard length pre-burst period was required for each burst duration.

For individual bursts within storms the pre-burst period may vary in length from 0 hours up to 168 hours. Figure 14, for example, shows the length of the pre-burst period for each of the bursts in the samples for 100km^2, 12-hour and 72-hour bursts within coastal storms. The pre-burst

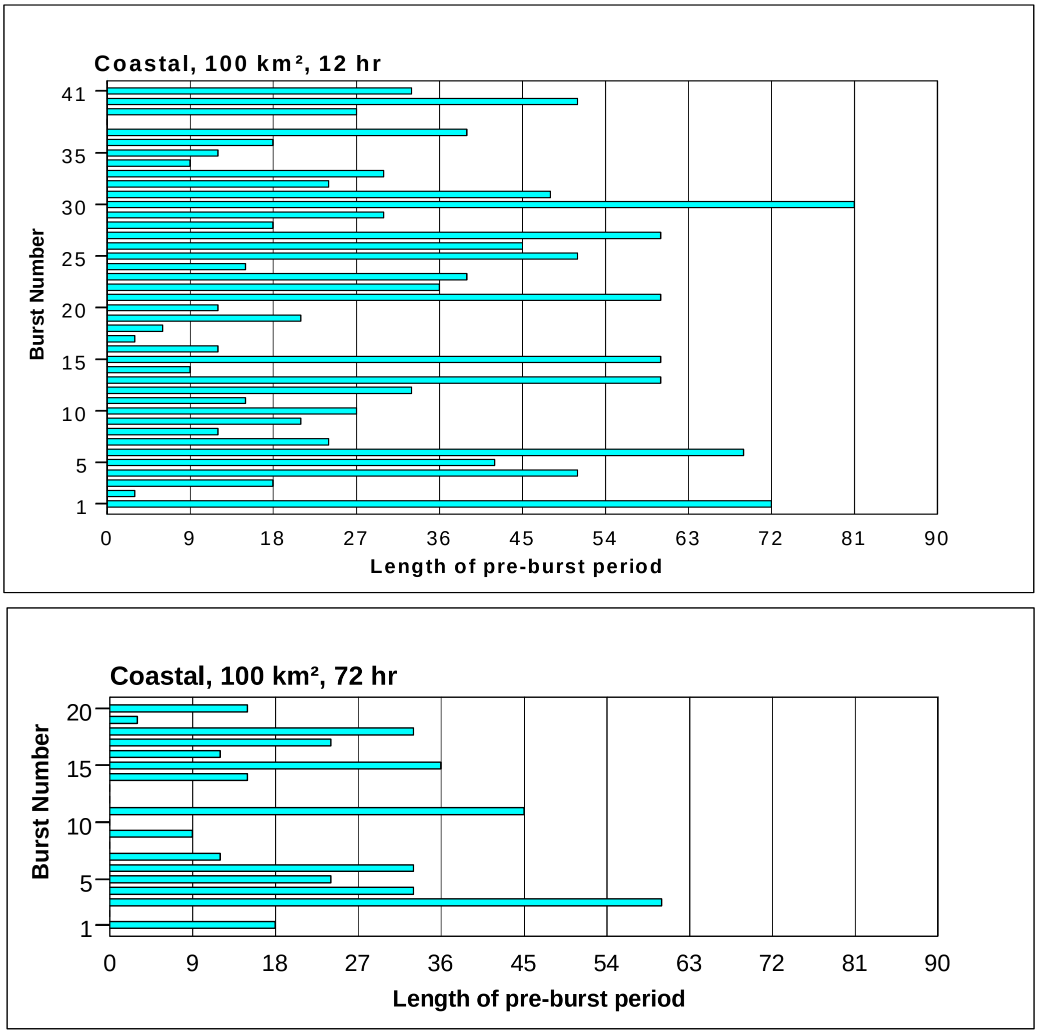

Figure 14: Example of the Variability Observed in the Length of Pre-Burst Period of Individual Bursts of 12 and 72 hours Duration

period for 12-hour bursts thus varies in length from 0 up to 81 hours, while that for 72-hour bursts varies from 0 up to 60 hours. In general the upper end of the range of lengths diminishes, and the number of zeroes increases, as the burst duration increases.

To ensure that the standard-length pre-burst periods were representative of the storms in the sample, but also varied sensibly with burst duration, standard periods that were inclusive of approximately two-thirds of each sample were adopted. Thus for the 12-hour sample in Figure 14 the standard length adopted was 39 hours. For the 72-hour sample the standard length adopted was 15 hours. Different lengths were adopted for inland and coastal storms. No systematic trend with area-size was observed so a single set of lengths was adopted for all areas at each burst duration. In keeping with the temporal resolution of the pre-burst sequences all pre-burst periods are aligned to 3-hourly intervals. The full set of standard-length pre-burst periods are given in Table 6 and their variation with burst duration is displayed in Figure 15.

Table 6: Standard-Length Pre-Burst Periods (hours) for Each Burst Duration

	Burst Duration (hours)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
Coastal	39	33	27	21	15	9	3
Inland	24	21	18	15	6	0	0

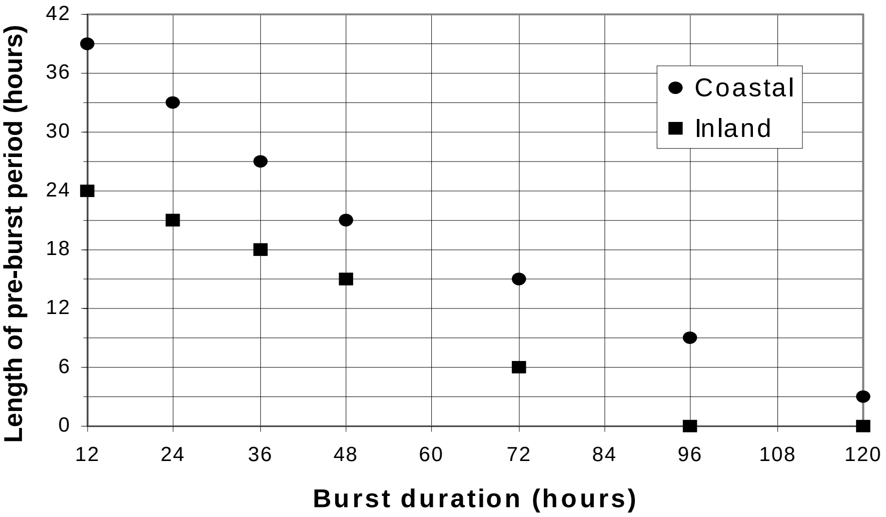

Figure 15: Standard-Length Pre-Burst Periods, Coastal and Inland, for Each Burst Duration.

From the above it is clear that ‘typically’ there is no rainfall prior to large 96- and 120-hour rainfall bursts within inland storms in the GSAM region: bursts of these durations generally constitute complete storms.

All pre-burst sequences were constrained to the above standard-length periods. Where these lengths were greater than the pre-burst period of individual bursts it was necessary to fill from the

storm beginning to this length with zeroes. Where these lengths were lesser the sequences were truncated.

4.5 Combining Sequences

The set of standard-length, normalised pre-burst sequences were then combined to give a single pre-burst temporal distribution ‘typical’ of the sample.

It was not at all clear what method would be most appropriate for developing a ‘typical’ pre-burst temporal distribution from these individual sequences. Although there were some points of commonality, there was also a great deal of variability both within and between individual sequences. Figure 16 shows an example of this variability in the period prior to the 24-hour bursts of the coastal storms, at 100km^2. While most of this variability would be expected as a consequence of being at the temporal edge of the storm (i.e. outside the heaviest burst) there is no doubt that some is also the result of dividing the 3-hourly rainfalls by a variety of burst depths in the normalisation procedure.

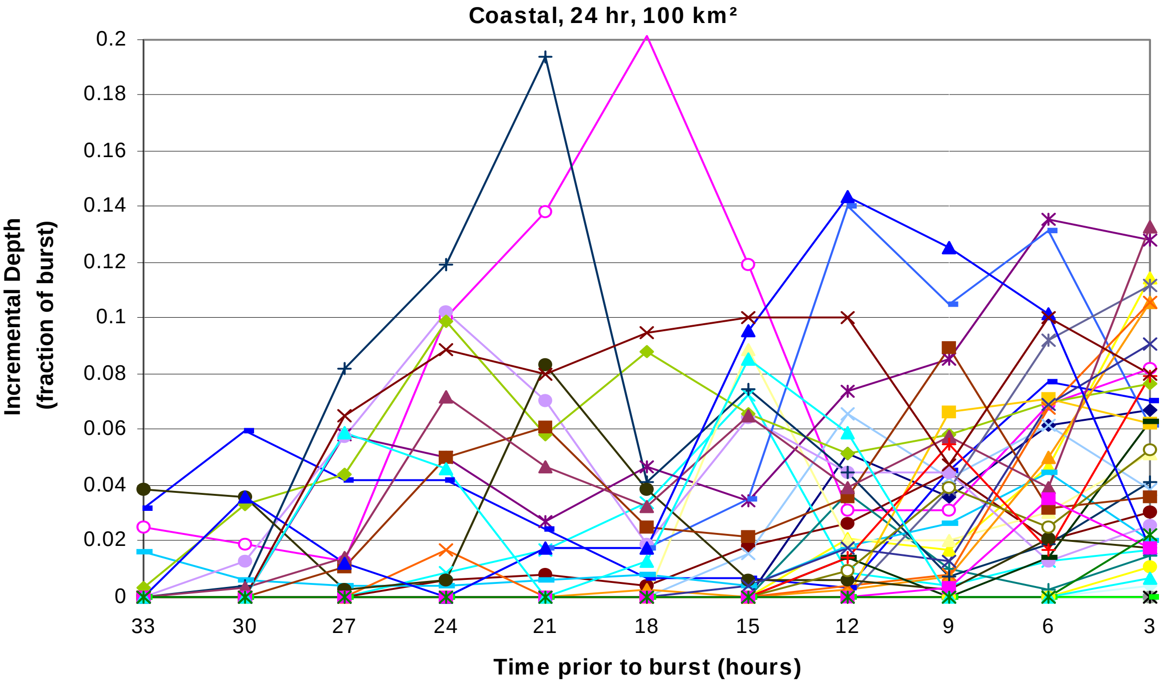

Figure 16: Example of the Variability Observed Within and Between Sequences of Pre-Burst Rainfall

Despite this marked variability, it is clear that, in general, pre-burst depths are greatest immediately prior to the burst, and that the number of zero pre-burst depths increases rapidly as you move backward in time from the burst. Whilst the inherent variability of these pre-burst sequences suggests that the derivation of a ‘typical’ sequence is a dubious undertaking, it seemed possible nonetheless to derive a ‘generic’ sequence with depths of the right order of magnitude and with the right structural features.

