The Embedded Design Storm Concept - A Critical Review

E. H. Rigby, Director, Forbes Rigby Pty Ltd, Consulting Engineers, Wollongong, NSW
D. J. Bannigan, Drainage Engineer, Forbes Rigby Pty Ltd, Consulting Engineers , Wollongong, NSW

Summary In 1958 Australian Rainfall and Runoff introduced a procedure for estimation of design discharges from storm burst intensity - frequency - duration and temporal data which has now served the profession well for over 30 years. Difficulties in applying this procedure with the current generation of rainfall runoff models has however generated a need to review this procedure. This paper explores these dificulties and attempts to locally quantify the impact of extracting a burst from a storm, on predicted discharges. The IFD profile of historic storms in the Illawarra Region is examined and an alternate procedure for creation of a design storm presented. The impact of embedment on predicted discharges is shown to be most significant when short duration design bursts are applied to catchments with substantial natural or man made storages. The implementation of an embedded design storm procedure in the rainfall runoff model WBNM is discussed and the Authors' conclusions in respect to the need for an alternative to the present burst approach presented.

1. INTRODUCTION

In 1958, Australian Rainfall and Runoff (AR&R)(1) introduced a procedure for estimating a flood discharge of given Average Recurrence Interval (ARI) from storm burst Intensity - Frequency - Duration (IFD) data.

During the course of evolution of this procedure, much discussion and research took place with subsequent editions of AR&R in 1977(2) and 1987(3) formalising the procedure and incorporating substantial improvements in the quality of the IFD and temporal pattern data upon which the storm burst procedure was based.

Notwithstanding the considerable time over which this procedure has evolved, the fundamental presumption that a flood discharge can be reliably derived from a storm burst (as distinct from a storm) has received little attention. With use of computer based rainfall/runoff models to calculate design flood discharges now common place, it is the authors' view that it is time to review this presumption.

Whilst simple flood estimation models dealing only with the peak of the flood hide the distinction between a storm and storm burst - almost all of the present range of computer based rainfall/runoff models need some rather arbitrary adjustment to losses and starting storage, if a design storm burst is to be used to predict flooding with an ARI similar to that of the storm burst.

This problem is most evident in catchments with relatively short response times, significant flood storage and high losses. In such circumstances, the response of the catchment to a burst, relative to a storm 'typical' of the dataset from which the burst was extracted, is likely to differ in the following areas.

- The critical design burst is likely to be of much shorter duration than the 'typical' storm it was extracted from, with consequential impact on flow volume and duration.
- Lack of flow over catchment surfaces, in channels and on floodplains and lack of storage in basins at the commencement of a design burst, all result in attenuation of peak flow relative to that of the 'typical' parent storm.
- Inclusion of losses in a design burst based on losses in historic storm events does not reflect the impact of lead up rainfall on losses, further reducing peak flows relative to the 'typical' parent storm.

In a recent review of flooding in the Parramatta River by Phillips, Lees and Lynch (4), it was concluded that the above factors were responsible for an underprediction of the 100yr ARI flood surface by up to 500mm.

In the following sections, the evolution of the present storm burst based procedure is reviewed and the limitations of this procedure explored. An alternate procedure, to construct an embedded design storm from existing burst IFD and temporal data is presented and implementation of this procedure in the Watershed Bounded Network Model (WBNM)(5) discussed.

2. THE AR&R STORMBURST PROCEDURE

In the 1987 edition of AR&R, a procedure is set out for the derivation of a design peak flood discharge of given ARI from a design storm burst of equivalent ARI.

In summary this procedure includes :

- Selection of appropriate design storm burst IFD data for the site.

- Selection of an appropriate temporal pattern for the design storm burst.

- Selection of appropriate design storm burst losses for the site and chosen ARI/Duration.

- Application of an appropriate rainfall/runoff model to establish the design storm burst duration producing the greatest discharge - this maximised design discharge then being accepted as the design discharge of the specified ARI.

