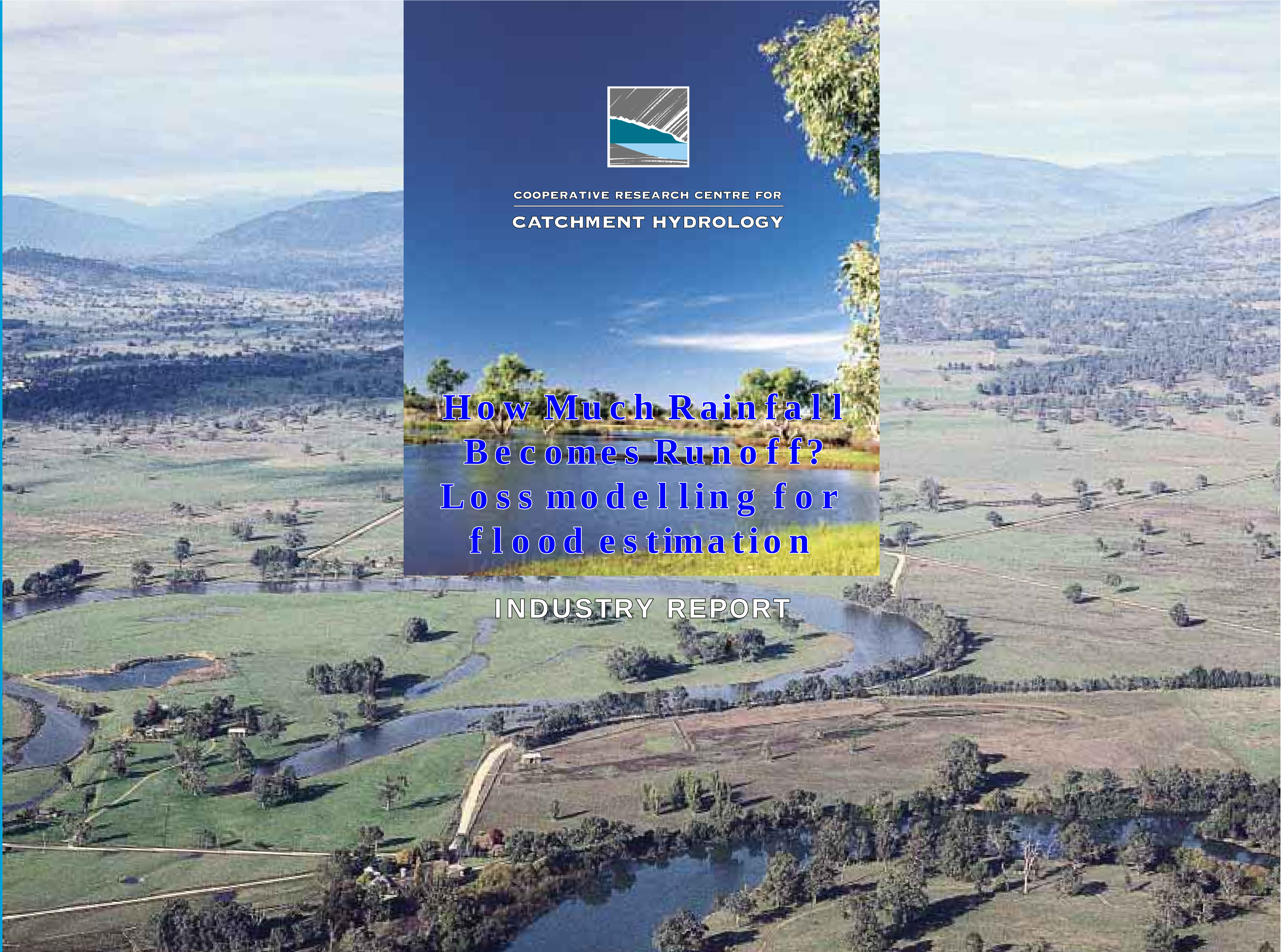


COOPERATIVE RESEARCH CENTRE FOR

CATCHMENT HYDROLOGY

How Much Rainfall Becomes Runoff? Loss modelling for flood estimation

INDUSTRY REPORT

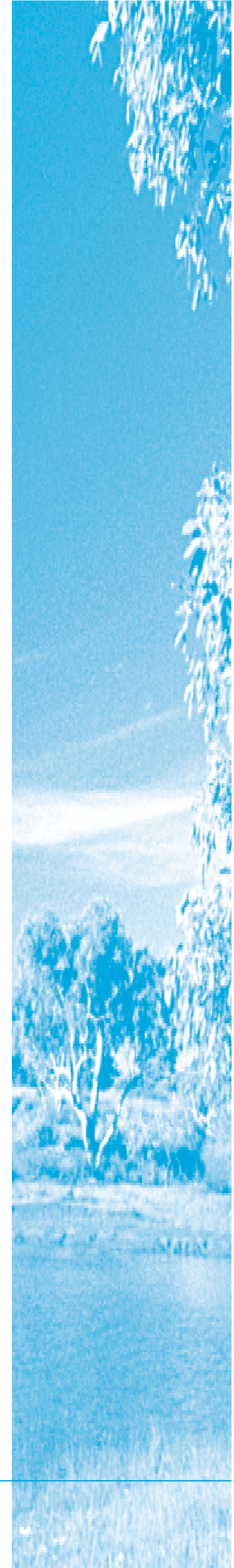
How Much Rainfall Becomes Runoff?
Loss modelling for flood estimation

by

Peter Hill, Russell Mein and Lionel Siriwardena

COOPERATIVE RESEARCH CENTRE FOR
CATCHMENT HYDROLOGY

Industry Report
Report 98/5
June 1998



Hill, P. I. (Peter Ian)
How much rainfall becomes runoff?: loss modelling for flood estimation.

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ISBN 1 876006 26 9.

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551.4880994

ISSN 1039-7361

Keywords

Floods and Flooding
Rainfall/Runoff Relationship
Modelling (Hydrological)
Frequency Analysis
Design Data
Infiltration
Water Flow
Catchment Areas
Flood Forecasting

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Photographs were provided by:

- Ian Rutherfurd (front and back cover)
- Mat Gilfedder
- Bureau of Meteorology – Mike Rosel

Background cover photo: Aerial view of Murray River billabong near Albury, NSW.

F o r e w o r d

This Industry Report is one of a series prepared by the Cooperative Research Centre (CRC) for Catchment Hydrology to help provide the Australian land- and water-use industry with improved ways of managing catchments.

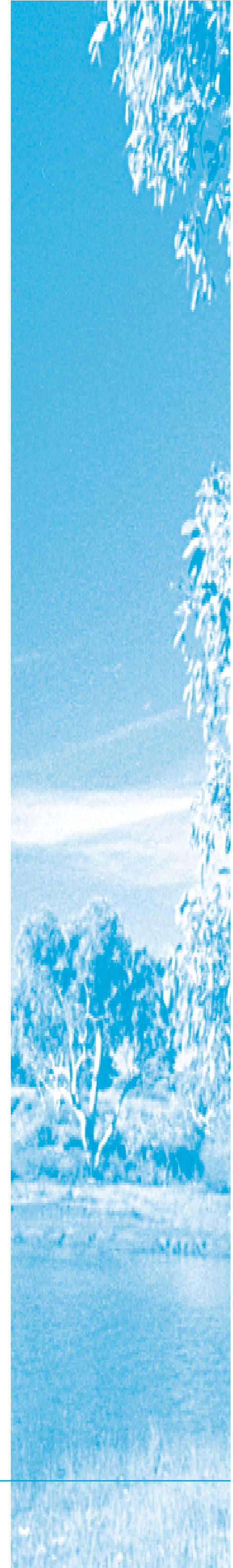
Through this series of reports and other forms of technology transfer, industry is now able to benefit from the Centre's high-quality, comprehensive research on salinity, forest hydrology, waterway management, urban hydrology and flood hydrology.

This particular Report represents a major contribution from the CRC's flood hydrology program, and presents key findings from the project entitled 'Improved Loss Modelling for Design Flood Estimation and Flood Forecasting'. (More detailed explanations and research findings from the project can be found in a separate series of Research Reports and Working Documents published by the Centre.)

The CRC welcomes feedback on the work reported here, and is keen to discuss opportunities for further collaboration with industry to expedite the process of getting research outcomes into practice.

Russell Mein

Director, CRC for Catchment Hydrology



Preface

This report summarises the Cooperative Research Centre (CRC) for Catchment Hydrology's research on Project D1: 'Improved Loss Modelling for Design Flood Estimation and Flood Forecasting'.

The need for research to quantify losses from rainfall was identified by a technical advisory group (TAG) comprising researchers and practitioners involved in flood estimation. The group suggested a number of lines of research to pursue, and these were followed up. The empirical analysis of the large database of rainfall and runoff events collated for the study was a key to the successful project outcomes.

This report concentrates on the derivation of new loss parameters, and on the development of a new loss model for real-time flood forecasting. These outcomes are seen to be of immediate use to practitioners. Other sub-projects, not discussed here, were:

- extension of data sets using continuous models (Elma Kazazic)
- measurement of the spatial distribution of soil moisture in forested catchments (Leon Soste)
- application of point infiltration equations at catchment scale (Jason Williams)
- development of a design flood estimation procedure using data generation and a daily water balance model (Walter Boughton and Peter Hill).

People involved in this project were Peter Hill (Project Leader) and Lionel Siriwardena, assisted by Nanda Nandakumar (in the early stages), Upula Maheepala, Leon Soste, Elma Kazazic and Russell Mein (Program Leader). The project reference panel (Jim Elliott, Tom McMahon, Russell Mein, Rory Nathan and Erwin Weinmann) gave important guidance on the work. Walter Boughton was a significant contributor.

