Australian Rainfall & Runoff

Revision Projects

PROJECT 6

Loss Models for Catchment Simulation – Rural Catchments

STAGE 3 REPORT

P6/S3/016B

OCTOBER 2014

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AUSTRALIAN RAINFALL AND RUNOFF
REVISION PROJECT 6: LOSS MODELS FOR CATCHMENT SIMULATION: PHASE 4 ANALYSIS OF RURAL CATCHMENTS

PHASE 4 ANALYSIS OF LOSS VALUES FOR RURAL CATCHMENTS ACROSS AUSTRALIA

OCTOBER, 2014

Project Project 6: Loss models for catchment simulation: Phase 4 Analysis of Rural Catchments	**ARR Report Number** P6/S3/016B
Date 23 October 2014	**ISBN** 978-085825-9775
Contractor Jacobs SKM	**Contractor Reference Number** VW07245
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ACKNOWLEDGEMENTS

This project was made possible by funding from the Australian Federal Government. This report and the associated project are the result of a significant amount of in kind hours provided by Engineers Australia Members.

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FOREWORD

ARR Revision Process

Since its first publication in 1958, Australian Rainfall and Runoff (ARR) has remained one of the most influential and widely used guidelines published by Engineers Australia (EA). The current edition, published in 1987, retained the same level of national and international acclaim as its predecessors.

With nationwide applicability, balancing the varied climates of Australia, the information and the approaches presented in Australian Rainfall and Runoff are essential for policy decisions and projects involving:

- infrastructure such as roads, rail, airports, bridges, dams, stormwater and sewer systems;
- town planning;
- mining;
- developing flood management plans for urban and rural communities;
- flood warnings and flood emergency management;
- operation of regulated river systems; and
- prediction of extreme flood levels.

However, many of the practices recommended in the 1987 edition of ARR now are becoming outdated, and no longer represent the accepted views of professionals, both in terms of technique and approach to water management. This fact, coupled with greater understanding of climate and climatic influences makes the securing of current and complete rainfall and streamflow data and expansion of focus from flood events to the full spectrum of flows and rainfall events, crucial to maintaining an adequate knowledge of the processes that govern Australian rainfall and streamflow in the broadest sense, allowing better management, policy and planning decisions to be made.

One of the major responsibilities of the National Committee on Water Engineering of Engineers Australia is the periodic revision of ARR. A recent and significant development has been that the revision of ARR has been identified as a priority in the Council of Australian Governments endorsed National Adaptation Framework for Climate Change.

The update will be completed in three stages. Twenty one revision projects have been identified and will be undertaken with the aim of filling knowledge gaps. Of these 21 projects, ten projects commenced in Stage 1 and an additional 9 projects commenced in Stage 2. The remaining projects will commence in Stage 3. The outcomes of the projects will assist the ARR Editorial Team with the compiling and writing of chapters in the revised ARR.

Steering and Technical Committees have been established to assist the ARR Editorial Team in guiding the projects to achieve desired outcomes. Funding for Stages 1 and 2 of the ARR revision projects has been provided by the Federal Department of Climate Change and Energy Efficiency. Funding for Stages 2 and 3 of Project 1 (Development of Intensity-Frequency-Duration information across Australia) has been provided by the Bureau of Meteorology. Funding for Stage 3 has been provided by Geoscience Australia

Project 6: Loss Models for Catchment Simulation

This project aims to develop design losses for the whole of Australia on rural and urban catchments.

Mark Babister
Chair Technical Committee for
ARR Research Projects

Assoc Prof James Ball
ARR Editor

ARR REVISION PROJECTS

The 21 ARR revision projects are listed below :

ARR Project No.	Project Title	Starting Stage
1	Development of intensity-frequency-duration information across Australia	1
2	Spatial patterns of rainfall	2
3	Temporal pattern of rainfall	2
4	Continuous rainfall sequences at a point	1
5	Regional flood methods	1
6	**Loss models for catchment simulation**	**2**
7	Baseflow for catchment simulation	1
8	Use of continuous simulation for design flow determination	2
9	Urban drainage system hydraulics	1
10	Appropriate safety criteria for people	1
11	Blockage of hydraulic structures	1
12	Selection of an approach	2
13	Rational Method developments	1
14	Large to extreme floods in urban areas	3
15	Two-dimensional (2D) modelling in urban areas.	1
16	Storm patterns for use in design events	2
17	Channel loss models	2
18	Interaction of coastal processes and severe weather events	1
19	Selection of climate change boundary conditions	3
20	Risk assessment and design life	2
21	IT Delivery and Communication Strategies	2

PROJECT TEAM

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BACKGROUND

ARR Project 6 - Loss models for catchment simulation - consists of four phases of work as defined in the outcomes of the workshop of experts in the field held in 2009. These are:

- **Phase 1** – Pilot Study for Rural Catchments. A pilot study on a limited number of catchments that trials potential loss models to test whether they are suited for parameterisation and application to design flood estimation for ungauged catchments.

- **Phase 2** – Collate Data for Rural Catchments. Streamflow and rainfall data for a large number of catchments across Australia will be collated for subsequent analysis.

- **Phase 3** – Urban Losses. The phase involves analysis of losses for urban areas and estimation of impervious areas.

- **Phase 4** – Analysis of Data for Catchments across Australia. Loss values will be derived in a consistent manner from the analysis of recorded streamflow and rainfall from catchments across Australia. The results will then be analysed to determine the distribution of loss values, correlation between loss parameters and variation with storm severity, duration and season. Finally, prediction equations will be developed that relate the loss values to catchment characteristics.

This report details the outcomes of **Phase 4**.

TABLE OF CONTENTS

1. Introduction

Engineers Australia has embarked upon the revision of Australian Rainfall and Runoff (ARR). The revision is being undertaken over 4 years and is being underpinned by 21 projects which address knowledge gaps or developments since the last full revision in 1987. ARR Project 6 - Loss models for catchment simulation - consists of four phases of work:

- *Phase 1 – Pilot Study for Rural Catchments* (SKM, 2012b; Hill et al., 2011). Involved a pilot study on a limited number of catchments that trialled potential loss models to test whether they are suited for parameterisation and application to design flood estimation for ungauged catchments.
- *Phase 2 – Collation of Data for Rural Catchments* (SKM, 2012a). Streamflow and rainfall data for a large number of catchments across Australia was collated for subsequent analysis.
- *Phase 3 – Urban Losses*. The phase involves analysis of losses for urban areas and estimation of impervious areas.
- *Phase 4 – Analysis of Loss Values for Rural Catchments across Australia*. Loss values have been derived in a consistent manner from the analysis of recorded streamflow and rainfall from catchments across Australia and then analysed to determine the distribution of loss values. Finally, prediction equations were developed that relate the loss values to catchment characteristics.