It is important to note that both the IFD data and temporal patterns presented in AR&R are for storm bursts, not storms. This is made clear in Section 3.2 of the 1987 edition of AR&R where the "NATURE OF DESIGN PATTERNS", is discussed.

The procedure outlined above first appeared in the 1958 edition of AR&R as a means of determining the peak discharge of a given ARI using a unit hydrograph based model. As pointed by French and Walsh (6), this procedure appeared without explanation, at a time when respected texts such as Linsley et al (7) made no mention of such a procedure.

In the 1977 edition of AR&R, the quality of data had much improved but the distinction between storm bursts and storms remained blurred. Losses were treated much more deliberately but without distinction between design and historic storms, other than to recommend "*Selection of design values of initial and continuing loss is best based upon consideration of many such values derived for recorded storms on the catchment concerned*".

Whilst more clearly stated in the 1977 edition of AR&R, the design storm burst procedure in AR&R 1977 is the same as that set out for the unit hydrograph procedure in the 1958 edition of AR&R. Considerable discussion and explanation is provided in AR&R 1977 on the derivation and limitations of both the IFD data and design storm burst temporal patterns. No comment is made on the appropriateness of using a design storm burst of a given ARI to calculate the peak design flood discharge of a similar ARI.

In the current (1987) edition of AR&R a considerable body of additional data has been collected and collated, markedly increasing the level of confidence inherent in the IFD data and storm burst temporal patterns. The distinction between storm bursts and storms is now clearly stated and consistently presented in the document. No further explanation as to the rationale behind the use of a storm burst in lieu of a storm to predict a peak discharge of given ARI is however provided.

With respect to losses, the 1987 edition of AR&R notes that "*for estimating the runoff excess from an actual storm as distinct from the design situation, allowance must be made for the condition and wetness of the catchment immediately prior to the event*" and "*for design, as discussed in Chapter 1, an average value is usually needed and .... the median of the derived values is probably the most appropriate to design*".

3. DESIGN STORM BURST LIMITATIONS

Whilst the procedure set out in the 1987 edition of AR&R is quite clear and readily implemented, it does present some difficulties in practice.

For the most part these difficulties arise as a consequence of the differences between the response of a catchment to a design storm burst and a design storm.

Given that the present design storm burst IFD data and temporal patterns have been extracted from a range of historic storms, it does not seem reasonable to expect a design storm burst to be able to simulate the discharge occurring in the storm from whence it was extracted.

In short duration design bursts (typically extracted from storms of duration greater than the burst under consideration) losses would, at the instant the burst commences in the storm, be much reduced relative to losses applicable to the start of the storm.

Many practitioners have responded to this concern by setting initial losses to zero when modelling short duration design storm bursts. This is however rather arbitrary and leaves unresolved the question as to when the burst duration is long enough for the initial loss to be reintroduced.

A further concern arises from the impact of lead up rainfall on natural and man made flood storages. In modelling the behaviour of such systems, using the design burst approach, the system commences its response with all storages empty - attenuating peak discharges relative to discharges that would have been calculated had the full storm been modelled. Where man made storages are present, some models permit an analysis to be made with the storages partly full, to reflect the likelihood that some storage will be present at the commencement of the design storm burst. As with initial losses, this is however an arbitrary approach which at best can only indicate the sensitivity of discharge to starting storage.

It should be noted that the above concerns are strongest when modelling short duration design storm bursts. For larger catchments with "critical" burst durations of a day or more, it seems reasonable to assume that the average intensity and temporal pattern of the design storm burst is typical of a full storm.

4. REGIONAL STORMS AND BURSTS

Given the basic derivation of both the present 1987 AR&R IFD and storm burst temporal data, it is relevant to ask what the differences in predicted discharge are between the full storm from whence storms bursts were extracted and the burst themselves. If the extracted bursts can not adequately reproduce peak discharges occurring in their parent storms, then it is not reasonable to assume that a storm burst can be used to model storm discharges.

