Analysis of loss values for Australian rural catchments to underpin ARR guidance

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Abstract

As part of ARR Project 6, loss values were derived for a range of events on 38 rural catchments from across Australia. Based upon an earlier pilot study, the IL/CL and SWMOD loss models were selected for analysis. Loss values were estimated for each loss model for more than 1,000 events. The loss values are presented as both median values for each catchment and also as empirical distributions. The large data set allowed an investigation of how loss varies with rainfall characteristics including, event severity and antecedent rainfall. A range of catchment characteristics was also explored to see whether they could explain the variability in the derived loss values. Where possible, regional prediction equations were developed to estimate loss values for ungauged catchments. This analysis was used as the basis of developing recommendations for guidance in ARR for selection of loss values for design flood estimation.

1. INTRODUCTION

Loss is defined as the precipitation that does not appear as direct runoff, and is typically attributed to processes such as interception by vegetation, infiltration into the soil, retention on the surface (depression storage), and transmission loss through the stream bed and banks. While the processes that contribute to loss may be well defined at a point, it is difficult to estimate a representative value of loss over an entire catchment.
Lack of guidance on losses has long been regarded as one of the greatest gaps in Australian design flood estimation and ARR Revision Project 6 has investigated losses for design flood estimation. Losses for urban catchments are documented in Phillips et al (2014) and not covered in this paper.

The work on losses for rural catchments has occurred over the last few years and has been documented in the following technical reports: discussion paper (Hill, 2010), pilot study for rural catchments (SKM, 2012a), collation of data for rural catchments (SKM, 2012b) and analysis of rural catchments (Hill, et al. 2014b). The work has also been documented in a series of conference papers (Hill, 2011; Hill et al 2012; Hill et al 2014a).

This paper provides a high level summary of the work undertaken as part of the final phase of ARR Project 6 which involved the analysis of data for catchments from around Australia. Readers are referred to the ARR technical reports and conference papers for further background to conceptual loss models for design flood estimation, the limitations of the current ARR guidance, the rationale for the scope of work and more detailed results of the study.

2. STUDY CATCHMENTS

The empirical analysis of loss values requires catchments with concurrent periods of pluviograph and streamflow records. Sufficient rainfall stations are required to adequately capture the total volume of catchment rainfall. The catchment should be sufficiently small so that routing effects are not significant and hence estimated loss values are not sensitive to the catchment routing assumptions. The greatest constraint on the selection of appropriate catchments for inclusion in the study was found to be representative rainfall records for the catchments. The adopted criteria for selection of the catchments were:

- catchment area between 20 and 100 km²
- unregulated (free from transfers and lake systems)
- minimum of 20 years of streamflow record with a preference for a longer period
- close proximity of a pluviograph gauge to the catchment centroid, preferably within 5 km
- at least 20 years of overlapping streamflow and pluviograph data
- mix of catchments covering different regions of Australia

A total of 38 catchments were ultimately included in the study and are shown in Figure 1.

