Application of Spatial and Space-Time Patterns of Design Rainfall to Design Flood Estimation

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Abstract

Rainfall exhibits both spatial and temporal variability at all spatial and temporal scales that are of interest in flood hydrology. The space-time pattern of rainfall for an individual flood event will often have an appreciable influence on the flow hydrograph generated at the outlet of a catchment. Two rainfall events may have identical total volumes over a defined catchment area and duration but differences in their space-time patterns may produce very different hydrographs at the outlet of the catchment. Rainfall-runoff routing models and hydraulic models that are available to practitioners provide them with the capacity to specify the space-time pattern of rainfall to be adopted for the event to be modelled.

The 1987 edition of Australian Rainfall and Runoff (ARR) provided very little guidance on how spatial patterns of rainfall should be applied to calibration of flood models and production of design flood estimates. The spatial and space-time rainfall patterns chapter of Australian Rainfall Runoff is being re-drafted for the 2015 update of ARR. The purpose of the updated chapter of ARR is to provide guidance to practitioners on how to derive space-time patterns and spatial patterns of rainfall for use in design flood estimation.

A very high quality rainfall data set from a well instrumented catchment, the Stanley River in south-east Queensland, was used to analyse the spatial and space-time patterns of rainfall at a catchment scale. For this catchment it was found that that the spatial gradient is relatively consistent for 13 observed events and that a spatial pattern of rainfall derived from the BOM (2013) IFD analysis was a very good surrogate to the mean of the spatial patterns from the 13 observed events.

Simulations of design floods at the catchment outlet, performed using stochastic simulations with a RORB model showed that design peak inflow floods to Somerset Dam were insensitive to whether a uniform or non-uniform spatial pattern was adopted as long as random sampling of temporal patterns is included in the Monte-Carlo simulation. Design peak inflow floods to Somerset Dam were also insensitive to whether space-time patterns are randomly sampled or only temporal patterns are randomly sampled in the Monte-Carlo simulation.

1. INTRODUCTION

Rainfall runoff-routing have been widely used by practitioners to estimate the characteristics of design flood events. These models include components that estimate the time series of runoff across the spatial domain represented by the model (either model subareas or grid cells) and components that route the generated runoff within the model domain. In this paper, rainfall-runoff routing models are referred to as “catchment models”, as the concepts are equally applicable to other simulation approaches, such as those based on rain-on-grid modelling. Simulation of design flood events from catchment models are influenced by the assumptions made by the designer about how the catchment average rainfall depth is distributed in space and time.

The 1987 edition of Australian Rainfall and Runoff (ARR) (Pilgrim (ed.), 1987) provided very little guidance on how spatial patterns of rainfall should be applied to calibration of flood models and production of design flood estimates. The spatial and space-time rainfall patterns chapter is being re-drafted for the 2015 update of ARR, to provide contemporary guidance to practitioners on how to derive space-time patterns and spatial patterns of rainfall for use in design flood estimation.

It has been recognised for many decades that the temporal patterns applied in design flood estimation using catchment models have an appreciable influence on the resulting flood hydrographs at the catchment outlet. However, there has been comparatively little attention paid to the influence that spatial or space-time patterns have on design flood estimation outcomes. ARR1987 is largely silent on the issue and the common position used on most design flood estimation practice has been the adoption of uniform spatial pattern for most events. However for large and extreme events, Nathan and Weinmann (1998) specifically recommended the adoption of non-uniform spatial patterns reflecting the spatial variability that is reflected in generalised estimates of probable maximum precipitation. David Pilgrim, who authored the relevant section of ARR1987, also endorsed the use of non-uniform spatial patterns derived from an intensity-frequency-duration (IFD) analysis for use in design flood estimation for several flood studies in the period after the publication of ARR1987.

It makes intuitive sense that non-uniform spatial patterns should be adopted across the full range of design flood estimation practice and that there should be a reasonable level of consistency between the approaches used for estimation of relatively common and more extreme floods. The outstanding issue is how spatial and/or space-time rainfall patterns should best be used in design flood estimation to preserve the AEP neutrality in estimation of design floods from catchment models in a manner that can be practically implemented by practitioners.

