Storms, storm bursts and flood estimation: a need for review of the AR&R procedures *

Ted Rigby
Forbes Rigby Pty. Ltd., Wollongong NSW
Michael Boyd
School of Civil Mining & Environmental Engineering
University of Wollongong
Steven Roso
Forbes Rigby Pty. Ltd., Wollongong NSW
Rudy VanDrie
Balance Research & Development, Kiama NSW

SUMMARY: *The present recommendations of Australian Rainfall & Runoff (AR&R) for design flood estimation involve the estimation of a flood discharge of given ARI from a storm burst of comparable ARI, with minimal consideration of the impact of lead rainfall on burst response. While losses can be modified to reflect conditions likely at commencement of the design burst, pre-burst flow and storage are much more difficult to estimate and are mostly ignored when applying this procedure. This paper quantifies the likely magnitude of errors arising from omission of lead rainfall from the AR&R procedure. A design flood estimation procedure based on historic storms, rather than storm bursts, is recommended to address uncertainty in the AR&R procedure, and to more realistically simulate historic flooding. An Embedded Design Storm procedure is described meeting this need.*

1 INTRODUCTION

1.1 Background to the issues

Over the last three decades, the increasing availability, ease of use and power of computers to model complex processes, led to the development of a new generation of computer based rainfall-runoff models. These new models were more complex and capable than their manual predecessors and required more data to support this increased capability.

In 1977 and 1987, the National Code of Practice in Hydrology, Australian Rainfall and Runoff (AR&R) was revised, incorporating on each occasion substantially enhanced design IFD and burst temporal pattern data, in support of these more advanced models.

Over this period of change, the fundamental premise that a design discharge of given ARI could be simulated from an isolated 'critical duration' storm burst, of comparable ARI, received little attention.

This paper questions this key assumption and presents an alternative procedure for design flood estimation using computer based rainfall-runoff models, that overcomes the limitations of the present burst based procedure.

To illustrate the authors' concerns with the present AR&R procedure[1], the hyetograph of the August 1998 storm, recorded at Bulli Pass in Wollongong, is reproduced in Fig 1.

Catchments in this area have a critical duration of the order of two hours.

With the most intense two-hour burst occurring well into this event, it is readily apparent that considerable rainfall occurred prior to this burst.

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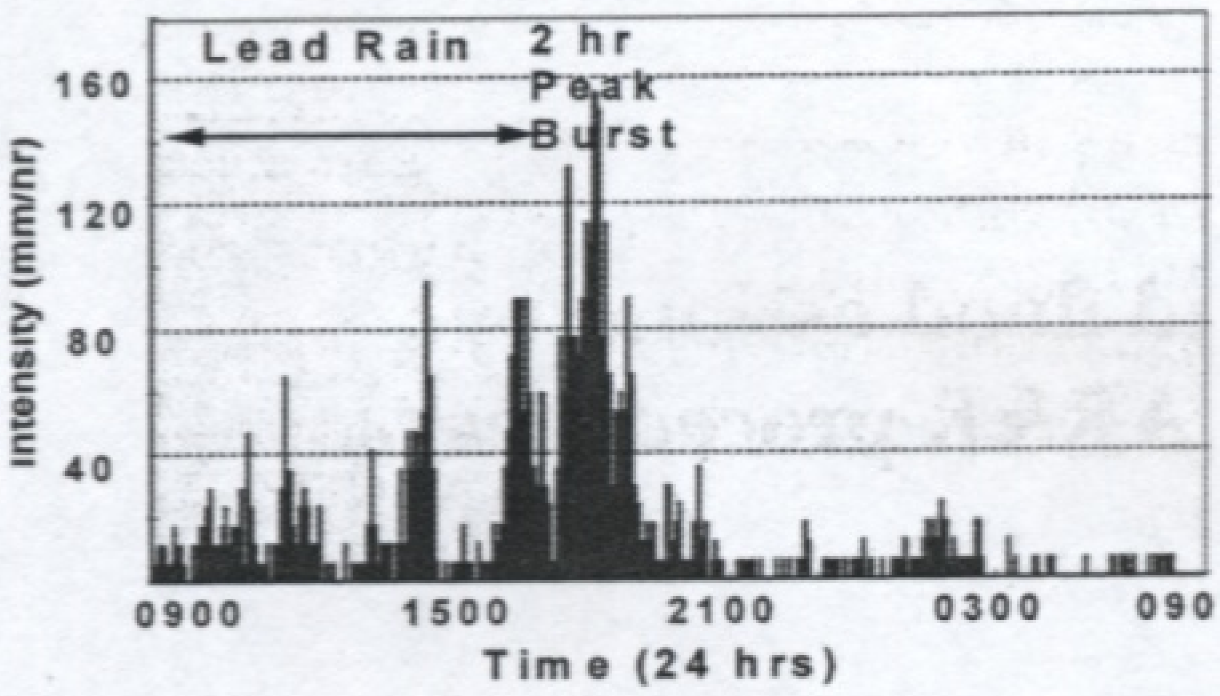

Figure 1: Storm Hyetograph Bulli pass August 1998.

It is equally apparent that at the commencement of this burst, lead rainfall would have generated significant surface and stream flows, together with flood storage on the surface, in streams and in the several basins present in these catchments.