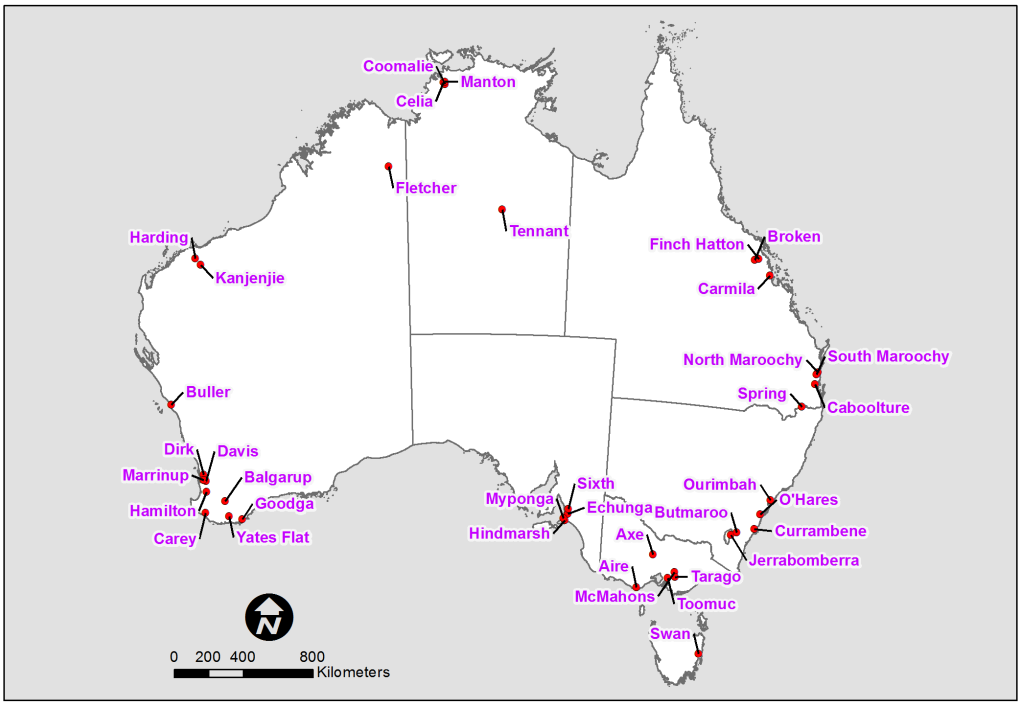

Figure 1 Study Catchments

3. SELECTION OF CONCEPTUAL LOSS MODELS

Despite the obvious attraction of using infiltration equations, the uncertainties of characterising catchment properties (particularly soil) do not justify the use of anything more than the simplest models. To overcome this difficulty, lumped conceptual loss models are widely used for design flood estimation. They combine the different loss processes and treat them in a simplified fashion. The focus of these conceptual models is less on the representation of the loss processes themselves, but is rather on representing their effects in producing the rainfall excess.

The key requirements for a loss model for design flood estimation are to (Weinmann, pers. comm.):

- close the volume balance in a probabilistic sense such that the volume of the design flood hydrograph for a given AEP should match the flood volume derived from the frequency analysis of flood volumes;
- produce a realistic time distribution of runoff to allow the modelling of the peak flow and hydrograph shape;
- reflect the variation of runoff production with different catchment characteristics to enable application to ungauged catchments; and,
- reflect the effects of natural variability of runoff production for different events on the same catchment to avoid probability bias in the transformation of rainfall to flood.

As part of the pilot study a range of conceptual loss models were considered and a selection applied to 10 catchments. Based upon these results, the IL/CL and SWMOD models were selected for further application to the larger data set (SKM, 2012a; Hill et al 2012 & 2014).

3.1. Initial Loss – Continuing Loss

The most commonly-used model in Australia is the initial loss-continuing loss (IL-CL) model. The initial loss occurs in the beginning of the storm, prior to the commencement of surface runoff. The continuing loss is the average rate of loss throughout the remainder of the storm. This model is consistent with the concept of runoff being produced by infiltration excess, ie runoff occurs when the rainfall intensity exceeds the infiltration capacity of the soil. Lang et al (2014) provides further discussion on the estimation of IL and CL from the analysis of recorded data.

3.2. SWMOD

SWMOD is a probability distributed storage capacity model developed for use in the south west of Western Australia where saturation excess overland flow is held to be the dominant runoff mechanism for storm events (Stokes, 1989 and Water and River Commission, 2003). The model incorporates the ability of the different landforms in the catchment to store water during the storm event. When the accumulated rainfall is greater than the infiltration capacity, the sub-catchment will generate saturation-excess overland flow for any additional rainfall. Infiltration capacity is assumed to vary within an area due only to soil depth. The infiltration capacity over a sub-catchment is defined below:

$$C_f = C_{max} - (C_{max} - C_{min}) \times (1-F)^{1/B} \quad (1)$$

Where C_f is the infiltration capacity at fraction F of the sub-catchment

F is the saturation fraction of the sub-catchment

B is the shape parameter

C_{max} is the maximum infiltration capacity

C_{min} is the minimum infiltration capacity

The application of SWMOD results in an initial loss (determined by the initial water content and the value of C_{min}) followed by variable proportional loss (which is a function of the range and shape of the distribution of soil capacity). The distribution of profile water holding capacity is inferred from soils information and hence the model only has one parameter, namely the initial moisture content.

Initial application of the one parameter model to the pilot catchments demonstrated that it did not provide sufficient flexibility to calibrate the model to recorded hydrographs and therefore an additional parameter was incorporated which scaled the maximum profile water holding capacities for all soil types in a catchment by the same amount. This resulted in a two parameter loss model comprising:

- Initial Moisture (IM_S) which is assumed to be the same for all soil types across the catchment (i.e. the moisture is evenly redistributed between events).

- Capacity Factor (CF) which scales the maximum profile water holding capacities in a catchment.

