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A hydroinformatic approach to development of design temporal patterns of rainfall

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Abstract Estimation of the design rainfall for design flood estimation remains a problem for many engineering hydrologists despite many research studies into appropriate methodologies. An important aspect of flood flow estimation through catchment simulation is the design rainfall. Presented herein is a new approach for estimation of the temporal pattern of rainfall during a hypothetical design storm. The basis of the approach is a conditional random walk in non-dimensional space to create a finite number of storm patterns based on the probability that the storm event is convective or frontal and the probability that the storm centre of mass is located at the beginning, middle, or end of the storm event. It is shown that the resultant storm patterns more closely reflect historical patterns than alternative methods for estimating the design temporal pattern of rainfall.

Key words temporal patterns; rainfall; design; flood

INTRODUCTION

Estimation of the design rainfall for design flood estimation remains a problem for many engineering hydrologists. In many situations, advice is required regarding flood magnitudes for design of culverts and bridges for roads and railways, design of urban drainage systems, design of flood mitigation levees and other flood mitigation structures, design of dam spillways, and many other situations.

Where data are available, this problem of flood flow estimation can be undertaken using at-site flood frequency techniques such as those presented by Kuczera (1999), Jin & Stedinger (1989), Martins & Stedinger (2000) and Wang (2001). However, for the far more common case of an absence of suitable data, catchment simulation techniques are commonly used to provide predictions of the desired flood quantile.

An important aspect when flood quantiles are estimated using catchment simulation is the design rainfall used to predict the catchment response. There are three components to the design rainfall:

(a) Average intensity of rainfall (or its counterpart which is the rainfall depth) over the storm burst duration;
(b) Spatial distribution of the rainfall; and
(c) Temporal distribution of the rainfall.

The concern here is the third aspect of design rainfall, namely that of estimating the temporal distribution of rainfall during the design storm burst. While the assumption of a constant rainfall intensity over the storm burst can be adopted, Ball (1994) showed that this assumption resulted in a lower bound to potential flood quantiles estimated from the peak flow of the resultant predicted hydrograph.

For this reason among others, the temporal pattern of the storm burst to be used in design flood estimation has been the focus of many studies; examples are Keifer & Chu (1957), Huff (1967), and Pilgrim & Cordery (1975). The approach adopted for development of the design rainfall hyetograph in these studies varied between the studies. Keifer & Chu (1957) aimed at developing a hyetograph that ensured that the design rainfall intensity for varied catchment response times was experienced by each component of the system. The study by Huff (1967) considered the probabilities associated with cumulative rainfall totals with the implicit assumption that rainfall early in the storm event, or burst, was the worst situation for design. Of these studies, only that by Pilgrim & Cordery (1975) explicitly stated that the aim of the hyetograph developed was to ensure that the annual exceedence probability (AEP) of the rainfall depth or intensity was transformed into the AEP of the resultant peak flow. To achieve this stated aim, Pilgrim & Cordery (1975) proposed that a storm pattern with average variability would not impact on the AEP transformation and, hence, developed a technique for development of design rainfall hyetographs which incorporated average variability in patterns. These techniques were used subsequently in the development of the recommended temporal patterns for design flood estimation in Australia (Pilgrim, 1987).

However, while the temporal patterns presented in *Australian Rainfall and Runoff* (Pilgrim, 1987) have been adopted for design flood estimation, their application in practical situations has resulted in the need to consider alternatives. Of particular concern are:

- the dominance of particular durations which bear no relationship to catchment response times;
- internal bursts within the storm which have a higher AEP than the design AEP for the full storm burst; and
- the increasing need to consider flood volume – particularly where the volume of flood storage being considered is a significant fraction of the flood hydrograph.

To mitigate some of these issues, Phillips (1994) and Rigby *et al.* (2003) proposed the use of embedded design storms instead of using only the peak storm burst. This approach is based on embedding the design burst inside a historical storm burst. When using this approach, the influence of the historical portion of the storm event on the resultant flood hydrograph is assumed not to be significant and, therefore, not to influence the translation of the rainfall probability into the flood flow probability.

Presented herein is a new approach for estimation of the temporal pattern of rainfall during a hypothetical design storm with the aim of overcoming the problems noted above. However, rather than developing a single temporal pattern of rainfall, a suite of potential patterns result which enables the designer to assess the sensitivity of the peak flow estimate to the temporal pattern of rainfall.