This report covers the work undertaken as part of Phase 4. The following chapters of the report are summarised below:

- Chapter 2 outlines the basis of selecting catchments and summarises the adopted catchments for the study;
- Chapter 3 introduces and discusses the conceptual loss models applied which builds on the outcomes of the Pilot Study undertaken as part of Phase 1.
- Chapter 4 describes the selection and characterisation of events analysed, with particular emphasis on rainfall occurring immediately prior to these bursts of rainfall
- Chapter 5 describes the approach used to estimate the loss values.
- Chapter 6 presents the estimated loss values and explores relationships with antecedent conditions and storm severity
- Chapter 7 explores the relationship between the loss values and catchment characteristics and prediction equations for each of the loss parameters for different hydroclimatic regions across Australia.
- Chapter 8 covers conclusions and recommendations from the study.

2. Study catchments

The estimation 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 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. There is hence an implicit trade-off between analysing a greater number of catchments and the quality of the spatial coverage of rainfall.

Phase 2 of ARR Project #6 involved the identification and collation of data sets for rural catchments. The adopted criteria for selection of the catchments were:

- catchment area between 20 and 100 km^2
- 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 preliminary list of compliant catchments based on catchment area and streamflow record was made using the Bureau of Meteorology (BoM) Water Resource Station Catalogue (WRSC). This database includes sites maintained by BoM and other agencies.

The catchments were initially defined using the national 9” (9 second) Digital Elevation Model (DEM). This DEM covers the whole of Australia and has a grid spacing of 9 seconds in longitude and latitude, which equates to approximately 250 metres. It has been “hydrologically enforced” to consolidate and incorporate streamline flow paths and other topological features. The hydrological enforcing used flow direction from the 9 second DEM and the gauge locations to define a preliminary catchment boundary and area. An approximate catchment centroid location was determined for each catchment and used to obtain the closest pluviograph stations to each catchment based on the WRSC dataset.

The preliminary catchment boundaries were used to determine that the catchment fulfilled the criteria listed above for being free of significant water bodies and not located in urban areas. The period of hourly rainfall record at the pluviograph stations identified was compared to the period of streamflow record. Where the period of concurrent streamflow and hourly rainfall was greater than 20 years, the catchment was considered eligible for the Phase 2 database.

The streamflow and pluviograph data was collected from state agencies and the Bureau of Meteorology. As part of Phase 2 preliminary data checks were done collected data, including comparison of the mean annual rainfall calculated from the received data and the mean annual rainfall determined from the BoM Average Annual Rainfall raster dataset. Mean annual streamflow was also checked by plotting against mean annual rainfall for each site. These checks were used to identify any gross errors in the data.

A number of catchments were then excluded from the analysis based on problems with the collected data, including missing periods, shorter periods of record or timing issues. Some other catchments were excluded because they occurred in areas of high density of eligible catchments (for example SW WA). Of the available catchments in these areas, those with the longest period of overlapping streamflow and pluviograph data and the closest distance between the pluviograph and the catchment centroid were selected. Appendix A shows a list of catchments that were initially identified as potentially fulfilling the criteria but subsequently excluded, and the reason for the exclusion.

A total of 38 catchments were ultimately included in the Phase 4 analysis. Ten of these were the pilot catchments from the Phase 1 Pilot Study. The final set of catchments is listed in Table 2-1 and shown in Figure 2-1. Maps of each catchment are included in Appendix B.

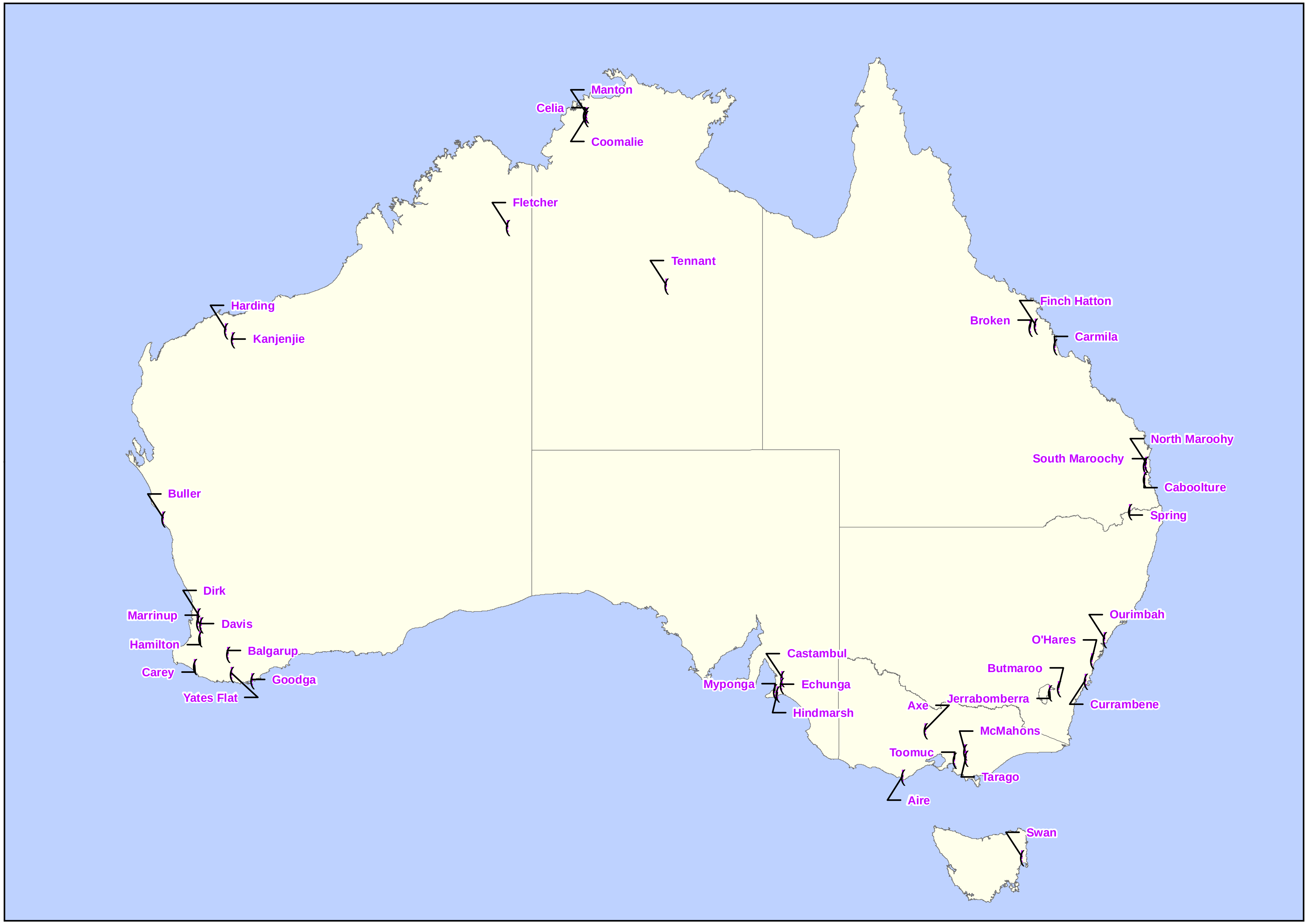
The investigation of the loss values described in Section 6 showed the influence of different hydroclimatic regions across Australia. From preliminary analysis of the data, the regions defined by the BoM in the development of the generalised PMP estimates were adopted as they are based upon the prevalent storm types and appeared useful in explaining the variability of loss values. These groups of catchments have been subsequently used in summarising the results and developing prediction equations.