In this event, catchment conditions antecedent to the critical duration burst, clearly have the potential to influence the magnitude of the subsequent runoff peak. It is clearly unreasonable to assume that an isolated rainfall burst, extracted from an historic storm, will always be able to reliably simulate the flow peak generated by the parent storm, without recognition of catchment conditions antecedent to the extracted burst.

While the profession has for some time recognised the need to consider antecedent catchment conditions when applying the AR&R design burst based procedure, only losses are routinely adjusted to reflect the omission of lead rainfall in this procedure.

Some advanced, joint probability based strategies have been developed for initial storage levels in larger basins. In general use however, the AR&R procedure is applied without knowledge of, or adjustment for, likely pre-burst flow and/or storage conditions.

In addition to peak flow estimation concerns, the burst based design flood hydrograph often has a considerably shorter duration than the flood hydrograph of historic storms, from which the design burst was initially derived. This has significant implications for modeling, in areas such as scour and sediment transport and in flood evacuation planning, where the duration of flow, land inundation and overtopping of structures are important considerations.

Phillips, Lees and Lynch[2] concluded that failure of the AR&R design storm burst procedure to adequately reflect conditions antecedent to the design burst, led to an under-prediction of the 100Yr ARI flood surface in the Parramatta River by up to 500mm. An 'Embedded Design Storm' approach was recommended to address this under-prediction.

Rigby and Bannigan[3] presented a critical review of the AR&R'87 design flood estimation procedure, demonstrating on a limited dataset that failure to allow for antecedent conditions prior to a design burst can lead to an underestimation of peak discharge by up to 40%. They also recommended the adoption of an 'Embedded Design Storm' procedure to overcome the potential for under-estimation of peak flows, inherent in the AR&R'87 design burst based procedure.

This present paper extends the earlier work by Rigby and Bannigan[2], identifying and quantifying the conditions under which the AR&R procedure is likely to under-predict peak discharges. The paper also provides guidance on the selection of 'Embedded Design Storm' envelope ARI and duration, and demonstrates the ability of this procedure to closely simulate peak discharges from a disparate range of catchments, across a wide range of ARIs and durations.

2 HISTORIC STORMS – RAINFALL

2.1 Introduction

For large catchments, with AR&R critical design burst durations approaching the duration of historic storms, typical flows and/or flood storage antecedent to the design burst would be minimal, with in turn, minimal impact on peak discharge. Flood volume and duration related modelling, using the AR&R procedure would, in such circumstances, be similar to that occurring in historic storms.

For many catchments however, where AR&R critical burst durations are much shorter than the duration of historic storms[4], conditions antecedent to the burst have the potential to significantly impact both the subsequent flow peak and flood volume. Duration related estimates may also differ significantly from those associated with historic storms in the region.

Wollongong is one area in which typical flood producing storms are of much longer duration than the critical duration of catchments in the area. Given the authors' familiarity with the area and range of available data, this area was chosen to explore these issues further.

2.2 Study storms

Over the last 30 years, Wollongong has been subjected to almost annual minor flooding in some part of the city and several quite severe storms have generated major storm and flood damages.

Since the focus of this study was in respect to storms generating significant flooding, only those storms that generated significant flooding over the last 30 years were however included in the study dataset.

Where available, three gauges near the areas of heaviest flooding were selected to represent each storm. An overview of storms included in this study is set out in Table 1. 'Ds' is the total storm depth (mm) and 'Dura' is the storm duration (hours).

Table 1
Study storms - overview.

ID	Date	Spatial Extents	Gauge Location	Ds(mm	Dura(hrs)
75a	*10-03-75*	Widespread over most	Mt Keira	714	48.0
75b		Wgong & Shellharbour	Pt Kembla	452	30.0
83a	*14-10-83*	Heavy rainfall restricted	Unanderra	269	14.3
83b		to northern suburbs	Wgong Univ	172	9.2
83c			Mt Keira	291	12.5
84a	*17-02-84*	Heavy rainfall restricted	Wongawilli	795	24.0
84b		to southern suburbs	Calderwood	563	23.3
84c			Avondale	715	24.3
88a	*29-04-88*	Heavy rainfall restricted	Bulli Pass	367	53.8
88b		to northern suburbs	Wombarra	378	42.0
88c			Helensburgh	770	60.0
91a	*06-06-91*	Heavy rainfall restricted	Dombarton	686	126.0
91b		to southern suburbs	Wongawilli	712	126.0
91c			Nth Macquarie	852	125.0
98a	*17-08-98*	Heavy rainfall restricted	Corrimal STP	317	23.7
98b		to northern suburbs	Bulli Pass	403	19.7
98c			Rixons Pass	433	20.0

2.3 Storm characteristics

For each of the tabulated storms, a range of characteristic values was extracted and is summarized in Table 2. 'Tp/Dura' is the relative time to peak and 'Dp/Ds' is the proportion of rain falling prior to the peak. The ARI of bursts, for various durations are also tabulated providing an indication of the IFD characteristic of each storm.

Table 2
Study storms - characteristics.