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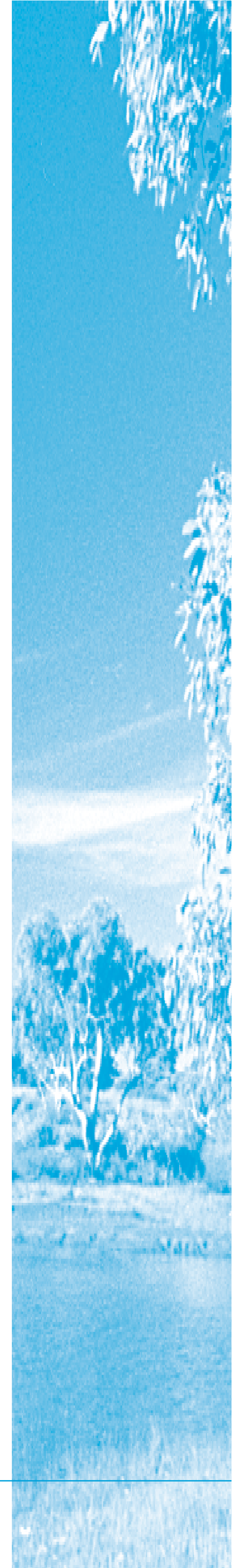


Introduction

The answer to the question "How much rainfall becomes runoff?" is of fundamental hydrologic importance. In flood hydrology, the proportion of runoff from a storm has a major influence on the size of the resulting flood. The amount of rain which does not become runoff is termed "loss".

The objectives of CRC Project D1 'Improved Loss Modelling for Design Flood Estimation and Flood Forecasting' were to:

- develop loss models which reduce the uncertainty in design flood hydrographs (used for sizing of hydraulic structures); and
- develop loss models for real-time flood forecasting (to make forecasts of flood levels more accurate).

This section briefly covers the concept of rainfall losses, and the importance of predicting them at catchment scale.

Then follow two main sections, corresponding to the two objectives above:

Part A describes losses for design flood estimation. Limitations of the currently recommended design losses are outlined, and the development of new losses consistent with the design information in *Australian Rainfall and Runoff* (*AR&R*, 1987) described.

An independent test was then undertaken to check:

- the application of existing design parameters, and
- the new design losses and areal reduction factors developed by the CRC for Catchment Hydrology.

Part B describes the estimation of losses for real-time flood forecasting. Two different measures of soil moisture are examined:

- the antecedent precipitation index, and
- pre-storm baseflow

to find the best predictor of loss.

A new variable proportional loss model, suitable for real-time flood forecasting, is described.

The conclusions summarise the main findings of both sections.

What is rainfall loss?

Rainfall loss is that part of storm precipitation that does not appear as the immediate runoff after a storm.

This loss is mostly caused by (see Figure 1):

- interception by vegetation
- infiltration into the soil
- retention on the surface (depression storage)
- loss through the stream bed and banks (transmission loss).

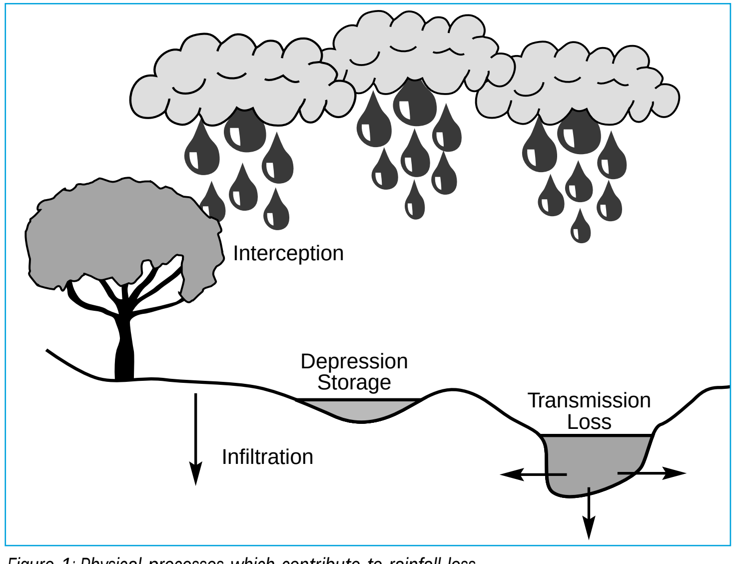


Figure 1: Physical processes which contribute to rainfall loss

Losses at catchment scale

The processes that contribute to rainfall loss may be well defined at a point; the difficulty occurs in trying to estimate a representative value of loss over an entire catchment. Spatial variability in topography, catchment characteristics (such as vegetation and soils) and rainfall makes it difficult to link the loss to catchment characteristics.

To overcome this, simplified lumped conceptual loss models are used. They combine the different loss processes and treat them in a simplified fashion.

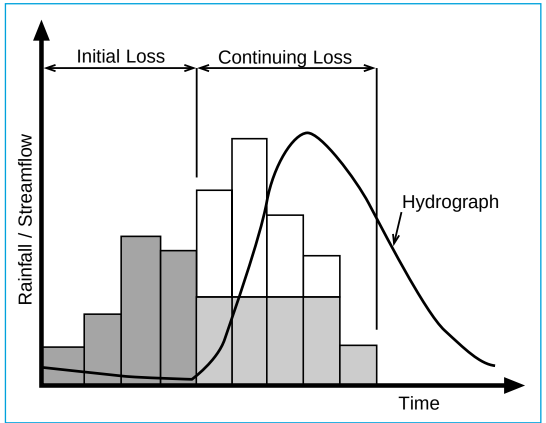


Figure 2: Initial loss – continuing loss model

The most commonly-used model in Australia is the *initial loss – continuing loss model* (Figure 2). 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, i.e. runoff occurs when the rainfall intensity exceeds the infiltration capacity of the soil.

In recent years a second runoff-generating mechanism, saturated overland flow, has been identified. This assumes that runoff is generated from the saturated portions of the catchment; this area increases with the duration and severity of the storm.

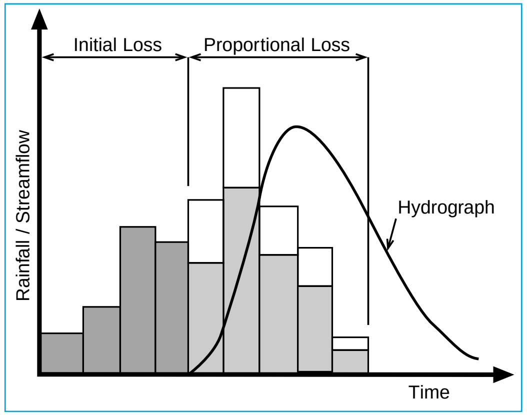


Figure 3: Initial loss – proportional loss model

The saturated overland flow concept is consistent with the *initial loss – proportional loss model* (Figure 3). The initial loss is as defined above. The proportional loss is a (constant) fraction of the rainfall after surface runoff has commenced, and can be regarded as 100 percent runoff from the saturated portion of the catchment, and zero runoff from the remainder. For simplicity, the proportional loss coefficient for a storm is usually taken as a constant.

Both the initial loss – continuing loss and the initial loss – proportional loss models were investigated. Only the initial loss – continuing loss model work is presented here since the initial loss – proportional loss model was found to be inferior in estimating the correct design flows.

Applying a point infiltration equation

A pilot study was undertaken on nine catchments to see if the application of a ‘theoretically correct’ loss model based upon a point infiltration equation (Green-Ampt) provided superior results to the simplified models at the catchment scale. Although the Green-Ampt equation was able to be successfully applied to each catchment, the results were not on average superior to those produced using the simplified loss models. Hence, this approach was not pursued further.

PART A: Losses for design flood estimation

Hundreds of millions of dollars are spent annually in Australia on works whose size or location depends on an estimate of a design flood. For all rainfall-based estimation methods, the design loss is a key factor in the estimation of a design flood of a given chance of occurrence.

Rainfall-based design flood estimation

Guidelines for rainfall-based design flood estimation are contained in *Australian Rainfall and Runoff* (*AR&R*, 1987). This document recommends an event-based methodology, and provides estimates of the different parameters to be used in design.

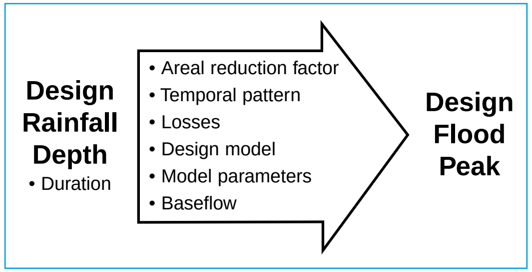


Figure 4: Event-based design flood estimation

The estimation of a design flood hydrograph with a specified annual exceedance probability (AEP) for a catchment, begins with a design rainfall of the same AEP. As indicated in Figure 4, the probability of the calculated design flood peak will depend upon the choice of the critical storm duration, areal reduction factor, rainfall temporal pattern, design losses, runoff model, model parameters and the baseflow.

Each component has a distribution of possible values, and the probability of the calculated flood peak should theoretically account for the effect of the combined probabilities. Because there is currently a lack of information on the true distribution of each of the components and the complexity involved, *AR&R* recommends taking some 'central' or 'typical' value for each of the key inputs.

Losses recommended in Australian Rainfall & Runoff (1987)

The losses recommended in *AR&R* are 'typical' values obtained from analysing the largest flood events observed in a catchment being studied.

Location	Median values of parameters
ACT	Initial loss zero Continuing loss 1.0–3.6 mm/h (depending on average recurrence intervals)
New South Wales East of the western slopes	Initial loss 10–35 mm, varying with catchment size and mean annual rainfall. Continuing loss 2.5 mm/h
Arid Zone, mean annual rainfall < 300 mm	Initial loss 15 mm Continuing loss 4 mm/h
Victoria South and east of the Great Dividing Range	Continuing loss 2.5 mm/h Initial loss 25–35 mm (Melbourne Water) Initial loss 15–20 mm (Rural Water Commission)
North and west of the Great Dividing Range	Probably as for similar areas of NSW

Table 1: AR&R recommended design losses

A summary of the recommended design losses for south-eastern Australia contained in *AR&R* is shown in Table 1. No recommendation is made for initial loss for Tasmania. There is a large range of values, with no guidance as to how the losses may vary with catchment characteristics. In addition there is no separate information available for the areas of Victoria north and west of the Great Dividing Range.