The GTSMR (Generalised Tropical Storm Method – Revised) region covers those areas of Australia affected by storms of tropical origin. The storms within the GSTMR can be broadly classified as tropical cyclones, ex-tropical cyclones, Monsoon activity and extratropical systems. Each of these types of storms can be limited to certain areas and to certain times of the year. Thus, the BoM has divided the GTSMR zone into sub-zones to represent the particular type of storm mechanism that would be important (BoM, 2003). The regions are Coastal, Inland and Southwest WA (although none of the Project 6 catchments lie in the GTSMR inland region)

The remainder of Australia is the defined as the GSAM (Generalised South eastern Australia Method). The GSAM region has been divided into two zones, Coastal and Inland, separated by the Great Dividing Range. This zonal division reflects a working hypothesis that within the two zones the mechanisms by which large rainfalls are produced are genuinely different. The corollary is that within each zone there is an assumed homogeneity (BoM, 1996).

Table 2-1 Summary of study catchments

Catchment gauge no.	Gauge Name	State	Catchment area (km^2)	Adopted pluvio	Distance to catchment centroid (km)	Overlap years
216004	Currambene Creek @ Falls Ck	NSW	95	P68076	5.2	28
213200	O'Hares Creek @ Wedderburn	NSW	73	568065	4.9	30
211013	Ourimbah Creek @ U/S Weir	NSW	83	P61351	3.8	29
2219	Swan River upstream Hardings Falls	TAS	38	2219	2.5	24
235219	Aire River @ Wyelangta	VIC	90	P90083	4.4	36
229106	McMahons Creek @ Upstream Weir	VIC	40	586056	5.4	31
228206B	Tarago River @ Neerim	VIC	78	502236A	6.4	25
228217	Toomuc Creek @ Pakenham	VIC	42	586201	2.6	33
410743	Jerrabomberra Creek @ Four Mile Creek	ACT	52	570973	4.0	27
411003	Butmaroo Creek @ Butmaroo	NSW	65	570338	4.6	31
AW503506	Echunga Creek upstream Mt Bold Res.	SA	34.2	AW503533	1.9	23
AW501500	Hindmarsh River @ Hindmarsh Vy Res Offtake	SA	56	P23824	1.9	38
AW502502	Myponga River upstream Dam and Rd Br	SA	76.5	AW502502	5.4	21
A5040523	Sixth Creek @ Castambul	SA	44	A5040559	1.3	27
				P23801	4.6	32
406216A	Axe Creek @ Sedgewick	VIC	34	406216A	4.1	23
G8150151	Celia Creek @ U/S Darwin R Dam	NT	52	R8150332	4.7	38
G8170066	Coomalie Creek @ Stuart HWY	NT	82	R8150332	5.0	48
G8170075	Manton River upstream Manton Dam	NT	29	R8150332	7.5	45
G0290240	Tennant Creek @ Old Telegraph Stn	NT	72.3	R0290240	2.2	29
120216A	Broken River @ Old Racecourse	QLD	78	P33172	1.2	38
142001A	Caboolture River @ Upper Caboolture	QLD	94	142001	5.2	21
126003A	Carmila Creek @ Carmila	QLD	82	126003	4.5	22
125006	Finch Hatton Creek @ Dam Site	QLD	36	533010	1.2	26
				533004	6.5	35
141009	North Maroochy River @ Eumundi	QLD	41	P40059	4.7	28
				141009	6.0	20
141001B	South Maroochy River @ Kiamba	QLD	33	P40282	5.9	23
422321	Spring Creek @ Killarney	QLD	32	P41056	3.9	38
809312	Fletcher Creek Trib. @ Frog Hollow	WA	30.6	502013	2.1	28
709007	Harding River @ Marmurrina Pool U-South	WA	49.4	505017	4.6	24
708009	Kanjenjie Creek Trib. @ Fish Pool	WA	41.1	505034	1.5	20
609005	Balgarup River @ Mandelup Pool	WA	82.4	510041	0.6	24
701006	Buller River @ Buller	WA	33.9	508025	4.0	26
608002	Carey Brook @ Staircase Rd	WA	30.3	509296	3.1	36
614047	Davis Brook @ Murray Valley Plntn	WA	65.7	509122	0.6	26
614005	Dirk Brook @ Kentish Farm	WA	36	509135	1.7	27
				509245	5.1	27
				P9874	1.7	3
602199	Goodga River @ Black Cat	WA	49.2	509011	3.7	38
612004	Hamilton River @ Worsley	WA	32.3	509106	0.9	27
614003	Marrinup Brook @ Brookdale Siding	WA	45.6	509213	2.3	20
603190	Yates Flat Creek @ Woonanup	WA	53	509022	4.1	38



Legend

Catchment location

[GCS GDA94]

0 750

Kilometres

DATA SOURCES
This document incorporates data which is:
Geodata3 (Geoscience Australia)
Bureau of Meteorology - Pluviograph Station Locations

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Figure 2.1 - Catchment Location Map

3. Selection of conceptual loss models

3.1. Introduction

Loss is defined as the precipitation that does not appear as direct runoff, and the loss 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. Other factors, such as the spatial variability in topography, catchment characteristics (such as vegetation and soils), and rainfall makes it very difficult to link the loss to catchment characteristics.