Since only limited data was available to the author, a review of this relationship was made for four storms only, all responsible for significant flooding in the Illawarra Region. As such, the results are not intended to reflect a national position, but to indicate the order with which a storm burst is able to simulate a full storm discharge. A series of four historic storms were applied to seven catchments ranging in size from about 0.5 km^2 to 10 km^2. This exercise was then repeated by extracting the most intense burst with a duration equal to the critical duration for the catchment, from the storm, and rerunning the model with this storm burst. An outline of catchments considered is presented in Table 1. The ratio of predicted discharge from the full storm to that predicted by the extracted burst is reproduced in Table 2.

Catchment (Subcatchment)	Catchment Area	Critical Duration
1. Carricks Ck (Full catchment)	0.64 km^2	120 min
2. Bellambi Ck (Raths Gully)	0.91 km^2	120 min
3. Bellambi Lake (Full Catchment)	2.83 km^2	120 min
4. Byarong Ck (Millbrook Site)	3.96 km^2	120 min
5. Hewitts Ck (Full Catchment)	6.14 km^2	120 min
6. Horsley Creek (Full Catchment)	9.60 km^2	120 min
7. Little Lake (Full Catchment)	12.10 km^2	120 min

Table 1 : REGIONAL TEST CATCHMENTS

Given the significant under prediction in discharge produced by the extracted burst relative to the parent storm, on some catchments, one must conclude that the extracted storm burst can not reliably simulate runoff from the parent storm. Whilst there is a considerable spread in results, both across catchments and across storms, it is relevant to note that both catchments exhibiting consistent underprediction (Bellambi Creek and Little Lake) contain significant natural and man made storages.

Catchment No.	Feb 1975 Port Kembla	Mar 1984 Wongawilli	April 1988 Bulli	June 1991 Port Kembla
1	1.00	1.01	1.08	1.04
2	1.60	1.48	1.46	1.72
3	1.06	1.15	1.12	1.08
4	1.05	1.13	1.13	-
5	1.01	1.16	1.08	-
6	1.06	1.12	1.12	1.07
7	1.19	1.20	1.14	1.26

Table 2 : RATIO OF DESIGN STORM TO BURST DISCHARGES FOR REGIONAL STORMS

0

In modelling discharges from the storms, an initial loss of 15 mm with 2.5 mm/hr continuing loss was assumed. In modelling discharges from storm bursts, an initial loss of zero was assumed with 2.5 mm/hr continuing loss.

Had the 'full storm' initial loss been applied to the 'burst', burst discharges would reduce, further increasing the gap between storm and burst discharges.

5. THE EMBEDDED DESIGN STORM

Traditionally, earlier design procedures such as the rational method were based on the concept of critical duration bursts and IFD data for these bursts. It is only the more recent rainfall runoff models that make the distinction between a full storm and storm burst, a significant consideration.

In developing a design storm based procedure. the basic objective is to recreate for a given ARI and duration, a design storm with the average intensity and pattern that would be extracted from a rainfall data set appropriate to the site. Whilst simply stated, the complexity of deciding when a storm starts and finishes, and magnitude of the data extraction task makes achievement of this objective very difficult.

The following procedure is a relatively simple compromise, for creation of an embedded design storm using existing design burst IFD and temporal data, to simulate the above design storm. This procedure assumes :

- Existing design burst IFD and temporal pattern data are typically those of storms for the longer durations and of bursts within storms for the shorter durations.

That in order to best relate the ARI of the design discharge to that of the design rainfall using an embedded design storm approach;

- Average losses should apply as determined from a range of historic storms.

- The temporal pattern of both the critical duration burst and storm envelope into which it is to be embedded should be similar to the patterns of average variability as presently defined in AR&R 1987.

- The peak of the critical duration burst temporal pattern should coincide with the peak of the longer duration storm temporal pattern.