This paper uses a very high quality rainfall data set from a well instrumented catchment, the Stanley River catchment to Somerset Dam, to analyse the spatial and space-time patterns of rainfall at a catchment scale and these patterns are then compared to spatial patterns derived from IFD analysis. The paper then examines the sensitivity of design flood estimates from a number of different simulations using a RORB rainfall-runoff-routing model of the same catchment that were run with different approaches to representing the design space-time patterns of rainfall.

2. SPACE-TIME VARIABILITY OF RAINFALL

Rainfall exhibits both spatial and temporal variability at all spatial and temporal scales that are of interest in flood hydrology. High resolution recording instruments have identified temporal variability in rainfall from time scales of less than one minute to several days (Marani, 2005). Similarly, observations of rainfall from high resolution weather radar and satellites have demonstrated spatial variability in rainfall at spatial resolutions from 1 km to more than 500 km (Lovejoy and Schertzer, 2006).

When combined, the spatial and temporal variability of rainfall is referred to as the space-time variability of rainfall. The space-time pattern of rainfall over a catchment or study area is therefore defined in three dimensions: two horizontal dimensions, which are normally latitude and longitude or easting and northing and one temporal dimension. In practice, the space-time pattern of rainfall will often be described as a three-dimensional matrix, with the value in each element of the matrix representing either the accumulated rainfall or the mean rainfall intensity for a grid cell over the catchment and a specified period of time for the event.

Design rainfall information for flood estimation is generally made available in the form of point rainfall intensities for example from the rainfall intensity-frequency-duration information provided by the Bureau of Meteorology (BOM, 2013). However, most flood estimates are required for catchments of significant size and will thus require a design estimate of the areal average rainfall intensity over the catchment. The ratio between the design values of areal average rainfall and point rainfall, computed for the same duration and annual exceedance probability (AEP), is called the areal reduction factor (ARF). It allows for the fact that larger catchments are less likely than smaller catchments to experience high intensity storms simultaneously over the whole of the catchment area.

It should be noted that the ARF provides a correction factor between the catchment rainfall depth (for a given combination of AEP and duration) and the mean of the point rainfall depths across a catchment (for the same AEP and duration combination). Applying an ARF is a necessary but not necessarily sufficient requirement for providing design flood estimates from a catchment model that preserves a probability neutral transition between the design rainfall and the design flood characteristics. The ARF merely influences the average depth of rainfall across the catchment, it does not account for variability in spatial and/or space-time patterns of its occurrence over the catchment.

3. ANALYSIS OF SPACE-TIME RAINFALL PATTERNS FOR THE STANLEY RIVER CATCHMENT

The Stanley River catchment drains into Somerset Dam, which is in the upper part of the Brisbane River basin in Southeast Queensland. Figure 1 shows a map of the 1324 km² catchment area, with Somerset Dam located in the southwestern corner. Seqwater developed a library of 39 historical rainfall and flood events for the Stanley River catchment, which were then used to calibrate an URBS rainfall-runoff routing model. The URBS model of the Stanley catchment has 76 subcatchments. Rainfall data from daily read and pluviograph gauges was available for all thirty-nine flood events that occurred during the period between 1955 and 2014 inclusive (Seqwater, 2013). For each of these rainfall events, hourly sequences of subcatchment average rainfall were produced for each of the 76 subcatchments in the Stanley River model. Quality control was first performed by Seqwater on the recorded rainfall data. Then Seqwater performed a spatial interpolation of the event rainfall total for each event using the data from all rainfall gauges, both daily and pluviograph gauges. Event rainfall totals for each subcatchment were then disaggregated using the temporal pattern of rainfall observed for the event at the nearest pluviograph station that recorded valid data for the event. The Seqwater data provided a rich data source for investigating the spatial and temporal patterns of multiple flood events across a catchment.

A significant feature of the Stanley River catchment is the appreciable gradient in rainfall that is typically observed during large rainfall events. Tropical cyclones, ex-Tropical Cyclones, East Coast Lows and other rainfall producing systems typically feed moisture into the catchment from the Pacific Ocean. Since the north eastern part of the catchment is only 20 km from the coast but the western side of the catchment is almost 70 km from the coast, the typical direction of storm movement results in a gradient of rainfall totals that reduce from east to west across the catchment in most rainfall events. The strength of the rainfall gradient is enhanced by orographic effects with the highest totals typically also occurring in the north eastern part of the catchment (see Figure 2).