RAINFALL DATA

The present study is limited to two sites (Sydney and Richmond) in eastern New South Wales, Australia (Fig. 1). Rainfall characteristics for these two sites from the Australian Bureau of Meteorology (2008) are used: Sydney has an average annual rainfall of 1215.2 mm with the highest rainfall occurring between February and June; and Richmond has an average annual rainfall of 810.4 mm, with the highest rainfalls occurring between December and April.

The rainfall data for the two sites comes from the digitized pluviograph records for Sydney Observatory Hill and Richmond RAAF weather stations. These stations were chosen due to the length of record; the record for Sydney Observatory Hill begins in October 1913 while that for Richmond RAAF begins in May 1953. While data were available for Sydney Observatory Hill to December 2005, that for Richmond RAAF ended in December 1993. Hence 92 years of record were available at Sydney Observatory Hill and 40 years of record at Richmond RAAF. For both sites, the original records were digitised from pluviographs in 6-minute increments and hence the data were available only in 6-minute time periods.

One of the issues affecting the resultant database of storm events when the information is available only at discrete time intervals is the occurrence of an intense burst within the storm of interest covering two intervals; this problem is illustrated in Fig. 2. The burst of rainfall occurring in the time period prior to and post 12:12 h is disaggregated into two parts, with one part being in the period 12:06 h to 12:12 h and the second part in the period 12:12 h to 12:18 h. This problem of restricted time periods is documented in the literature (e.g. see Dwyer & Reed, 1995) when the time period of interest is 1 day. While this issue is important for implementation of the proposed methodology for practical applications, the focus herein was on "proof of concept" and hence no modification to the database was undertaken.

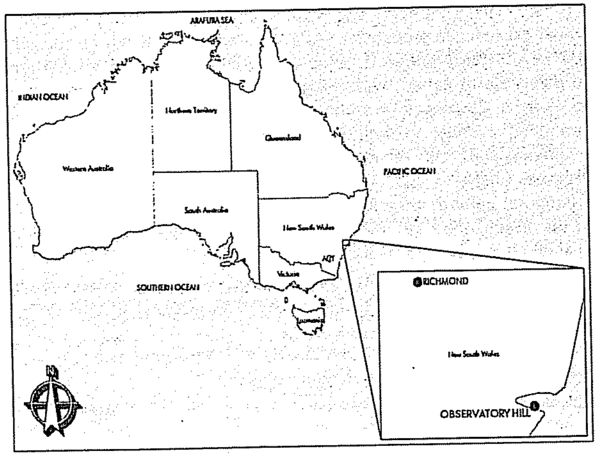

Fig. 1 Location of case study sites.

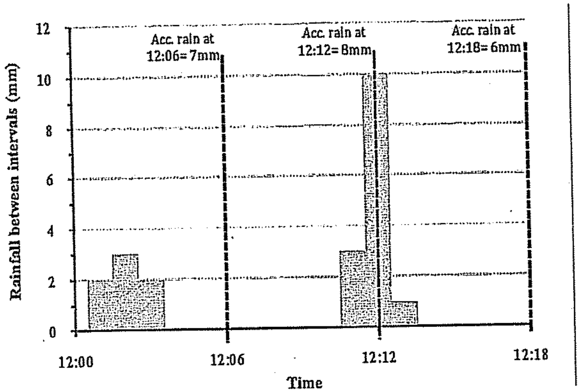

Fig. 2 Problem of restricted time periods.

Several other issues regarding data quality were also found during consideration of the data. Firstly, large periods of rainfall (up to 9 hours in some cases) with constant intensities of rainfall were found in the database; these periods suggest disaggregation using linear techniques had occurred. As storms do not have long consecutive periods of uniform rainfall intensity, a filter was applied with the criteria of selecting storms where four or more consecutive values of the same rain depth occurred; these storms were then deleted from the subsequent analysis.

STORM DEFINITION

A clear and agreed definition of a storm event and its start and end points of a storm event is not available in the literature, with many researchers using alternative definitions to suit the purpose of their investigations. Hence, a definition to define the occurrence of a storm and its characteristics was developed.

For the purpose of this study, a storm was defined as a rainfall event having a total depth greater than 5 mm with more than 1 mm occurring within a 30-minute period. Furthermore, a minimum period of 1 hour was assumed between different events; bursts of rainfall occurring either side of a period greater than 1 hour were assumed to be separate storm events.