- The average intensity of the critical duration burst should have an ARI equal to that of the desired flood discharge. The design burst should be embedded in a design storm envelope with an intensity/duration profile similar to that of storms common to the area.

- A range of embedded burst durations may need to be considered (as in the present AR&R 1987 procedure) to establish the critical storm burst duration to embed in the design storm envelope.

A review of data for storms in the Illawarra Region associated with past flooding, indicates most such storms had storm durations in the range of 12 to 24 hours. Whilst some flood producing storms had durations longer than 24 hours, few storms for which data is available had storm durations less than 12 hours. Hyetographs and intensity/duration plots for four of the most significant recent flood producing rain storms in the Illawarra region are reproduced in Figures 1 and 2.

Whilst a limited data set, the intensity/duration relationships presented in Figure 2 suggest that in typical flood producing rains in the Illawarra region, the 1 to 2 hour burst intensity is generally of the order of or of lower ARI than that of the 24 hour burst in the same storm.

Notwithstanding the small number of events analysed, the frequency with which high ARI long duration burst or storm intensities occurred relative to short duration burst intensities of similar ARI, does raise some additional questions as to the appropriateness of the present IFD curves in the Illawarra Region.

Based finally on a largely subjective view of the duration of past storms and their IFD relationships, an embedded design storm procedure has been developed for the Illawarra Region incorporating the previously outlined assumptions in which a design burst of critical duration for the catchment under consideration is embedded in a design storm envelope of 24 hours duration. The ARI of both the critical storm burst and design storm envelope are set equal to that of the flood discharge being modelled.

The 24 hour and 2 hour IFD profiles for a design storm burst of 100 Yr ARI at Port Kembla are shown in Figure 3, together with the IFD profile of a 2 in 24 hr 100Yr ARI embedded design storm. As will be apparent from a comparison of these