The catchment average rainfall totals across the entire Stanley River catchment (to Somerset Dam) were computed for the highest bursts with durations of 6, 9, 12, 18, 24, 36, 48 and 72 hours for each of the 39 events in the Seqwater (2013) data set. The catchment totals for each burst duration, in each event were compared with IFD estimates to estimate the approximate AEP of each burst. This process resulted in the selection of 13 events, as listed in Table 1 that all had bursts of 12, 18 and 24 hours within them that all exceeded the 20% AEP design rainfall depth for the Stanley River catchment. Twelve of these events also exceeded the 20% AEP design rainfall depth for 6 and 9 hours and ten of these events also exceeded the 20% AEP design rainfall depth at 36 and 48 hours. The analysis in this paper was limited only to these 13 events as they were likely to be representative of space-time patterns of rainfall events for this catchment that could produce flood inflows to Somerset Dam if antecedent conditions in the catchment were sufficiently wet.

Spatial patterns were mapped for the selected 13 events for critical burst durations of 6, 9, 12, 18, 24, 36, 48 and 72 hours within each event. The rainfall depths for each subcatchment were normalised by dividing by the catchment average rainfall for the event and burst duration. There was remarkable similarity in the spatial patterns of rainfall between events, due to the orographic and moisture availability influences on rainfall across the catchment. The spatial pattern is appreciably different from a uniform spatial pattern, as shown in Figure 2(a), with rainfall depths up to 45% greater than the mean in the north-eastern part of the catchment and 35% less than the mean in the southern part. The 24 hour, 1% AEP design rainfall depths from the BOM (2013) IFD analysis were extracted at each of the subcatchment centroids. Figure 2(b) shows that these are an excellent predictor of the mean of the spatial patterns from the 13 observed events. Since the spatial patterns of different events demonstrate such consistency in the Stanley River catchment, either the mean spatial pattern from the 13 selected events or the pattern derived from the BOM IFD (2013) would provide a good surrogate for the spatial pattern in any individual large rainfall event for this catchment. It was therefore reasonable to adopt the BOM (2013) IFD analysis, 24 hour duration and 1% spatial pattern for design rainfall events in the Stanley River catchment.