Not knowing *a priori* which derivation method was most appropriate a number of different approaches were tried:

(i) the Average Variability Method (Pilgrim et al, 1969)
(ii) the Median depth at each time segment
(iii) the Average depth at each time segment.

(i) Average Variability Method

As its name implies, the Average Variability Method (AVM) derives temporal distributions with average or typical variations in rainfall intensity. It does this using the following steps:

1. Rainfall depths in each time segment of the period are ranked in order of descending magnitude;
2. The average rank of each time segment is calculated;
3. The segment with the lowest average rank is designated as rank 1, and so on;
4. Rainfall depths for all rank 1 segments are averaged, and so on;
5. The average rainfall for all rank1 segments is assigned to the designated rank 1 segment, and so on.

The method has previously been used by Srikanthan and Kennedy (1991) on pre-burst temporal distributions of point rainfall. Nathan (1992) also used it successfully to derive design within-burst temporal distributions of GSAM PMP estimates. It thus seemed a natural choice for the derivation of our design pre-burst temporal distributions. It is interesting to note, however, that the authors of this method, whilst promoting its use in deriving typical within-burst sequences, did not themselves seek to use it to derive typical pre-burst sequences in a later paper (Pilgrim and Cordery, 1975). They instead suggested an average or median.

(ii) Median

Because all values above the median, and all values below the median have the same probability of occurring, the median is an attractive central tendency descriptor. It is also a simple matter to calculate the median depth at each time segment of the pre-burst period and thus derive a ‘median’ pre-burst sequence. But, because the samples of pre-burst sequences are relatively small and the sequences highly variable, median pre-burst sequences can be quite erratic.

(iii) Average

The average is a standard and well-recognised central tendency descriptor. An ‘average’ pre-burst sequence is simply derived by averaging the depth at each time segment of the pre-burst period. The disadvantage of the average is that it is strongly influenced by extreme values, particularly in small samples.

Figure 17 shows the sequences derived via these three methods for the period prior to 24-hour bursts of coastal storms, at 100km^2.

From this figure, and from the discussion above, we can see that the AVM tends to create strong peaks in the pre-burst sequence at the first time segment prior to the burst. These peaks in the AVM sequences are bigger than those in either the ‘average’ or the ‘median’ sequences because the AVM calculates its rank 1 average depth from the highest depths across the whole pre-burst period. Thus the extreme values in Figure 16, at 18 and 21 hours prior to the burst, are included in the average depth that is assigned to the time segment at 3 hours prior to the burst in Figure 17.

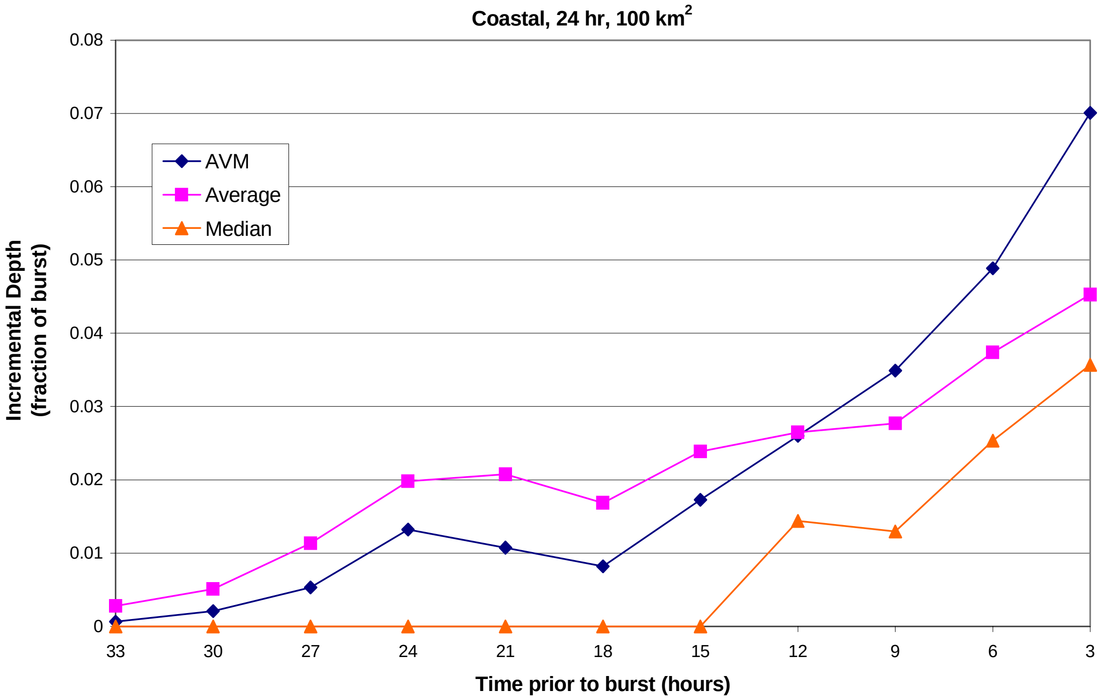

Figure 17: Testing Various Methods (AVM, Average and Median) for Deriving a ‘Generic’ Pre-Burst Temporal Distribution from the Sample of Pre-Burst Sequences in Figure 16

This tendency of the AVM to amplify the significance of extreme values in the pre-burst sequence was regarded as undesirable, and so the method was rejected.

Unfortunately, but as anticipated, for most burst durations, the sample size was too small for a well-defined median, and this method was also rejected.

The ‘average’ pre-burst sequences also appeared to be strongly influenced by the extremes in the samples. Large values in the pre-burst sequence may result from large rainfall totals at these times, but equally may result from dividing by a relatively small burst depth. It is an unfortunate incongruity that the values which have the greatest influence on the average value may have derived from the least significant bursts. The ‘average’ pre-burst sequence does, however, capture the desired ‘generic’ features of the sample.

With no acceptable alternative, averaging was adopted as the derivation method, in full cognisance of the inadequacy of the approach. Since there appeared to be very little difference in the average sequences at each area size, a single ‘one-size-fits-all’ average pre-burst temporal distribution was calculated. An example of this lack of variation is shown in Figure 18. It should be noted that whilst the 60 000 km² and 40 000 km² patterns are not consistent with the patterns for all other areas, they contribute only 20 of the 292 coastal, 12-hour bursts (Table 5).

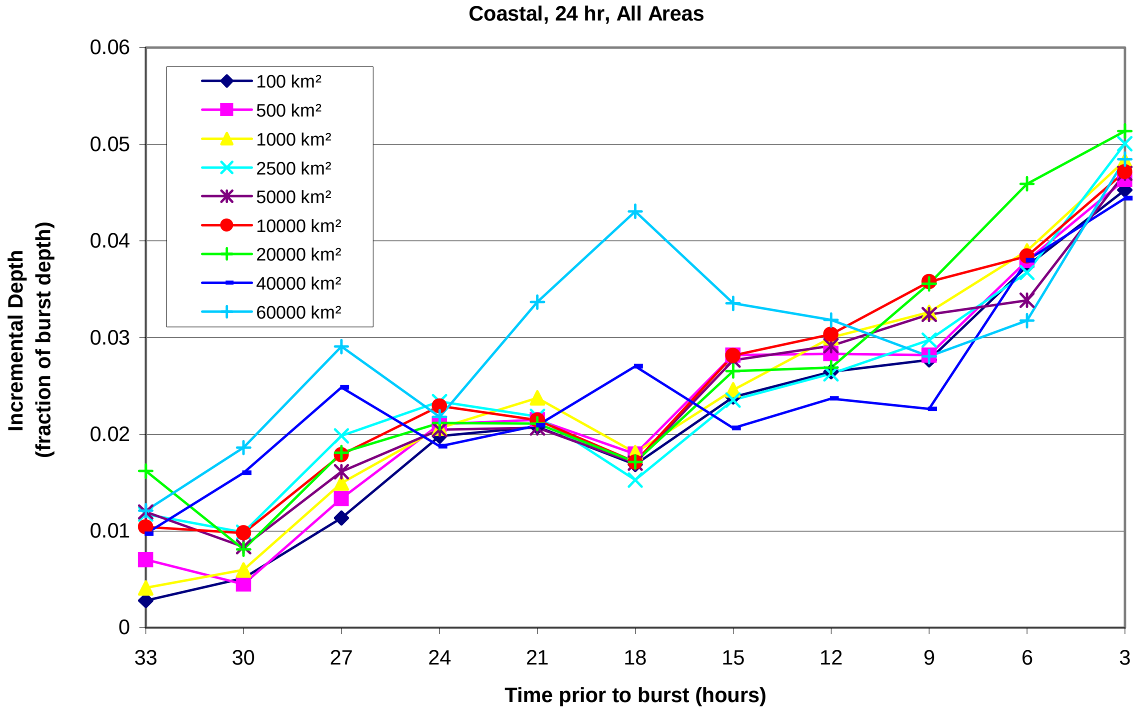

Figure 18: Example of the Lack of Variation in the Average Sequences at Different Area Sizes

Averaging was achieved by pooling the sequences at all area-sizes for each burst duration and averaging across all at each time segment. The increase in sample-size effected by this pooling led to a smoother set of derived temporal distributions. The full set of average coastal and inland pre-burst temporal distributions are given in Figures 19 and 20, respectively.