The application of SWMOD is discussed further in Hill et al (2014a&b).

The distribution of profile water holding capacity was estimated using the hydrologic interpretation of the Atlas of Australian Soils (McKenzie et al. 2000). For the majority of catchments, the SWMOD capacity factor was greater than 1.0 which is consistent with other studies which found that the values from the Atlas of Australian Soils typically underestimate the hydrologic capacity.

4. ESTIMATION OF LOSS VALUES

The events used to estimate the loss values were selected on the basis of rainfall, rather than flow, to ensure that they were not biased towards wet antecedent conditions. Rainfall bursts were selected for durations of 3 and 24 hours and then complete storms defined to allow the estimation of losses. The storm durations were typically a few days and therefore, although the events were selected on the basis of shorter bursts of rainfall, the losses were estimated for longer duration events.

The loss values were estimated using RORB models created for each catchment. For each of the two loss models a fixed routing parameter was adopted for all events on each catchment based upon matching modelled and recorded hydrographs. Choice of loss model was shown to affect the preferred routing parameter with the value for SWMOD being approximately 75% of that for the IL/CL model. This demonstrates that the selection of the loss parameters and routing model are not independent. The routing parameters for south west WA were consistently higher than the catchments from other locations in Australia and indicates a different catchment response, possibly characterised by higher levels of interflow.

5. LOSS VALUES

5.1. Median Values

The median loss values are summarised in Table 1. For each catchment, the individual loss values varied over a large range and further details are provided in Hill et al 2014b). The range of values reflects the influence of antecedent conditions, uncertainties in the inputs (particularly the catchment average rainfall) and data errors.

Table 1. Median loss values

Region	Gauge	Catchment	State	Events	IL_s (mm)	CL (mm/h)	IM_s (mm)	CF
GSAM – Coastal	216004	Currambene	NSW	17	35	3.9	0	1.3
	213200	O'Hares	NSW	22	60	1.6	7.5	0.6
	211013	Ourimbah	NSW	24	40	3.7	45	1.0
	2219	Swan	TAS	19	40	0.5	-35	0.3
	235219	Aire	VIC	30	17	3.1	25	1.6
	229106	McMahons	VIC	21	20	3.7	45	2.8
	228206B	Tarago	VIC	22	24	3.9	60	2.1
	228217	Toomuc	VIC	25	24	2.5	0	1.6
GSAM – Inland	410743	Jerrabomberra	NSW	20	22	2.1	6.5	0.6
	411003	Butmaroo	NSW	21	40	2.6	-7	0.9
	AW503506	Echunga	SA	13	25	2.2	40	0.7
	AW501500	Hindmarsh	SA	33	15	3.2	55	1.5
	AW502502	Myponga	SA	15	23	2.6	5	0.6
	A5040523	Sixth	SA	24	15	3.3	45	1.3

	406216	Axe	VIC	12	28	6.0	5	1.0
GTSMR – Coastal	G8150151	Celia	NT	15	25	5.4	60	2.2
	G8170066	Coomalie	NT	30	50	8.1	35	4.4
	G8170075	Manton	NT	32	42	1.6	15	1.3
	G0290240	Tennant	NT	24	0	5.2	20	1.3
	120216A	Broken	QLD	34	68	6.2	-20	1.2
	142001A	Caboolture	QLD	20	50	1.4	2.5	0.4
	126003A	Carmila	QLD	19	70	3.1	-25	0.4
	125006	Finch Hatton	QLD	30	23	5.2	70	0.8
	141009	North Maroochy	QLD	23	20	2.2	10	1.1
	141001	South Maroochy	QLD	22	38	2.7	10	0.7
	422321	Spring	QLD	27	30	5.1	0	4.5
	809312	Fletcher	WA	19	30	10.4	40	1.7
	709007	Harding	WA	17	60	8.3	-10	2.6
	708009	Kanjenjie	WA	13	40	0.8	-5	0.4
GTSMR – SW WA	609005	Balgarup	WA	13	25	2.5	5	0.9
	701006	Buller	WA	14	32	3.8	0	0.6
	608002	Carey	WA	19	20	3.8	50	2.7
	614047	Davis	WA	18	25	8.1	40	7.4
	614005	Dirk	WA	20	14	6.7	60	4.5
	602199	Goodga	WA	27	30	4.8	10	2.7
	612004	Hamilton	WA	13	47	3.3	50	4.2
	614003	Marrinup	WA	19	16	7.3	60	2.7
	603190	Yates Flat	WA	17	27	0.8	15	0.4