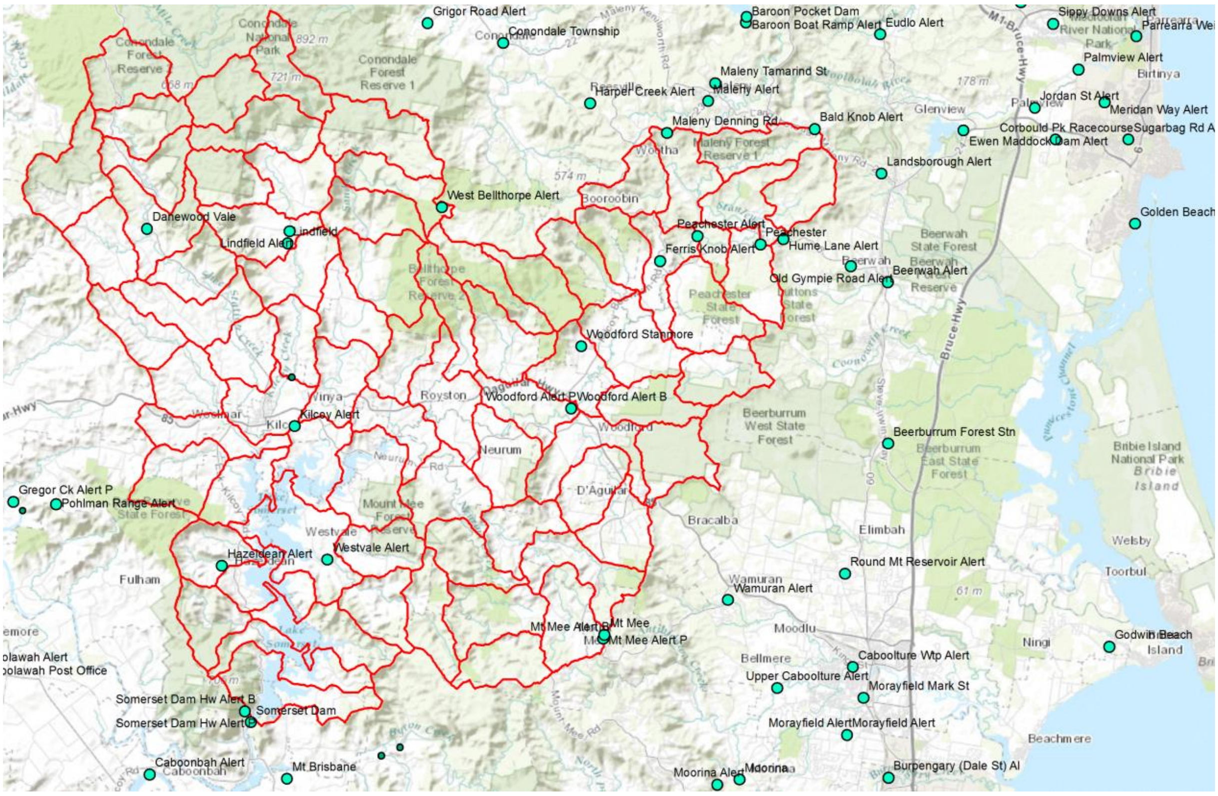

Figure 1 Map of the Stanley River catchment, showing the URBS and RORB model subcatchments and the locations of daily rainfall and pluviograph gauges

Table 1. Stanley River catchment rainfall events selected for analysis of space-time patterns

Event	**Rainfall Burst Depth (mm) for Duration (h)**			**Approximate Estimated AEP of Rainfall Burst for Duration (h)**		
	12	24	72	12	24	72
Mar 1955	182	258	338	2.4%	3.3%	8.3%
Jan 1968	118	196	336	14.2%	9.8%	8.5%
Feb 1972	138	183	263	8.1%	12.3%	18.1%
Jul 1973	137	232	335	8.2%	5.1%	8.6%
Jan 1974	186	258	470	2.1%	3.3%	2.4%
Jun 1983	133	173	193	9.3%	14.7%	38.5%
Early April 1989	188	216	298	2.0%	6.7%	12.5%
Late April 1989	129	168	265	10.4%	16.3%	17.8%
Dec 1991	176	240	259	2.8%	4.5%	19.1%
Mar 1992	143	205	256	7.0%	8.2%	19.7%
Feb 1999	157	268	403	4.7%	2.8%	4.4%
Jan 2011	176	243	491	2.8%	4.3%	2.0%
Jan 2013	166	244	347	3.7%	4.2%	7.6%

