Rainfall antecedent to large and extreme design rainfall events over Southeast Australia

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Summary
In estimating design floods from design rainfalls, the adopted initial losses can have an appreciable effect upon the resulting flood. To provide guidance on the appropriate values of initial loss to use with design rainfalls, such as the probable maximum precipitation, the Bureau of Meteorology has analysed the rainfall prior to the 110 largest storms on record in southeastern Australia. Temporal distributions of area-mean rainfalls within these storms and in the 15 days prior were derived. The pre-storm part of each temporal distribution showed antecedent storms to be rare. The pre-burst rainfalls within storms were combined to provide a set of design pre-burst temporal distributions for use with large and extreme design rainfall bursts, though doubts were raised about the appropriateness of such an approach.

Introduction
Rainfall-based estimation of large and extreme floods in Australia is currently hampered by a lack of knowledge of the appropriate initial losses to use [1]. Current guidelines, which attempt to follow a probability-neutral approach to the transformation of design rainfalls to floods, may well have these losses specified too low [2]. Since the values used can appreciably affect the size of the estimated flood peak and volume [3], there is a need for better understanding of what these losses should be. Since, in general, the initial losses associated with large and extreme rainfall events cannot be measured directly, guidance is sought from the examination of the rainfall antecedent to such events, where these events are complete storms and bursts within storms.

Prior work in Australia on antecedent rainfall has mostly dealt with rainfall events of relatively high probability of occurrence: rainfall events with Annual Exceedance Probabilities (AEPs) more frequent than 1in 100 [4], [5], [6], [7], [8], [9], and [10]. The main findings of these various works are that the amount of rainfall prior to rainfall bursts decreases with increasing burst duration. Prior work in the US, where rainfall-based flood estimation is also practiced, has been primarily concerned with rainfall prior to large and extreme storms, not bursts. The main finding of this work is that antecedent storms are highly variable and nearly independent of the main storm [11]. The few studies that have focussed on the rainfall prior to extreme bursts found that rainfall prior to a 24-hour burst will tend to exceed the average rainfall for the location and season, but that this rainfall amounts to less than 15% of the main event [12].

This paper describes the investigation of rainfall in the 15 days prior to the largest storms and bursts on record in southeast Australia. The investigation focusses separately on the pre-storm and the pre-burst periods, examining the rainfall as areal averages with a temporal resolution to 3 hours where possible, daily otherwise. Pre-burst rainfalls were specifically examined with the assumption that from these could be developed design pre-burst temporal distributions ‘typical’ of large and extreme design rainfall bursts. The corollary assumption is that 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 Probable Maximum Precipitation (PMP).

Database
The investigation made use of an existing database of the largest storms on record over southeast Australia [13]. This database was compiled for a major research project on the development of a generalised method of estimating PMP for the region, known as the Generalised Southeast Australia Method (GSAM) [14]. The database contains the dates, locations and areal extents of 110 storms occurring between the years of 1889 and 1990. Figure 1 shows the location of the centres of these storms: 75 Coastal storms are located along the coastal strip from the NSW-Qld border to north and east Tasmania, and 35 Inland storms are spread across the interior of NSW, Vic and SA. The storms vary in duration from 1-7 days and extend to areas of up to 60,000 km^2. While the precipitation mechanisms at work within these storms vary, the storms display an essential common feature of sustained moisture feed from the tropics. The database covers all seasons but is biased towards Summer and Autumn. Table 1 gives the number of storms of each duration and season.