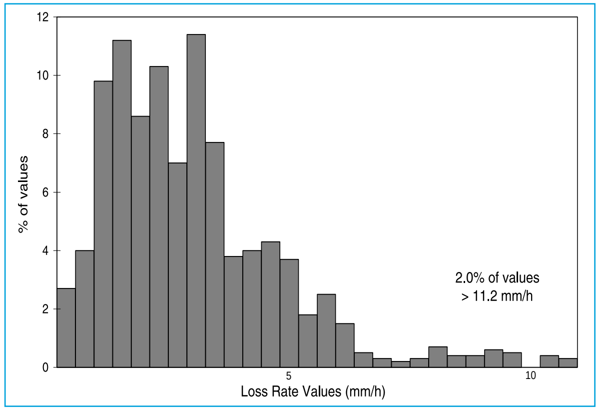


Figure 5: Frequency distribution of individual loss rate (from AR&R*)*

The recommended continuing loss values in Table 1 are average values. In practice, continuing loss for a catchment is highly variable, as shown in Figure 5.

In addition to the scarcity of information on design losses, most loss values were derived from analysing large runoff events. *AR&R* identifies two inadequacies in the loss values:

- The selection of large runoff events for loss derivation is biased towards wet antecedent conditions, as not all high rainfall events result in high runoff events. i.e. Losses tend to be too low.
- Loss values related to complete storm events (storm losses) do not account for the nature of the design rainfall information in Chapters 2 and 3 of *AR&R*, which has been derived from intense bursts of rainfall within longer duration storms. i.e. Losses tend to be too high.

AR&R recognises that these two inadequacies should have opposite effects; it is implicitly assumed by users of the current design loss values that they compensate one for the other.

DEVELOPING NEW DESIGN LOSSES

A study was undertaken to derive new design losses. Catchments were selected using the following criteria:

- *availability of good quality concurrent rainfall and streamflow data;*
- *small to medium sized rural catchments (catchment areas less than approximately 150 km^2);*
- *unregulated streamflow (no effects from storages upstream).*

Losses were calculated for the 22 catchments from Victoria and the ACT shown in Table 2. The location of the catchments is shown in Figure 6.

(Note: The identification code is used to label figures in this report)

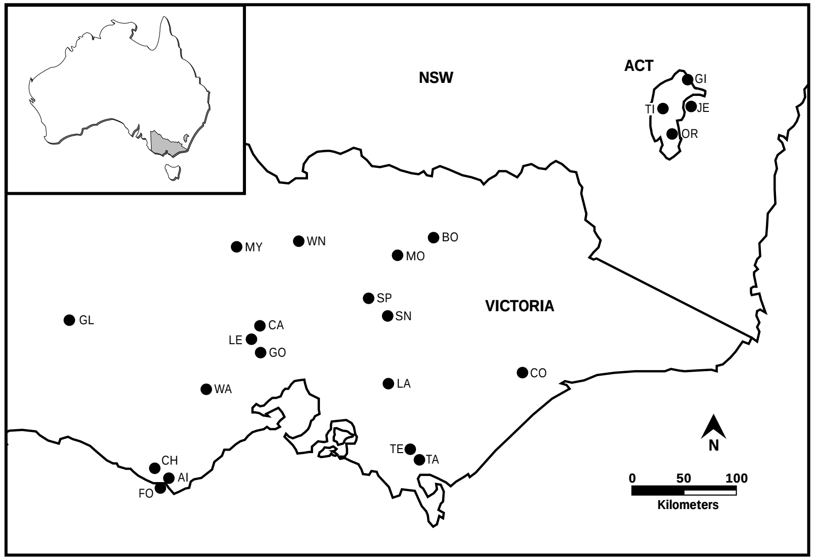


Figure 6: Locations of selected catchments

Losses were calculated to be consistent with the design rainfalls, i.e. estimated from intense bursts of rainfalls embedded within longer duration storms. This avoided the problem with losses calculated from events selected on the basis of runoff. All bursts of rainfall that had an average recurrence level (ARI) of more than a year were selected. Losses were calculated for 1,059 bursts of rainfall over the 22 catchments.

Catchment	Code	Area (km^2)	Rainfall (mm)
Tidbinbilla Ck @ Mountain Creek	TI	25	1120
Chapple Ck @ Chapple Vale	CH	28	1520
Goodman Ck above Lerderderg Tunnel	GO	32	800
Campaspe River @ Ashbourne	CA	33	960
Tarwin River East Branch @ Mirboo	TA	43	1140
Ginninderra Ck u/s Barton Highway	GI	48	640
Snobs Ck @ Snobs Ck Hatchery	SN	51	1660
Myers Ck @ Myers Flat	MY	55	520
Jerrabomberra Ck @ Four Mile Creek	JE	55	610
Ford River @ Glenaire	FO	56	1520
Glenelg River @ Big Cord	GL	57	680
Warrambine Ck @ Warrambine	WA	57	660
Spring Ck @ Fawcett	SP	60	720
La Trobe River @ Near Noojee	LA	62	1480
Orroral River @ Crossing	OR	90	750
Aire River @ Wyelangta	AI	90	1880
Moonee Ck @ Lima	MO	91	1060
Cobbannah Ck @ Bairnsdale	CO	106	840
Boggy Ck @ Angleside	BO	108	1080
Wanalta Ck @ Wanalta	WN	108	540
Tarwin R East Branch @ Dumbalk Nth	TE	127	1140
Lerderderg River @ Sardine Ck	LE	153	1080

Table 2: Selected catchments

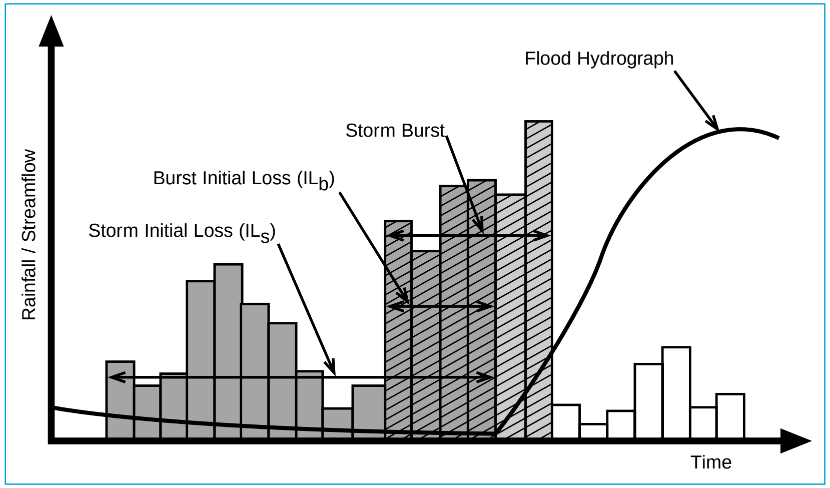


Figure 7: Initial loss for an embedded rainfall burst

For each selected rainfall event, the time of first surface runoff (if any) was noted to calculate storm initial loss. The continuing loss was determined to preserve the volume balance of rainfall and runoff.

It was then necessary to consider the estimation of losses for bursts of rainfall embedded within longer duration storms. The difference between the initial loss for a burst and for a storm is illustrated in Figure 7. The initial loss for the storm is assumed to be the depth of rainfall before surface runoff begins. The initial loss for the burst, however, is the part of the storm initial loss which occurs within the burst. The burst initial loss depends on the position of the burst within the storm. It can range from zero (if the burst occurs after surface runoff has commenced) up to the full storm initial loss.

The initial loss values contained in *AR&R* represent storm initial losses. However, the burst initial loss should be used for design.

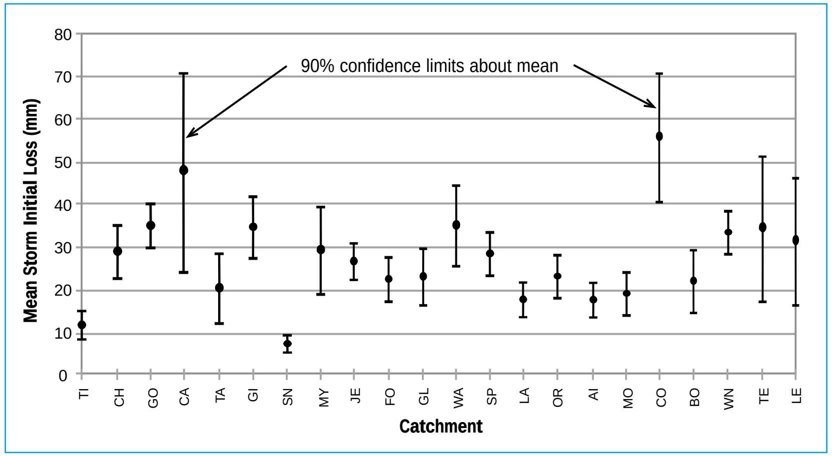


Figure 8: Mean storm initial loss by catchment (identification codes in Table 2)

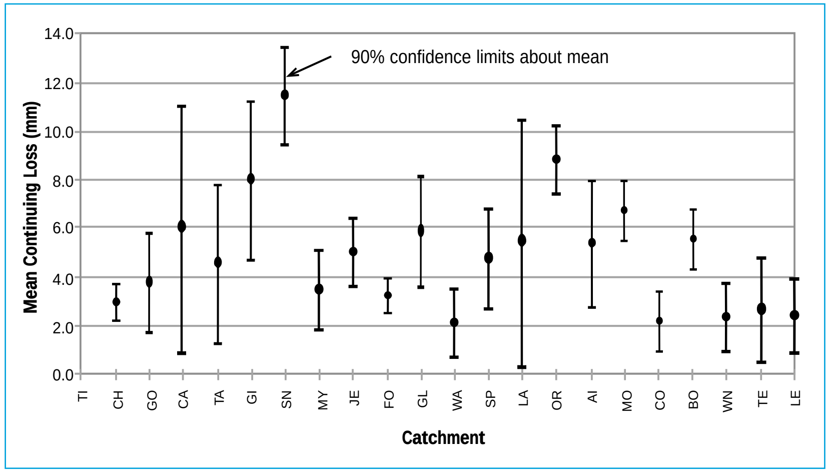


Figure 9: Mean continuing loss by catchment (identification codes in Table 2)

Results

The mean storm losses and the typical range of variation between events for each catchment are shown in Figures 8 and 9.

It is worth noting that several of the mean values of storm initial loss are outside (generally higher than) the range of values given in *AR&R* (Table 1). For continuing loss, most values are higher than the recommended 2.5 mm/h.

