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The Impact of Embedded Design Storms on Flows Within a Catchment

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Abstract: Previous investigations into design flood estimation, found that the AR&R burst based procedure can under-predict discharges at a catchment's outlet, relative to those obtained from an embedded design storm (EDS) approach. This under-prediction was quite significant in some catchments (up to 40%), causing concern as to the ability of the present AR&R burst based procedure to adequately simulate design discharges from 'storage sensitive' catchments. Application of the EDS procedure in recent studies further suggested that the AR&R burst based procedure could result in even greater levels of under-prediction at internal locations within a catchment. An investigation into these internal flows was therefore undertaken to quantify and better understand the differences between AR&R burst based discharges and EDS discharges within a catchment. This paper reports on the findings of this investigation. A series of catchments located in Wollongong, ranging in size from 0.5 km^2 to 105 km^2, were used to explore these impacts. All catchments were relatively complex partly urbanized catchments, with a number of storages and diversions present in each. WBNM was used to simulate the hydrologic response of each catchment. All catchments modelled with a burst responded with decreased internal discharges (relative to an EDS approach), at times less than half that of the EDS based discharge. In each catchment investigated, the difference between the EDS and AR&R discharges were much higher internally than at the outlet. This work reinforces, in the authors view, the inability of the AR&R burst based procedure to properly represent design flows in storage sensitive catchments, and their earlier conclusion that it is time to replace the present burst based procedure for design flood estimation with a storm based procedure, such as that provided by an embedded design storm.

Keywords: Embedded, Design, Storm, Flood, Estimation, Hydrology

1. INTRODUCTION

1.1 Embedded Design Storm Concept

The Embedded Design Storm (EDS) procedure proposed by Rigby and Bannigan [1996] is an enhancement of the traditional design flood estimation procedure described in Australian Rainfall & Runoff (AR&R), IEAust [2001].

In developing the 1987 AR&R burst based design flood estimation procedure, design storm bursts of various durations were extracted from a large body of recorded storm events. Their average intensities and temporal patterns were then analysed to provide the IFD and temporal patterns included in Volume 2 of AR&R.

When modelling a catchment in accordance with the current AR&R burst based procedure, a design hyetograph is constructed from a burst with duration equal to the catchment's critical duration. This burst based approach ignores the potential impact of antecedent rainfall on subsequent discharges, which may be significant when storages are present within a catchment. It was found by Rigby and Bannigan [1996] that these impacts become significant when the adopted duration of the design rainfall burst is less than about 4 to 6 times the catchment lag.

The EDS procedure involves the embedment of a critical duration AR&R design burst of a given Average Recurrence Interval (ARI), inside a second longer duration AR&R design storm envelope of the same ARI but duration equivalent to the average duration of local flood producing storms in the region. The burst is inlaid into the storm hyetograph using peak intensities to register the burst, replacing the storm intensities in this zone. Outside of this zone, the storm wings are scaled down such that the overall volume of the composite EDS storm is equivalent to the overall volume of the longer duration AR&R storm envelope.

Application of this procedure results in a composite Embedded Design Storm, reflecting the intensity and temporal characteristics of the original burst and the duration and volume characteristics of the typical flood producing storms from which the bursts were originally extracted.

This procedure is described graphically in Figure 1 below and is discussed in further detail by Rigby and Bannigan [1996] and Rigby et al [2003].

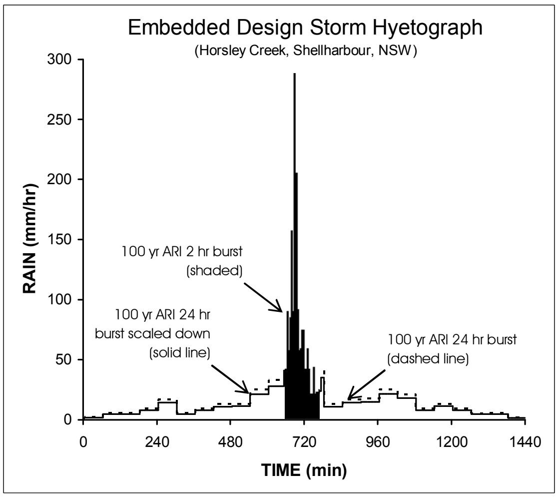

Figure 1: Embedded Design Storm Hyetograph

Since the EDS now reflects antecedent rainfall, initial design losses can be given realistic values for the catchment being considered, eliminating the need to use zero initial loss for design flood estimation when using short duration design rainfall bursts.

1.2 Previous Investigations

Previous investigations have been undertaken by the authors and others, establishing the need for an embedded design storm approach, and to provide guidance on application of the procedure. Papers of particular relevance to this subject include those by Phillips, Lees and Lynch [1994], Rigby and Bannigan [1996], Rigby et al [2003].