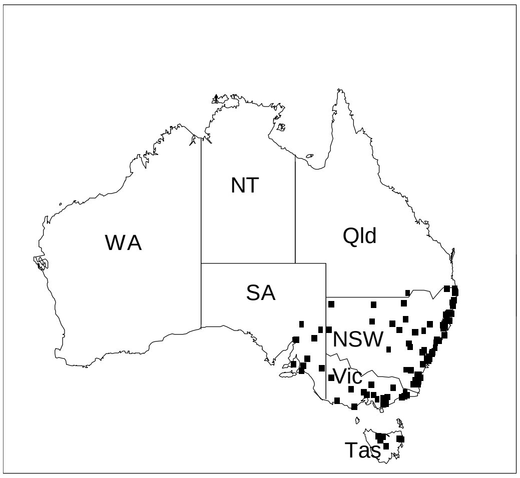

Figure 1 Locations of the GSAM storms

Table 1 Number of GSAM storms of each duration and season

Duration (days)	*Summer*		*Autumn*		*Winter*		*Spring*		*Total*	
	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
Total	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
Total	25	100	7	100	1	100	2	100	35	100

Investigation

The investigation utilised daily-read and continuously-recorded rainfall data from the Bureau of Meteorology national rainfall archive. Rainfall totals from recording stations within each storm extent were extracted for the days of the storm and the 15 days prior. An earlier study of the Inland subset of storms [15] had concluded that the rainfall 1-3 months antecedent to these storms was not significantly different from normal, so that 15 days was considered a sufficient antecedent period for this investigation. Typically a storm will be defined by rainfall from 100-300 daily-read stations (where a day is 9am-9am) and 0-5 continuously recording pluviometer stations. The sparsity of pluviometer stations has meant that only 59 of the 110 storms have been analysed at sub-daily intervals. Where pluviometer data were available rainfall sequences were analysed at 3-hourly intervals. The data were subjected to extensive quality control prior to further processing.

Areal averages at each time interval were calculated, using Thiessen-weighting of the daily station totals and manual-weighting of the pluviometer station totals, for a set of standard-sized areas of 100-60,000km^2.

The investigation then proceeded along two paths: (i) *Pre-Storm* - an examination of the rainfall prior to each storm; and (ii) *Pre-Burst* - an examination of the rainfall prior to all bursts within each storm.

In the pre-storm investigation, the daily-resolved areal averages at $100km^2$ were examined in detail for the occurrence of antecedent rainfall, and 'antecedent storms' in particular. Antecedent rainfall was 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 rain day, or (b) the antecedent rainfall (over all contiguous rain days) totaled more than 5% of the main storm.

The pre-burst investigation was further broken into two parts: (i) an examination of the daily-resolved areal averages prior to 1-5 day bursts (this used all 110 storms), and (ii) an examination of the 3-hourly areal averages within the storm but prior to 12-120 hour bursts (59 storms). For (ii) the storm start time was re-examined and refined for consistency with the 3-hour temporal resolution. The highest 'within-storm' rainfall bursts were then located and the 3-hourly rainfalls prior to the burst but within the storm were isolated. To compare one pre-burst sequence of rainfall with another it was necessary to normalise each sequence by dividing each 3-hourly rainfall in the pre-burst period by the burst depth. Each set of normalised, areal-burst temporal distributions were then combined to give a single distribution 'typical' of the sample. Finally, the combined pre-burst temporal distributions were scaled for consistency with the depth-duration profile of PMP events.

Results

Pre-Storm

Of the 110 storms in the GSAM database, 46 (43%) were preceded by a storm at some time in the 15-day antecedent period. For these 46, the average depth of the antecedent storm was 16% of the main storm, the average duration of the antecedent storm was 2 days, and the average duration of the dry period between the two storms was 7.3 days. The length of this dry period is consistent with the time of passage of ordinary 'synoptic' scale events in the region.

The frequency of antecedent storms of various sizes is shown in Figure 2. This histogram shows the percentage of all storms in the database which are preceded by storms of various size, where the size of the antecedent storm has been expressed as a percentage of the main storm. It also includes antecedent non-storms: occasions where contiguous antecedent rainfall amounted to less than 5% of the main storm. From this histogram it appears, firstly that significant antecedent rainfall is rare: 64% of the GSAM database is preceded by rainfalls totalling less than 5% of the main storm, and secondly that occasions of significant antecedent 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, and might speculatively be identified as average frontal events. A small number (8 out of 46) are between 30 and 75% of the main storm and might be identified as similar in character to the main storm.