Burst initial loss

In the previous section, the mean storm initial losses are summarised. They do not however account for the embedded nature of the design rainfalls contained in *AR&R*, ie they are bursts of rainfall within longer duration storms. It is therefore expected that the initial loss suitable for design (the burst initial loss; IL_b) should be lower than that obtained for the complete storm (the storm initial loss; IL_s).

Examination of the mean ratios of IL_b to IL_s showed a weak trend with mean annual rainfall (MAR); wetter catchments having generally lower values of IL_b/IL_s . In order to derive a value of IL_b for design, an equation was fitted to the mean values of IL_b/IL_s from each duration and catchment.

$$IL_b = IL_s\left\{1 - \frac{1}{1 + 142\frac{\sqrt{(duration)}}{MAR}}\right\} \quad N=75,\ r^2=0.43,\ SE=18\% \qquad (1)$$

While the relatively low values of r^2 indicate considerable scatter about the fitted line, even after allowing for the effect of mean annual rainfall, the relationship should provide a satisfactory basis for probability-based design. Nevertheless, it should be remembered that there is a significant chance of IL_b/IL_s being close to zero, even for longer duration bursts.

Seasonal variation of losses

In the above sections, mean losses were derived for each catchment without considering how these losses varied seasonally. Initial loss, and possibly continuing losses, are related to antecedent moisture; hence a seasonal variation in derived losses is likely.

The number of storms for individual catchments was not sufficient to study the seasonal variation of derived losses for individual catchments, so the data were standardised by dividing by the mean loss for each catchment and then pooled. The mean standardised loss for all catchments was then calculated for each month, and a sinusoidal curve fitted (Figures 10 and 11) to the values.

These curves confirm that there is a distinct seasonal variation of losses which is adequately represented by sinusoidal relationships.

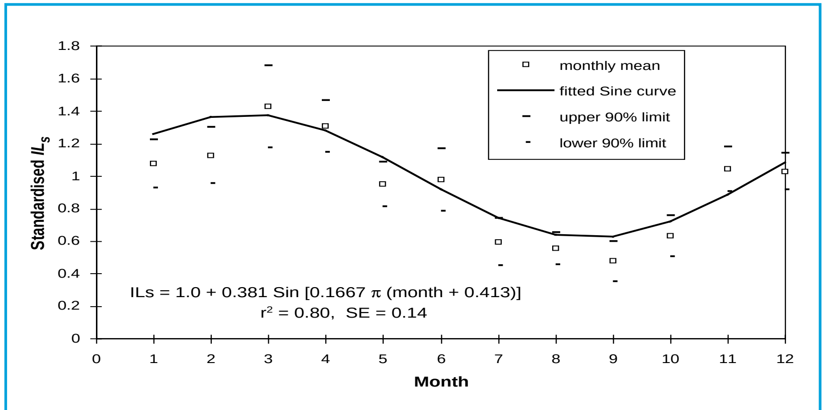


Figure 10: Monthly variation of storm initial loss (pooled data)

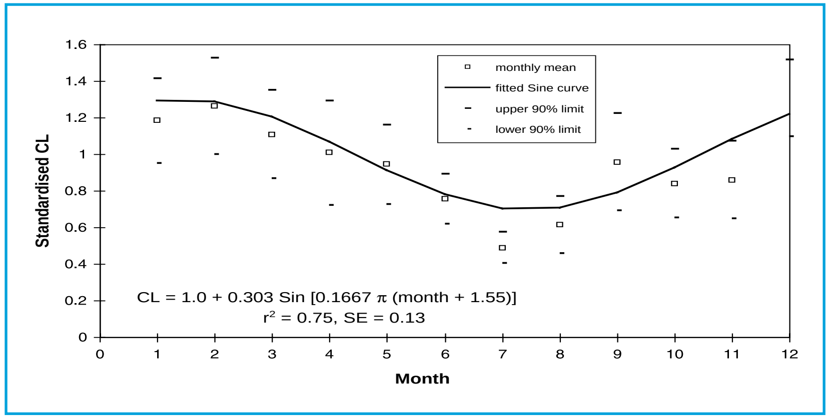


Figure 11: Monthly variation of continuing loss (pooled data)

How does loss vary with rainfall severity?

The answer is difficult because of the lack of severe rainfall events in the recorded data (see Figure 12). More than half of the bursts analysed had average recurrence intervals (ARIs) of less than two years; only 4 percent of bursts had ARIs of greater than 20 years.

There were not enough individual-catchment events to study the variation of losses with ARI, so the data were again standardised by dividing by the mean loss for the catchment and then pooled.

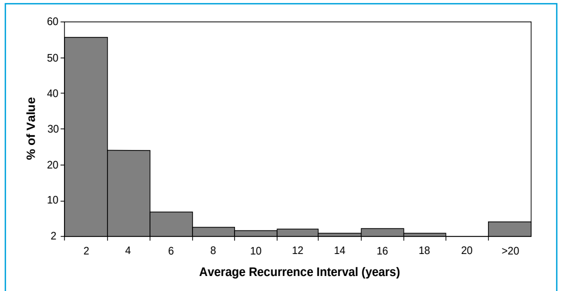


Figure 12: Distribution of burst ARIs

The derived loss parameters for each of the bursts are plotted against ARI in Figures 13 and 14, and show that it is difficult to determine any loss trends with ARI. The data were also grouped into three ranges according to their ARI, but no significant trend was observed. The conclusion is that this study has produced no evidence that the design loss rate varies with rainfall severity.

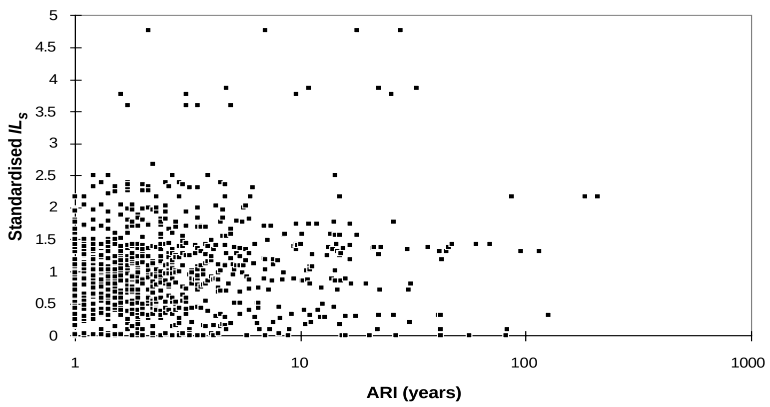


Figure 13: Variation of storm initial loss with ARI (all catchments)

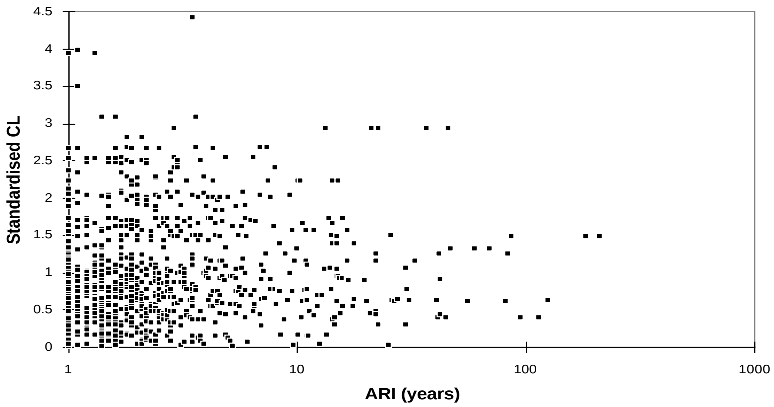


Figure 14: Variation of continuing loss with ARI (all catchments)

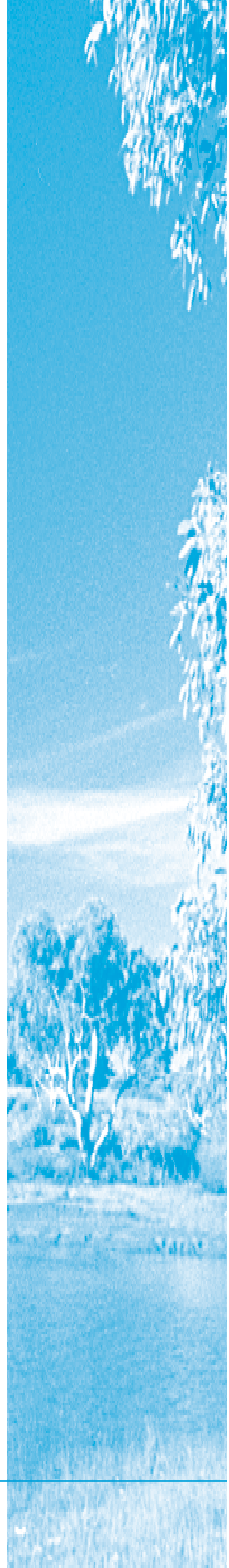
PREDICTION EQUATIONS

The aim was to produce estimates of losses for any catchment in the region represented by the data. For this, the results obtained from individual catchments must be generalised – a process called regionalisation.

Difficulties

Many authors have concluded there is no relationship between mean losses and characteristics of soil and vegetation at catchment scale. This failure to relate losses to catchment characteristics may be due to the following:

- Variability that is not related to catchment characteristics may result from difference in methods to estimate losses for different catchments.
- The loss from any storm depends strongly on antecedent conditions; therefore the mean loss for a catchment will be affected by the sample of events (storms) used. This is especially important given the strong seasonal variation of losses noted earlier in this report.
- Calculated loss values reflect any errors in rainfall and streamflow data. The variability of rainfall over an area, and the usually limited number of raingauges, mean that estimates of catchment average rainfall (and so the values of losses) are not reliable.
- Catchment characteristics vary spatially; soil hydraulic properties can vary enormously over an area which seems to be similar terrain. This makes it difficult to estimate representative parameters for a catchment.
- Little information is available on the hydraulic properties of soils. The current classification of soils in Australia is based upon texture; little work has been done on the classification of soils according to hydraulic properties.



The CRC study was better able to relate losses to catchment characteristics because it used the same methods to estimate losses in each catchment, and accounted for antecedent conditions. However, it was still hindered by the last three factors above. The derived mean losses for each catchment were successfully related to catchment characteristics, once the seasonal variation had been taken into account.