The general focus of these previous studies has been to quantify the potential for the AR&R design burst based procedure to under-predict peak discharge and therefore flood level at a catchments outlet relative to a ‘whole of storm’ based approach.

1.3 Current Concerns

Following recent hydrologic modelling of a rather complex partly urbanised catchment, it became apparent that these earlier (outlet based) investigations may not have fully identified the potential for under-prediction of discharges by the AR&R burst based procedure, at points internal to a catchment.

This paper explores this issue and presents the results of comparative modelling that demonstrates a potential for high levels of under-prediction by a burst based approach, at points internal to a catchment, under certain conditions.

2. STUDY CATCHMENTS

To explore these issues, six New South Wales catchments located in the Wollongong and Shellharbour Local Government Areas were modelled. These are: Horsley Ck (C1), Hewitts/Woodlands Ck (C2), Macquarie Rivulet (C3), Slacky Ck (C4), Thomas Gibson Ck (C5), and Tramway Ck (C6). Their physical and general hydrologic characteristics are summarised in Table 1 below. The six catchments modelled have varying levels of size, urbanisation, complexity and hydrologic response and therefore provide a sound basis for this investigation.

Table 1: Modelled Catchment Characteristics

	C1	C2	C3	C4	C5	C6
CArea (km^2)	9.2	3.8	105	2.8	0.8	0.5
%Urban	50	25	5	20	50	100
No. Subs	145	60	49	30	24	6
No. Basins *[a]*	26	2	6	3	1	1
No. Divs	18	1	0	0	4	2
Cd (min) *[b]*	120	120	540	120	120	120
Lag (min) *[c]*	39	27	139	46	9	33

[a] No. Basins incl’ explicitly modelled flood storages
[b] Critical Duration (Cd) computed for outlet
[c] Lag computed for 100yr ARI

Modelling of the above catchments was undertaken using the Watershed Bounded Network Model (WBNM) developed by Boyd, Rigby and VanDrie [2005]. Since 1994, this model has had the ability to directly generate and run a simulation using an EDS storm.

Each catchment was modelled using both an AR&R design burst and EDS approach. For the burst approach a loss model was applied using a 0 mm initial loss and 2.5 mm/hr continuing loss. For the EDS approach a 15 mm initial loss and 2.5 mm/hr continuing loss was applied. The critical burst duration for the catchment was derived in the conventional (AR&R) manner and this burst was then embedded in a storm envelope of 24 hour duration and equal ARI, as recommended by Rigby and Bannigan [1996], to create the EDS design storm.

All other model parameters for both burst and EDS approaches were comparable.

To explore the sensitivity to event ARI, these six models were run for the 5 year, 100 year and 500 year ARI events.

Figure 2 below shows the level of under-prediction of discharge by the burst based approach, at the outlet (expressed as the ratio of Qpeak-bust to Qpeak-EDS) plotted against the critical burst duration (Cdura)divided by lag for each catchment. Burst under-prediction is zero when the Qburst/Qeds ratio is one and becomes progressively more significant as this ratio falls below one.

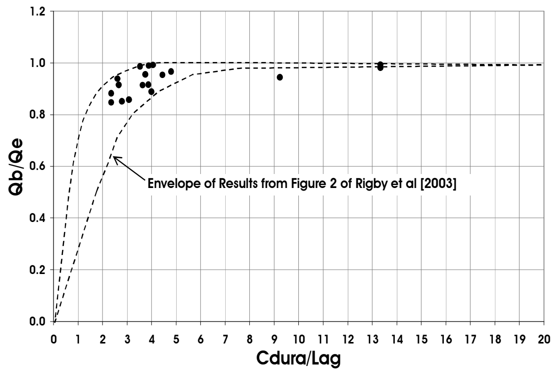

Figure 2: Qburst/Qeds vs Cdura/Lag at outlet

By way of comparison, the envelope of burst to parent storm responses modelled by Rigby *et al* [2003] is overlaid on these datasets. This new data again demonstrates the general trend for a reduced burst error as the ratio of critical duration to lag increases. As previously found by Rigby et al [2003], this under-prediction from a burst based approach is minimal once the ratio of Cdura/Lag becomes greater than about 6.

Of the catchments modelled, Thomas Gibson Creek has the highest ratio of Cdura/Lag of 13.3 for both the 100yr and 500yr events and also has one of the smallest burst errors Qburst/Qeds of 0.98. At the other extreme, Horsley Creek has a very low ratio of Cdura/Lag of 2.4 for the 5 year ARI event and has a correspondingly high level of under-prediction by the design burst approach of 0.85 (i.e implying 15% under-prediction of peak discharge by the AR&R design burst approach, at the catchment outlet).