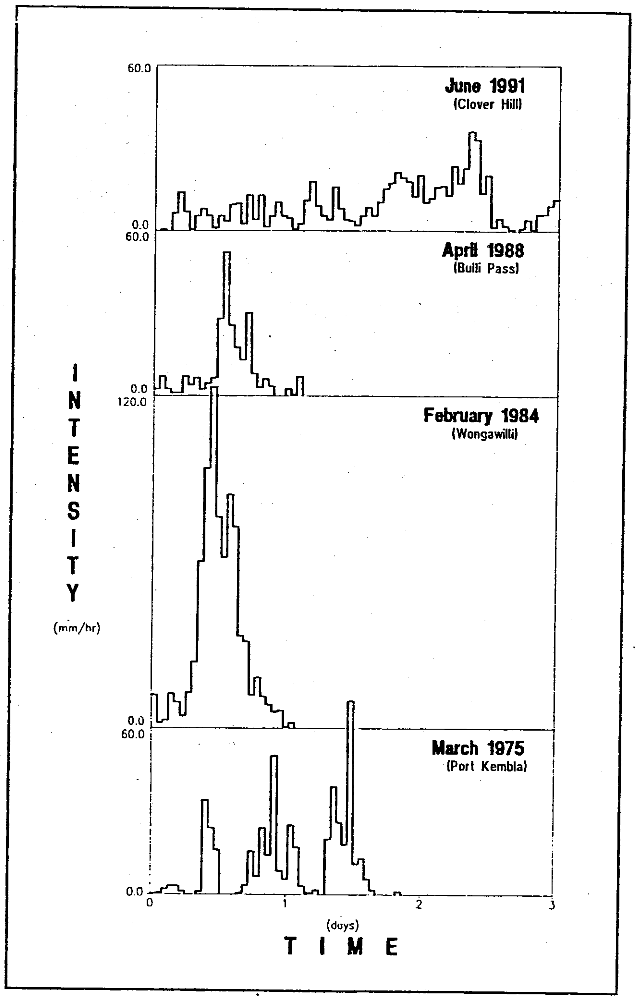

Figure 1 : **HISTORIC STORMS HYETOGRAPHS**

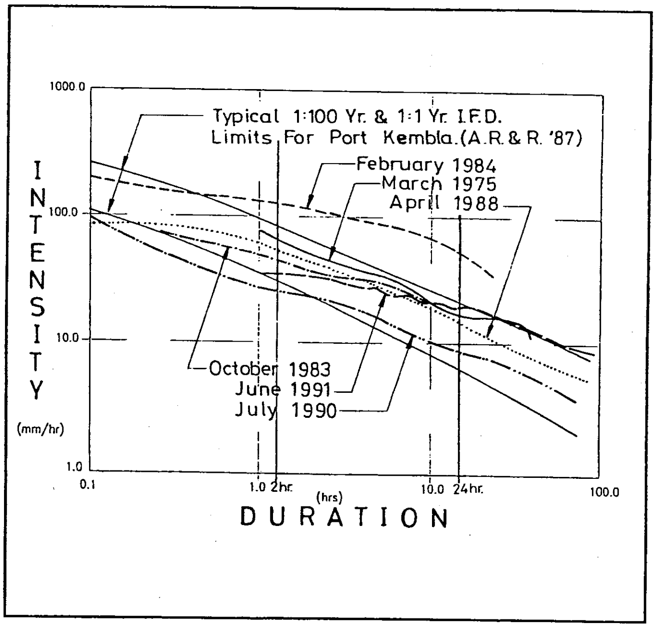

Figure 2 : **HISTORIC STORMS INTENSITY - DURATION PROFILES**

curves, the embedded design storm is close to a 100Yr ARI event across the full range of durations up to 24 hours. (similar to the US "Chicago" style design storm.) Whilst this would normally be expected to produce a flood event of increased ARI, due to joint probability considerations - the events examined suggest such a profile does typically exist in flood producing rains in the Illawarra. In Figure 4, the hyetograph of a 100Yr ARI 2 hour design storm burst is shown embedded in a 24 hour duration burst of similar ARI, creating a 2 in 24 hour, 100Yr ARI embedded design storm.