Results

The prediction equations below are recommended for use with the temporal patterns in *AR&R* (Chapter 3), as well as with the new areal reduction factors developed by the CRC for Catchment Hydrology (in a separate project, Siriwardena and Weinmann, 1996).

In these equations:

BFI – the baseflow index is the volume of baseflow divided by the total streamflow volume. It is a fixed value for a given catchment, determined as an average ratio over a long time period. [Range of values used in the equation was 0.08 to 0.81]

MAR – mean annual rainfall in mm, obtained from Duncan (1982) or similar [Range 520 to 1880mm]

PET – the mean annual potential evaporation, estimated from climate or pan evaporation data. Alternatively it can be derived from maps in Grayson et al (1996) or HydroTechnology (1995). [Range 1000 to 1610mm]

duration – the design rainfall duration in hours. [Range 2 to 72h]

The storm initial loss (IL_s) should first be calculated using Equation 2, and then the burst initial loss (IL_b) for each duration using Equation 3. The burst initial loss accounts for the embedded nature of the design rainfalls within storms and should be used in design. The continuing loss is estimated using Equation 4.

Storm initial loss:

$$IL_s = -25.8\,BFI + 33.8 \qquad r^2=0.55 \quad SE=5.1 \qquad (2)$$

Burst initial loss:

$$IL_b = IL_s \left\{ 1 - \frac{1}{1 + 142\dfrac{\sqrt{(duration)}}{MAR}} \right\} \qquad r^2=0.43 \quad SE=18\% \qquad (3)$$

Continuing loss:

$$CL = 7.97\,BFI + 0.00659\,PET - 6.00 \qquad r^2=0.60 \quad SE=1.5 \qquad (4)$$

Seasonal adjustment

This study has shown that storm initial loss and continuing loss vary significantly with season. The regional prediction equations have been derived using losses adjusted for this seasonal variation. If the distribution of events is considered to be uniform throughout the year, the given loss values can be used without correction. However, if the uneven distribution of events found in the sample is considered typical, then the average annual value of storm initial loss used for design should be increased by 8 percent, and continuing loss should be increased by 5 percent. If design flood estimates for a specific season are required, the design loss values can be corrected for seasonality effects as shown in Figures 10 and 11.

Predicting baseflow index for ungauged catchments

The baseflow index (BFI), a useful indicator of catchment loss, is only directly available for gauged catchments; however it appears to vary quite smoothly between gauge locations. Appendix A shows a plot of derived BFI values; from it a reasonable estimate of BFI can be made for locations in much of Victoria.

Alternatively, Lacey (1996) has examined the prediction of BFI for ungauged catchments. In his work, the native vegetation was identified and classified for each catchment and combined with the underlying geology to form geology – vegetation classes. Geology – vegetation classes explained approximately 85 percent of the variation in BFI. This work allows prediction of BFI for ungauged catchments based upon:

- the native vegetation, which is available from reports such as the Land Conservation Council Victoria Reports or from an inspection of the catchment
- the underlying geology, which is readily available from 1:250,000 geological maps.

Testing new design inputs

An independent test was undertaken to determine the effect on design flood estimates of using

- existing AR&R parameters
- new areal reduction factors
- new design losses.

The testing was by comparison with results of flood frequency analysis, and was undertaken for annual exceedance probabilities (AEPs) of 1 in 10 and 1 in 50.

Selected catchments

The testing was undertaken on 10 catchments (nine in Victoria and one from the ACT) ranging in area from 32 to 332 square kilometres. The catchments are listed in Table 3 (eight were used to derive the new losses, but the test procedure is still an independent assessment, as shown below).

Catchment	Code	Area (km^2)	Streamflow data start	end	years
Goodman Ck	GO	32	1971	1995	25
Ford River	FO	56	1970	1986	17
Orroral River	OR	90	1968	1995	28
Aire River	AI	90	1968	1995	28
Moonee Ck	MO	91	1963	1995	33
Wanalta Ck	WN	108	1961	1995	35
Tarwin River	TE	127	1971	1995	25
Lerderderg River	LE	153	1960	1995	36
Avon River	AV	259	1965	1995	31
Seven Cks	SE	332	1964	1995	32

Table 3: Summary of selected catchments

The catchments are shown in Figure 15; they represent a geographic spread covering a large part of Victoria (with one in the ACT).

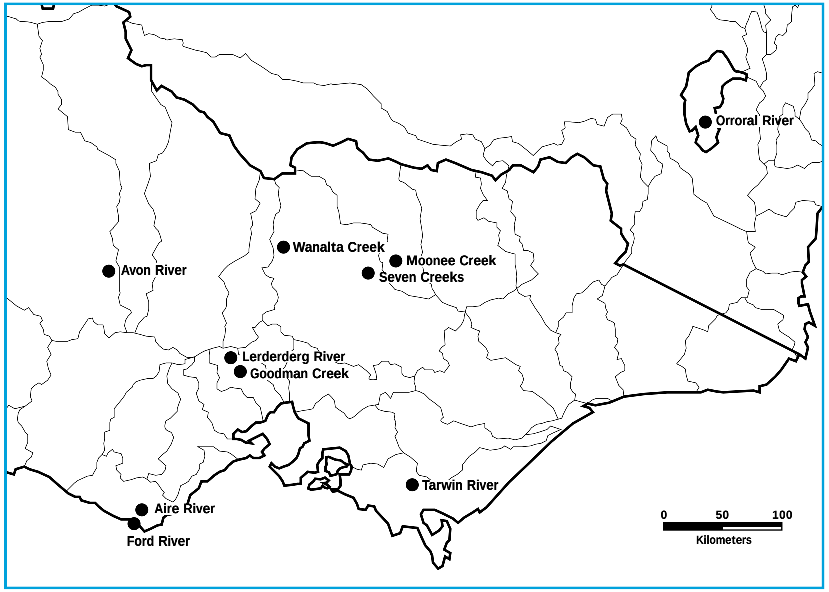


Figure 15: Location of study catchments

Flood frequency analysis

A flood frequency analysis of recorded peak flows was undertaken for each catchment, with the log-Pearson III distribution being used for this purpose. Flood estimates from the analysis were used to test the performance of the 'old' and 'new' rainfall-based, design peak flow estimates.

The occurrence of low flows in the annual series can have a significant effect on fitting a frequency distribution to an annual series of flood peaks. The annual series were checked for low flows. If present, these flows were omitted and the probability adjustment recommended in *AR&R* applied.

RORB modelling

A RORB model was developed for each of the 10 catchments in Table 3. The model subtracts losses from rainfall to produce rainfall-excess and routes this through the catchment to produce a hydrograph at the point of interest. The catchment is subdivided into a number of sub-areas to account for catchment and channel storage, and allow spatially non-uniform rainfall over the catchment. A consistent model definition and calibration approach for the different catchments is important to reduce result variability.

The RORB models were calibrated using the largest recorded flood events which had streamflow and rainfall data. For each catchment, at least six events were selected for calibration. Some of these events had data errors or inconsistencies that affected the calibration; these events were discarded. The final number of events used for calibration varied from four to eight per catchment.

Apart from the two loss parameters in RORB, there are two routing parameters that can be used for calibration:

m a measure of the catchment's non-linearity: a value of 1 implies a linear catchment

k_c a measure of the storage in the catchment; the principal parameter of the model.

In this study m was set to 0.8. The initial loss was varied so that the rising limb of the calculated hydrograph matched the recorded hydrograph. The k_c was varied to match the peak flow.

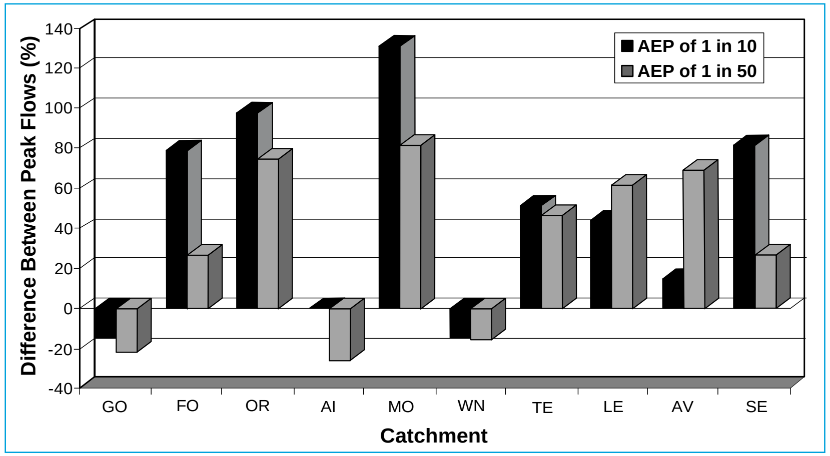


Figure 16: Comparison of flood estimates using frequency analysis of observed data and runoff routing using AR&R *parameters*

Results using *AR&R* design values

For this study, an initial loss of 20 mm and a continuing loss of 2.5 mm/h were adopted for all catchments to represent design losses recommended in *AR&R*.

Information on design rainfall depths (IFD data), temporal patterns and areal reduction factors was taken directly from *AR&R*. The losses were applied to the design rainfalls, and the resultant rainfall excess routed through the RORB models using the calibrated parameters. Design storms from 1 to 72 hours were routed through the RORB model, and the critical duration was estimated as that which gave the largest peak flow.

Following *AR&R*, the design surface runoff was then converted to a design total flow by adding an estimate of the baseflow to the surface runoff (the average of the baseflow for the calibration events).
The resulting peak flow was taken as the design peak flow for the given annual exceedance probability, and compared to that obtained from the flood frequency analysis.

Figure 16 shows the differences between the peak flows obtained using the rainfall-based approach with *AR&R* design values, and using flood frequency analysis. Clearly, from this figure, the use of the *AR&R* design values results in over-estimation of the peak flows for seven of the 10 catchments. The average over-prediction is 47 percent for an AEP of 1 in 10 and 32 percent for an AEP of 1 in 50.

This independent test represents the application to ungauged catchments, i.e. where design losses cannot be calibrated against the results from flood frequency analysis.

Effect of new areal reduction factors

Areal reduction factors (ARFs) convert point rainfall intensities to average rainfall intensities over a catchment of a given area. They take into account the observation that larger catchments are less likely than small catchments to have high intensity rainfall over the whole catchment.