3. EDS IMPACT INTERNALLY

The above analysis reinforces earlier observations on the potential for burst under-prediction at a catchment's outlet, but does not provide any quantification of flow behavioural changes that might occur at points internal to a catchment, when subject to an EDS storm.

It was the author's earlier view that the range of catchment sizes and configurations included in the earlier studies had provided a generalised view of the level of under-prediction possible, when using the AR&R burst based approach. Recent modelling of a relatively complex partly urbanised catchment with several storages and diversions made clear however, that the level of under prediction of internal flows can be much greater than is apparent at the catchment outlet.

Having considered possible reasons for this behaviour, it became clear that points internal to a catchment may vary considerably in Cdura/lag when compared to the value at the catchment outlet, since the mix of critical duration, storage and resulting lag can be quite different to that at the outlet. In addition, there is potential for the diversion of flow from a storage to be much less when subject to a design burst than when subject to a an EDS storm. Should this diversion be into a small head sub-catchment, the change in peak flow through that head sub-catchment can be extreme. By the time flows have however reached the catchment outlet, all internal diversions have recombined and considerable averaging of flow peaks from the various arms has also occurred. On the basis of the above, it is clear that the level of under-prediction of internal flows from an AR&R design burst should indeed vary considerably from that at the outlet.

To explore this impact further, peak flows in the three ARI events, at all nodes in the six models were extracted and are shown plotted in Figure 3.

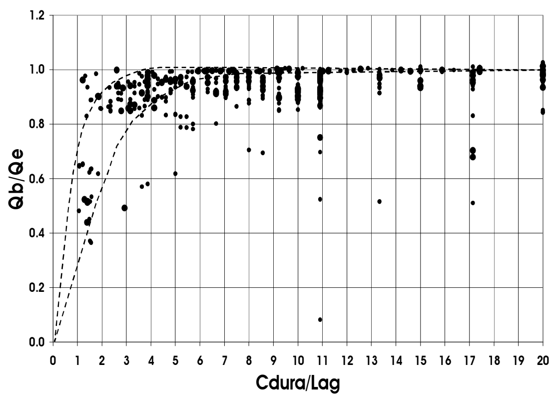

Figure 3: Qburst/Qeds vs Cdura/Lag all nodes (5yr, 100yr and 500yr ARI)

This is the same graph as that shown in Figure 2 but now has peak flow at all points in each catchment shown. The most apparent difference between the two graphs is the number of outliers now evident in Figure 3. This figure shows that there are some internal nodes where burst under-prediction is highly significant (as low as 0.1) despite a high ratio of Cdura/lag.

To better understand the various factors influencing the level of burst under-prediction, the Qburst/Qeds data shown in Figure 3 was replotted against the position of each node on its arm in the catchment. In Figure 4, each node's position in its catchment arm is represented by the ratio of each subarea node's Tributary Area (TA) to the overall Catchment Area at the outlet (CA). When approaching 1.0 the node is located well down the catchment and has a large tributary area draining through it. When small, it is a head catchment. While a head catchment is at the head of its local catchment arm. It may occur physically anywhere in the catchment.

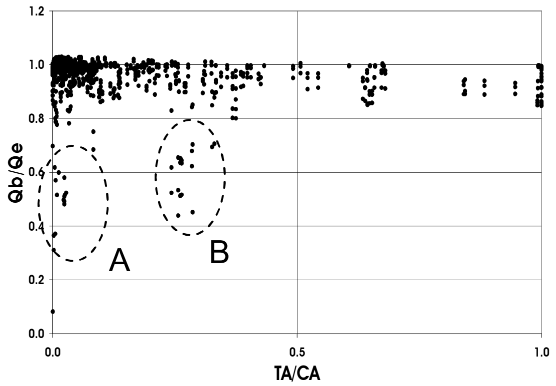

Figure 4: Qburst/Qeds versus Position in Catchment

As is apparent in Figure 4 the most significant levels of burst under-prediction tend to fall into two groups, some of those nodes near the head of their respective catchment arms (A) and a group of nodes part way down their respective catchment arms (B).

The following section explores the various factors influencing the pattern apparent in Figure 4 and makes some observations in respect to the identification of locations in other catchments that might be subject to significant under-prediction when modelled with the AR&R burst based procedure.

4. FACTORS INFLUENCING ERROR

Since the data plotted in Figure 4 is a composite of all ARI, the three ARI events have been separately identified in Figure 5 to explore any pattern linkages with ARI.