ID	Tp/Dura	Dp/Ds	ARI 1	ARI 2	ARI 12	ARI 24	A12/A2
75a	0.50	0.49	20	40	100	100	2.5
75b	0.87	0.78	15	12	35	100	2.9
83a	0.91	0.82	3	4	30	30	7.5
83b	0.51	0.51	1	2	5		2.5
83c	0.83	0.76	1	2	5		2.5
84a	0.47	0.38	200	600	2000	1000	3.3
84b	0.51	0.52	10	30	500	200	16.7
84c	0.48	0.38	40	350	800	500	2.3
88a	0.72	0.49	5	5	7	5	1.4
88b	0.87	0.58	10	20	20	10	1.0
88c	0.73	0.48	15	50	500	400	10.0
91a	0.80	0.73	1	1	5	7	5.0
91b	0.80	0.79	1	1	7	10	7.0
91c	0.79	0.74	1	2	10	20	5.0
98a	0.46	0.72	25	10	20	15	2.0
98b	0.51	0.65	50	90	100	50	1.1
98c	0.50	0.60	100	180	100	50	0.6
99a	0.98	0.87	50	20	5	4	0.3

2.4 Observations

Key observations in respect to historic storms in this region are;

a) All historic flood producing storms investigated are of much longer duration than the AR&R critical design burst durations applicable to catchments in the area. Excluding the atypical storm of June'91, the average storm duration tabulated is of the order of 28 hours.

b) On average, rainfall peaks occurred about two thirds of the way into the storm with about two thirds of the rain falling prior to the peak.

c) For critical design burst durations in the region (typically 0.5 to 4hr), considerable rain would have fallen in each historic storm before commencement of the critical duration burst. Each of the tabulated catchments would therefore have had significant flow and/or surface storage present at the commencement of the critical duration burst.

d) On average, the IFD curves of historic flood producing storms show a slightly upward trend in ARI for bursts from 1 to 24 hours duration.

3 HISTORIC STORMS – RUNOFF

3.1 Introduction

A key assumption inherent in the ARR '87 burst based procedure for design flood estimation, is that lead rainfall, typically present in historic storms prior to a burst of critical duration, is not significant in its impact on peak discharge.

To test this key assumption, a series of bursts of various durations, containing the rainfall peak, were extracted from historic storms and applied to a range of local catchments. The resulting flow estimates were then compared.

3.2 Study catchments

A spread of local catchments were selected, ranging from the relatively small, urbanized and steep, Thomas Gibson Creek in the northern suburbs of Wollongong, to Macquarie Rivulet, a relatively large and for the most part undeveloped catchment to the south.

Details of these catchments are presented in Tables 3 and 4. 'CDura' is the AR&R critical duration (minutes) and 'Lag' is the time between peak of rainfall and runoff (minutes). While the ratio of CDura to Lag is impacted in this area by the dominance of the two-hour temporal pattern, low ratios are generally indicative of catchments with high levels of dynamic storage.

Table 3
Catchments – overview.

ID	Name	Location	Type
TGC	Thomas Gibson Ck	Northern Wgong	Mixed FCR
HEC	Hewitts Ck	Northern Wgong	Mixed F&R
SLC	Slacky Ck	Northern Wgong	Mixed FCR
RAG	Raths Gully	Northern Wgong	Mixed FMR
CTC	Cabbage Tree Ck	Central Wgong	Mixed FCR
AMC	American Ck	Central Wgong	Mixed F&R
MQR	Macquarie Rivulet	Shellharbour	Mixed F&P
HOC	Horsely Ck	Shellharbour	Mostly R
LLK	Little Lake	Shellharbour	Mostly R&C
Type	F - Forested	R - Residential	I - Industrial
	P - Pasture	C - Commercial	M - Mining

Table 4
Catchments – characteristics.

ID	A(km2)	%Imp	L(km	Sm/km	Lag	Cdura	Cd/Lag
TGC	0.86	24	1.6	38.0	13	120	9.6
HEC	3.77	14	3.2	64.1	28	120	4.4
SLC	2.78	11	4.6	69.4	48	120	2.5
RAG	0.91	2	2.0	141.0	55	120	2.2
CTC	12.76	29	4.6	49.0	20	120	6.0
AMC	26.88	13	10.6	19.7	83	360	4.3
MQR	105.6	1	15.0	16.5	128	540	4.2
HOC	9.4	13	3.5	25.0	33	120	3.7
LLK	10.69	19	6.1	4.0	78	120	1.5

3.3 Burst –v– Storm runoff

Storm bursts were extracted from a representative range of historic storms, ranging in duration from a fraction of the catchment lag to several times that lag. These bursts were then input to regionally calibrated hydrologic models of each catchment and the resulting runoff peaks compared. The parent storm was modeled with 15 mm initial loss and 2.5 mm/hr continuing loss (as recommended in AR&R). The extracted bursts were modeled with zero initial loss and 2.5mm/hr continuing loss.

The ratio of burst peak flow to storm peak flow for each extracted burst is shown plotted against the relative burst duration (ratio of burst duration to catchment lag) in Fig 2.