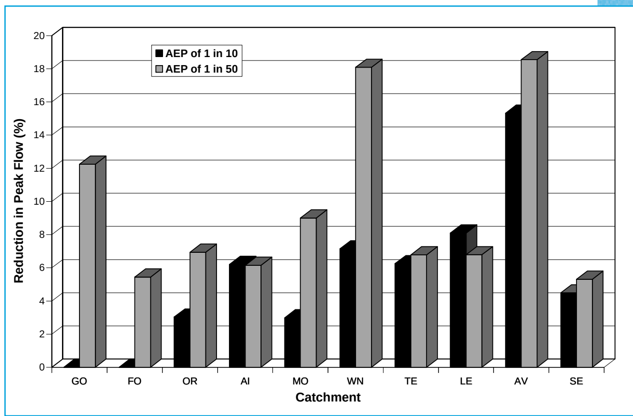


Figure 17: Effect of using new ARFs on the design flood peak

The ARFs in *AR&R* are based upon studies done in Chicago and Arizona in the USA, because of a lack of Australian data. A major study was therefore initiated, as part of CRC for Catchment Hydrology Project D3, to derive new ARFs for Victoria (Siriwardena and Weinmann, 1996).

The new ARFs are considered applicable for Victoria and for regions with similar hydrometeorological characteristics; they are approximately 5 percent lower for a duration of 24 hours and approximately 10 percent lower for a duration of 2 hours than the respective *AR&R* values.

The effect of using the new ARFs was tested. The design flood estimates from the previous section were repeated, with the same losses, using the new ARFs. The average reduction in peak flows was 6 percent for an AEP of 1 in 10, and 9 percent for an AEP of 1 in 50 (although peak flows were reduced by 18 percent for some specific catchments) see Figure 17. There was no reduction for Goodman Creek and Ford River (for an AEP of 1 in 10).

Catchment	Code	Area (km^2)	BFI	PET (mm)	MAR (mm)	IL_S (mm)	CL (mm/h)
Goodman Creek	GO	32	0.13	1080	800	33	2.3
Ford River	FO	56	0.58	1050	1520	20	5.8
Orroral River	OR	90	0.54	1410	750	22	8.0
Aire River	AI	90	0.58	1050	1880	20	5.8
Moonee Creek	MO	91	0.65	1125	1060	18	7.0
Wanalta Creek	WN	108	0.08	1175	540	34	2.5
Tarwin River	TE	127	0.39	1000	1140	26	3.9
Lerderderg River	LE	153	0.41	1100	1080	25	4.8
Avon River	AV	259	0.09	1110	565	34	2.1
Seven Creeks	SE	332	0.47	1150	925	23	5.6

Table 4: Predicted design losses

New design losses

Design losses were estimated for each catchment using the new prediction equations. Table 4 shows the new storm loss values, and the burst initial loss was calculated for each duration. These losses were then applied to the design rainfall depths from *AR&R* (with the new ARFs), and the excess routed through the catchment to produce design flows for AEPs of 1 in 10 and 1 in 50.

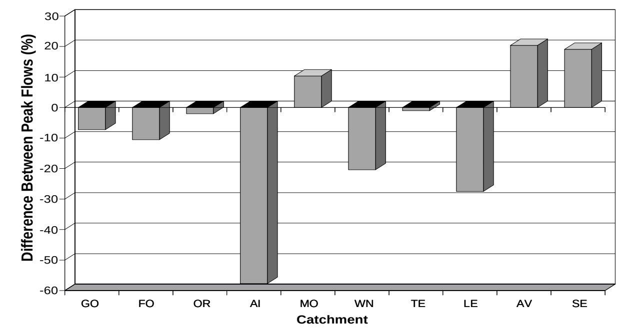


Figure 18: Comparison of flood estimates using frequency analysis of observed data and runoff routing using new ARFs and loss parameters (AEP of 1 in 10)

In Figure 18, the peak flows for an AEP of 1 in 10 are compared with the new flows obtained from the flood frequency analysis. Clearly, estimated peak flows are more consistent with flood frequency analysis results.

Apart from the peak flow for the Aire River, which was underestimated by 58 percent, the peak flow is now estimated to within approximately 25 percent using this method.

Summary of design loss work

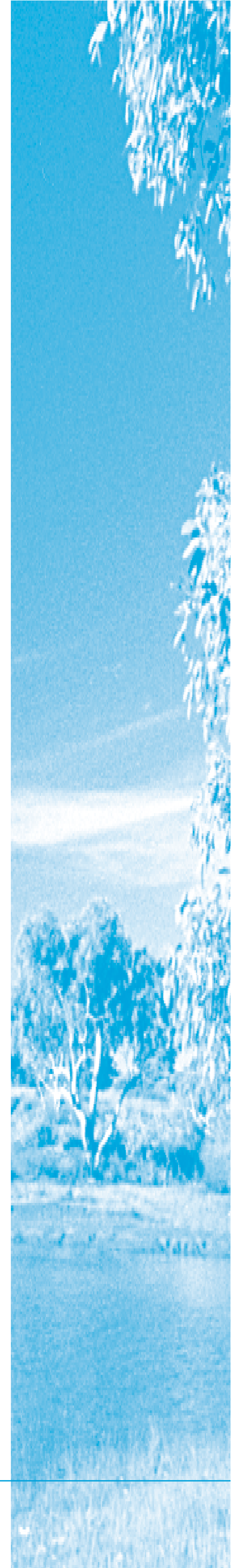
Application of design values in *AR&R* consistently overestimated peak flows; use of the new loss values with the new ARFs has removed this bias. However, verification of design losses depends upon the choice of all key inputs in the modelling process; different assumptions about any input could affect conclusions about the others.

The new design loss values are recommended for design flood estimation for south-east Australia because:

- they are based on a detailed study using a methodology consistent with the derivation of design rainfalls
- they can be estimated from prediction equations which incorporate plausible relationships with catchment and climatic characteristics
- they produced satisfactory results when tested on 10 catchments.

The areas and mean annual rainfalls of the catchments used in the derivation and testing of the losses should be noted. The losses appear applicable to the majority of catchments in Victoria with catchment areas up to 500 square kilometres. It is recommended that similar analyses be undertaken in other states, to derive design losses consistent with design rainfalls.

Given sufficient benchmarking and testing by the profession, it is proposed that the loss values contained in this report be incorporated in future updates of design guidelines for design flood estimation (including *Australian Rainfall & Runoff*).



PART B: Losses for flood forecasting

Real-time flood forecasting

In flood forecasting, the parameters of an actual event (including loss parameters) are required. This differs from design flood estimation, where 'average' parameter values are adopted. The estimation of initial loss is often critical, as it determines the initial rise and in many cases the peak of the flood hydrograph.

The amount of initial loss is indirectly related to the moisture condition of the catchment at the start of the storm. However, no single observation is appropriate to define the pre-existing soil moisture of a catchment, and observed soil moisture data are not usually available. Hence most of the investigations on empirical relationships of initial loss are based on a simple representative index of catchment moisture.

Soil moisture

A pilot study was undertaken on 10 Victorian catchments to investigate the relationship between initial loss and different soil moisture indices. The principal indices investigated were:

- the antecedent precipitation index
- pre-storm baseflow.

The antecedent precipitation index (API) is a function of the current and preceding days' rainfall. It is the most commonly used index.

The pre-storm baseflow is the recorded streamflow prior to an event which is not directly from surface runoff, but comes from drainage of groundwater. This baseflow comes from the whole catchment.

Pilot study results

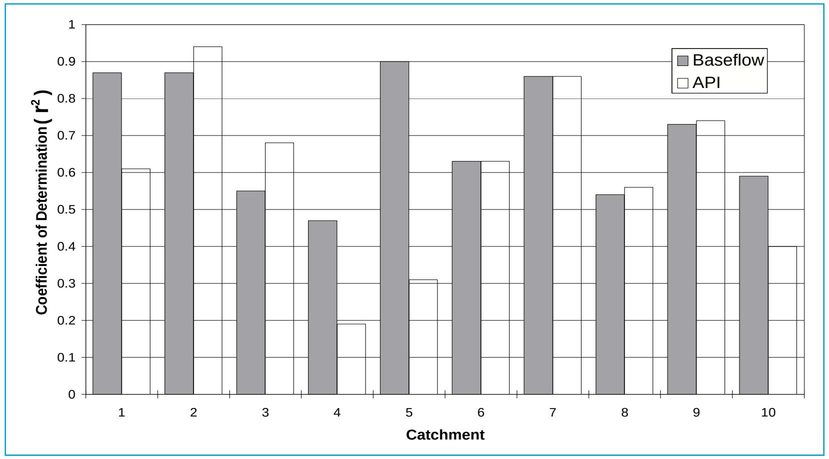


Figure 19: Summary of relationships between initial loss and soil moisture indices

The initial loss and soil moisture indices were calculated for approximately 12 events for each of the 10 catchments. The indices were varied to determine the best relationship with initial loss. A summary of the results for each catchment is shown in Figure 19.

The figure shows that both the baseflow and API were useful predictors of initial loss, with the baseflow performing slightly better than the API over the range of catchments.

A VARIABLE PROPORTIONAL LOSS MODEL

A possible relationship between the runoff factor, the pre-storm baseflow and rainfall depth was investigated using the results of the pilot study.

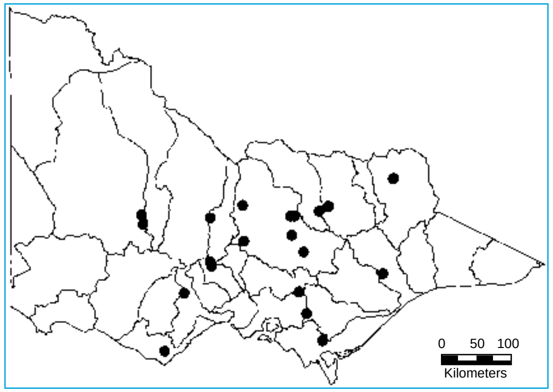


Figure 20: Location of study catchments

The lumped conceptual models currently used for both design and real-time applications are gross approximations of the processes contributing to total rainfall loss. Some studies have attempted to incorporate the concept of saturation areas (source areas) in loss modelling. In these studies, a runoff factor is related to a soil moisture index, the storm rainfall and catchment characteristics.