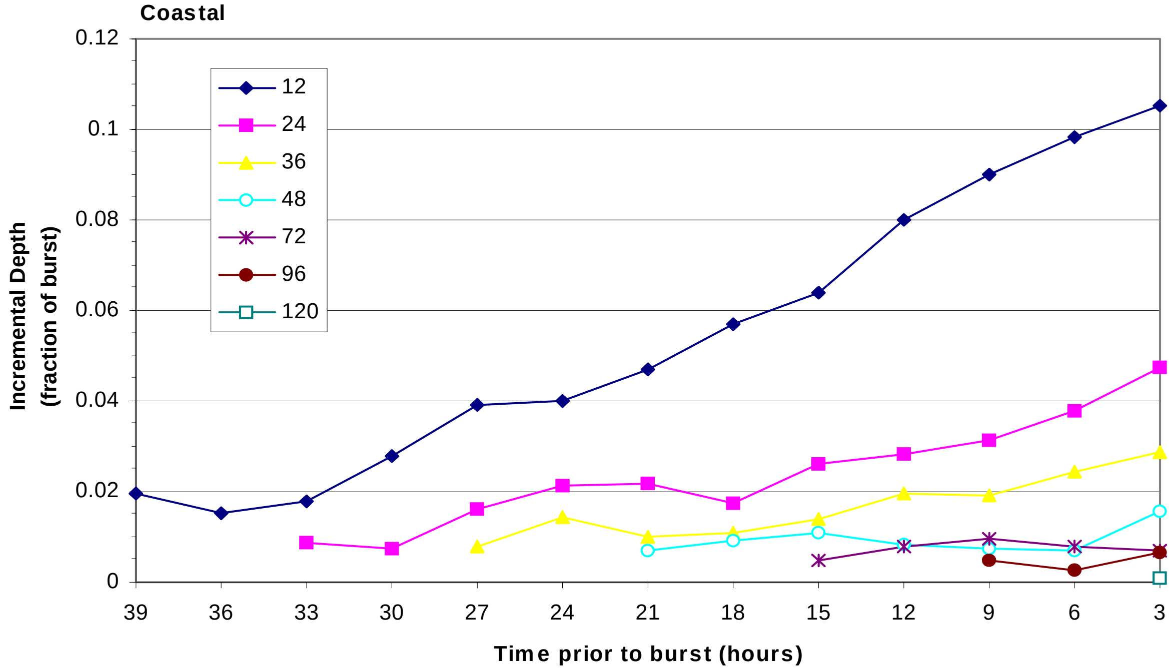

Figure 19: Average Coastal Pre-Burst Temporal Distribution at Each Burst Duration

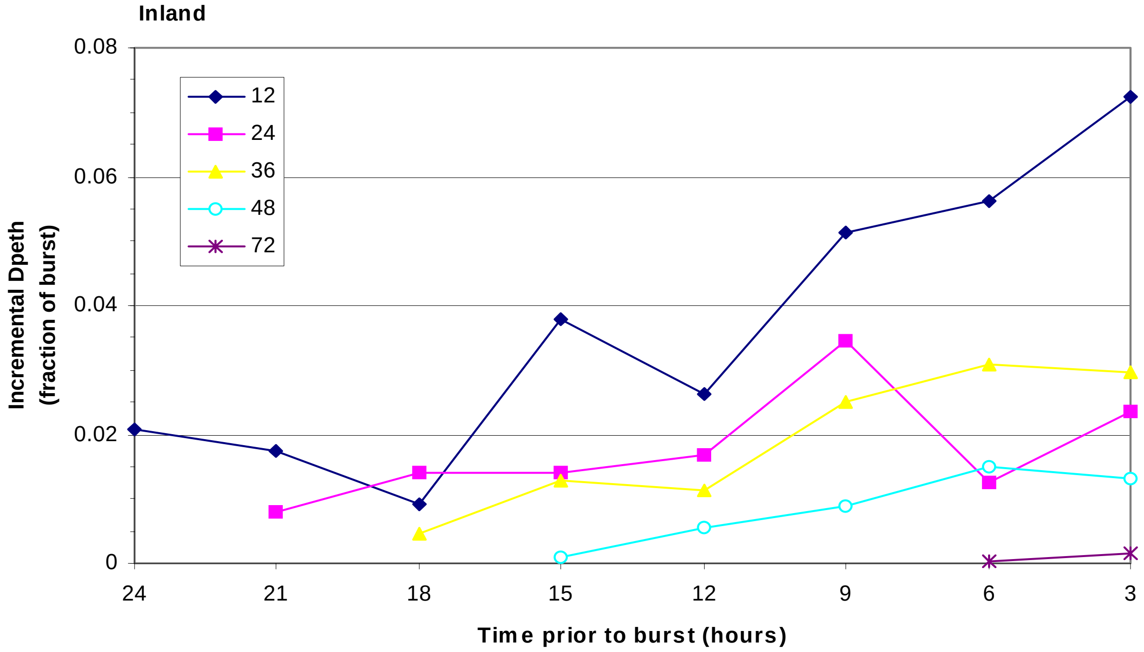

Figure 20: Average Inland Pre-Burst Temporal Distribution at Each Burst Duration

4.6 Scaling for Consistency with the PMP Depth-Duration Profiles

The final step in the development of design pre-burst distributions was to ensure that they were consistent with the depth-duration profile of PMP estimates. For example, it was necessary to ensure that the 24-hour PMP plus 12 hours of pre-burst rainfall was always less than the 36-hour PMP, etc. That such an inconsistency might arise was entirely possible given firstly, the problems encountered in deriving a ‘generic’ pre-burst sequence, and secondly that PMP estimates are end products of a long and complex manipulation of real data and do not necessarily reflect the depth-duration profiles of the storms on which they are based.

To determine whether such an inconsistency might arise, the increments of the average pre-burst temporal distributions were checked against the ratios of different duration PMP estimates. That is, the minimum ratio of the n-hour PMP to the m-hour PMP (where n>m) determines what the maximum cumulative (n-m)-hours of pre-burst rainfall can be for an m-hour PMP burst. For this check, use was made of a database of GSAM PMP estimates compiled over the course of six years and comprising estimates for over 100 catchments. Thus, the cumulative depth arising from the 12 hours immediately prior to the 24-hour burst was checked against the minimum ratio of 36-hour to 24-hour PMP estimates from the database, and so on.

Unfortunately the minimum PMP ratios were often very small: in many cases the 36-hour PMP was not substantially greater than the 24-hour PMP, in proportional terms. The minimum 36/24 ratio from the database was just 1.068. For that particular catchment at least, it is inconsistent to add 12 hours of pre-burst rainfall which amounts to more than 6.8% of the 24-hour PMP.

Through these checks most of the average pre-burst temporal distributions were found to deliver excessive amounts of pre-burst rainfall, and could not, therefore, be used in conjunction with PMP estimates.

The prevalence of this inconsistency, between the PMP depth-duration profiles and the volume of pre-burst rainfall, stems from the different ways in which these two design rainfall estimates were derived. PMP estimates derive from envelopes of storm depth-duration-area curves: envelopes of the single largest events in the GSAM storm sample. The average pre-burst sequences derive from a subset of the GSAM storm sample, which may or may not include the largest GSAM storms, but do generally include the mediocre. In essence this means that the sample of pre-burst sequences is not, and cannot be ‘typical’ of the PMP situation.

To derive a set of pre-burst temporal distributions which could be used in conjunction with PMP estimates, we first attempted to compile a sample of ‘PMP-consistent’ pre-burst sequences and to average these. The compiled sample, however, was very small and the derived averages were much smaller than was required to achieve ‘PMP-consistent’ pre-burst temporal distributions.

Ultimately it was decided that the best approach was simply to scale the average sequences downwards until they were ‘PMP-consistent’. These re-scaled coastal and inland pre-burst temporal distributions are given in Figures 21 and 22, respectively. Comparison of these figures with Figures 19 and 20 reveals the substantial effect of this re-scaling. Since different scaling factors have been applied over different parts of the pre-burst period, very little of the ‘generic’ structure remains, apart from the order of magnitude and the length of the sequences. What the scaling has ensured, is that the total volume of pre-burst rainfall is always less than the volume increases of PMP rainfall with increasing PMP duration.