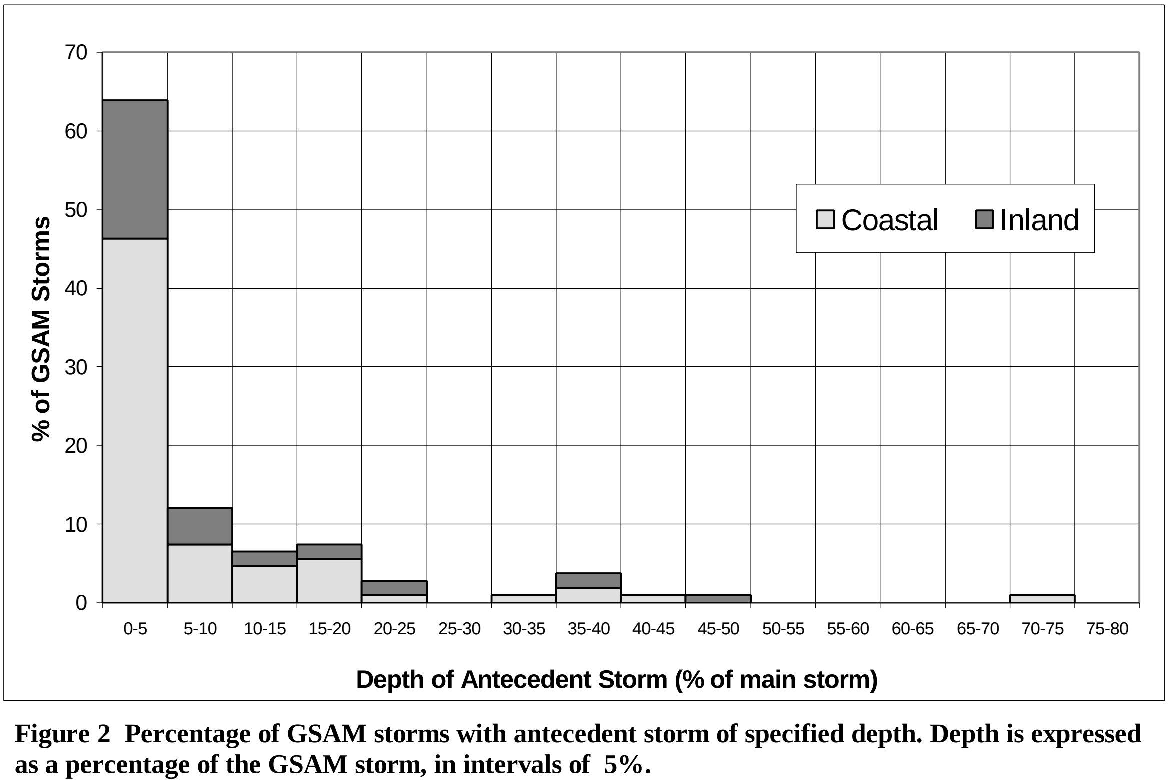

Figure 2 Percentage of GSAM storms with antecedent storm of specified depth. Depth is expressed as a percentage of the GSAM storm, in intervals of 5%.

Pre-Burst (i) – daily resolution

The percentage of 1-5 day rainfall bursts that were accompanied by rain on any one of the 10 days prior to the burst is shown for the 100km^2 area-size in Figure 3. The plot shows that on any day in the preceding 10-day period there is a 25% chance or greater of recording rain. 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 at day$_{-1}$ 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 database than of the inland storms (see Table 1).