Twenty unregulated Victorian catchments were selected for the study on the basis of the availability of rainfall and streamflow data. Their locations are shown in Figure 20. The catchment areas ranged from 44 to 609 km^2.

For each catchment, the volumetric runoff coefficient was calculated for between 25 and 80 different events as:

$$\text{volumetric runoff coefficient} = \frac{\text{volume of surface runoff}}{\text{volume of storm rainfall}} \qquad (5)$$

For each event, the volumetric runoff coefficient was plotted against the pre-storm baseflow and each point was labelled with the storm rainfall. An example of such a plot is shown in Figure 21 for Cobbannah Creek. There is a tendency for the runoff coefficient to increase with increasing pre-storm baseflow and storm rainfall. The challenge was to find a mathematical relationship to reproduce the trend indicated by the data.

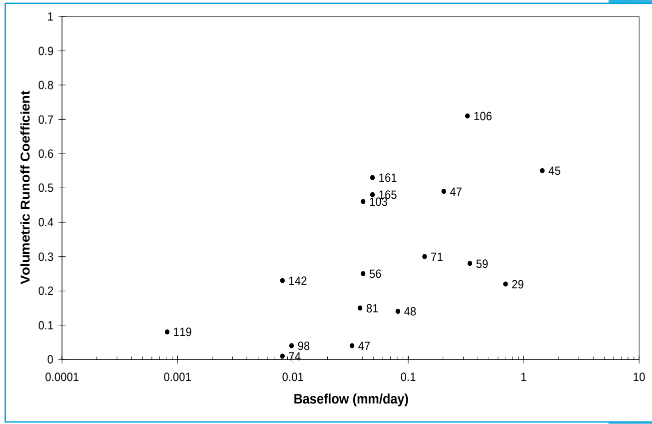


Figure 21: Example of a plot of runoff coefficients for Cobbannah Creek

A logistic function was fitted to the data set from each catchment. The advantage of using a logistic function is that it has an upper bound of 1 and initial loss can be modelled by using a value of d greater than 1.

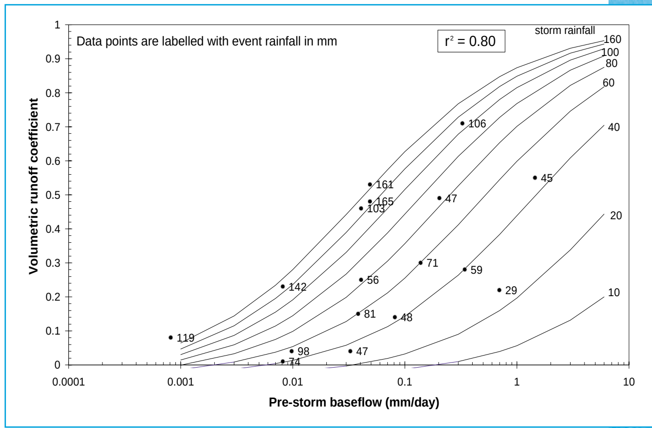


Figure 22: Example of a fitted logistic equation for Cobbannah Creek

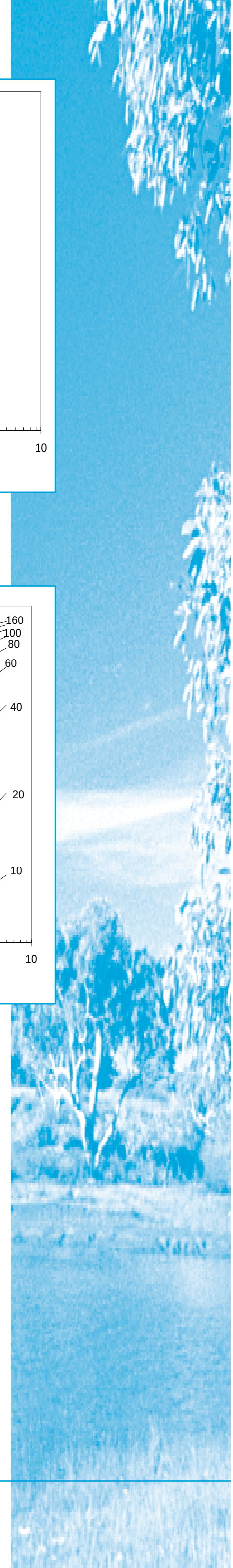
$$roc = (1-d) + \frac{1}{\frac{1}{d} + aBF^{b}RAIN^{c}} \qquad (6)$$

where: *roc* is the volumetric runoff coefficient

BF is the pre-storm baseflow in mm/day

RAIN is the storm rainfall in mm

a, b, c, d are coefficients determined by regression



An example is shown in Figure 22 for Cobbannah Creek. The equation adequately represents the relationship between volumetric runoff coefficient, rainfall amount and pre-storm baseflow.

Logistic functions were fitted to the data sets from each catchment. The goodness of fit is indicated by the coefficient of determination (r^2) summarised in Figure 23. For 80 percent of the catchments, a satisfactory relationship could be established (r^2>0.50). However, even in these catchments, the standard error in the estimated runoff coefficient is quite high (typically 30–40 percent).

A relationship could not be successfully fitted to data from the La Trobe River (Catchment 4) which has high levels of sustained baseflow. For this catchment, pre-storm baseflow is not a good indicator of antecedent wetness.

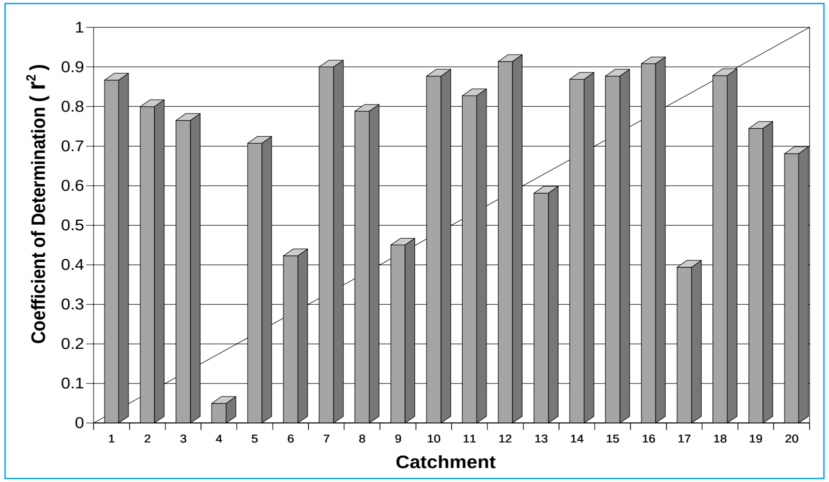


Figure 23: Performance of fitted logistic functions

APPLYING THE MODEL

Once the parameters have been calibrated for a given catchment, the variable proportional loss model can be used to estimate incremental (or progressive) runoff from the pre-storm baseflow and the storm rainfall. This is illustrated in Figure 24.

The variable proportional loss model can be applied using the following steps:

- determine the pre-storm level of baseflow
- estimate the initial loss (if any) as the value of storm rainfall that intersects the horizontal axis at the value of the known baseflow
- for given cumulative storm rainfall depths, read off the progressively increasing values of the volumetric runoff coefficient.

In this manner, the pattern of loss throughout the whole storm can be found.

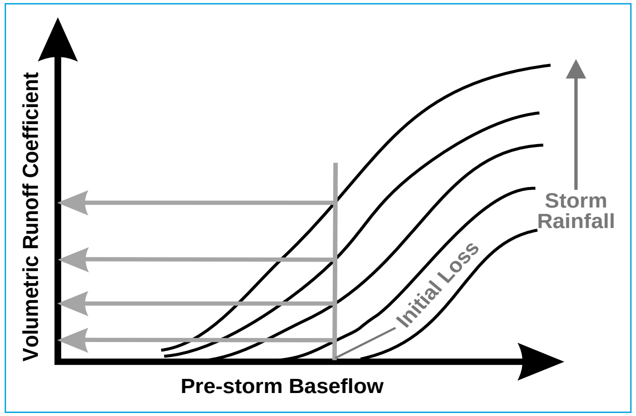


Figure 24: Applying the variable proportional loss model

Regionalisation of model parameters

Before relating loss model parameters to catchment characteristics, the function had to be simplified to a smaller number of parameters. Consideration of calibrated parameters showed that parameters *b, c* and *d* are less variable than parameter *a*. Parameters *b, c* and *d* were therefore fixed at their average values, which simplified the function to Equation 7.

$$roc = -0.035 + \frac{1}{0.966 + a.\,BF^{\text{[illegible]}}.\,RAIN^{\text{[illegible]}}} \qquad (7)$$

The simplified one-parameter equation was refitted to all catchments (with a decrease in the r^2 for some catchments of up to 20 percent) and the parameter *a* was then related to catchment characteristics. The following two prediction equations for parameter *a* were developed. The first is recommended for catchments where streamflow data is available to estimate the baseflow index (BFI). In the absence of streamflow data, Equation 9 is recommended. Alternatively, BFI can be estimated as outlined on page 10 of this report.

$$a = 2.68 + 861.\,BFI^{\text{[illegible]}}\,S1085^{\text{[illegible]}} \qquad r^2=0.98 \qquad SEE=22\% \qquad (8)$$

where: *BFI* is the baseflow index;

S1085 is the mainstream slope between the 10 and 85 percentile of mainstream from the catchment outlet.

$$a = 57.1 + 0.004.\,MAR^{\text{[illegible]}}.\,S1085^{\text{[illegible]}} \quad r^2=0.74 \quad SEE=73\% \qquad (9)$$

where: *MAR* is the mean annual rainfall (mm)

Using Equation 8 or 9, the parameter *a* can be estimated from easily measurable catchment characteristics. Once *a* has been estimated, incremental runoff coefficients can be obtained for different rainfall depths and a known pre-storm baseflow.

Depending on the availability of data, the model can be applied to a specific catchment in either of two principal ways:

- Fitting a logistic function of the form of Equation 6 to runoff coefficients determined from recorded storm rainfall and runoff. This is only possible for gauged catchment and requires considerable effort, but produces more reliable results.
- Use of the one-parameter regional equation (Equation 7) with either of the prediction equations (Equations 8 and 9). This is applicable to any catchment with similar characteristics as the ones represented in the data analysed, but involves a larger standard error of estimate.