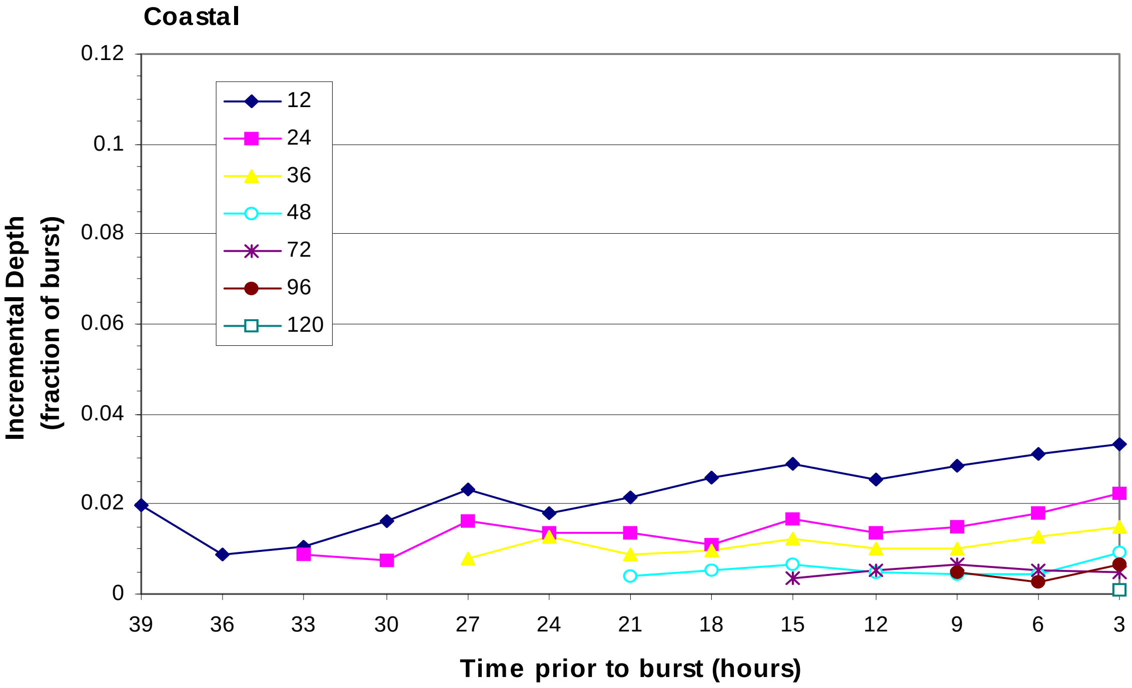

Figure 21: Scaled Coastal Pre-Burst Temporal Distribution at Each Burst Duration

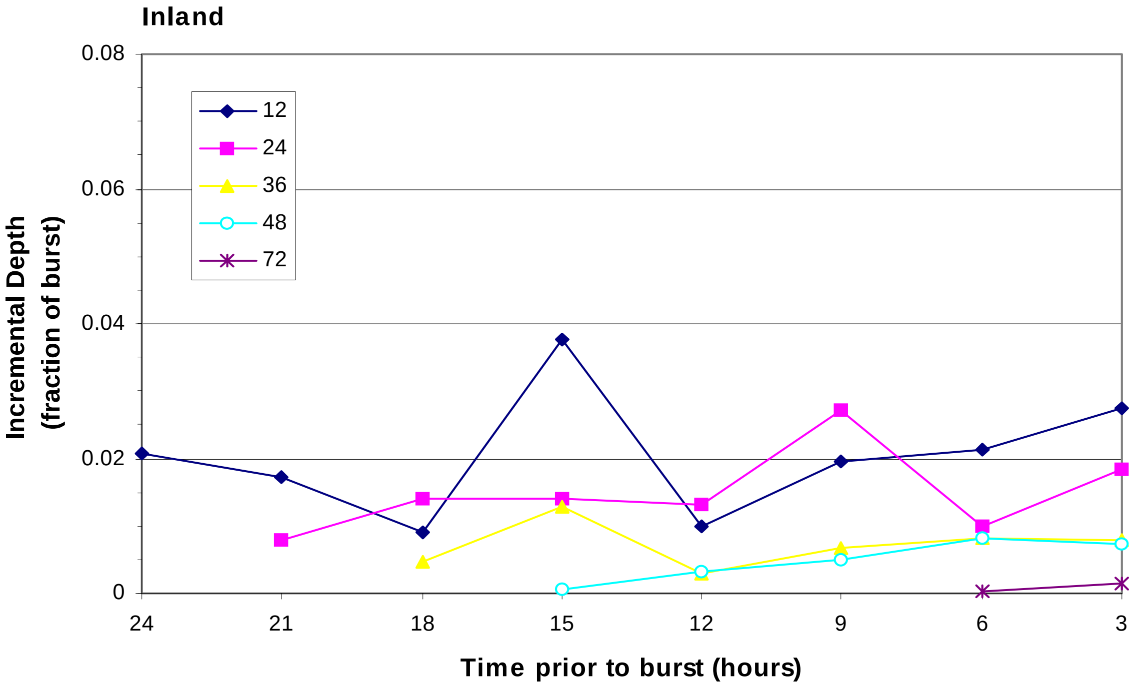

Figure 22: Scaled Inland Pre-Burst Temporal Distribution at Each Burst Duration

Cumulative versions of the re-scaled, now design, pre-burst temporal distributions are given in Figures 23 and 24. Incremental and cumulative design pre-burst depths are given in tabular form in Appendix B.

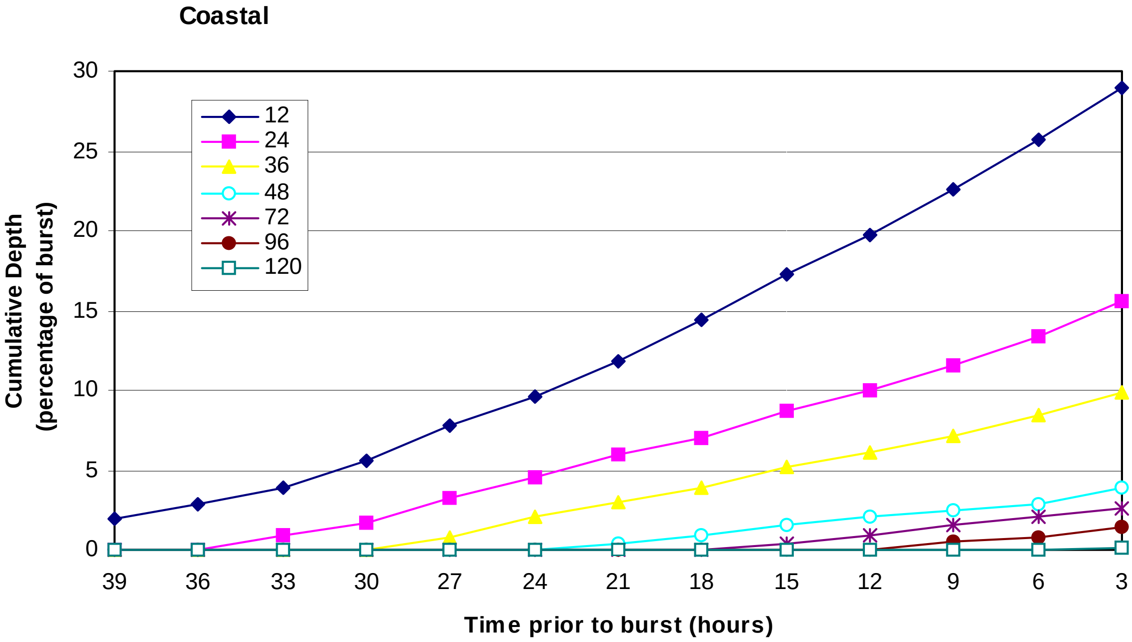

Figure 23: Coastal Design Pre-Burst Temporal Distribution at Each Burst Duration

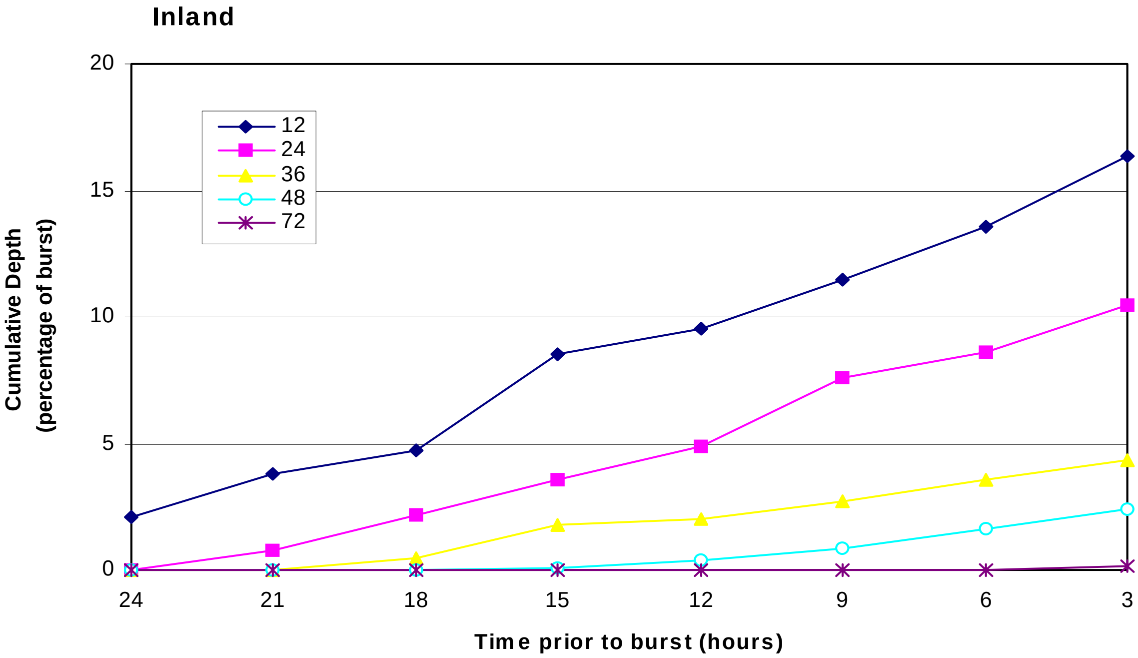

Figure 24: Inland Design Pre-Burst Temporal Distributions at Each Burst Duration

5. APPLYING DESIGN PRE-BURST TEMPORAL DISTRIBUTIONS

5.1 Regions and Zones

The design pre-burst temporal distributions, as developed, are intended for use with estimates of design rainfall bursts for catchments within the GSAM region. This region is defined, by default, as that part of Australia outside the region of applicability of the Generalised Tropical Storm Method (GTSM) of estimating PMP but also excludes the west coast region of Tasmania. The geographical boundary between the three regions follows the boundaries of certain drainage basins.