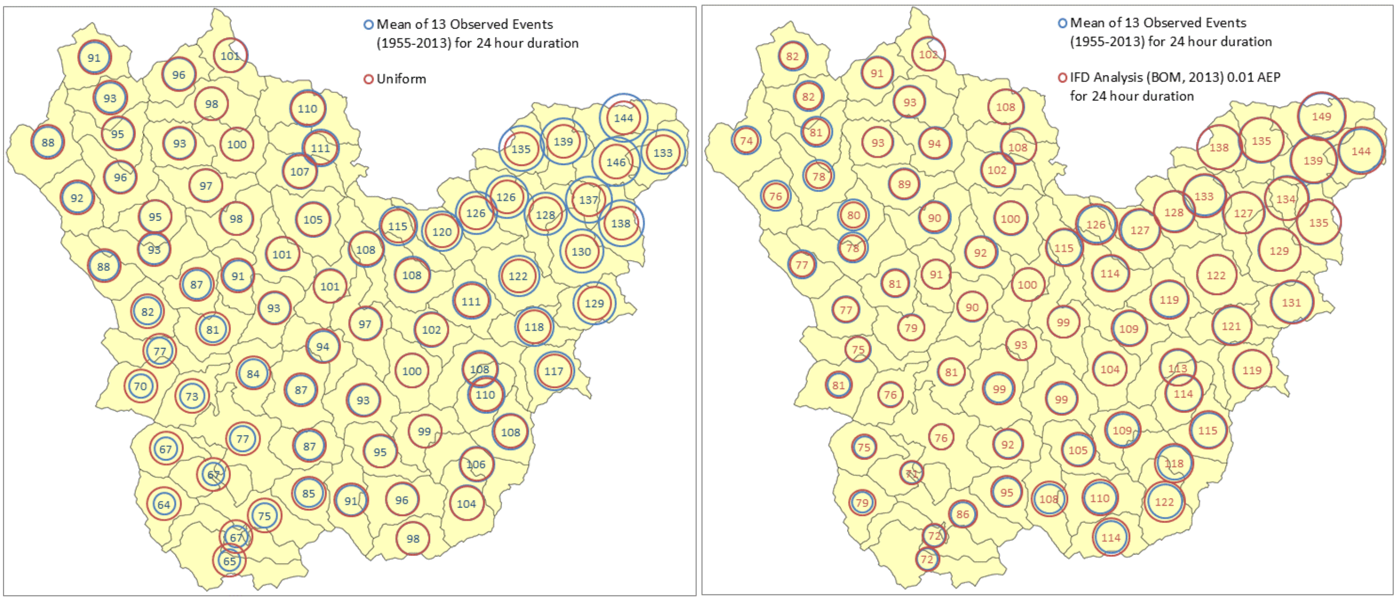

Figure 2 Comparison of rainfall spatial patterns across Stanley River catchment, comparing mean spatial pattern from 13 observed events with (a) uniform spatial pattern, (b) IFD analysis at centroid of each subcatchment from Bureau of Meteorology (2013) for 1% AEP and 24 hours. Depth for the subcatchment as a percentage of the catchment average depth is shown in the centre of each circle and the circle diameters were scaled in proportion to the rainfall depths.

4. APPLICATION OF SPATIAL PATTERNS OF DESIGN RAINFALL TO DESIGN FLOOD ESTIMATION FOR THE STANLEY RIVER CATCHMENT

4.1. Method

Design flood peak estimates were produced for the Stanley River at its outlet (inflow to Somerset Dam) using a RORB rainfall runoff routing model of the catchment. The catchment file for the RORB model was developed by converting the URBS model that was developed by Seqwater (2013), maintaining the same 76 subcatchment boundaries and the same stream reaches and effective lengths for stream routing.
Design peak flow estimates at Somerset Dam inflow were produced from a number of Monte-Carlo simulations that were implemented within RORB. There were a number of common elements to all of these simulations:

- all adopted the same catchment average design IFD information from BOM (2013) multiplied by the areal reduction factor for the applicable duration from Jordan et al. (2013);
- all were run using the stratified Monte-Carlo sampling scheme that is implemented within RORB;
- all were run for rainfall burst durations of 6, 9, 12, 18, 24, 36 and 48 hours, with the design peak flow defined by the highest flow from among these durations at each AEP;
- all simulations sampled from the same non-dimensional probability distribution of initial loss values defined by Hill et al. (2012) based on data derived by Illahee (2005), scaled by a median initial loss of 40 mm;
- all adopted a constant continuing loss rate of 1.7 mm/hour across all subcatchments;
- all adopted a RORB non-linearity parameter, m, value of 0.8;
- all simulations adopted RORB routing delay parameter, kc, values of 20 for the catchment upstream of Peachester, 20 for the catchment between Peachester and Woodford, 16 for the catchment upstream of Mount Kilcoy and 45 for the residual catchment to Somerset Dam inflow.

The Monte-Carlo simulations differed from one another in their approach to sampling of spatial, temporal and space-time patterns across the catchment, as shown in Table 2.

Table 2. RORB Model Cases Run

Case	Spatial Pattern(s)	Temporal Pattern(s)
1	Single uniform spatial pattern	Design spatial pattern for Zone 2 for average recurrence intervals of more than 30 years from *ARR1987*
2	Single uniform spatial pattern	Random sampling from a set of 13 temporal patterns for each duration, derived from the bursts of the corresponding duration within the 13 selected events listed in Table 1
3	Single spatial pattern derived from BOM (2013) IFD analysis, 24 hour duration and 1% spatial pattern	Random sampling from a set of 13 temporal patterns for each duration, derived from the bursts of the corresponding duration within the 13 selected events listed in Table 1
4	Random sampling from a set of 13 space-time patterns for each duration, derived from the bursts of the corresponding duration within the 13 selected events listed in Table 1	

Sinclair Knight Merz (2013) fitted a Generalised Extreme Value (GEV) distribution using L-Moments to the estimated annual maxima inflows to Somerset Dam over the period between 1955 and 2013. The estimated inflow flood peak for the 1893 flood of 6200 m^3/s was included as a censored flow in the analysis. The distribution fitted to the estimated observed inflows was used to test the performance of the RORB model simulations.