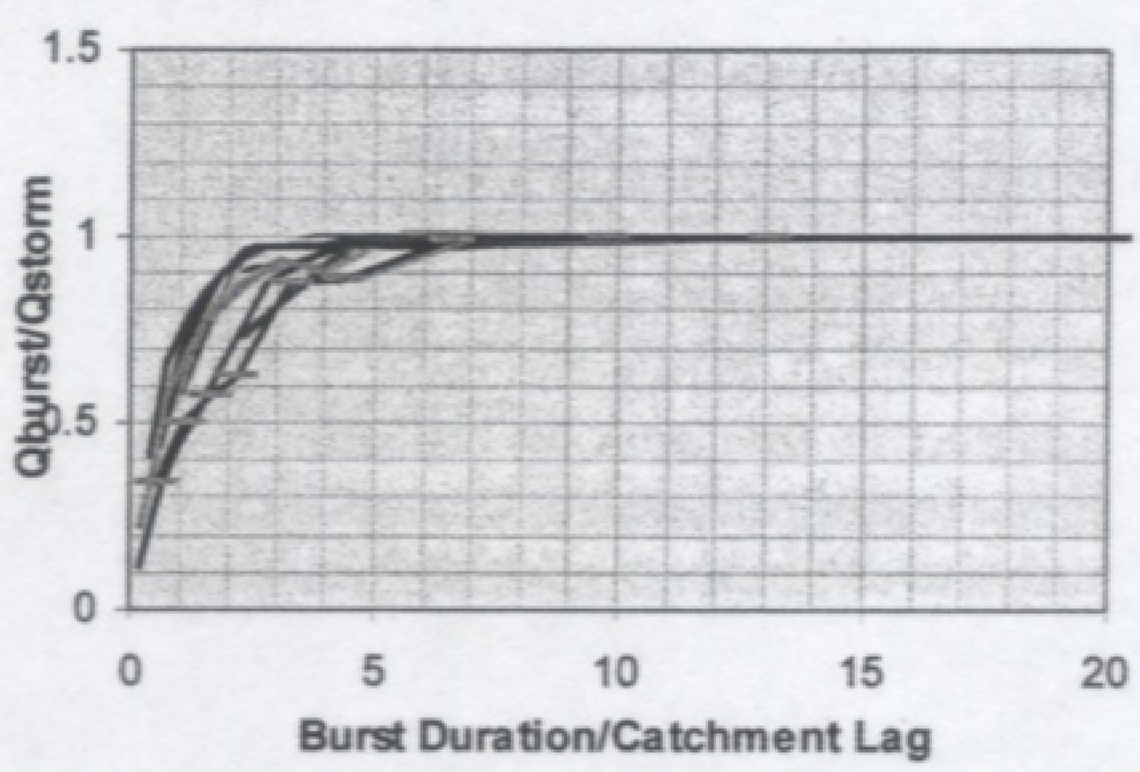

Figure 2: Burst Flow Ratio -v- Relative Burst Duration.

3.4 Observations

With respect to the significance of typical pre-burst rainfall on peak flows, it is apparent from the above that;

a) Extracted bursts with durations greater than about six times the catchment lag, produce peak discharges typically within 5% of the parent storm's peak flow.

b) When extracted burst durations fall below about six catchment lags, the burst peak flow begins to under-estimate the parent storm's peak flow.

c) When the extracted burst duration falls to about two catchment lags, burst peak flows can lie anywhere between 60% and 95% of the parent storm's peak flow. At this short relative duration, lack of recognition of pre-burst flow and storage can be highly significant.

d) On the basis of the above, it is not reasonable to expect a burst-based procedure to be able to reliably reproduce the peak discharge of a parent storm, once the burst duration falls below about six catchment lags.

4 THE AR&R'87 DESIGN FLOOD ESTIMATION PROCEDURE

4.1 Procedure outline

Since the AR&R design flood estimation procedure will be familiar to most of the intended audience of this paper, it is not reproduced in this paper. An overview of this procedure is presented in Rigby & Bannigan[3] and the procedure is described in full in Volume 1 of Australian Rainfall & Runoff.[1]

5 AR&R DESIGN –V- HISTORIC STORM DISCHARGES

5.1 Comparative discharges

As previously noted, a key assumption of the AR&R procedure is that it can provide realistic estimates of peak flow from an isolated rainfall burst without the need to consider flow and/or storage conditions antecedent to the burst. If this is correct, the AR&R procedure should be able, on average, to simulate the peak discharges from historic storms when applied with an equivalent average intensity design burst.

To explore this assumption, the AR&R critical durations for each of the study catchments were calculated (table 4 column 7). The average intensity of the most intense burst of this duration was then extracted from each historic storm and used with the standard AR&R temporal patterns to estimate the peak burst discharge (Qarr in Fig 3 below). Losses were as previously noted for bursts. Fig 3 shows the average of the AR&R estimated peak flow, divided by the peak flow for the historic storm on each catchment. This averaged flow ratio is plotted against the ratio of critical duration to catchment lag.