The GSAM region is further divided into two zones, Coastal and Inland, reflecting the two different classes of storm in the GSAM Storm Catalogue. Design pre-burst temporal distributions have been developed separately for these two zones to accommodate this difference. The boundary between the two zones is defined by the Great Dividing Range.

The boundaries between the regions and zones are shown in Figure 25 .

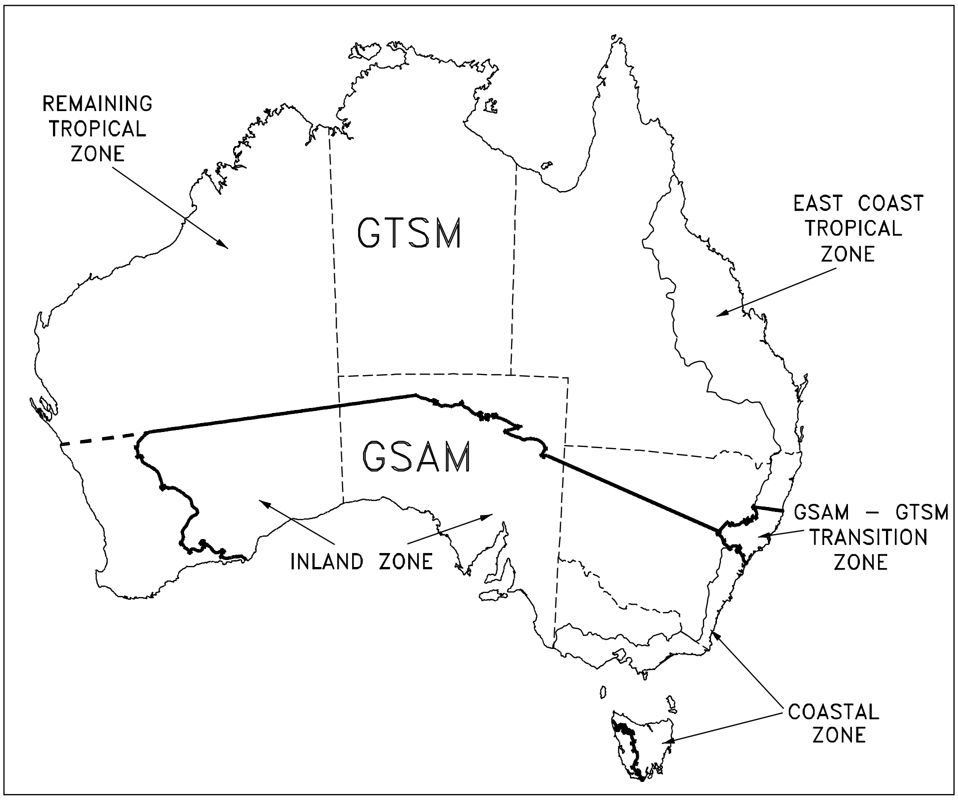

Figure 25: Boundaries Between Application Regions and Zones

For inland catchments with a boundary adjacent to the zonal boundary an overlap treatment is used for GSAM PMP estimates. No special treatment of design antecedent rainfall, however, appears warranted for these catchments, and so Inland design pre-burst temporal distributions should be applied as per all other Inland catchments.

For catchments located within the GTSM-GSAM Transition Zone no advice on appropriate values of antecedent rainfall to use in conjunction with design rainfall estimates is available at this time.

5.2 Durations and Areas

Design pre-burst temporal distributions have been developed for use with burst durations from 12 to 120 hours. Since rainfall prior to large 96- and 120-hour bursts within inland storms is rare, no pre-burst temporal distributions have been developed for the Inland Zone for these burst durations.

The design pre-burst temporal distributions have been developed from large-area storms of 1-7 day's duration. The largest 12-hour bursts for the region, however, are expected to derive from small-area storms of less than 1 day's duration. Storms of this type are not included in the GSAM Storm Catalogue. Thus pre-burst temporal distributions developed in this project for use with12-hour bursts should only be applied to design rainfall estimates for catchments that are relatively large, that is, greater than 1,000km^2. At this time, no advice on appropriate values of antecedent rainfall to use in conjunction with 12-hour design rainfall bursts on catchments smaller than 1,000km^2 is available.

Since no significant variation with area-size could be identified in the average pre-burst sequences, an 'all-area' design pre-burst temporal distribution has been developed for each burst duration within each zone. With the exception of the 12-hour, as above, the design pre-burst temporal distributions may be applied to catchments of any size up to 60,000km^2.

5.3 Design Storm Rainfall

Dimensionless temporal distributions of pre-burst rainfall have been developed so that, by simply multiplying by the appropriate design rainfall burst, a design antecedent rainfall may be calculated for any catchment within the GSAM region. When applied in conjunction with the appropriate burst temporal distribution for the catchment, the temporal variation of the complete design storm may be described. As an example, Figure 26 shows the design storm scenario that is built from the combination of burst and pre-burst temporal distributions for the 24-hour PMP over a coastal zone catchment of 100km^2. The burst temporal distribution is taken from Meighen and Minty (1998, Table A.1, pg 11). The pre-burst temporal distribution is as given in Table B.1 (pg 51) of this report.

5.4 Spatial Distribution of Design Pre-Burst Rainfall

No information on the spatial distribution of the rainfall antecedent to the bursts within the GSAM storms was compiled for this project. Indeed only a weak spatial pattern, if any, is expected from pre-burst rainfall. For the design scenario therefore there are two options for the spatial distribution of pre-burst rainfall:

- (i) a uniform distribution; or
- (ii) the same spatial distribution as used with the design burst.

There are valid reasons for choosing either option. The first is candid about the level of sophistication that is justified for these design rainfall estimates, and has been recommended in a US report (US Weather Bureau, 1969). The second marks the physical 'within-storm' connection between the pre-burst and the burst rainfall. On a practical level, the second option may be preferable simply because the flood model may not allow for a change of spatial distribution during the modelling of a single flood event.

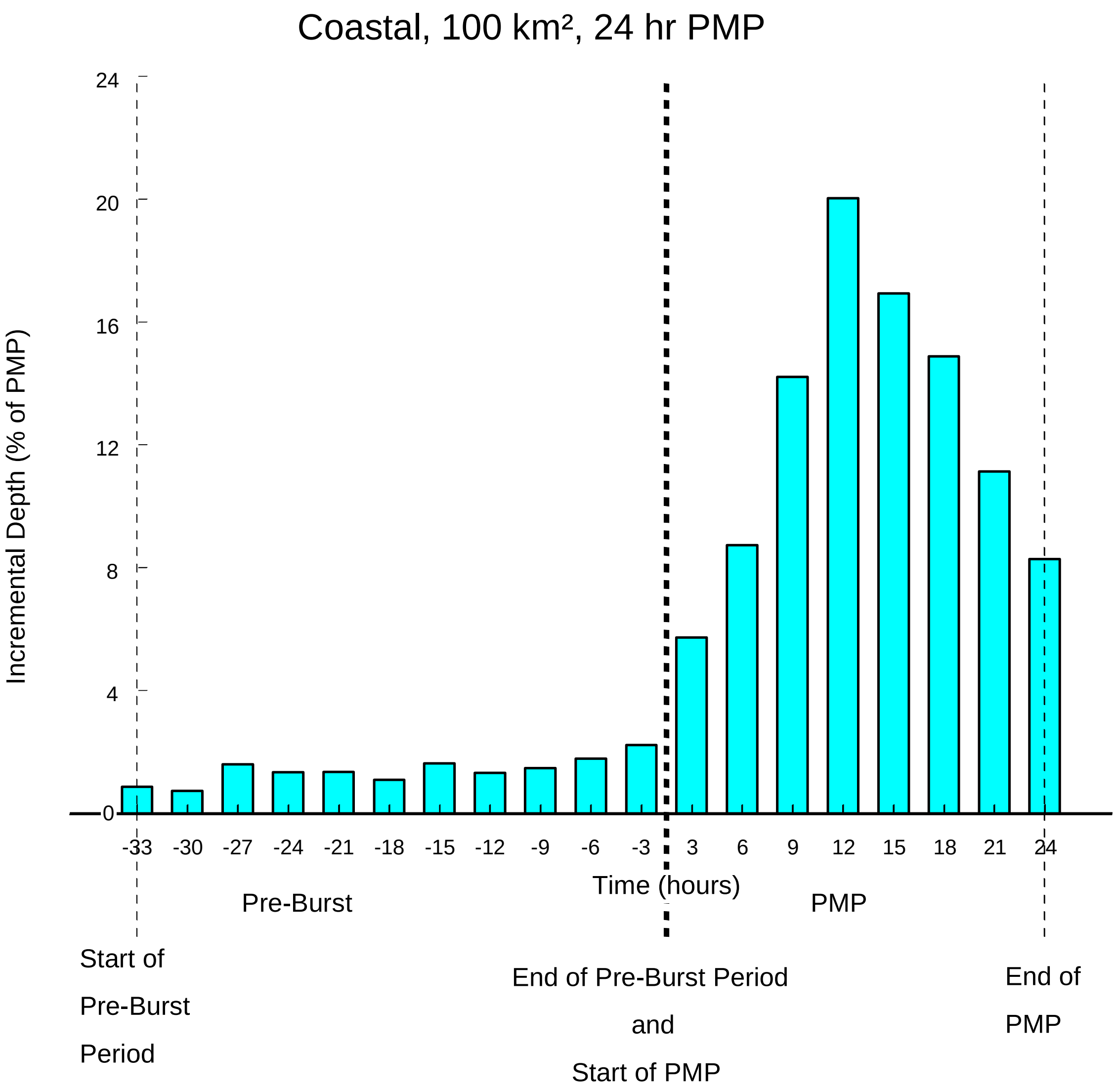

Figure 26: Example Design Storm: Coastal, 100km^2, 24 hr PMP plus Pre-Burst Rainfall.