Inter-event times (the time between different storm events) of two hours have been used in several studies (e.g. see Eagleson, 1978; Heneker *et al.*, 2001). However, when this parameter was used it was found that many storms had significant periods of low rainfall with the suspicion that multiple storm generation mechanisms were present. Furthermore, storms lasting more than 24 hours have a high probability of originating from more than one storm generation process (Pilgrim *et al.*, 1969) with, typically, short duration storms embedded within a longer duration storm. As the focus of the study reported herein was based on single storm events, it was desired that these multiple storms within a storm be discriminated. This discrimination was achieved with the shorter inter-event time of 1 hour and, hence, this value was adopted.

For each of the storms identified in the continuous rainfall records, the highest rainfall intensities were calculated for periods of 6, 12, 18, 24, 30 minutes and 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5.5, and 6 hours. The storms having the 50 highest intensities for each period were then extracted for further analysis. For the studied period, 128 storms were extracted from the Sydney Observatory Hill record and 156 storms were extracted from the Richmond RAAF record.

STORM CATEGORISATION

As part of the analysis of storm patterns, the selected storms were subdivided into those with a frontal origin and those with a convective origin. Storms originating from frontal events tended to have lower intensities but occurred over longer durations, while storms classified as convective had higher intensities but were of shorter durations. In order to achieve this classification, the following storm characteristics were extracted from each storm:

- date of occurrence;
- total rainfall (mm);
- duration (hours);
- average intensity (mm/h) and the most intense rain increment (mm per 6 minute period);
- proportion of total rainfall depth in the most intense period;
- the period in the storm when the temporal semi-variogram obtained the value of 1;
- median rain increment;
- root mean squared error (RMSE) of the storm rainfall; and
- beta parameter. as defined by Llasat (2001).

Semi-variograms have been used previously by Umakhantan & Ball (2005) to assess rainfall homogeneity in space and time within the Sydney area. Following that approach, a standardised semi-variogram in the temporal dimension can be defined by:

$$\gamma^*(k) = \frac{1}{2(T-k)\sigma_i^2}\sum_{t=1}^{T-k}[P_i(t) - P_i(t+k)]^2 \qquad (1)$$

where T represents the total number of time intervals within a storm, k is the lag time, σ_i^2 is the variance of the storm rainfall depth increments, and $P_i(t)$ is the rainfall increment at time t. When the semi-variogram is plotted against different lag times, a rapid rise of the function to the value of 1 will indicate a non-homogeneous storm in time, while a slower rise will indicate a more uniform storm.

Convective storms tend to have higher temporal variation and hence the correlation structure of the storm will be lower, as indicated by the semi-variogram obtaining a value of 1 with fewer lags than would be the case for frontal storms. Figures 3 and 4 show the hyetographs and semi-variograms for two typical storm events at Richmond. The first storm corresponds to a frontal

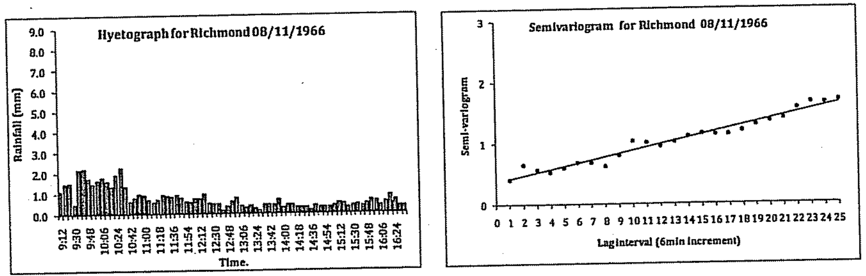

Fig. 3 Storm at Richmond on 8 November 1966.

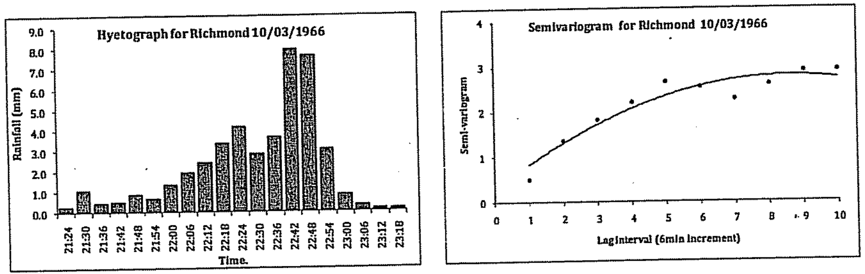

Fig. 4 Storm at Richmond on 10 March 1966.

event which occurred on 8 November 1966, while the second event represents a convective event which occurred on 10 March 1966. For the first event, the semi-variogram reaches the value of 1 after 13 time lags, or 78 minutes, while for the second event, the semi-variogram function reaches a value of 1 approximately at the first lag time. These results illustrate the longer persistence and greater uniformity for frontal storm events and the greater heterogeneity that occurs during convective events.