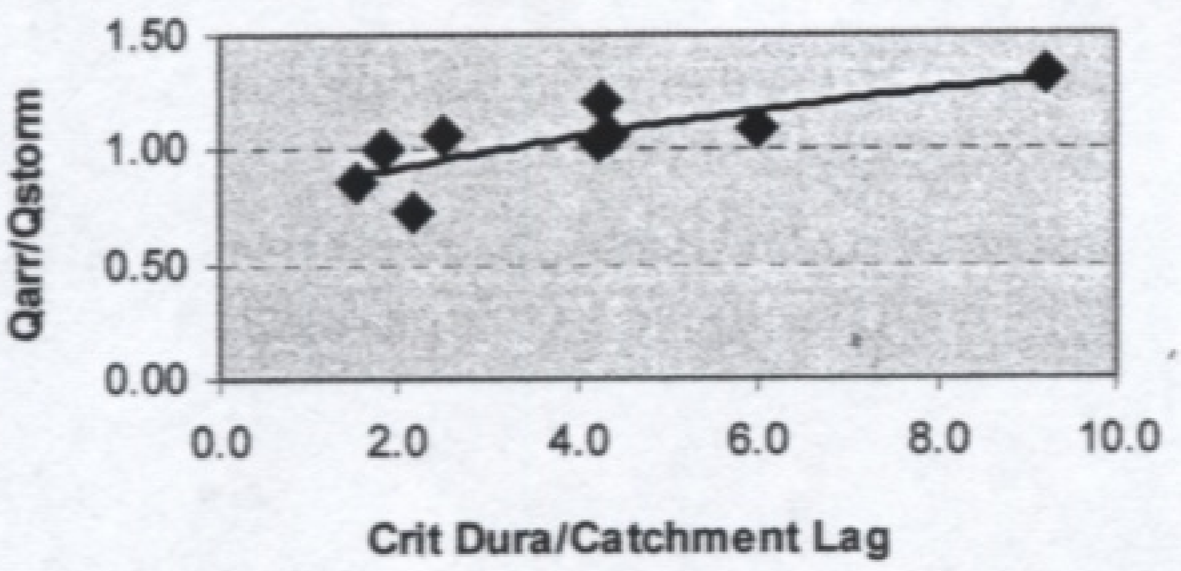

Figure 3: Qarr/ Qstorm-v-Relative Duration.

Variations in historic storm burst temporal patterns, from the standard patterns presented in AR&R, can create differences in peak discharge estimates from bursts of the same average intensity. In the storms studied, these variations were often significant and the AR&R flow estimates were therefore re-calculated, based on the historic storm patterns, so that peak flows could be compared with flow estimates from individual historic storms without being influenced by pattern differences.

Using this approach, peak discharges from the burst based procedure, using the historic storm's temporal patterns, (Q*arr in Fig 4) are compared with those of the historic storm. In Fig 4, the average of these flow ratios for each catchment is plotted against relative rainfall duration. Differences in peak flow ratios from those of Fig 3 are solely due to differences in burst temporal patterns. The resulting plot is a direct indication of the AR&R procedure's ability to simulate the peak discharge of individual historic storms and indirectly a reflection of the procedure's ability to simulate flooding of a specified ARI.

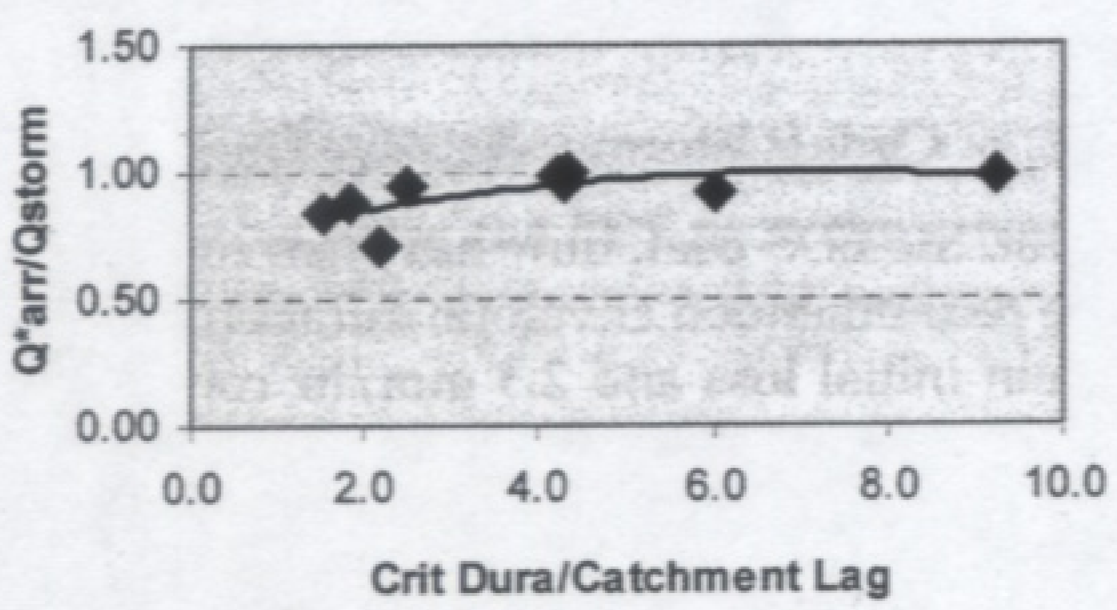

Figure 4: Q*arr/Qstorm-v-Relative Duration.