5.5 Testing Design Pre-Burst Distributions in Flood Estimation Studies

Both the 'Average' (un-scaled) and the 'PMP-consistent' (scaled) pre-burst temporal distributions were tested in flood estimation studies on six inland (Hill et al, 1999a) and one coastal (Hill et al, 1999b) catchment in the GSAM region. The addition of pre-burst rainfall to the design scenario obviated the necessity to prescribe a burst initial loss in the flood estimation exercise, and the storm initial losses were simply those determined from the calibration of the flood model with recorded events.

It had been intended that the 'Average' distributions would be applicable to large to extreme design rainfall bursts, while the 'PMP-consistent' would be reserved for use with GSAM PMP estimates. Unfortunately the use of both sets of pre-burst temporal distributions proved problematic on two counts: firstly, it was not at all clear where in the AEP domain the switch over from one set of distributions to the other should occur; and secondly, wherever the switch over occurred it caused an unrealistic discontinuity in the derived flood frequency curve. Ultimately it was decided that the ‘PMP-consistent’ (scaled) pre-burst temporal distributions should be used over the whole AEP domain: from 1 in 50 year events up to and including the PMP. While some reservations remained about the appropriateness of applying to other, more frequent design rainfall events, pre-burst distributions which had been specifically scaled to PMP estimates, it was felt that any inappropriate scaling would be absorbed in the calibration of the storm initial losses.

5.6 Recommendations for Use

The revised edition of *Australian Rainfall and Runoff,* Book VI, ARR (Nathan and Weinmann, 1999) recommends the use of these design pre-burst temporal distributions in the estimation of large to extreme floods on catchments in the GSAM region. The document gives specific guidance on their use and a worked example.

6. CONCLUSIONS AND FUTURE WORK

The investigations of the GSAM-Antecedent Rainfall Project indicate that, over southeast Australia at least, large and extreme storms are only very rarely preceded by storms of similar magnitude. These investigations and that of Sinclair Knight Merz (1997) indicate that any significant pre-storm rainfall is unusual, and, by implication, that the rain falling in the days and months preceding a large or extreme storm should not be significantly greater than normal for the location and time of year. Thus storm initial losses for large and extreme storms should be similar to those of smaller, more frequent storms.

A set of design pre-burst temporal distributions have been developed, and in the absence of any better approach, should be useful in defining the pre-burst rainfall of large and extreme rainfall bursts. When applied in conjunction with the appropriate burst temporal distribution, the temporal variation of the complete design storm may be calculated simply by multiplying by the design rainfall burst.

This should obviate the necessity to define a burst initial loss in design flood estimation. The design distributions, however, are much averaged and much constrained, and are a long way from any of the individual pre-burst sequences that went into their construction. This is because the derivation of a ‘typical’ pre-burst rainfall distribution from example sequences is not really plausible given the great variability within and between the examples. A move by the hydrological community away from the use of such ‘typical’ temporal distributions, whether they are burst or pre-burst distributions, to a joint probability approach, where the temporal distribution is treated as a random variable, is to be encouraged. The planned publication in digital form of the individual storm pre-burst distributions compiled as part of this project should facilitate just such an approach.

7. ACKNOWLEDGEMENTS

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APPENDIX A

GSAM STORM CATALOGUE

Table A.1: GSAM Storm Catalogue

Storm Name	Region	Date Ended	Duration (Days)	Zone	State	GSAM Season	Co-ordinates of Areal Extent (Latitude °S Longitude °E)							
TR1APR89	Truro	2/ 4/1889	1	Inland	SA	Autumn	-32.90	137.40	-32.90	138.90	-35.70	140.10	-35.70	138.60
ST4APR89	Stirling	17/ 4/1889	4	Inland	SA	Autumn	-33.50	137.40	-33.50	139.50	-35.40	139.50	-35.40	137.40
SY6MAY89	Sydney	29/ 5/1889	6	Coastal	NSW	Autumn	-33.15	149.95	-33.15	151.55	-34.65	151.55	-34.65	149.95
HA3MAR93	Hastings	10/ 3/1893	3	Coastal	NSW	Summer	-30.00	152.00	-30.00	153.30	-32.00	153.30	-32.00	152.00
MP4MAR93	Morpeth	10/ 3/1893	4	Coastal	NSW	Summer	-32.25	150.80	-32.25	152.40	-33.50	152.40	-33.50	150.80
BU5DEC93	Butcher's Ridge	31/12/1893	5	Coastal	VIC	Summer	-36.10	149.90	-37.70	150.10	-38.80	145.90	-37.20	145.70
CO2FEB96	Cobar	12/ 2/1896	2	Inland	NSW	Summer	-29.80	144.60	-29.80	147.20	-32.10	147.70	-32.10	145.10
UL4FEB98	Ulladulla	15/ 2/1898	4	Coastal	NSW	Summer	-35.30	149.40	-35.30	150.50	-37.60	150.00	-37.60	148.90
OR1MAR00	Orange	21/ 3/1900	1	Inland	NSW	Summer	-32.20	148.60	-34.50	151.10	-34.80	149.70	-32.50	147.20
WA7APR01	Warragul	26/ 4/1901	7	Coastal	VIC	Autumn	-36.90	144.90	-36.90	146.40	-38.40	146.40	-38.40	144.90
SY4JUL04	Sydney	12/ 7/1904	4	Coastal	NSW	Winter	-33.05	150.35	-33.05	151.45	-35.10	151.00	-35.10	149.90
WV1MAR10	Western Victoria	6/ 3/1910	1	Inland	VIC	Summer	-35.00	140.80	-35.00	143.00	-37.80	143.00	-37.80	140.80
CN1JAN11	Coonamble	12/ 1/1911	1	Inland	NSW	Summer	-29.00	148.00	-31.80	150.80	-32.80	149.70	-30.00	146.90
WO5MAR14	Wollongong	24/ 3/1914	5	Coastal	NSW	Summer	-34.00	150.30	-34.00	151.30	-36.30	150.30	-36.30	149.20
ED3FEB19	Eden	27/ 2/1919	3	Coastal	NSW	Summer	-36.00	149.00	-36.00	151.50	-37.50	151.50	-37.50	149.00
WI3MAR21	Wilmington	1/ 3/1921	3	Inland	SA	Summer	-30.70	136.60	-32.90	139.40	-33.40	137.40	-31.20	134.80
MA2MAY21	Maclean	16/ 5/1921	2	Coastal	NSW	Autumn	-28.35	152.90	-28.35	153.76	-29.90	153.36	-29.90	152.50
MA5MAY21	Maclean	16/ 5/1921	5	Coastal	NSW	Autumn	-28.90	152.90	-28.90	153.60	-31.10	153.10	-31.10	152.40
KI5JUL22	Kiama	29/ 7/1922	5	Coastal	NSW	Winter	-34.30	150.00	-34.50	150.90	-37.10	150.00	-36.90	149.10
BU1MAY25	Burrinjuck	27/ 5/1925	1	Inland	NSW	Autumn	-34.40	148.10	-34.60	149.80	-36.00	149.80	-35.80	148.10
BU4MAY25	Burrinjuck	28/ 5/1925	4	Inland	NSW	Autumn	-34.30	148.75	-35.70	149.55	-36.00	148.65	-34.60	147.85
KI5MAY25	Kiama	28/ 5/1925	5	Coastal	NSW	Autumn	-34.75	149.00	-34.75	151.40	-37.00	151.40	-37.00	149.00

Table A.1 (cont.)