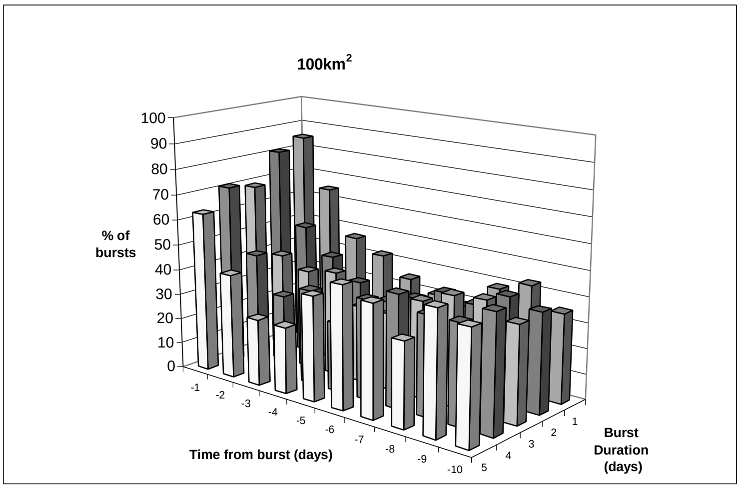

Figure 3 Percentage of 1-5 day bursts that were preceded by rain on specified days.

The average depth of rain in the 10 days prior to 1-5 day bursts is shown for the 100km^2 area-size in Figure 4. In this plot daily depth has been expressed as a percentage of the average daily burst depth, i.e. daily depths prior to the 5-day burst have been divided by 1/5th of the 5-day burst depth and multiplied by 100. Note that the 'Burst duration' axis in this figure is the reverse of that in Figure 3. Figure 4 shows that the average depth within this period varies greatly from one day to the next. In general, the plot concords with the 6-8 day 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 at day$_{-3}$, which derives from only 26% of bursts, indicates that where 1-day events <u>are</u> embedded in longer events those longer events are generally double-peaked. Similar results to these were obtained at all area-sizes.

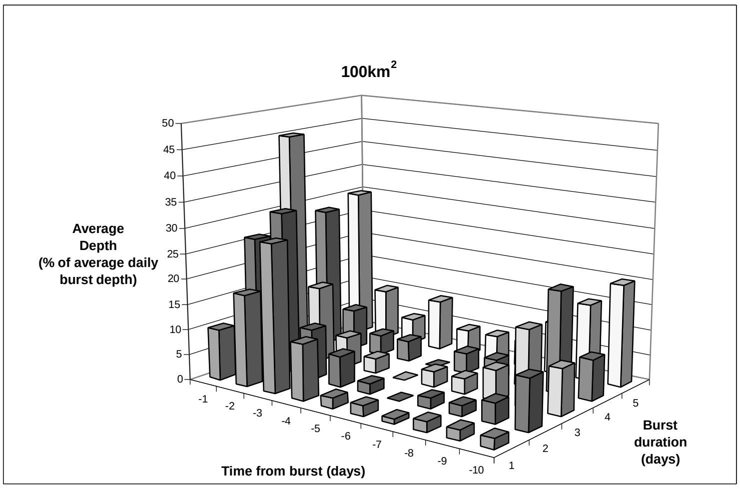

Figure 4 Average depth of rain on specified days preceding 1-5 day bursts.

Pre-Burst (ii) – 3-hourly resolution
The pre-burst rainfall of 3-hourly resolution (not shown) exhibited features similar to that of daily resolution though with greater variability.

For individual bursts within storms the pre-burst period may vary in length from 0 to 168 hours. To combine the pre-burst sequences of individual storms into a single, average sequence, a standard length pre-burst period was required for each burst duration. To ensure that these periods were representative of the storms in the sample, but also varied sensibly with burst duration, standard periods that were inclusive of at least 2/3 of the sample were adopted. These are given in Figure 5. Where these standard length periods were greater than the pre-burst period of individual bursts it was necessary to fill from the storm beginning to this length with zeroes.

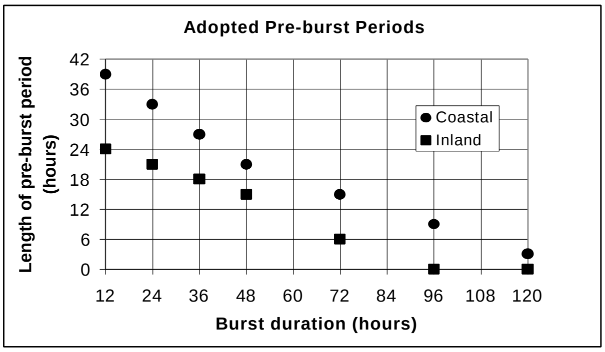

Figure 5 Standard length pre-burst periods adopted for derivation of a design pre-burst temporal distribution.