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 (Mein and Goyen, 1988). 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.

In the Phase 1 Pilot Study (Hill et al., 2013) a number of criteria were used to assess candidate loss models; namely it was required that the model :

1) produces a temporal distribution of rainfall-excess that is consistent with the effect of the processes contributing to loss
2) is suitable for extrapolation beyond calibration and hence applicable to estimate floods over a full range of AEPs
3) has inputs that are consistent with data readily available across Australia
4) is parsimonious (i.e. preferably requires no more than two parameters to be fitted)
5) has parameters that have been linked to catchment characteristics, or it is considered reasonable that such a link could be established
6) is readily accessible and well documented ; and,
7) can be easily incorporated into rainfall-runoff models

The four loss models selected for further consideration were:

1) Initial loss – constant continuing loss (IL/CL)
2) Initial loss – constant proportional loss (IL/PL)
3) Initial loss – variable continuing loss; and,
4) Probability distributed storage capacity loss model.

The IL/PL model provided satisfactory results when used to estimate loss values but when combined with other design inputs there was a tendency to underestimate peak flows when compared to those from the frequency analysis of recorded peak flows. This reinforces the difficulties of applying the IL/PL model to derive design estimates beyond the range of events found in the historical record.

Based upon consideration of infiltration theory it would be expected that the infiltration rate should decrease with the volume of water infiltrated. For the IL/CL model this would suggest that the Continuing Loss should decrease as the event progresses and such a reduction with duration (as a surrogate for volume of infiltration) has been observed from the empirical analysis of data by Ishak and Rahman (2006) and Ilahee and Imteaz (2009). The Phase 1 pilot study did not identify a reduction in the continuing loss rate with duration or infiltrated volume.

Thus, it was recommended that Phase 4 concentrate on deriving parameter values for IL/CL and SWMOD.

3.2. Initial Loss – Continuing Loss

The most commonly-used model in Australia is the Initial Loss - Continuing Loss (IL/CL) model (Figure 3-1). The initial loss occurs in the beginning of the storm, prior to the commencement of surface runoff. It should be noted that when analysing recorded streamflow data the start of the hydrograph rise reflects the runoff response from the parts of the catchment closest to the gauging station and the commencement of runoff from the upper parts of the catchments is not readily discernible because of routing delays. This limitation is overcome if the initial loss is inferred from a routing-routing model.

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.

A number of models (such as URBS and HEC-HMS) include loss models that allow recovery of the Initial Loss after a substantial dry period. The recovering loss model is represented as a simple initial loss single bucket model. When rainfall is less than the potential loss in a time step, the deficit is made up in part from the initial loss store. Although accounting for the recovery of Initial Loss may be important for long duration events which have multiple bursts, it is unlikely to be significant for design flood estimation which is based upon design bursts or design storms where the rainfall is reasonably continuous over the event.

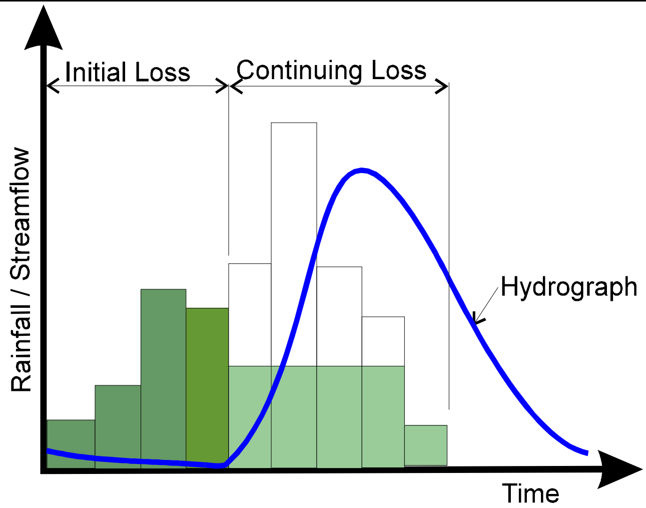


Figure 3-1 Initial Loss – Continuing Loss model

3.3. SWMOD

3.3.1. Distributed storage capacity models

Most conceptual loss models are lumped in that a similar parameter value is assumed over a catchment or sub-catchment. Moore (1985) introduced the concept of probability distributed models which can be used to account for the spatial variability in runoff generation across a catchment. This variability can account for:

- differences in overall water storage capacity between sub-catchments (topography, soils, vegetation);
- spatial variation of water storage capacity within sub-catchments (potential loss distribution);
- stochastic variation of initial water storage status between events (different antecedent conditions); and
- gradual variation of water storage status during an event (progressive wetting).

The dominant mode of runoff production will depend on a range of factors including climate, soil, vegetation and topography. In general it is expected that the runoff mechanism in drier catchments is more likely to be controlled by infiltration rate whereas saturated excess is more likely to generate runoff for wetter catchments.

These models are run in a continuous or semi-continuous fashion (updated during an event) and therefore can explicitly account for the antecedent conditions as well as the variation within an event.

Those models based upon variable storage capacity reflect the subsurface saturation excess mechanism and include Xinanjiang (Ren-Jun et al. 1980; Ren-Jun 1992; Tachikawa, et al., 1995; Hu, et al., 2005), SWMOD (Stokes, 1989; and Water and Rivers Commission, 2003) and the Revitalised Flood Hydrograph (ReFH) model in the UK.