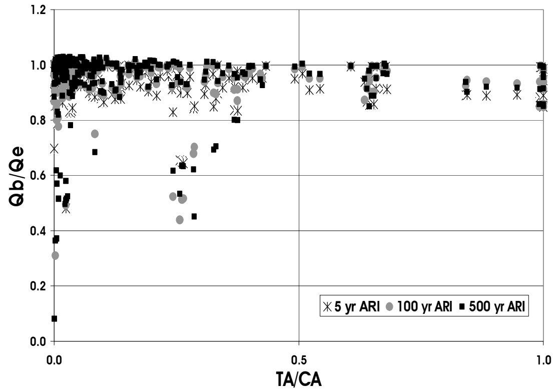

Figure 5: Qburst/Qeds versus Position in Catchment (highlighting event ARI)

As is apparent in Figure 5, there is no significant influence on the pattern of under-prediction from a 5 year ARI to 500 year ARI event, all ARI being present where Qburst/Qeds is less than 0.8.

Each catchment was then identified and the full dataset re-plotted in Figure 6.

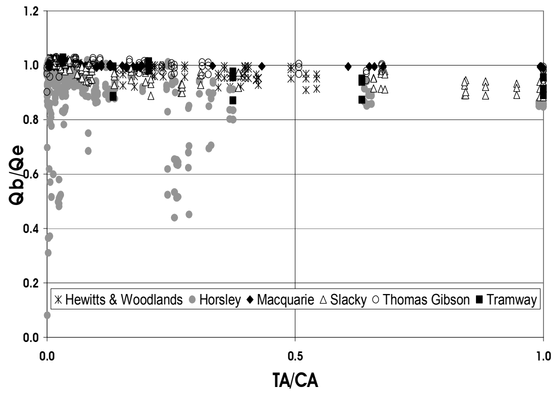

Figure 6: Qburst/Qeds versus Position in Catchment (highlighting each catchment)

As is apparent in Figure 6, the Horsley catchment contains most of the nodes with high levels of under-prediction (Qburst/Qeds <0.8), with Macquarie Rivulet the least. As Macquarie Rivulet is a relatively simple (mostly natural) catchment and Horsley a complicated partly urbanised catchment, an investigation into the impact of structures added during urbanisation was the obvious next step.

To isolate and display the impact of these structures on the pattern of behaviour observed in Figure 4, four upstream conditions were defined as listed below and a value assigned to each node.

- Natural above node
- Diversion(s) above node
- Basin(s) above node
- Basin(s) and Diversion(s) above node

The data from Figure 4 was then re-plotted to highlight the upstream condition at each node.

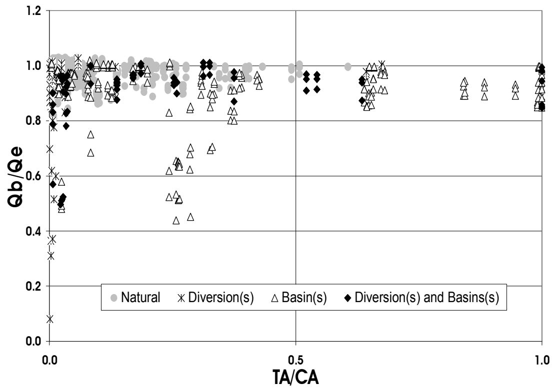

Figure 6: Qburst/Qeds versus Position in Catchment (highlighting upstream condition)

Figure 6 shows that the locations where the greatest levels of burst under-prediction occur (generally where Qburst/Qeds < 0.8), are points downstream of a basin or diversion or both, and that locations with a 'natural' upstream condition have the lowest level of burst under-prediction (none less than 0.8).

The above examples confirm that when a catchment is subject to design rainfall with duration of more than about 6 catchment lags:

- the level in under-prediction of peak flow at the catchment outlet produced by the present AR&R burst based procedure will be minimal, <u>however,</u>

- The level of under-prediction of internal peak flows is not guaranteed by such a condition. Internally the level of burst under-prediction is very sensitive to the presence of flow diversions and the configuration of storages within a catchment. Such structures are inherently non linear in their hydraulic behaviour, leading to changes in local hydrologic behaviour that bear little connection with behaviour at the catchment outlet.

5. CONCLUSIONS

The following conclusions may be drawn from this investigation:

1. Earlier conclusions that burst under-prediction of discharge at a catchment's outlet will be minimal if the burst duration is longer than about six catchment lags, is supported by this additional investigation.
2. Burst under-prediction at points internal to a catchment can be much more significant than under-prediction present at the catchment outlet.
3. Burst under-prediction at points internal to a catchment can be significant even when burst under-prediction at the catchment outlet is minimal.
4. Burst under-prediction is not related to the ARI of the storm being modelled.
5. A strong correlation exists between burst under-prediction and the presence of storages and diversions in a catchment. Such structures typically result in a high probability of burst under-prediction in subareas downstream of these structures.
6. In order to create a realistic simulation of hydrologic behaviour, a storm based approach (such as that provided by an EDS) should be used whenever;
   - The AR&R design burst duration falls below about six catchment lags <u>-or-</u>
   - There are significant storages and/or diversions present in the catchment.

6. REFERENCES

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