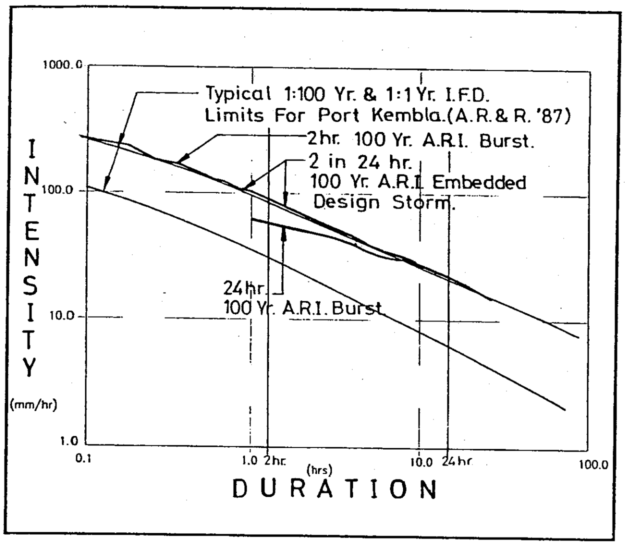

Figure 3 : AR&R BURST & EMBEDDED DESIGN STORM IFD PROFILES

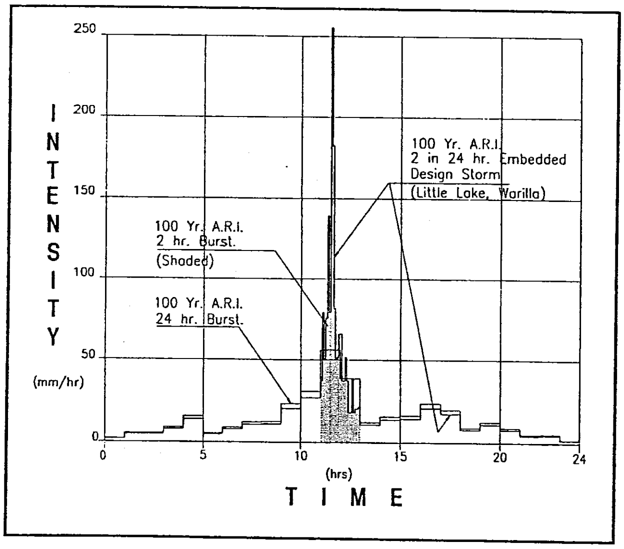

Figure 4 : EMBEDDED DESIGN STORM HYETOGRAPH

Intensities are adjusted each side of the embedded burst, to maintain the specified average intensity for the design storm, following the AR&R temporal pattern for a design burst of the specified storm duration.

In Figure 5, the various design hydrographs resulting from a 100Yr ARI 2 hour design storm burst, design 24 hour storm burst, and 2 in 24 hour embedded design storm burst are contrasted. It is of relevance to note that the ratio of the 2 in 24 hour embedded design storm burst discharge to that of the 2 hour design storm burst discharge is of the order of 1.2 - a similar ratio to that of a historic storm on the catchment to an extracted 2 hour burst.

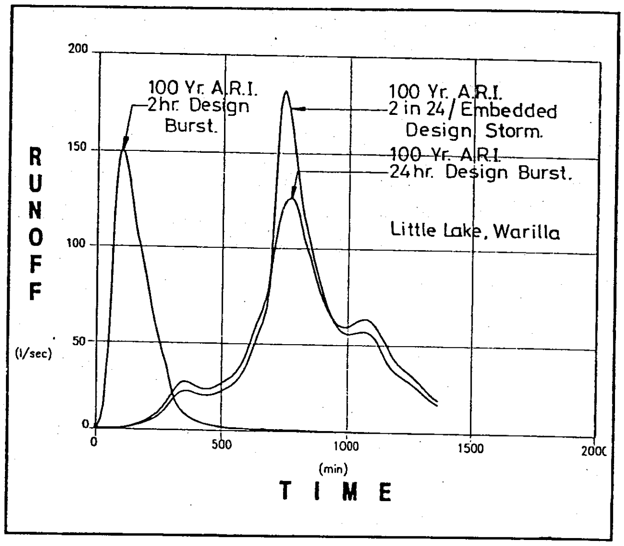

Figure 5 : DESIGN HYDROGRAPHS

6. WBNM IMPLEMENTATION

The above procedure for creation of an embedded design storm has been incorporated into the rainfall runoff model WBNM. Since the procedure outlined above is likely to change as the procedure evolves, the present implementation of embedded design storms in WBNM is both optional (users may follow the standard AR&R burst procedures if they wish) and generic (both burst duration and storm duration being input by the user together with a factor to adjust the average intensity of the design storm envelope). To automatically invoke the embedded design storm routines, a user adds the specified storm duration and desired multiplication factor for the intensity of the design storm envelope to the line containing the design storm burst ARI, duration and areal reduction factor flag;

When these optional data entries are absent, design follows the standard 1987 AR&R burst procedure.

In operation, WBNM subdivides the design storm in to time steps matching those of the design burst, locates the central portion of the peak of the design storm and overlays the storm with the burst, centred on the design storm peak.

The average intensity of the design storm is then calculated, factored up or down by the user specified multiplication factor, and the remaining ordinates of the design storm adjusted such that the factored average embedded design storm intensity is as specified.

On completion, an embedded design storm with a storm duration equal to that of the requested storm, containing the specified design storm burst is available for further processing by WBNM. (in the same way as for an AR&R 1987 design storm burst).