Advantages

The proposed variable proportional loss model has the following advantages when compared to the API method of predicting initial loss described earlier:

- because total volumes of rainfall and runoff are used, there is no need to estimate the initial loss
- the model is therefore less susceptible to timing errors
- the distribution of loss over time is more realistic.

Limitations

The new loss model has several limitations.

- There is limited applicability for ephemeral streams, as it requires an estimate of pre-storm baseflow.
- Depletion of soil moisture during rainless periods is not modelled; this can lead to the overestimation of runoff coefficients towards the end of protracted storms.
- Streams with very high levels of sustained baseflow are not modelled well because for these catchments pre-storm baseflow is not a good indicator of catchment wetness.
- The method requires natural streamflow data and therefore has limited applicability for streams which are regulated or affected by snowmelt.
- Applying the single parameter regional equation results in less reliable estimation of losses than if the model is fitted to catchment-specific rainfall and runoff data.

In future work, the variable proportional loss model could be applied in the design context. This would involve the selection of average or 'typical' values of pre-storm baseflow. This area holds some promise, but further work is required before parameters suitable for design can be recommended.

Summary of flood forecasting work

This work has shown that pre-storm baseflow is a good indicator of antecedent wetness. On a pilot study of 10 Victorian catchments the pre-storm baseflow better predicted initial loss than the antecedent precipitation index (API).

A variable proportional loss model – suitable for real-time flood forecasting was developed. The model related incremental runoff coefficients to pre-storm baseflow and rainfall depth.

Given sufficient rainfall and streamflow data, the four parameters can be calibrated for any particular catchment. Alternatively, the simplified function can be used and the single parameter estimated from catchment characteristics.

The model is less susceptible to timing errors and gives a more realistic distribution of losses over time than conventional lumped conceptual loss models. However, it has limited application to ephemeral streams, and for derivation of its parameters it requires unregulated streamflow data that is not influenced by snowmelt.

Conclusions

Rainfall loss is the precipitation that does not appear as surface runoff. Because of the difficulties in defining loss at the catchment scale, lumped conceptual models are often adopted which are gross simplifications of the relationships between the spatial variation of rainfall and catchment characteristics.

Part A: Losses for design flood estimation

The design parameters currently recommended in *Australian Rainfall and Runoff* (1987) suffer from being incompatible with design rainfall information and no link has been established between losses and catchment characteristics. Their use, in combination with other design information contained in *AR&R*, leads to consistent over-estimation of design peak flows when compared with a frequency analysis of recorded peak flows. For an annual exceedance probability (AEP) of 1 in 10, the average over-prediction is 47 percent.

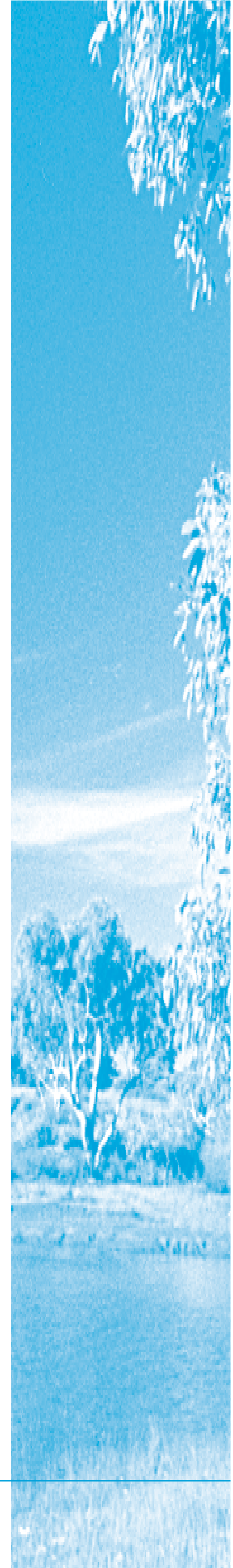
New design losses have been derived from the analysis of rainfall and streamflow data from 22 catchments, in a manner consistent with the design information contained in *AR&R*. Prediction equations have been developed that relate design loss to easily measurable catchment and climatic characteristics.

Application of the new design losses and new areal reduction factors developed by the CRC for Catchment Hydrology removes the bias in predicted design peak flows. For nine of the 10 catchments, the 1 in 10 AEP design flow was predicted to within 25 percent of that estimated using flood frequency analysis.

Part B: Losses for flood forecasting

The study has also shown that pre-storm baseflow is a good indicator of antecedent wetness. On a pilot study of 10 Victorian catchments the pre-storm baseflow was a better predictor of initial loss than was the antecedent precipitation index (API).

A new loss model has been developed for real-time flood forecasting. The variable proportional loss model is consistent with the assumption of runoff from saturated areas and relates the incremental runoff coefficient to the pre-storm baseflow and storm rainfall depth. Regional prediction equations for the model parameter have been developed to allow application on ungauged catchments.



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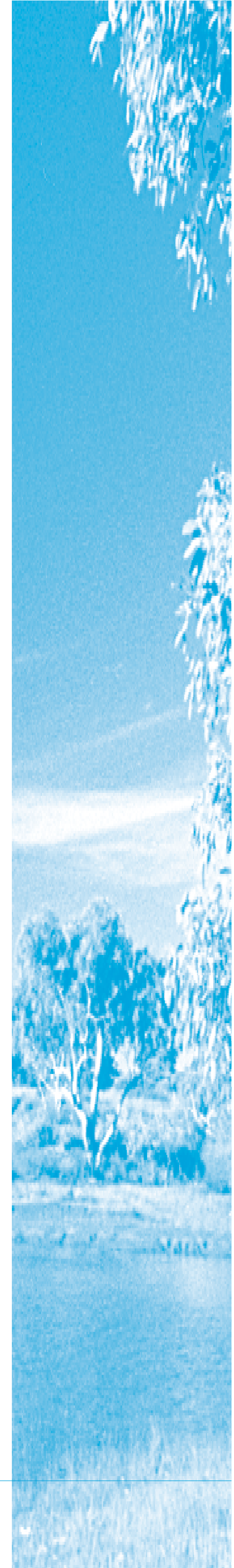

Appendix A - Values of baseflow index

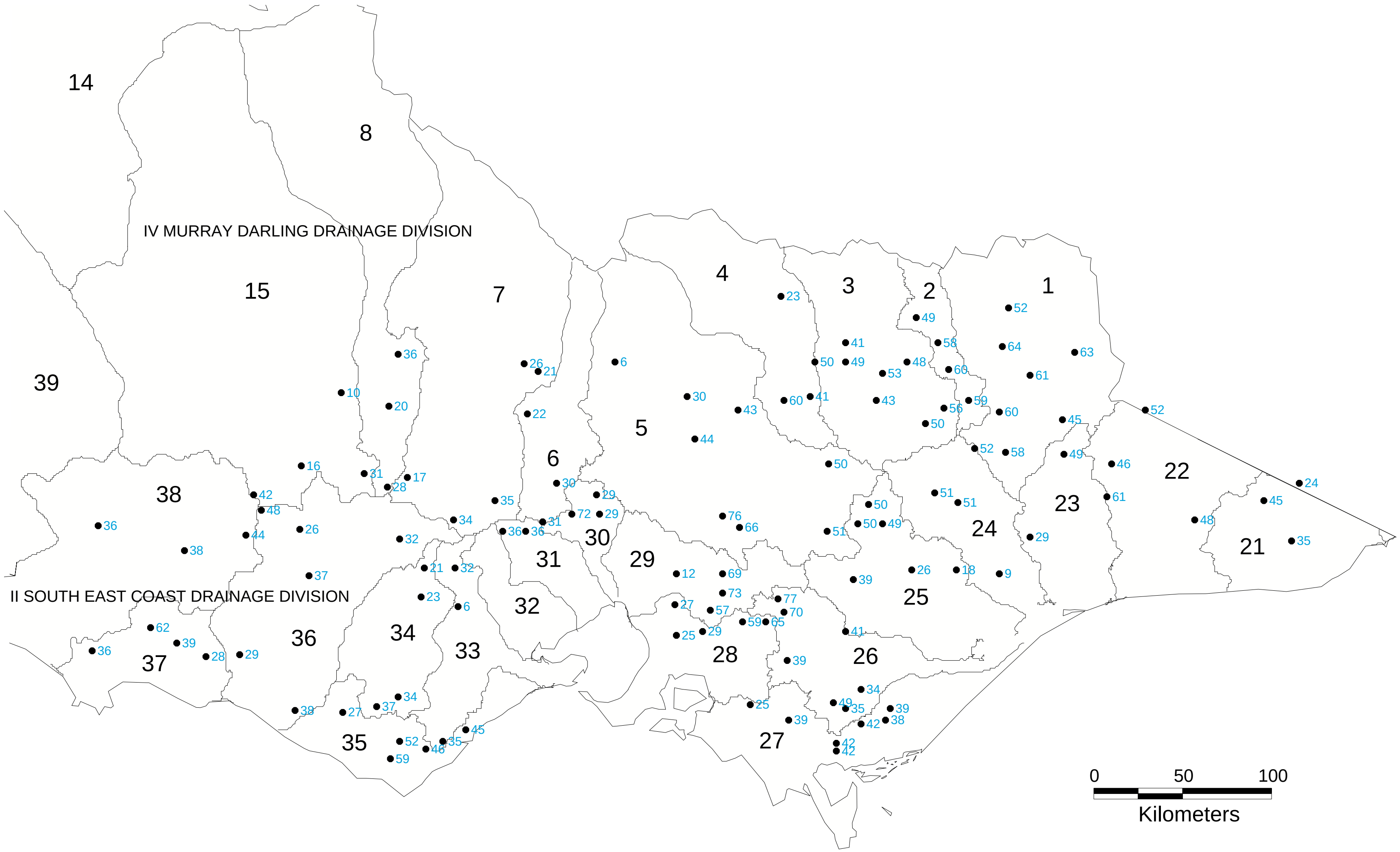

Figure A-1. Plot of calculated baseflow index (BFI) valuer for sites in Victoria. Drainage subdivisions are shown; BFI values are expressed as percentages. [Data source; HydroTechnology (1995)]

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Associates:
Department of Land and Water Conservation, NSW
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