4.2. Results and Discussion

Figure 3 shows that Cases 2, 3 and 4 of the RORB model simulations all provide an excellent match to the fitted flood frequency quantiles across the range between 5% and 0.2% AEP. Design peak inflow floods to Somerset Dam were insensitive to whether a uniform or non-uniform spatial pattern was adopted as long as random sampling of temporal patterns is included in the Monte-Carlo simulation (Case 2 versus Case 3). Design peak inflow floods to Somerset Dam were also insensitive to whether space-time patterns are randomly sampled or only temporal patterns are randomly sampled in the Monte-Carlo simulation (Case 4 versus Case 3).

Figure 3 shows that Case 1 produces biased estimates of design peak inflow floods to Somerset Dam, with peak inflows underestimated by an average of 10% across the range between 5% and 0.2% AEP. This demonstrates the potential for a single temporal pattern to produce unrepresentative results for design flood estimation and the need for random sampling of temporal patterns at least to be included in design flood estimation.

The insensitivity in the peak flow estimates generated from the RORB model to the approach made to space-time patterns in the simulation for the Stanley River catchment was caused by the design rainfall depths exceeding the losses in all subcatchments in the model, regardless of the approach taken to space-time disaggregation. When the non-uniform spatial pattern or non-uniform space-time patterns (Cases 3 and 4) were applied to the design flood simulations, the drier subcatchments to the south and west of the catchment were still simulating runoff. The simulations that applied uniform spatial patterns (Cases 1 and 2) and hence redistributed the design rainfall from the north and east of the catchment to the south and west, modified where in the catchment that simulated runoff was generated but an average they made very little change to the total volume of runoff generated across the catchment as a whole. Consequently, there was little difference to the peak flow at the catchment outlet between the simulations for the design flood events.

Other catchments are likely to have initial and continuing losses that represent a larger proportion of design rainfall depths. In a catchment with higher relative losses, it is likely that there will be more difference in the design flood estimates introduced by adopting different approaches to space-time rainfall patterns for the design events.

It is straightforward with current computing approaches and catchment models, such as RORB, to incorporate spatial variability in design rainfall depths. It is therefore reasonable to adopt a spatial pattern for design rainfall simulation defined by the BOM (2013) IFD analysis for a similar duration to the estimated critical duration for the catchment upstream of the point of interest.