These models are based on the assumption that the catchment consists of many individual storage elements with a soil moisture capacity. The distribution of soil moisture storage over the catchment is probabilistic, in other words the different amounts of soil moisture storage are not assigned to specific locations in the catchment. The depth of water in each element is increased by rainfall and decreased by evaporation. When rainfall exceeds the storage capacity, direct runoff is produced. The model assumes that the soil moisture is redistributed between the elements between rainfall events.

The simplest form is the uniform PDM which assumes a linear distribution of soil moisture in the catchment as shown in Figure 3-2. This form of PDM has been applied in the Revitalised Flood Hydrograph (ReFH) model in the UK (Kjeldsen, et al., 2005).

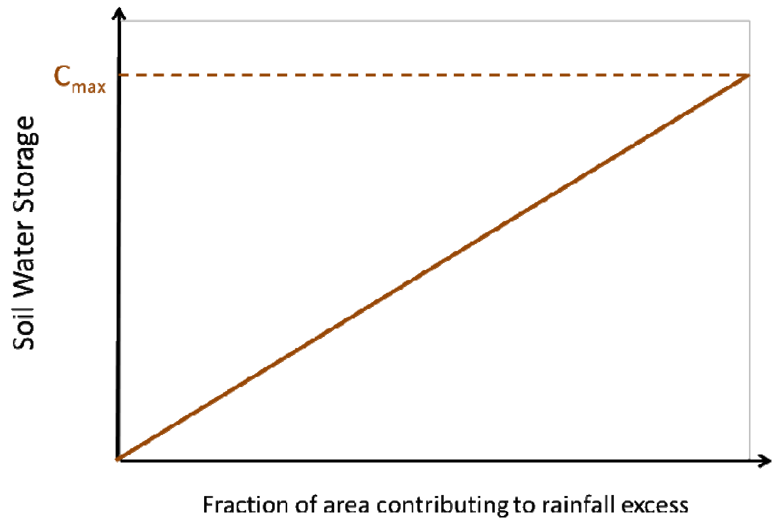


Figure 3-2 PDM distribution of catchment storage elements of different depths

The limitation of the above approach is that it assumes that a portion of the catchment has zero storage capacity and hence there is no initial loss. Many catchments in arid and semi-arid areas exhibit a significant initial loss and therefore the conceptual model has been extended such that the capacity varies between a minimum and maximum for the catchment. The simpler models assume that the capacities vary linearly while other models have introduced a shape parameter to describe the variation of capacity.

3.3.2. SWMOD overview

SWMOD is a version of PDM that has a capacity that varies between a minimum and a maximum. The model was 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. 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 (Water and Rivers Commission, 2003).

The infiltration capacity over a sub-catchment is defined as:

$$C_f = C_{max} – (C_{max} - C_{min}) \times (1-F)^{1/B} \; \mathrm{C_f} = \mathrm{C_{max\,–}}(\mathrm{C_{max}} - \mathrm{C_{min}}) \times (1 - \mathrm{F})^{1/\mathrm{B}} \qquad (1)$$

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

Soil types in the south-west of WA have been grouped into five main landform categories which have specific characteristics based on field investigations. Representative values of C_{min}, C_{max} and B values have been derived for each of the 5 landforms (Water and Rivers Commission, 2003) and the model can incorporate a mix of different landforms in a catchment.

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 resulting distribution of losses is similar in form to that proposed by Siriwardena and Mein (1996) who fitted a logistic function to the volumetric runoff coefficients for a range of events.

3.3.3. SWMOD conceptualisation

SWMOD was incorporated into the RORB rainfall-runoff model (Laurenson et al., 2007) in Phase 1 of this study. The distribution of profile water holding capacity is inferred from soils information and hence the model only has one calibration parameter, namely the Initial Moisture content. Initial application of the one parameter model demonstrated that this 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) which is assumed to be the same for all soil types across the catchment; if the Initial Moisture is less than the minimum soil capacity then the difference represents the “Initial Loss” required before runoff is generated.
- Capacity Factor (CF) which scales the maximum profile water holding capacities in a catchment.

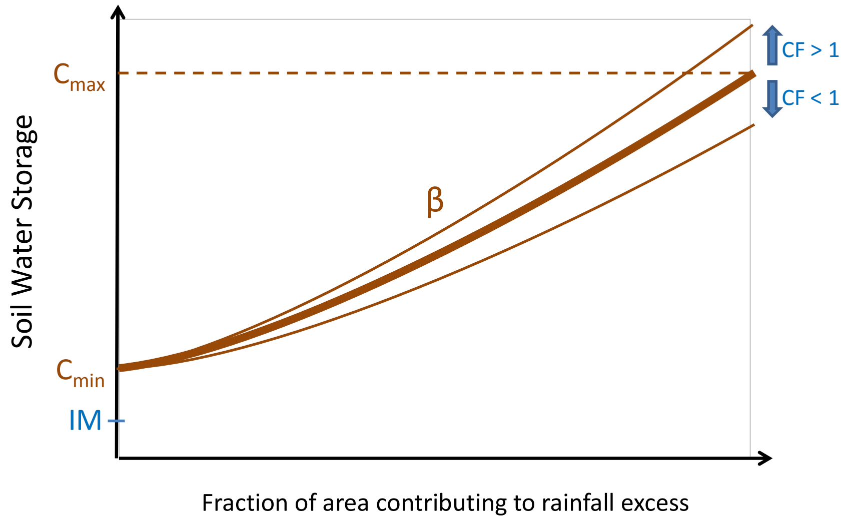


Figure 3-3 Conceptualisation of 2 parameter SWMOD model

3.4. Estimation of profile water holding capacity

3.4.1. Introduction

In Australia, the application of distributed storage capacity models, such as SWMOD, in Australia has historically been constrained by the lack of information on the hydraulic properties of soils. The requirement of consistent data that can be applied across all Australian catchments results in few options for characterising the soils for analysis.

The Atlas of Australian Soils (Northcote et al. 1960-1968) is the only consistent source of spatial information for the whole of the country. McKenzie et al (2000) provide data on soil physical properties for the 725 Principle Profile Forms (PPFs) identified in the Factual Key of Northcote (1979) and the dominant PPFs for each soil landscape type in the Digital Atlas of Australian Soils.