Llasat (2001) proposed the use of a Beta parameter to characterise convective storm events. In essence, this parameter relates the rainfall depth in periods during the storm where the depth is greater than a predefined threshold to the total rainfall over the storm duration. It is defined by:

$$\beta = \sum_{i=1}^{N} I(t_i)\,\theta(I-L) \Big/ \sum_{i=1}^{N} I(t_i) \qquad (2)$$

where L is the threshold depth fixed at 3.5 mm per 6-minute period (the time increment of 6 minutes corresponds to the pluviograph record), I is the rain increment for the time t_i, and $\theta(I-L)$ is the Heaviside function defined as:

$\theta(I-L) = 1$ if $I \geq L$; and
$\theta(I-L) = 0$ if $I < L$.

Any storm that had a β value greater than 0.3 was considered to be of convective origin.

A third methodology used to categorise the storms was based on the rainfall variability in the temporal dimension. To define this variability, the RMS variation from the average intensity was calculated for each storm. Consistent with the previous approaches, a higher rainfall variability was expected to occur in convective events when compared to frontal events. For frontal storm events, the average RMS was found to be 0.6 mm at Richmond and 1.0 mm at Sydney Observatory Hill while, for convective storm events, the average RMSE was found to be 2.5 mm at Richmond and 2.9 mm at Sydney Observatory Hill. The effect of storm duration on the variability of the storms is shown by the RMS in Table 1 where it can be seen that, as the duration of the storm increases, the variability within the storms decreases.

Table 1 Effect of storm duration on storm variability. D = Duration.

	Sydney Observatory Hill									
Duration	D ≤ 1h		1h < D ≤ 2h		2h < D ≤ 3h		3h < D ≤ 6h		6h < D ≤ 24h	
No. of storms	14		15		21		34		44	
Prob.	11%		12%		16%		27%		34%	
RMS	mm	%	mm	%	mm	%	mm	%	mm	%
Median	3.48	10.65	2.74	7.68	2.27	4.17	1.36	1.99	0.81	0.88
Average	3.76	10.74	3.08	7.17	2.36	4.38	1.59	2.11	0.89	0.93
	Richmond RAAF									
	D ≤ 1h		1h < D ≤ 2h		2h < D ≤ 3h		3h < D ≤ 6h		6h < D ≤ 24h	
No. of storms	42		21		14		37		42	
Prob.	27%		13%		9%		24%		27%	
RMS	mm	%	mm	%	mm	%	mm	%	mm	%
Median	2.26	12.18	1.62	5.18	0.84	3.26	0.48	1.52	0.33	0.70
Average	2.36	13.09	1.66	6.52	1.04	3.35	0.60	1.62	0.47	0.80

Ball (1994) showed that the pattern of rainfall can have a significant influence on the magnitude and location of the peak and on the shape of the hydrograph. Therefore, the storm events were further categorised into front-loaded, middle-loaded and back-loaded categories according to the location of centre of rainfall mass:

front-loaded – centre of mass located within first 33% of storm duration;
middle-loaded – centre of mass located within middle third of storm duration; and
back-loaded – centre of mass located within last 33% of storm duration.

Shown in Table 2 are the number of storms in each category and the resultant probabilities of occurrence for each category. The frontal storms have a higher probability of occurring at both locations with the probability at Richmond being slightly higher than Sydney. At both Sydney Observatory Hill and Richmond RAAF sites, there is a preference for the storm centre to occur in the middle third of the duration with approximately 2/3 of the selected storms being middle loaded storms.

Table 2 Number of storms and probabilities of categories.