5.2 Observations

a) If the AR&R storm burst patterns are a good representation of 'patterns of average variability' in the Illawarra, then the average over many storms of the ratios presented in Fig 3 should be one. The average of the rather limited dataset used in this study suggest a value somewhat greater than one, implying that the standard patterns may be a little too severe for this region. Further consideration is not within the scope of this paper but this result does appear worthy of further investigation.

b) The flow ratios of Fig 3 show a clear upward trend as the burst relative duration increases.

c) As evident in Fig 4, when the historic storm pattern is used in the burst based procedure, much of the upward trend evident in Fig 3 is eliminated, but the tendency for the flow ratios of the shorter relative duration catchments to drop below one is maintained.

d) Fig 4 reinforces earlier observations in respect to the potential for under-prediction of peak flows from a burst-based procedure, when the burst duration is less than about six catchment lags.

6 THE EMBEDDED DESIGN STORM (EDS) PROCEDURE

6.1 Development background

The fundamental objective of the embedded design storm (EDS) procedure is to recreate a design storm that;

a) Contains a rainfall burst of duration that is critical to the catchment and of the appropriate intensity and pattern for the selected ARI.

b) Embeds the critical duration burst in an envelope of average pattern variability and average intensity appropriate to an envelope ARI typically occurring, in conjunction with the specified burst ARI, in flood producing storms in an area.

c) Embeds the critical duration burst in an envelope of sufficient duration to have reduced the potential impact of lead rainfall on flow peaks to a minimal level.

d) Embeds the critical duration burst in an envelope of duration comparable to that of flood producing storms in the area, such that the resulting hydrograph reflects the typical duration of flooding experienced.

In this procedure, no change is proposed to the use of the present AR&R design IFD data or design storm burst temporal patterns. The EDS procedure simply extends the use of this data to the creation of an envelope of the appropriate pattern and average intensity for the selected envelope duration and ARI.

In forming the composite design storm, the critical burst is embedded in the envelope such that the peaks of both patterns coincide. Since embedment of the burst will slightly increase the overall storm's average intensity, it is necessary to scale down the envelope intensities so that both the critical burst average intensity and overall design storm average intensities remain appropriate to their durations and ARIs.

To check the impact of envelope duration on simulated peak discharge, the EDS peak discharge for envelopes of various durations was computed and compared to the peak discharge for an envelope with the EDS recommended duration (24 hours for the study region). The resulting flow ratio is plotted in Fig 5 against the relative envelope duration (ratio of envelope duration to catchment lag).

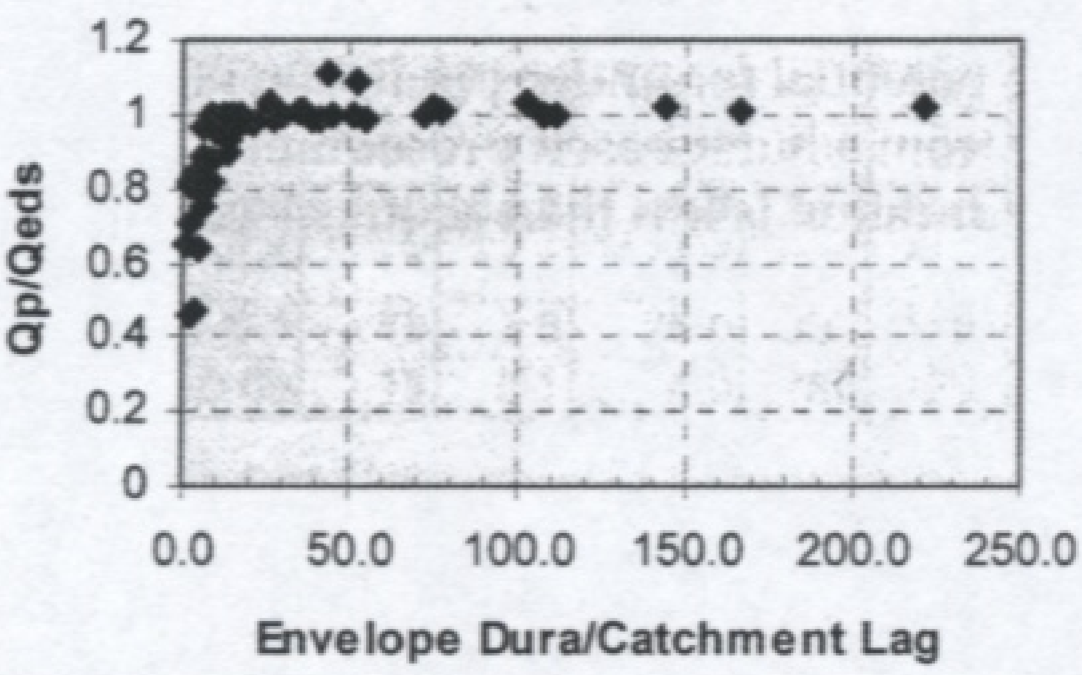

Figure 5: Qp/Qeds-v-Relative Duration.

As indicated in Fig 5, peak flows are not particularly sensitive to the envelope duration chosen, provided it is greater than about ten catchment lags.

As catchment size and lag increases, factoring the catchment lag to obtain minimum envelope duration would eventually lead to an envelope extending beyond the duration of typical flood producing rains in an area. Since it is an important objective of the EDS procedure that it should simulate a typical storm and, noting that the EDS procedure is insensitive to increasing envelope duration, the EDS procedure has adopted the average duration of flood producing storms in the region for the recommended EDS envelope duration.