Properties provided by McKenzie et al. (2000) were estimated using a two-layer model of soil using estimated characteristics for the A and B horizons. Estimates of thickness, texture, bulk density and pedality were used to estimate parameters describing the soil water retention curve, which then allow the calculation of the soil water holding capacity for each layer (McKenzie, 2000). Estimates were provided for the 5th percentile, median and 95th percentile.

Data extracted from the Atlas was used to characterise the soil storage capacity in each of the study catchments. The 5th and 95th percentiles of A and B horizon thickness were taken as approximates of the minimum and maximum thicknesses. The database provides a single A and B horizon water holding capacity per unit depth for each soil type. The proportions of each soil type in each pilot catchment was extracted from the Atlas and a distribution of catchment water holding capacity was calculated using the distribution of soil horizon thickness and water holding capacity.

3.4.2. Shape parameter

The influence of the SWMOD shape parameter (*B*) in defining the storage capacity relationships is show in Figure 3-4. A *B* value of unity implies that the relationship is linear. If the *B* is less than 1.0 the relationship is convex, and is concave upwards for a *B* great than 1.0.

As described above the shape parameter was fitted to the median, 5% and 95% values from hydrologic interpretation of the Atlas of Australian Soils. Given the large uncertainty involved in the estimates of soil profile water holding capacity, the range of *B* values were investigated to see if there was any consistency, or whether the values were distributed around 1.0 which might indicate that this simply reflected the uncertainty in the estimates.

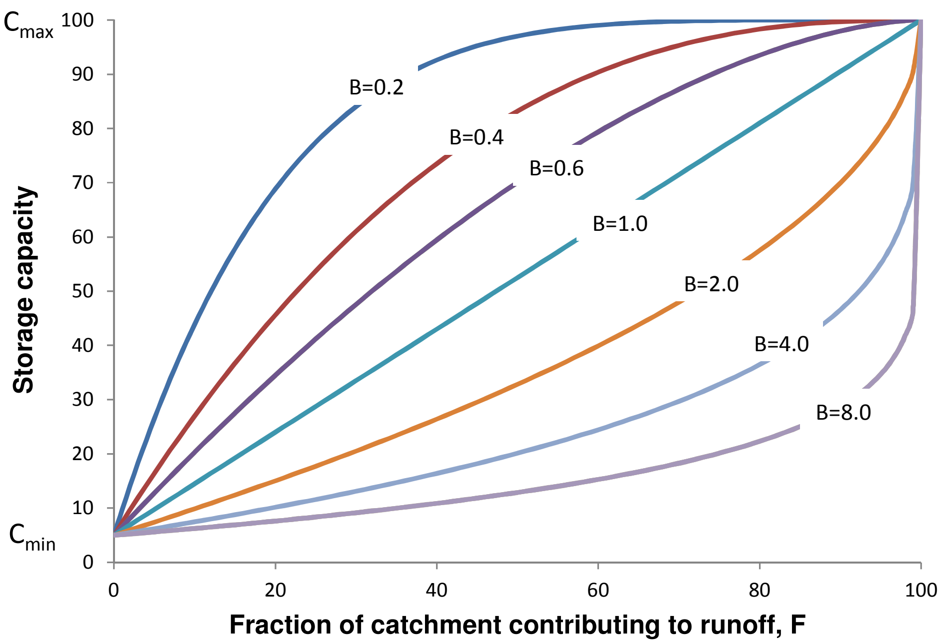


Figure 3-4 Influence of SWMOD shape parameter in defining storage capacity relationships

The shape parameter was calculated for each of the 2933 unique soil types in the Atlas of Australian soils and the results are summarised in Figure 3-5. Approximately 75% of the values are between 1.0 and 2.0 which shows that there is a tendency for the values to be great than unity and hence the shape parameter values estimated from each individual soil type were adopted in the analysis.