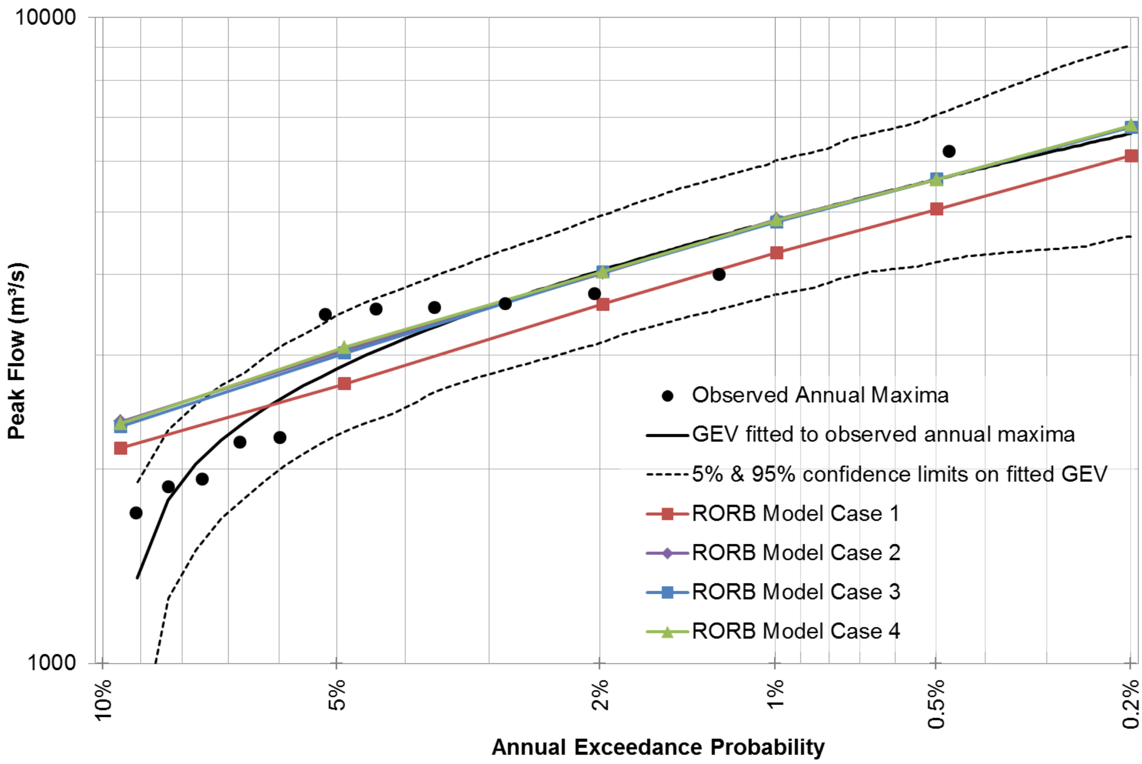

Figure 3 Flood frequency curves for Stanley River at Somerset Dam peak inflow derived from analysis of estimated annual maxima and from RORB model simulations

Flood inflows to Somerset Dam are generated from a rural catchment and are not appreciably affected by man-made infrastructure, such as large dams. Outflows from Somerset Dam, however, are controlled by releases from the flood gates on the dam. During flood events, outflows from Somerset Dam are managed in conjunction with outflows from the gated Wivenhoe Dam to mitigate flooding along the Brisbane River downstream of Wivenhoe whilst maintaining the safety of both dams. Space-time patterns of rainfall across the whole Brisbane River catchment have an important influence on gated flood releases from the dams and hence on design flood estimates downstream (Diermanse et al., 2014; Raymond, 2014; Jordan et al., 2014; Sinclair Knight Merz, 2013).

As a general principle, the approach that is selected to simulating spatial and space-time patterns of design rainfall is likely to appreciably influence design flood estimates in catchments that contain man-made infrastructure that modify flood behaviour such as dams and weirs.

5. CONCLUSIONS

A very high quality rainfall data set from a well instrumented catchment, the Stanley River catchment to Somerset Dam, was used to analyse the spatial and space-time patterns of rainfall at a catchment scale. Analysis of the 13 largest rainfall events across the catchment observed between 1955 and 2013 revealed that there is a significant spatial gradient across the catchment and that the spatial gradient is relatively consistent between these 13 events, albeit that there is variability in the patterns between the 13 events. A spatial pattern of rainfall derived from the BOM (2013) IFD analysis was a very good surrogate to the mean of the spatial patterns from the 13 observed events.

Simulations of design floods at the catchment outlet were performed using stochastic simulations with a RORB model of the catchment. Design peak inflow floods to Somerset Dam were insensitive to whether a uniform or non-uniform spatial pattern was adopted as long as random sampling of temporal patterns is included in the Monte-Carlo simulation. Design peak inflow floods to Somerset Dam were also insensitive to whether space-time patterns are randomly sampled or only temporal patterns are randomly sampled in the Monte-Carlo simulation.

Although the results for design peak flows from this rural catchment demonstrated little sensitivity to the approach selected for simulation of space-time patterns, it is likely that space-time patterns would be a significant influence on design flood estimates for catchments that contain man-made

infrastructure that appreciably modify flows, such as dams, or in catchments that have losses that are a larger proportion of the design rainfall estimates.
It is straightforward with current computing approaches and catchment models, such as RORB, to incorporate spatial variability in design rainfall depths and it is therefore reasonable to adopt a spatial pattern for design rainfall simulation defined by the BOM (2013) IFD analysis for a similar duration to the estimated critical duration for the catchment upstream of the point of interest.

6. ACKNOWLEDGEMENTS

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