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. While some of this variability would be expected as a consequence of being at the temporal edge of the storm, there is no doubt that some is also the result of the normalisation procedure. The Average Variability Method (AVM) [4] had previously been used by [5] on pre-burst distributions. The AVM, however, does not preserve the serial correlation of time segments within a sequence and this was one feature of the pre-burst distributions which was identifiable and therefore important to preserve. It is interesting to note 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 latter part of their seminal paper [4]. They instead suggested an average or median. Not knowing *a priori* which was most suitable both a median and an average sequence were calculated for each areal-burst combination. Unfortunately, for most burst durations, the sample size is too small for a well-defined median. But equally unfortunately, the averages appeared to be too influenced by the extremes in the highly variable samples. Large values in the pre-burst pattern 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 had the greatest influence on the average value may have derived from less significant bursts.

Since a single pre-burst distribution was required, averaging was adopted, in full cognisance of the inadequacy of the approach. The normalised depths at each time interval within the standard length pre-burst period were averaged. Since there appeared to be very little difference in the average distributions at each area size, a single 'one-size-fits-all' average pre-burst distribution was calculated.

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 events. 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 'typical' 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 ensure this didn't happen, the average pre-burst distributions were scaled downwards until they matched the worst case example from a database of 100 GSAM PMP estimates, which had been determined over the course of the last 6 years. The re-scaled, now design, pre-burst temporal distributions for the Coastal and Inland Zones of the GSAM are given in Figure 6.

Conclusions

Pre-storm
This investigation indicates that, over southeast Australia at least, large and extreme storms are only very rarely preceded by storms of similar magnitude. Both this investigation and that of [15] indicate that <u>any</u> significant antecedent 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.

Pre-burst

A set of design pre-burst temporal distributions has been produced, and in the absence of any better approach, should be useful in defining the pre-burst rainfall of large and extreme rainfall bursts. 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 determination of a 'typical' pre-burst rainfall distribution from example events 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 for this investigation should facilitate just such an approach.

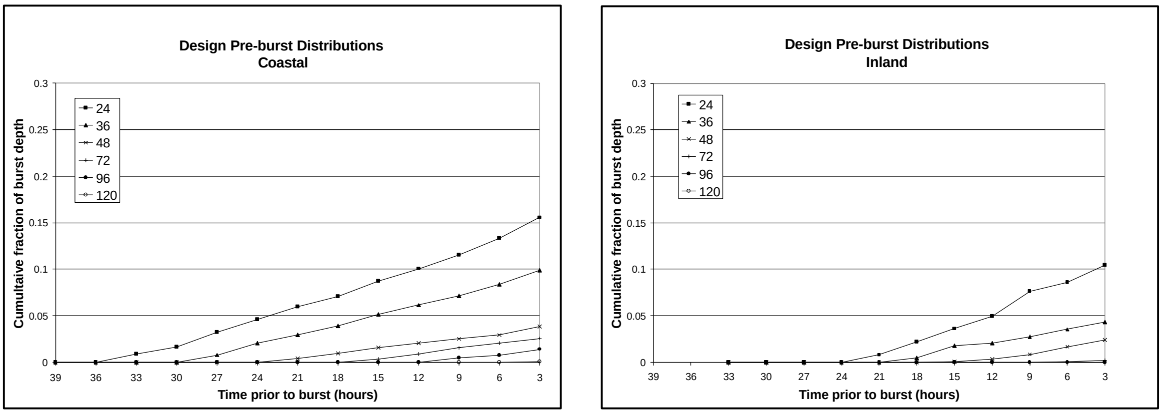

Figure 6 Design pre-burst temporal distributions for use with large and extreme rainfall bursts in the GSAM.

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