Storm Name	Region	Date Ended	Duration (Days)	Zone	State	GSAM Season	Co-ordinates of Areal Extent (Latitude °S Longitude °E)							
AD3MAR26	Alndale	25/ 3/1926	3	Inland	NSW	Summer	-30.30	148.90	-32.30	151.30	-33.50	149.80	-31.50	147.40
UN2FEB28	Ungarie	18/ 2/1928	2	Inland	NSW	Summer	-31.00	146.50	-31.60	148.50	-34.50	148.10	-33.90	146.10
HI6FEB29	Hickey's Creek	11/ 2/1929	6	Coastal	NSW	Summer	-29.90	153.50	-32.60	152.90	-33.20	150.80	-30.50	151.40
MT2APR29	Mathinna	5/ 4/1929	2	Coastal	TAS	Autumn	-40.60	144.90	-40.60	148.50	-42.40	148.50	-42.40	144.90
HA1JUN30	Hastings	19/ 6/1930	1	Coastal	NSW	Winter	-30.60	151.70	-31.00	153.30	-32.40	152.80	-32.00	151.20
HA5JUN30	Hastings	20/ 6/1930	5	Coastal	NSW	Winter	-31.00	151.50	-31.00	153.00	-32.50	153.00	-32.50	151.50
WD2DEC30	Woodend	7/12/1930	2	Inland	VIC	Summer	-36.65	143.95	-36.65	145.85	-37.85	145.85	-37.85	143.95
TH1FEB31	Tweed Heads	6/ 2/1931	1	Coastal	NSW	Summer	-27.60	152.90	-27.60	153.70	-29.20	153.70	-29.20	152.90
HA5APR31	Hastings	25/ 4/1931	5	Coastal	NSW	Autumn	-30.90	152.35	-30.90	153.45	-33.10	152.05	-33.10	150.95
BH1NOV33	Broken Hill	29/11/1933	1	Inland	NSW	Spring	-31.10	141.20	-32.10	144.00	-33.70	142.50	-32.70	139.70
AV2DEC33	Avoca	1/12/1933	2	Inland	VIC	Spring	-36.50	142.90	-36.50	145.30	-39.10	145.30	-39.10	142.90
BE5JAN34	Bega	9/ 1/1934	5	Coastal	NSW	Summer	-35.00	148.30	-35.00	150.30	-37.30	150.30	-37.30	148.30
WA5DEC34	Warragul	3/12/1934	5	Coastal	VIC	Summer	-37.20	145.55	-38.50	147.15	-38.90	145.95	-37.60	144.35
LA2DEC35	Lakes Entrance	27/12/1935	2	Coastal	VIC	Summer	-37.00	146.30	-37.00	149.40	-38.75	149.40	-38.75	146.30
ME4OCT37	Melbourne	19/10/1937	4	Coastal	VIC	Spring	-37.15	144.65	-37.15	146.60	-38.35	146.60	-38.35	144.65
TA6MAR39	Tallangatta	1/ 3/1939	6	Inland	VIC	Summer	-35.10	148.20	-36.40	148.90	-38.30	145.00	-37.00	144.30
FP3JAN41	Fleurieu Pen.	26/ 1/1941	3	Inland	SA	Summer	-33.60	138.00	-33.60	139.90	-36.00	139.40	-36.00	137.60
WO2MAY43	Wollongong	17/ 5/1943	2	Coastal	NSW	Autumn	-33.90	149.60	-33.90	151.10	-35.50	151.10	-35.50	149.60
WO5MAY43	Wollongong	20/ 5/1943	5	Coastal	NSW	Autumn	-33.90	150.00	-33.90	151.20	-35.60	150.70	-35.60	149.50
UL3APR45	Ulladulla	10/ 4/1945	3	Coastal	NSW	Autumn	-34.50	148.50	-34.50	151.00	-37.00	151.00	-37.00	148.50
YP2FEB46	Yorke Pen.	18/ 2/1946	2	Inland	SA	Summer	-30.80	136.40	-30.80	137.60	-36.00	138.40	-36.00	137.20
MO1FEB46	Moina	19/ 2/1946	1	Coastal	TAS	Summer	-40.60	145.10	-40.80	148.50	-42.60	148.50	-42.40	145.10

Table A.1 (cont.)

Storm Name	Region	Date Ended	Duration (Days)	Zone	State	GSAM Season	Co-ordinates of Areal Extent (Latitude °S Longitude °E)							
PO3MAR46	Portland	18/ 3/1946	3	Coastal	VIC	Summer	-37.50	141.00	-38.00	143.40	-38.90	143.60	-38.40	141.20
GF3MAR46	Grafton	26/ 3/1946	3	Coastal	NSW	Summer	-29.20	152.70	-29.20	153.40	-31.10	153.10	-31.10	152.40
NA4APR46	Narara	19/ 4/1946	4	Coastal	NSW	Autumn	-32.00	151.40	-32.30	152.50	-34.10	151.30	-33.80	150.20
TH1JAN47	Tweed Heads	24/ 1/1947	1	Coastal	NSW	Summer	-27.20	151.90	-27.20	153.40	-28.80	153.70	-28.80	152.20
RA5JUN49	Raymond Terrace	19/ 6/1949	5	Coastal	NSW	Winter	-32.10	151.10	-32.10	152.70	-34.90	150.90	-34.90	149.30
HA5AUG49	Hastings	29/ 8/1949	5	Coastal	NSW	Winter	-30.79	152.14	-30.79	153.17	-32.19	152.88	-32.19	151.85
WP2FEB50	Wilpena Pound	3/ 2/1950	2	Inland	SA	Summer	-30.25	137.50	-30.25	142.00	-33.00	142.00	-33.00	137.50
AR1MAR50	Arkaroola	17/ 3/1950	1	Inland	SA	Summer	-29.40	138.80	-32.50	141.30	-32.90	139.60	-29.80	137.10
RW4MAR50	Rushworth	20/ 3/1950	4	Inland	VIC	Summer	-35.40	145.30	-37.10	147.10	-37.70	145.30	-36.00	143.50
CA7MAR50	Canberra	23/ 3/1950	7	Inland	ACT	Summer	-33.75	147.25	-33.75	149.50	-36.00	149.50	-36.00	147.25
DO1JUN50	Dorrigo	24/ 6/1950	1	Coastal	NSW	Winter	-29.40	152.00	-29.40	153.50	-31.00	153.20	-31.00	151.70
DO5JUN50	Dorrigo	26/ 6/1950	5	Coastal	NSW	Winter	-29.10	152.30	-29.10	153.50	-31.20	153.10	-31.20	151.90
WA3FEB51	Warragul	20/ 2/1951	3	Coastal	VIC	Summer	-37.44	146.40	-38.52	147.25	-39.00	146.00	-37.92	145.15
BE5JUN52	Bega	18/ 6/1952	5	Coastal	NSW	Winter	-35.75	148.20	-35.75	150.20	-38.00	150.20	-38.00	148.20
VI5JUN52	Victoria	19/ 6/1952	5	Coastal	VIC	Winter	-37.20	144.10	-37.40	147.50	-39.20	146.50	-39.00	143.10
TH1FEB54	Tweed Heads	21/ 2/1954	1	Coastal	NSW	Summer	-27.70	152.70	-27.70	153.70	-29.00	153.70	-29.00	152.70
HA2FEB54	Hastings	21/ 2/1954	2	Coastal	NSW	Summer	-29.35	152.50	-29.35	153.50	-31.85	152.80	-31.85	151.80
DO5FEB54	Dorrigo	22/ 2/1954	5	Coastal	NSW	Summer	-29.86	152.35	-29.86	153.32	-31.12	153.05	-31.12	152.08
DU1FEB55	Dunedoo	24/ 2/1955	1	Inland	NSW	Summer	-30.00	146.00	-30.00	150.00	-34.00	150.00	-34.00	146.00
DU2FEB55	Dunedoo	25/ 2/1955	2	Inland	NSW	Summer	-30.70	151.00	-32.30	151.80	-33.10	148.00	-31.50	147.20
DU3FEB55	Dunedoo	26/ 2/1955	3	Inland	NSW	Summer	-30.70	151.00	-32.30	151.80	-33.10	148.00	-31.50	147.20
DU4FEB55	Dunedoo	26/ 2/1955	4	Inland	NSW	Summer	-30.70	151.00	-32.40	151.80	-33.10	148.00	-31.40	147.20

Table A.1 (cont.)

Storm Name	Region	Date Ended	Duration (Days)	Zone	State	GSAM Season	Co-ordinates of Areal Extent (Latitude °S Longitude °E)							
DO1JAN59	Dorrigo	22/ 1/1959	1	Coastal	NSW	Summer	-29.85	152.05	-29.85	153.25	-31.05	153.10	-31.05	151.90
DO5JAN59	Dorrigo	24/ 1/1959	5	Coastal	NSW	Summer	-29.85	152.05	-29.85	153.25	-31.05	153.10	-31.05	151.90
BA1APR59	Bathurst	2/ 4/1959	1	Inland	NSW	Autumn	-32.40	148.40	-32.40	149.70	-34.10	149.70	-34.10	148.40
SE2APR60	South Esk	23/ 4/1960	2	Coastal	TAS	Autumn	-41.50	146.10	-41.50	148.10	-43.60	148.00	-43.60	146.00
WO3NOV61	Wollongong	20/11/1961	3	Coastal	NSW	Spring	-33.90	150.15	-33.90	151.35	-35.10	151.35	-35.10	150.15
DO4MAY63	Dorrigo	10/ 5/1963	4	Coastal	NSW	Autumn	-29.75	152.20	-29.75	153.40	-31.75	153.00	-31.75	151.80
BL3JUN64	Blackheath	12/ 6/1964	3	Coastal	NSW	Winter	-32.90	150.30	-33.40	151.20	-34.30	150.10	-33.80	149.20
LA2FEB69	Lameroo	10/ 2/1969	2	Inland	VIC	Summer	-34.50	138.90	-34.50	143.70	-35.80	143.70	-35.80	138.90
BD2MAY69	Break O'Day	31/ 5/1969	2	Coastal	TAS	Autumn	-40.90	145.20	-40.90	148.40	-42.90	148.40	-42.90	145.20
LI3AUG70	Liena	25/ 8/1970	3	Coastal	TAS	Winter	-40.70	144.80	-40.70	148.40	-42.50	148.40	-42.50	144.80
VA1JAN71	Valencia Creek	30/ 1/1971	1	Coastal	VIC	Summer	-37.00	146.00	-37.00	148.50	-38.60	148.50	-38.60	146.00
ED5FEB71	Eden	8/ 2/1971	5	Coastal	NSW	Summer	-35.40	149.70	-35.40	150.50	-37.20	149.90	-37.20	149.10
TH1JAN74	Thallon	8/ 1/1974	1	Inland	NSW	Summer	-27.60	147.50	-27.60	149.60	-30.60	150.70	-30.60	148.60
MP4JAN74	Milparinka	13/ 1/1974	4	Inland	SA	Summer	-29.00	141.00	-29.00	143.00	-32.30	144.40	-32.30	142.40
TH2MAR74	Tweed Heads	11/ 3/1974	2	Coastal	NSW	Summer	-28.00	153.00	-28.00	153.80	-31.00	153.20	-31.00	152.40
TH5MAR74	Tweed Heads	14/ 3/1974	5	Coastal	NSW	Summer	-27.70	152.30	-27.70	154.00	-30.10	153.30	-30.10	151.60
NC5MAR74	North Coast	14/ 3/1974	5	Coastal	NSW	Summer	-29.45	152.55	-29.45	153.45	-32.05	152.95	-32.05	152.05
GE2MAR74	Germantown	23/ 3/1974	2	Coastal	TAS	Summer	-40.75	147.50	-40.75	148.50	-42.25	148.50	-42.25	147.50
CH2APR74	Coffs Harbour	22/ 4/1974	2	Coastal	NSW	Autumn	-29.70	152.50	-29.70	153.40	-31.10	153.10	-31.10	152.20
BU3AUG74	Burrinjuck	29/ 8/1974	3	Inland	NSW	Winter	-34.90	148.90	-34.90	150.00	-36.10	150.00	-36.10	148.90
WO3MAR75	Wollongong	11/ 3/1975	3	Coastal	NSW	Summer	-33.90	149.60	-33.90	151.10	-35.10	151.10	-35.10	149.90
LE1JUN75	Leura	21/ 6/1975	1	Coastal	NSW	Winter	-33.00	150.10	-33.20	151.10	-34.30	150.60	-34.10	149.60

Table A.1 (cont.)