7. CONCLUSIONS

It is the authors' conclusions that;

1. There is need to re-examine the fundamental logic behind the present AR&R 1987 design storm burst procedure.

2. Using modern computer based simulation models, it is not reasonable to expect storm bursts to reliably predict discharges of a given ARI without significant and for the most part arbitrary adjustment to model losses and starting storage levels.

3. In order to overcome difficulties inherent in the design storm burst approach, either a consistent means of adjusting models for the loss and storage problems present needs to be developed <u>or</u> a design storm based approach needs to be adopted.

4. Whilst losses can be adjusted to partly overcome the problem of applicable storm burst losses, adjustment of models to accommodate a burst with substantially less volume than the historic event from which it was extracted, is a much more difficult issue to resolve. It seems more logical and valuable in the long term to pursue development of a procedure for creation of design storms to replace the storm burst procedure, than to patch the present procedure.

5. Existing IFD and storm burst temporal data can be used to create an embedded design storm by merging a specified design storm burst of given ARI with a longer duration design storm(burst) pattern (typical of storms in the region). Care is needed to ensure that the relationship of the average intensity of the design storm to that of the design burst is typical of storms in the region. Joint probability issues may otherwise create runoff with an ARI different from that of the design burst.

6. In the Illawarra region a 24 hour base appears reasonable for the design storm duration into which a design burst of the specified (critical) duration is to be embedded. To reflect the pattern of historic flood producing storms in the region, the average intensity of the embedded design storm should be equal to that of a 24 hour burst of the same ARI as that of the embedded design storm burst (and flood to be modelled).

7. Whilst the impact of embedment on discharge depends greatly on the characteristics of the catchment, design discharges in the Illawarra are typically increased by 10 to 30 percent when a design storm burst is embedded in a design storm complying with the above recommendations. Where major storages (natural or man made) are present, this factor increases.

8. The procedure outlined should avoid most of the deficiencies of the design burst approach.

   In particular;

   Rainfall losses are subtracted from the design storm rather than the short duration design burst.

   Surface and channel flows from a design storm with a temporal pattern of near average variability and appropriate IFD profile exist at the commencement of the embedded burst, with natural and man made storages partly full.

   The catchment is 'warmed up' by this procedure in a logical manner consistent with the present concepts and data of AR&R 1987.

9. Whilst the above procedure avoids most of the deficiencies of the storm burst procedure it does not address the question of whether maximised discharge from a range of burst durations is necessarily the best estimate of a flood discharge of given ARI. This aspect is in need of further investigation.

9. REFERENCES

1. INSTITUTION OF ENGINEERS, AUSTRALIA "First report of The Stormwater Standards Committee of The Institution on Australian Rainfall and Runoff," 1958, IE Aust.

2. INSTITUTION OF ENGINEERS, AUSTRALIA "Australian Rainfall and Runoff. Flood analysis and design," ed. by A. Pattison, J.K.C. Ward, T.A. McMahon and B. Watson, 1977, IE Aust. ACT.

3. INSTITUTION OF ENGINEERS, AUSTRALIA "Australian Rainfall and Runoff. A guide to flood estimation Volume 1", ed. by D.H. Pilgrim, 1987, IE Aust.

4. PHILLIPS, B., LEES, S., LYNCH, S. "Embedded Design Storms - An Improved Procedure for Design Flood Level Determination", <u>Proc. Water Down Under '94</u>, 1994, Adelaide, IE Aust.

5. BOYD, M., RIGBY, E., SHARPIN, M., VAN DREI,

R. "Enhanced Runoff Routing Model WBNM94" Proc Water Down Under '94, 1994, Adelaide IE Aust.

6. FRENCH, R. & WALSH, M., "Increasing the Confidence of Australian Flood Design", Proc. Hydrology and Water Resources Symposium Christchurch NZ., 1989, IE Aust.

7. LINSLEY K, KOHLER M, PAULUS J "Hydrology for Engineers", 1958, McGraw Hill, New York.