In very large catchments, where critical burst durations actually exceed typical storm durations in the area, the EDS envelope would need to be extended to match the duration of the critical duration burst. In such circumstances there would be no rainfall typically present prior to the critical duration burst, and the AR&R procedure and EDS procedure would produce identical results.

With respect to the ARI of the EDS envelope, Table 2 shows that the ARIs of the 12 and 24hr bursts, in typical flood producing rainfall in the study area, are typically as high as or higher than the 1 or 2 hour burst ARIs. On this basis it is the current recommendation that both the burst and envelope ARI be set equal to the target flood ARI, in this region.

6.2 The EDS procedure

In summary, the recommended EDS design flood estimation procedure involves;

- Selection of a target flood ARI
- Selection of an envelope duration for the EDS equal to the average duration of flood producing storms in the area.
- Construction of a spectrum of composite EDS storms with the above envelope duration and a range of embedded burst durations. Burst and storm average intensities being those of the target ARI and site, selected from AR&R, with the burst and envelope temporal patterns also selected from AR&R.
- Construction and application of a hydrologic model of the catchment, for the above storm spectrum, to establish the 'critical' burst duration for the catchment (the burst duration producing the maximum peak discharge).
- Adoption of this maximized peak flow as the design flood discharge of the target ARI.

6.3 Comparative discharges

A comparison of peak discharge from the EDS procedure with that of historic storms on each catchment is presented in Fig 6.

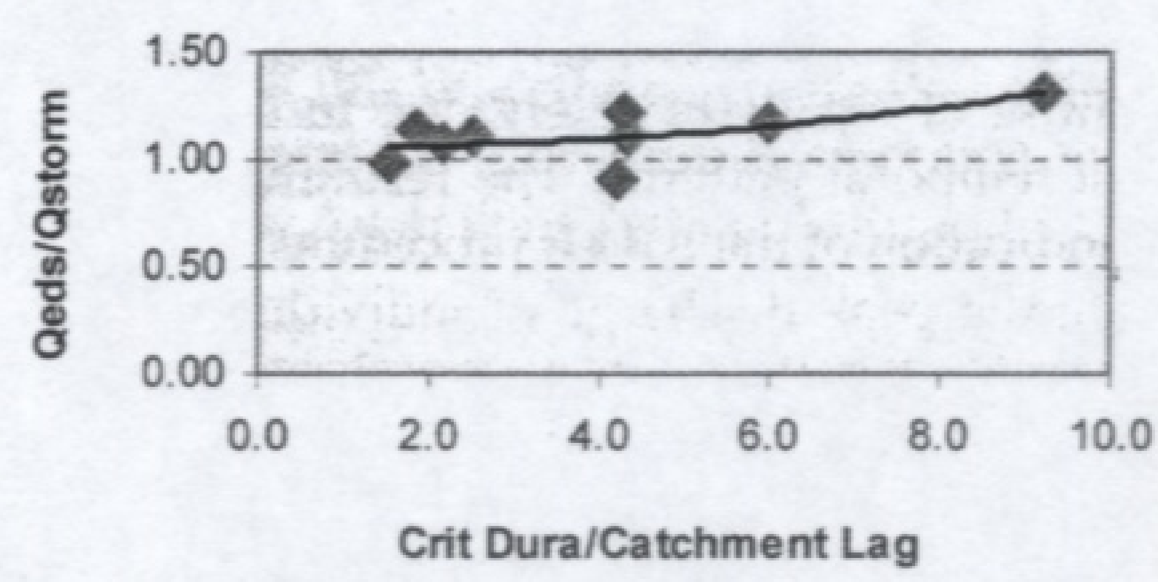

Figure 6: Qeds/Qstorm-v-Relative Duration.

In this plot, the EDS peak flow has been computed using the recommended envelope duration of 24hr, with 15mm initial loss and 2.5 mm/hr continuing loss. The ARI of a burst of critical duration, extracted from each historic storm at the nominated gauge, was used for both the EDS burst and envelope ARIs. This flow estimate has then been divided by the historic storm discharge, averaged for each catchment and plotted against the relative design storm duration.

To quantify the impact of temporal pattern differences on the EDS peak discharge, the EDS discharge was also computed using the historic burst temporal pattern and standard AR&R envelope pattern (Q*eds in Fig 7). Differences between the discharge ratios of

Figs 6 & 7 are then solely due to differences in the burst temporal patterns. In Fig 7, the resulting plot is a direct indication of the EDS procedure's ability to simulate the peak discharge of individual historic storms and indirectly a reflection of the procedure's ability to simulate flooding of a specified ARI.