5.2. Relationship between Storm Initial Loss and Initial Moisture

Both the Storm Initial Loss (IL_S) and the Initial Moisture (IM_S) parameters account for the different antecedent moisture for each event. The IL_S is the depth of rainfall required to generate runoff, whereas it is the difference between the IM_S and the minimum soil capacity that governs when runoff is generated for the SWMOD model. It would therefore be expected that the IL_S and IM_S would be highly negatively correlated. The proportion of variance explained (r^2) between the median IL_S and median IM_S values for each catchment is shown in Figure 2. It is clear from this figure that for some catchments the two parameters are highly correlated whereas for other catchments the r^2 is quite low.

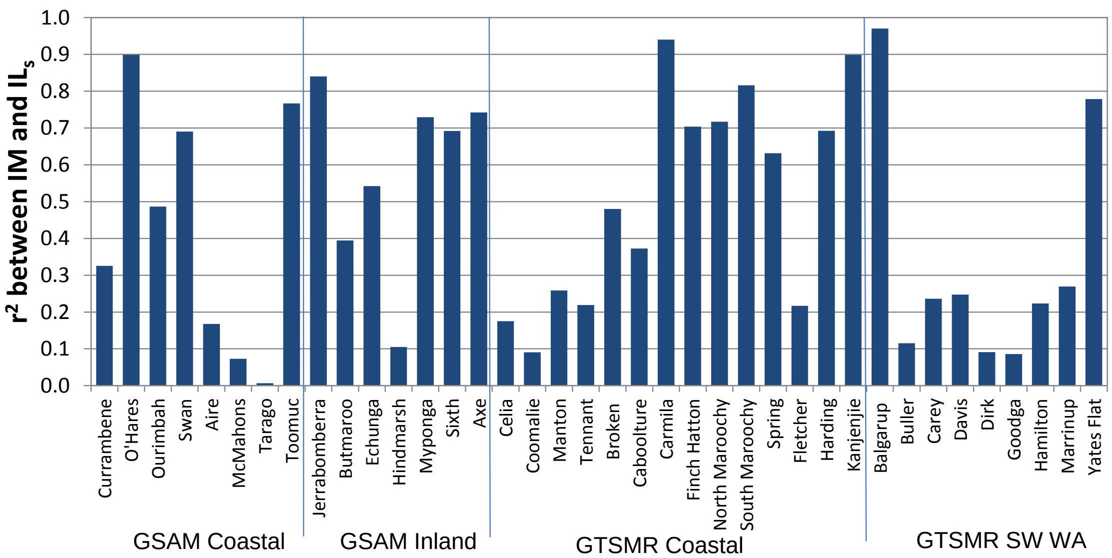

Figure 2 Proportion of variance explained (r²) between IMs and ILs

5.3. Relative performance of loss models

For each event, a subjective score was assigned to the goodness of fit which was used to infer the preference of loss model for each event. The results are shown in Figure 3. For example, for Currambene for 41% of the event it was assessed that SWMOD outperformed the IL/CL model, for 18% of events IL/CL was preferred and for a further 41% the models produced a similar quality of fit. Even for catchments where a particular loss model was preferred for a majority of events, there are still events where the alternate model is preferred. Across all 38 catchments, the distribution of preference is distributed approximately equally in thirds between IL/CL, SWMOD and "equal".