Location	Sydney Observatory Hill		Richmond RAAF	
	No. of storms	Prob.	No. of storms	Prob.
Convective	61	47.7%	63	40.4%
Frontal	67	52.3%	93	59.6%
Convective front loaded	18	29.5%	25	39.7%
Convective mid loaded	34	55.7%	30	47.6%
Convective back loaded	9	14.8%	8	12.7%
Frontal front loaded	3	4.5%	4	4.3%
Frontal mid loaded	53	79.1%	79	84.9%
Frontal back loaded	11	16.4%	10	10.8%

NON-DIMENSIONAL RAINFALL MASS CURVES

As part of the analysis undertaken, all storms were non-dimensionalised in terms of storm duration and storm depth; for this purpose, τ is the non-dimensional time defined by $\tau = t / t_d$ and δ is the non-dimensional rainfall depth defined by $\delta = d(t) / d(t_d)$ where $d(t)$ is the rainfall depth at time t and t_d is the storm duration. These non-dimensional mass curves preserved the following characteristics:

the mass curves started at $\tau = 0$, $\delta = 0$ and ended at $\tau = 1$, $\delta = 1$; and

the slope between any two points will be either 0 or some positive value.

Shown in Fig. 5 are the resultant non-dimensional mass curves for the frontal and convective events at both Sydney Observatory Hill and Richmond RAAF. Also shown are the average patterns for all six subcategories at the two locations. For purposes of generating alternative temporal patterns for storms, these non-dimensional mass curves were divided into 10 equally-spaced temporal intervals.

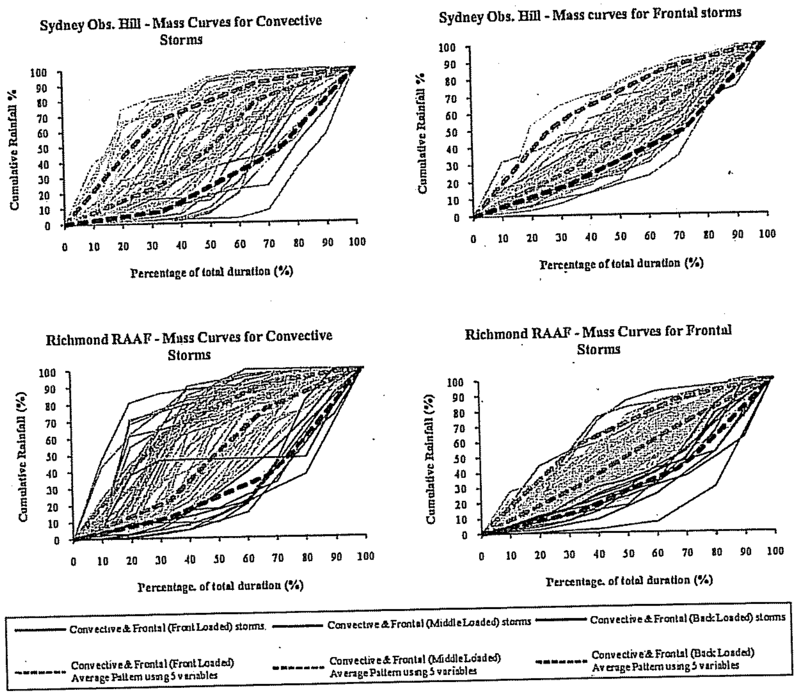

Fig. 5 Non-dimensional storm patterns.

GENERATION OF DESIGN STORMS

The procedure for the creation of random design storms was based on a uniform random selection of a conditional walk jump at each time decile. The number of possible combinations when creating random storms in this manner is the number of storms in each sub-category raised to the power of 9. This method does not need to resample the jump at each time because it will never exceed the upper limit $(1 - d_i)$. However, when sampling random storms to allocate them in the front-loaded, middle-loaded and back-loaded "bins", a reduced number of them (less than 3%) did not reproduce the correct location of the centre of mass. Therefore, these storms were eliminated from the sample.

Conditional random walk theory has been used to develop non-dimensionalised mass curves to enable the creation of storm patterns. The movement of any randomly generated storm within the dimensionless mass curve, from one point to another, is described by a discrete stochastic process. The limits for this movement are bounded from a positive jump (rainfall occurrence at time step) or no jump at all (no rainfall). The basis of this comes from the self-similarity concept studied by Woolhiser & Osborn (1985) and Koutsoyiannis (1993). Storms should preserve their internal structure conditions regardless of rainfall amount and duration.