Storm Name	Region	Date Ended	Duration (Days)	Zone	State	GSAM Season	Co-ordinates of Areal Extent (Latitude °S Longitude °E)							
YU1DEC75	Yunta	13/12/1975	1	Inland	SA	Summer	-30.60	138.50	-32.70	140.90	-33.60	139.20	-31.50	136.80
GG5OCT76	Googong	18/10/1976	5	Coastal	NSW	Spring	-35.40	149.30	-35.40	150.50	-37.50	150.10	-37.50	148.90
RA1MAR77	Railton	27/ 3/1977	1	Coastal	TAS	Summer	-40.50	144.60	-41.00	147.90	-42.30	147.90	-41.80	144.60
ME1APR77	Melbourne	8/ 4/1977	1	Coastal	VIC	Autumn	-37.20	144.32	-37.20	145.40	-38.25	145.40	-38.25	144.32
WO3MAR78	Wollongong	21/ 3/1978	3	Coastal	NSW	Summer	-34.00	150.25	-34.00	151.25	-35.00	151.25	-35.00	150.25
MW4MAR78	Mount Wilson	21/ 3/1978	4	Coastal	NSW	Summer	-33.00	150.10	-33.30	151.20	-34.40	150.60	-34.10	149.50
CA2APR78	Cabbage Tree	3/ 4/1978	2	Coastal	VIC	Autumn	-37.10	147.10	-37.10	149.40	-38.10	149.40	-38.10	147.10
TA2JUN78	Tanybryn	4/ 6/1978	2	Coastal	VIC	Winter	-37.40	143.80	-37.40	144.70	-39.00	144.00	-39.00	143.10
SC1FEB81	Stony Creek	7/ 2/1981	1	Coastal	NSW	Summer	-32.40	151.30	-32.55	152.05	-33.80	151.35	-33.65	150.60
OB2MAY81	Orbost	26/ 5/1981	2	Coastal	VIC	Autumn	-36.20	150.00	-37.70	150.10	-39.00	145.90	-37.50	145.80
CO3OCT82	Comboyne	12/10/1982	3	Coastal	NSW	Spring	-29.10	151.90	-29.10	153.70	-32.50	152.70	-32.50	150.90
DT1MAR83	Dutton	3/ 3/1983	1	Inland	SA	Summer	-33.70	138.50	-33.70	139.40	-35.20	139.30	-35.20	138.40
FB2MAR83	Fords Bridge	21/ 3/1983	2	Inland	NSW	Summer	-28.70	146.40	-31.90	147.20	-32.50	145.20	-29.30	144.40
DA2FEB84	Dapto	19/ 2/1984	2	Coastal	NSW	Summer	-34.00	150.00	-34.00	151.30	-35.10	151.30	-35.10	150.00
DO2JUL85	Dorrigo	10/ 7/1985	2	Coastal	NSW	Winter	-29.20	152.40	-29.20	153.80	-32.30	152.70	-32.30	151.30
SY1AUG86	Sydney	6/ 8/1986	1	Coastal	NSW	Winter	-33.20	150.80	-33.30	151.60	-34.90	151.00	-34.80	150.20
SY4AUG86	Sydney	7/ 8/1986	4	Coastal	NSW	Winter	-33.20	149.90	-33.20	151.40	-34.90	151.40	-34.90	149.90
SP4MAY87	Springbrook	12/ 5/1987	4	Coastal	NSW	Autumn	-27.50	152.70	-27.50	153.80	-29.60	153.80	-29.60	152.70
NY3APR89	Nyngan	3/ 4/1989	3	Inland	NSW	Autumn	-30.50	145.90	-30.50	148.20	-33.10	149.90	-33.10	147.60
NE3FEB90	Newcastle	4/ 2/1990	3	Coastal	NSW	Summer	-30.50	152.30	-32.20	152.60	-34.90	150.70	-33.20	150.40
NY7APR90	Nyngan	14/ 4/1990	7	Inland	NSW	Autumn	-31.30	146.20	-31.30	148.80	-33.60	149.40	-33.60	146.80
GI3APR90	Gippsland	22/ 4/1990	3	Coastal	VIC	Autumn	-36.30	148.40	-37.50	149.80	-38.80	146.40	-37.60	145.00

APPENDIX B

TABLES OF

DESIGN PRE-BURST TEMPORAL DISTRIBUTIONS

Key to Tables B.1 and B.2

Coastal:
Inland:
The GSAM zone for application of the design pre-burst temporal distributions. Figure 25, pg 35 shows the zone boundaries.

Burst Duration:
The standard burst duration in hours for which the design pre-burst temporal distribution applies.

Hours Prior:
The hours prior to the design rainfall burst in 3-hourly intervals.

Pre-Burst Depth:
Incremental:
The percentage of the total design rainfall burst falling in each 3 hourly interval prior to the burst.

Cumulative:
The percentage of the total design rainfall burst falling up to this many hours prior to the burst.

Table B.1: Coastal Design Pre-Burst Temporal Distributions

Coastal **Burst Duration (hours):** **12**

Hours Prior	**Pre-Burst Depth %**	
	Incremental	Cumulative
39	1.96	1.96
36	0.89	2.85
33	1.04	3.89
30	1.63	5.52
27	2.32	7.84
24	1.81	9.65
21	2.13	11.79
18	2.59	14.37
15	2.89	17.26
12	2.52	19.78
9	2.83	22.62
6	3.09	25.71
3	3.31	29.02

Coastal **Burst Duration (hours): 24**

Hours Prior	**Pre-Burst Depth %**	
	Incremental	Cumulative
33	0.88	0.88
30	0.75	1.63
27	1.60	3.23
24	1.35	4.59
21	1.37	5.95
18	1.11	7.06
15	1.65	8.71
12	1.34	10.05
9	1.48	11.53
6	1.79	13.32
3	2.24	15.56

Coastal **Burst Duration (hours): 36**

Hours Prior	**Pre-Burst Depth %**	
	Incremental	Cumulative
27	0.78	0.78
24	1.28	2.05
21	0.89	2.94
18	0.98	3.92
15	1.23	5.15
12	1.00	6.15
9	0.99	7.13
6	1.25	8.39
3	1.48	9.87

Coastal **Burst Duration (hours): 48**

Hours Prior	Pre-Burst Depth %	
	Incremental	Cumulative
21	0.41	0.41
18	0.54	0.95
15	0.64	1.59
12	0.48	2.06
9	0.44	2.50
6	0.42	2.92
3	0.93	3.85

Coastal **Burst Duration (hours): 72**

Hours Prior	Pre-Burst Depth %	
	Incremental	Cumulative
15	0.33	0.33
12	0.54	0.87
9	0.67	1.54
6	0.53	2.07
3	0.49	2.56

Coastal **Burst Duration (hours): 96**

Hours Prior	**Pre-Burst Depth %**	
	Incremental	Cumulative
9	0.49	0.49
6	0.25	0.73
3	0.67	1.40

Coastal **Burst Duration (hours): 120**

Hours Prior	**Pre-Burst Depth %**	
	Incremental	Cumulative
3	0.07	0.07

Table B.2: Inland Design Pre-Burst Temporal Distributions

Inland **Burst Duration (hours): 12**

Hours Prior	**Pre-Burst Depth %**	
	Incremental	Cumulative
3	2.75	16.34
6	2.14	13.59
9	1.95	11.45
12	1.00	9.50
15	3.78	8.50
18	0.91	4.72
21	1.73	3.81
24	2.08	2.08

Inland **Burst Duration (hours): 24**

Hours Prior	**Pre-Burst Depth %**	
	Incremental	Cumulative
21	0.78	0.78
18	1.41	2.19
15	1.41	3.60
12	1.31	4.91
9	2.71	7.62
6	0.98	8.60
3	1.85	10.45

Inland **Burst Duration (hours): 36**

Hours Prior	Pre-Burst Depth %	
	Incremental	Cumulative
18	0.47	0.47
15	1.29	1.76
12	0.30	2.05
9	0.66	2.71
6	0.82	3.53
3	0.79	4.32

Inland **Burst Duration (hours): 48**

Hours Prior	Pre-Burst Depth %	
	Incremental	Cumulative
15	0.05	0.05
12	0.31	0.36
9	0.48	0.84
6	0.82	1.66
3	0.72	2.38

Inland **Burst Duration (hours): 72**

Hours Prior	Pre-Burst Depth %	
	Incremental	Cumulative
6	0.02	0.02
3	0.16	0.17

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