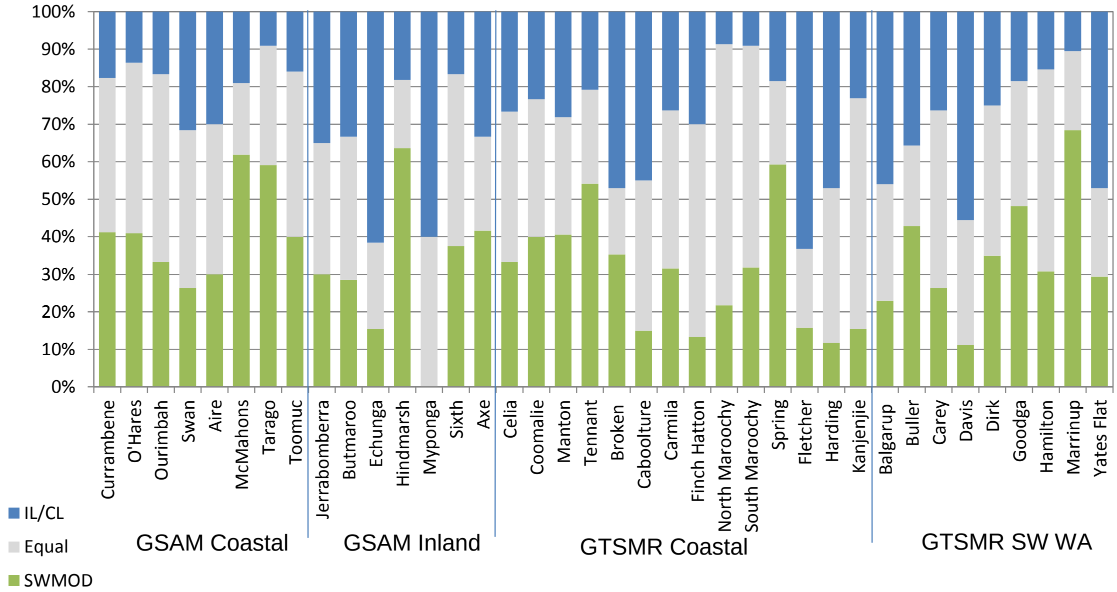

Figure 3 Relative performance of IL/CL and SWMOD models

5.4. Non-parametric distribution

Non-parametric distributions of loss values were derived by standardising the values by the median for each catchment. The exceedance percentiles for each of the standardised loss parameters for each catchment were extracted, and then averaged across all catchments to obtain a single non-dimensional curve. The standardised distributions of ILs and CL from the different regions are compared in Figure 4 and exhibit a remarkable degree of consistency. The results clearly show that while the magnitude of losses may vary between different regions, the shape of the distribution does not. Similar distributions were also developed for IMS and CF (Hill et al 2014b).

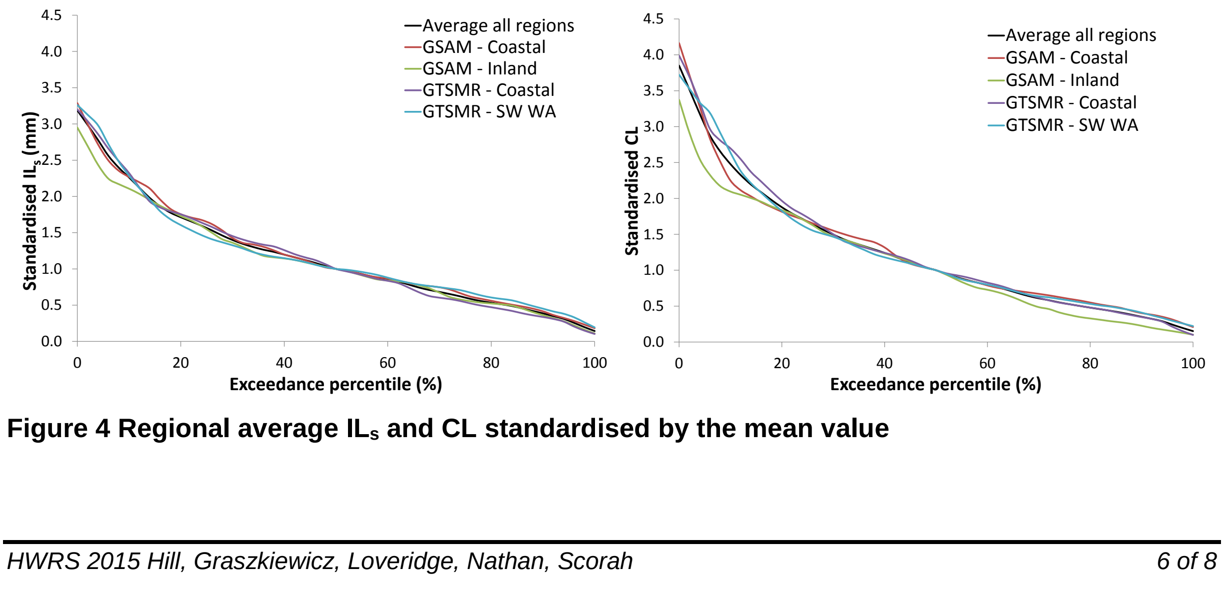

Figure 4 Regional average IL_s and CL standardised by the mean value

5.5. Relationship with severity

The variation of the loss values with event severity was investigated by plotting the (standardised) values against the AEP of the burst depth. There was no evidence of any variation with AEP. This supports the findings of a number of other studies that have not been able to identify a trend of loss values with storm severity.