For every storm, according to their sub-category type, a conditional walk jump was obtained at each decile by:

$$C_{jump} = \frac{(d_{i+1} - d_i)}{1 - d_i} \tag{3}$$

where C_{jump} is the jump from the dimensionless mass curve at a time step i, d is the value of the rain in the dimensionless mass curve. This formula represents the ratio of jump taking into account the remaining depth in the dimensionless mass curve. Periods of no rain are mixed with the values of the jumps at any time step, when they are present in the historical storms. Therefore, for any random storm created, the random dimensionless mass curve will be constructed as follows:

$$Rd_{i+1} = C_{jump} \times (1 - Rd_i) + Rd_i \tag{4}$$

where Rd_i is the random dimensionless mass curve increment at time I.

RESULTS

Using the techniques described above, a number of storms in each of the six categories were generated for the Sydney and Richmond locations. At each location, 210 frontal and 210 convective storms were generated. Within these categories, the probabilities of front-loaded, middle-loaded and back-loaded events were used to ensure the generated storms had similar characteristics to the historical storms.

Shown in Fig. 6 are the generated non-dimensional storm patterns for Sydney Observatory Hill with bounds developed from the maximum and minimum values of the historical storm patterns. Reproduction of the historical patterns is evident on inspection of this figure. In general, all of the generated storms fall within the boundaries of the historical storms; the exception is the front-loaded frontal storm category. This exception is considered to be the result of only a small number of historical storms for generating the random storm patterns under this category.

In order to evaluate the generated non-dimensional storm patterns, the non-dimensional storm patterns were converted into storm events using durations of 1, 3 and 6 hours with rainfall depths given by Average Recurrence Intervals (ARIs) of 5 and 10 years. These dimensional storms were analysed for internal rainfall intensities using fixed increments of the storm duration, namely 0.1, 0.2 and 0.3 of the storm duration.

While the storms had similar characteristics to the historical storm events, it was found that the internal rainfall intensities were greater than the ARI determined using the total storm duration. For example, the convective storms generated for durations of 1 and 3 hours for both ARIs contained internal bursts where the rainfall intensities were higher than the rainfall intensity for an ARI of 50 years obtained from the IFD diagram; this result occurred at both sites. This result, however, is consistent with many historical storm events as shown when the internal burst intensities are plotted on an IFD diagram; an example of this shown in Fig. 7 where the internal burst intensities for a number of storms at Sydney Observatory Hill are plotted on an IFD diagram. As shown in this figure, it is common for the intensity during an internal storm burst to be greater

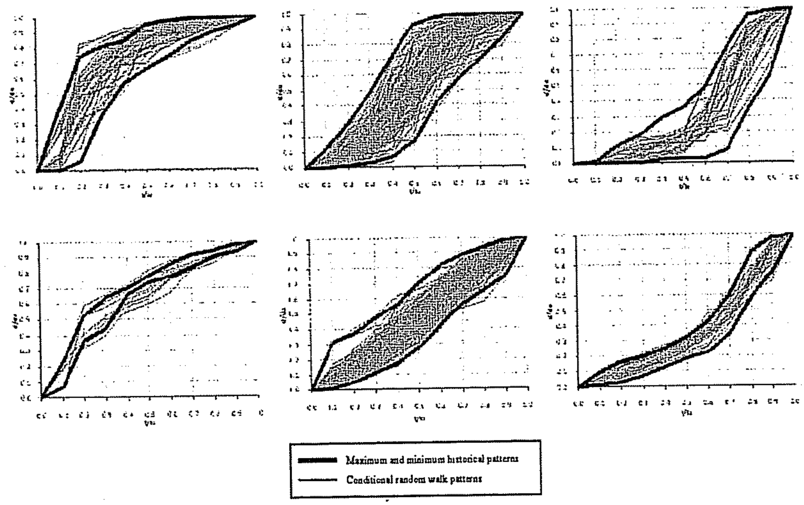

Fig. 6 Generated storm patterns at Sydney Observatory Hill.