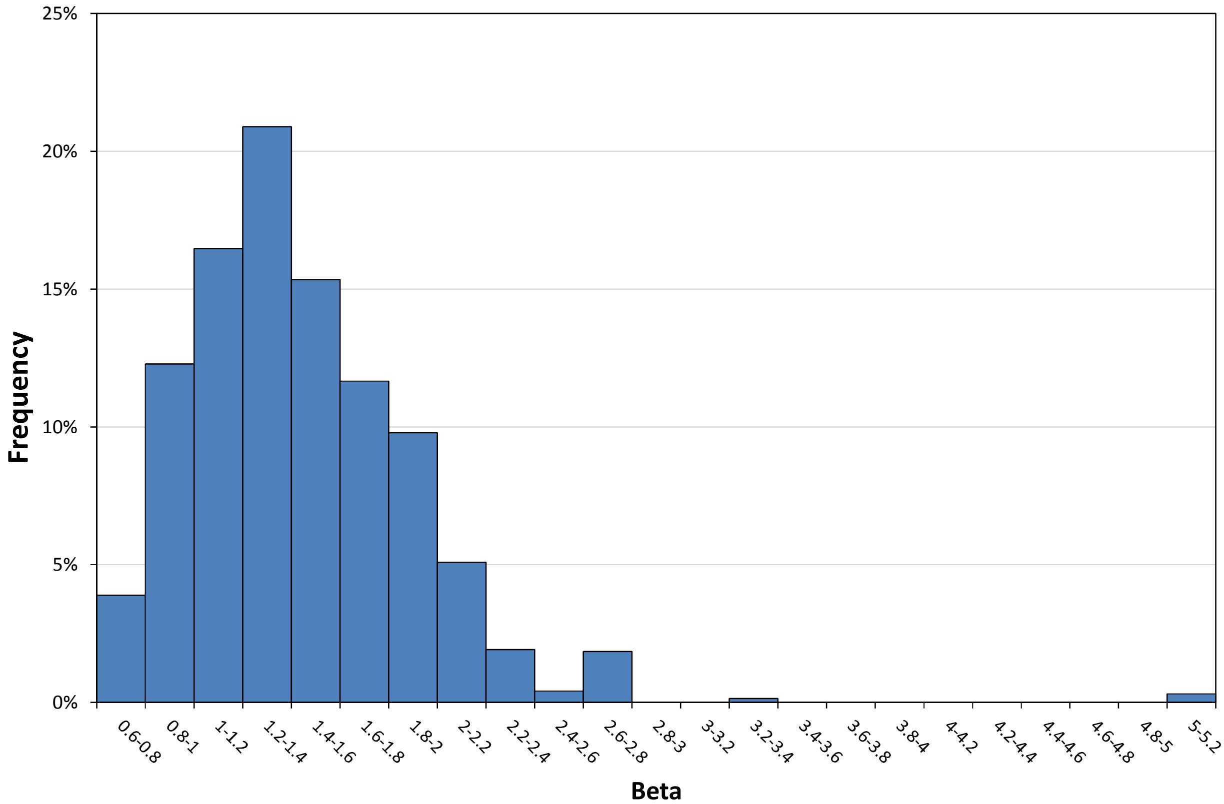


Figure 3-5 Frequency of shape parameter from fitting to Australian soils

3.4.3. Comparison with other studies

The Water Corporation in Western Australia have estimated water holding capacity for a number of catchments using the data collected by the Department of Water. Results were available for four catchments (Leanne Pearce, Water Corporation., pers. Comm.) and Table 3-1 shows a comparison of the water holding capacity determined from the method described above and that calculated by the DoW.

Table 3-1 Comparison of water holding capacity calculated using McKenzie et al. (2000) values and calculated using soil water storage relationships in SWMOD by DoW, WA

Catchment	Calculated using McKenzie et al. (2000) (mm)	Department of Water (mm)	Ratio of difference
Serpentine Creek	132	447	3.4
Samson Brook Dam	141	525	3.7
South Dandalup Dam	127	467	3.7
Wellington Dam	285	521	1.8

Table 3-1 shows that the soil water holding capacity calculated for south west WA sites using the usual SWMOD soil water relationships are significantly higher than those calculated using data from McKenzie et.al. (2000). This is consistent with the findings of Ladson et al. (2006) who compiled estimates of extractable soil moisture store based on field measurements and compared them with the soil moisture store from the Atlas. Results determined that 42% of estimates from the Ladson et al. (2006) were greater than twice the value from the Atlas. In general, they concluded that estimates of available water capacity from McKenzie et al. (2000) could be considered a reasonable lower bound on field based estimates of the extractable soil moisture.

Appendix G describes some sensitivity analysis undertaken after the completion of Stage 1 of ARR Project #6. This confirmed that increasing the storage capacity values (in this case by a nominal factor of 3) resulted in decreasing the value of the Capacity Factor. However, there was no clear basis for adjusting the values and therefore in this study the storage capacity values were adopted from McKenzie et al (2000) without modification.

4. Selection and characterisation of storm events

4.1. Embedded nature of design rainfall bursts

The rainfall data used in the derivation of Intensity Frequency Duration (IFD) information such as IFD2013 (the new IFD information developed by the Bureau of Meteorology as part of the revision of ARR; Green, et al. 2012) has been derived from the analysis of the most intense bursts of rainfalls, rather than complete storms. The nature of these embedded bursts should be accounted for when selecting loss values that are suitable for design (Hill and Mein, 1996; Rigby and Bannigan, 1996).

The difference between the Initial Loss for a burst and for a storm is illustrated in Figure 4-1. The initial loss for the storm is assumed to be the depth of rainfall prior to the commencement of surface runoff. The initial loss for the burst however is the portion 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) to the storm initial loss.

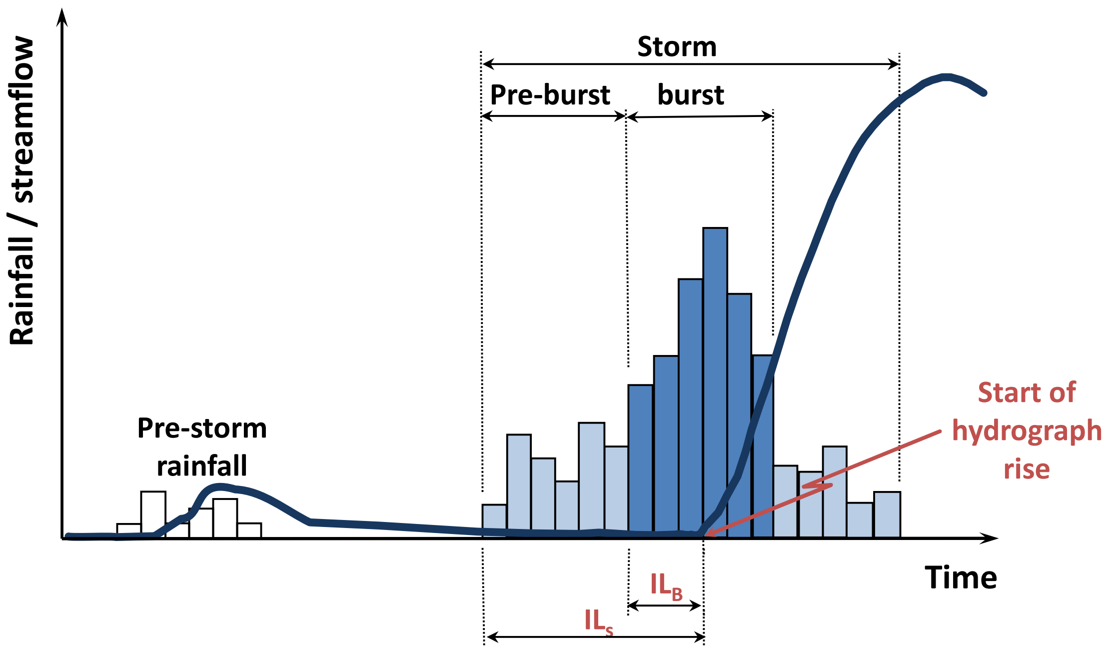


Figure 4-1 Initial Loss for an embedded rainfall burst

There has traditionally been a lack of information on the rainfall prior to bursts of rainfall and therefore this has often been overlooked which has led to inappropriate loss values being adopted. It is considered that this is likely to be more of an issue for catchments which have shorter critical durations as it is expected that for longer durations the bursts of rainfall used in the derivation of the IFD information start to approach full storms. A number of studies have identified this issue such as Phillips et al. (1994), Hill and Mein (1996), Rigby and Bannigan (1996), Farnsworth et al. (1996), Rigby et al. (2003), Roso and Rigby (2006).