5.6. Relationship with antecedent conditions

The antecedent precipitation index (API) is a measure of the initial wetness of a catchment. API is calculated by discounting the time series of daily rainfall prior to the event using an empirical decay factor and the basic equations is (Cordery, 1970):

$$API_d = P_d + k.P_{d-1} + k^2.P_{d-2} + \ldots$$

Where k is an empirical decay factor less than unity and P_d is rainfall for day d. The value of k is considered to vary seasonally and has been linked to the variation in potential evapotranspiration. For this study a fixed k was adopted throughout the year and values of 0.85, 0.90 and 0.95 were trialled. The relationship between the API and the IL_s and IM_s was explored by simple linear regression and the r^2 and the results are summarized in Figure 5. For some catchments the API explains a large proportion of the variance in IL_s and IM_s whereas for other catchments the loss values appear to be invariant with API. This would indicate that the variability of losses is driven by factors other than antecedent rainfall.

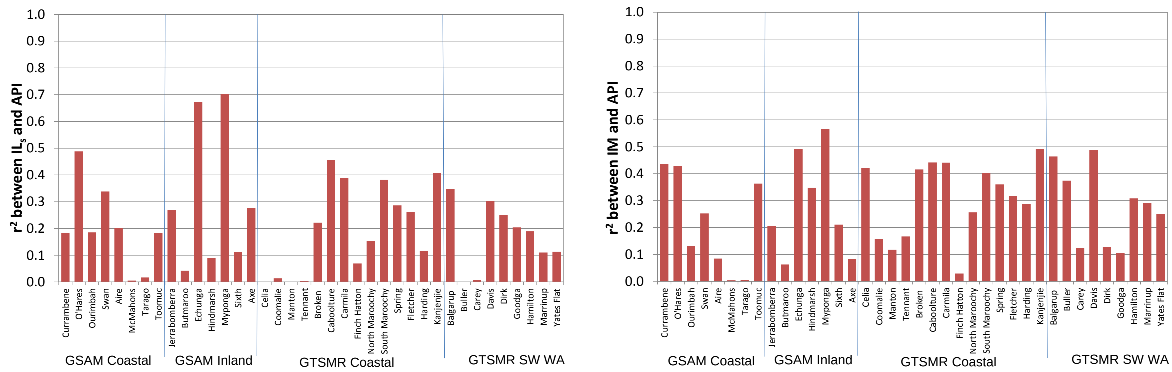

Figure 5 Proportion of variance explained (r^2) between (a) IL_s and (b) IM_S and API

6. DEVELOPMENT OF PREDICTION EQUATIONS

The physical processes contributing to loss are reasonably well understood however past studies have struggled to relate loss values from the analysis of data to any physical catchment or hydroclimatic characteristics. The linking of loss values to characteristics is confounded by a number of factors, including the variability of values due to antecedent conditions, the spatial variability of catchment characteristics, uncertainty in the observed rainfall and streamflow and the lack of hydrologic interpretation of catchment characteristics such as soils and vegetation.

A range of physical and hydroclimatic characteristics were examined to see if they could explain the observed variability in median loss values. Where possible, prediction equations were developed and checks were made to ensure that the variables and the signs of their coefficients were consistent with the dominant physical processes expected to contribute to the loss. Although prediction equations were developed for some loss parameters in some regions, the proportion of the variance explained by the prediction equation varies and the developed relationships are not sufficient to be the sole basis for providing design guidance in ARR.

7. CONCLUSIONS

ARR Project 6 involved the analysis of losses for a large number of catchments from across Australia which has allowed the investigation of how loss varies with catchment and hydroclimatic factors. The outcomes of the study will be used to underpin the guidance in ARR for loss values. The loss values derived in this study should be combined with the other key design inputs such as design rainfall depth, pre-burst rainfall, temporal and spatial pattern of rainfall and baseflow in a Monte-Carlo framework to check if they produce probability-neutral estimates of flows. Clearly, any discrepancies between the rainfall-based estimates and the flood frequency quantiles will be a function of any biases and uncertainties introduced at every step in the design process - from uncertainties in the measured data, conceptualisation and calibration of flood models through to each of the design inputs – so it may be difficult to assign any bias to any of the individual inputs. Nevertheless, this benchmarking step is essential to ensure that the combination of the new design inputs results in unbiased estimates of design floods.

8. ACKNOWLEDGMENTS

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