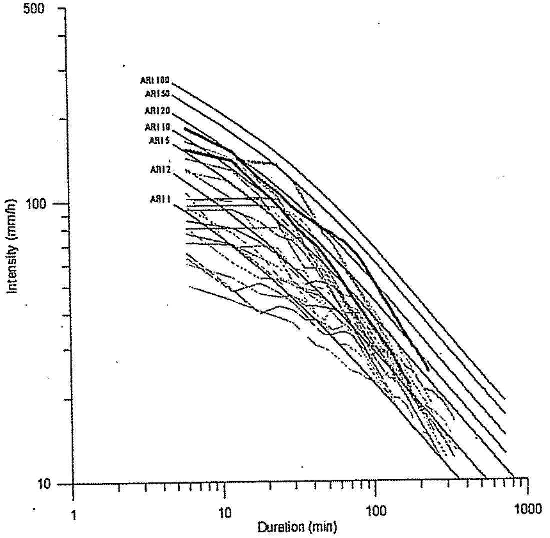

Fig. 7 Typical storm burst intensities.

than the average intensity over the storm duration as occurred in the generated storm events. Hence, it is considered that the appearance of bursts with an intensity equivalent to a rarer event (i.e. larger ARI) should not result in these events being rejected as a feasible realisation of a design storm event.

CONCLUSIONS

Average patterns do not properly represent storm pattern variability within the region. An additional alternative was presented by the use of a conditional random walk as a method to generate storms, based on the self-similarity concept that preserves the characteristics of historical storms.

Some issues regarding IFD characteristics of the conditional walk patterns arose in this study. Internal burst frequencies within ARR temporal patterns do not exceed the frequency of occurrence of the total storm. However, in the design of constrained random walk patterns, for both locations, it is possible to observe bursts with a rarer ARI than the design ARI of the storm (higher chance to occur in Sydney). Nonetheless, these situations often occur in real storms.

A change in the conditions of the storm selection filter may allow retrieval of a larger number of storms to be analysed. One of the most important factors that affected the selection of storms was the presence of consecutive rain intervals with the same value. As stated before, this is unlikely to exist in real life. Another possibility to improve the number of storms is going back to the raw data on those days when large storms occurred and consecutive values were found, and to extract the values again. By using a regional approach, the number of storms extracted should increase. This may lead to a higher variability in the random patterns produced in order to obtain a better representation of the temporal patterns in each zone, thus using an ARI threshold as a filter for selecting storms.

Another approach for conditional random walk might involve allocation of non-dimensional storms to different "bins" according to duration to resolve time scale problems. This will improve the selection of storm patterns. Intense bursts that occurred in short duration storms will not be dimensionalised into longer duration convective storms. In this case, a relatively long and good quality series record is needed.

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Hydroinformatics in Hydrology, Hydrogeology and Water Resources

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Preface

Hydroinformatics is a reflection of the intense development that has occurred in the application of information technology in the areas of Hydrology, Hydraulics and Water Resources. Despite having started within the computational hydraulics community and been an object of seminal support by the International Association of Hydraulics Research (IAHR), in the last two decades it has grown to embrace the whole of the water community. Many other areas of science have seen a similar progression ranging from health informatics to robotic systems. This widening interest in the water community was reflected by the foundation of the Joint Committee on Hydroinformatics at the Cardiff International Conference on Hydroinformatics held in the UK in July 2002. This was the fifth conference in a continuing series and recognised the support of the IWA and IAHS, who joined with IAHR to form the Joint Committee on Hydroinformatics.

Hydroinformatics has seen significant growth as an area of interest in the IAHS community and this has been reflected in the attendance by many hydrologists at Hydroinformatics events over recent years. The joint symposium between IAHS and the IAH recognised the increasing strength of interest in this area and sought to focus on applications of Hydroinformatics in Hydrology, Hydrogeology and Water Resources. It was the first time that IAHS had directly sponsored this area at either a scientific assembly, or indeed at any IUGG Congress, and clearly signals its future importance to the Association.

This publication comprises a collection of peer-reviewed papers presented at the joint symposium JS.4: *Hydroinformatics in Hydrology, Hydrogeology and Water Resources* that was held during the 8th IAHS Scientific Assembly and 37th IAH Congress, in Hyderabad, India, 6–12 September 2009. The symposium was jointly sponsored by the following IAHS commissions and working groups: HYINF, ICSW, ICWRS and ICRS, and also IAH. The volume contains 60 papers from more than 20 countries, reflecting the international dimension of the symposium.

The editors would like to thank all symposium participants for their scientific contributions. The invaluable support of Marghi Peacock from the UK - Flood Risk Management Research Consortium (FRMRC) was critical and the editors and participants owe her a great debt of gratitude. We also express special thanks to Cate Gardner, Penny Perrins and Frances Watkins from IAHS Press for their professional advice and help with the processing of the manuscripts and the production of this seminal IAHS publication.

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