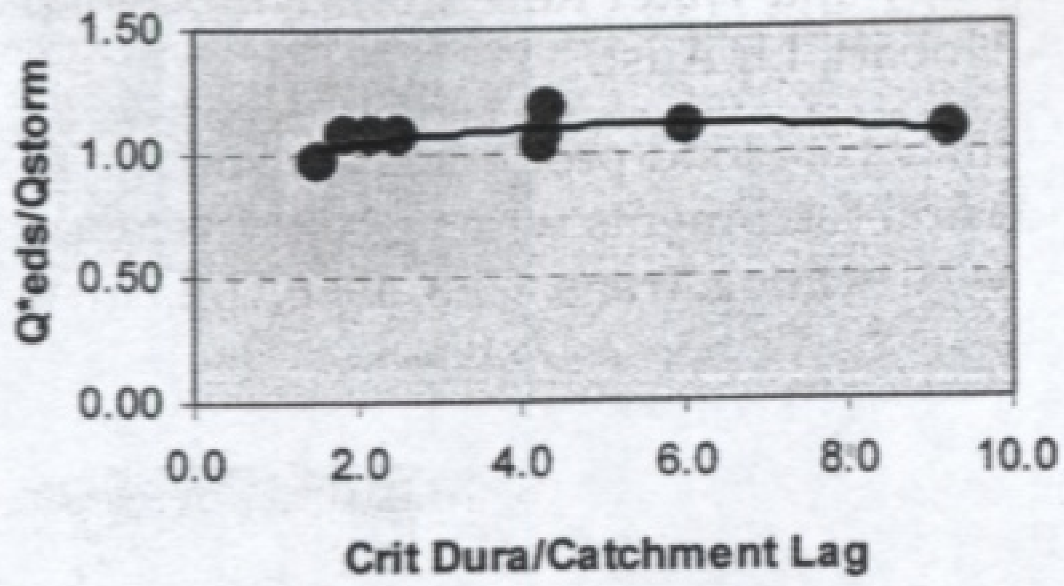

Figure 7: Q*eds/Qstorm-V-Relative Duration.

6.4 Observations

a) As observed in relation to the AR&R flow estimates, the average of the EDS peak flow ratios graphed in Fig 6 also lie slightly above one, reinforcing the need for further investigation into the AR&R temporal pattern's ability to produce runoff of the target ARI in the study area.

b) A weaker upward trend in flow ratios with relative duration is also present in Fig 6.

c) Notwithstanding questions raised regarding the appropriateness of the AR&R temporal patterns in the study area, Fig 7 clearly demonstrates the ability of the EDS procedure to closely simulate peak discharges from historic storms and within the limitations of the AR&R IFD and temporal data, to closely simulate design flows of a specified ARI.

7 CONCLUSIONS

Based on the preceding analysis and the author's experiences using the EDS procedure, we conclude that;

7.1 In circumstances where a catchment's critical duration is much less than the duration of typical flood producing storms in that area, and a catchment's critical burst duration is less than about six catchment lags, then the AR&R'87 design flood estimation procedure will begin to underestimate peak flows. For catchments with a critical duration less than about two catchment lags, this under-estimation can be very significant.

7.2 While the AR&R burst based procedure has served the profession well for several decades, uncertainty as to the accuracy of peak flow estimates in some circumstances and the inability of the procedure to reliably emulate historic flooding, raises the need for a storm based approach to future design flood estimation.

7.3 The EDS procedure is one such storm based procedure, which 'warms up' a catchment in a logically derived manner, eliminating for the most part, potential errors introduced by the AR&R design procedure's lack of recognition of the influence of lead rainfall on burst response.

7.4 The EDS procedure generates a hydrograph with a duration similar to that associated with historic storms, permitting more realistic estimates of periods of overtopping or inundation than those obtained from the AR&R'87 burst based procedure.

7.5 The EDS procedure described in this paper requires no additional data, being built from existing AR&R IFD and temporal pattern data.

7.6 The EDS procedure is relatively easy to incorporate into existing Australian hydrologic models. It has been included in the Watershed Bounded Network Model (WBNM) since 1996.

8 RECOMMENDATIONS

It is the authors' recommendation that;

8.1 All peak flow estimates for catchments with critical burst durations less than six catchment lags be undertaken with a storm based design procedure such as that provided by the EDS procedure described in this paper.

8.2 Any flood simulation that is to form the basis for advice on the duration of flood inundation or overtopping, during a design flood of a specified ARI, be undertaken with a storm based design procedure such as that provided by the EDS procedure.

8.3 A working group be established to review the present AR&R design flood estimation procedure, as a matter of some urgency, with a view to replacing the present burst based procedure with a storm based approach to design flood estimation.

8.4 The EDS procedure be tested beyond Wollongong to establish its validity on a national scale.

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TED RIGBY
Director, Forbes Rigby Pty. Ltd., Consulting Engineers, Wollongong NSW
Ted Rigby graduated from the University of Tasmania in 1967, completing his Master of Engineering Science at the University of NSW in 1970. After working for a range of private and governmental organisations he commenced practice in Wollongong in 1971. Serious local flooding in 1973, 1974 and 1975 triggered his interest in hydrology and flood hydraulics leading to his present interest and specialisation in these fields.

MICHAEL BOYD
Assoc Professor Faculty of Engineering University of Wollongong
Michael graduated in civil engineering from the University of New South Wales in 1977, and subsequently went to the University of Wollongong, where he is currently associate professor in the Faculty of Engineering.

His research interest are flood hydrology, urban stormwater management, and water resources, and he has published more than 70 papers in these areas. His research into flood hydrograph modeling, flood frequency analysis, flood detention basin design, and culvert hydraulics is referenced in the Institution of Engineers Australia Guide to Flood Estimation, Australian Rainfall and Runoff (1987, 1999).

STEVEN ROSO
Design Engineer, Forbes Rigby Pty. Ltd., Consulting Engineers, Wollongong NSW

RUDY VANDRIE
Director, Balance Research & Development, Kiama NSW