4.2. Selection and definition of storm events

4.2.1. Selection of bursts

The events for analysis were selected on the basis of rainfall rather than runoff, as selecting the largest flood events introduces a bias towards low losses. Adopting rainfall as the criteria for selecting events requires consideration of the duration. The Phase 1 Pilot Study adopted a 12-hour duration as it was considered to be representative of the critical durations for the pilot catchments.

For this analysis, separate samples of events were selected for burst durations of 3, 6, 12, 24, 48 and 72 hours. A partial series approach was adopted to identify the events for analysis, and for each duration the threshold was set such that the number of events was equal to the years of concurrent streamflow and pluviograph data for the catchment (refer Table 2-1). Thus, 1xN events were selected for each duration as the focus of this project is on design loss values for floods with AEPs less than (ie rarer) than 0.5.

Once the complete storms were defined (Section 4.2.2) a relatively small number of events with missing, aggregated or disaggregated pluviograph data were excluded which meant that in some cases the number of events available was slightly less than the years of concurrent streamflow and pluviograph data for the catchment shown in Table 2-1.

The bursts were selected separately for each duration and therefore there were a number of events common across different durations. For example, 45% of the events selected on the basis of 24 hour bursts were common with the sample from the 3 hour bursts.

The definition of complete storms and the analysis of pre-burst rainfall (refer Sections 4.2.2 and 4.3) were undertaken for each of the 6 durations. There is considerably more effort required to estimate the loss values using a flood event model than defining the complete storm and therefore loss values were only estimated for the sample of events based upon 3 and 24-hour bursts of rainfall. It was subsequently shown that the median loss values derived for the complete storms were not sensitive to duration of bursts used to select the events (refer Section 6.3).

4.2.2. Definition of complete storms

Having identified the burst of rainfall it was necessary to define the start and end of the complete storm for which the loss values were to be derived. Start and end times were manually set for each storm from inspection of the time series of pluviograph data and surface runoff. The adopted criteria were:

- Start times were set to capture the beginning of the storm (indicated by a period of approximately 12 hours of no significant rain);
- End times were set such that the surface runoff had effectively ended (notionally a few percent of the peak value);

- Start and end times were set to 9:00 am to allow daily rainfall to be incorporated in defining the spatial distribution of rainfall.

For some events it was not possible to satisfy all criteria and therefore start and end times were based upon a compromise between the competing objectives.

As discussed in Section 4.2.1, the same storm event could be selected on the basis of different duration bursts. In these cases a check was made to ensure that consistent start and end times were adopted for the same storm.

The resulting median storm durations for each burst duration are shown in Figure 4-2. This figure demonstrates that the duration of the complete storms analysed is typically a few days and hence are considerably longer than the duration of bursts used in their identification.

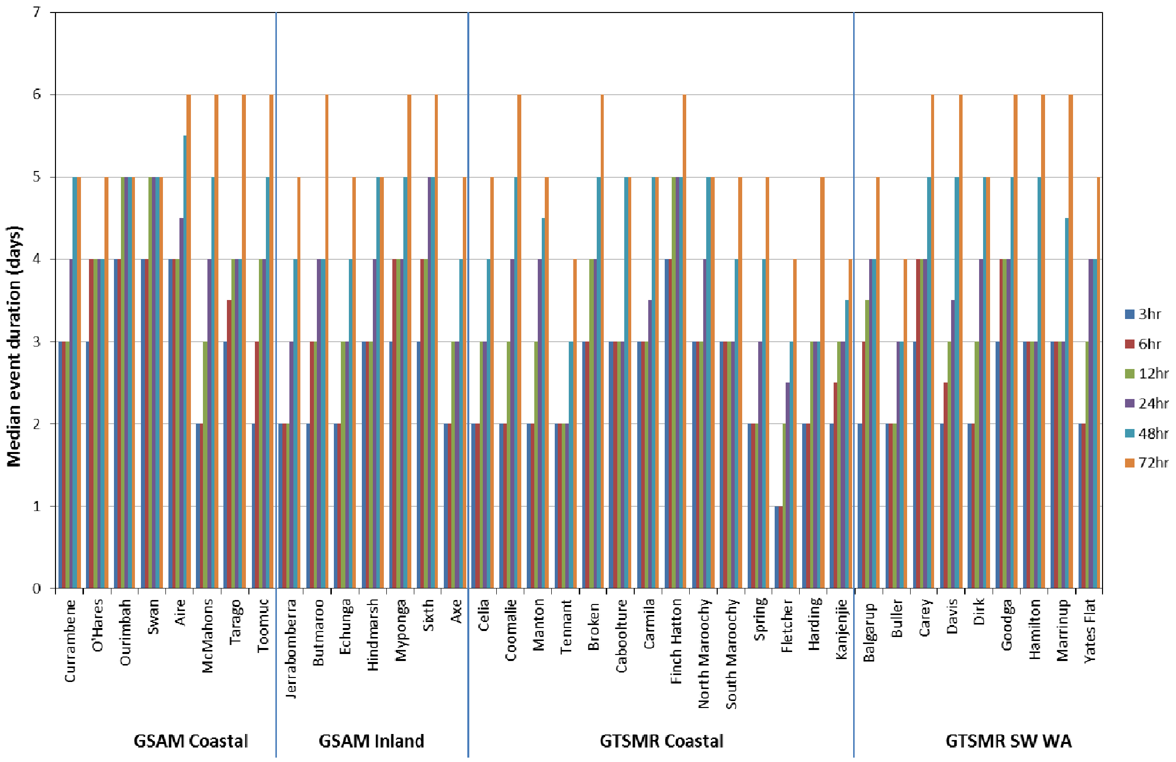


Figure 4-2 Median storm duration of events selected for each burst duration

4.3. Pre-burst rainfall

For each event the pre-burst rainfall was calculated as the depth of rainfall in the storm which occurred before the commencement of the burst. The range of values for 3 hours is shown in Figure 4-3, with other durations presented in Appendix C. It is clear that the pre-burst rainfall varies for different events for the same site. For example, for 3-hour bursts on the O'Hares catchment, the median value is 52.5 mm but the individual values vary from zero to over 200mm.

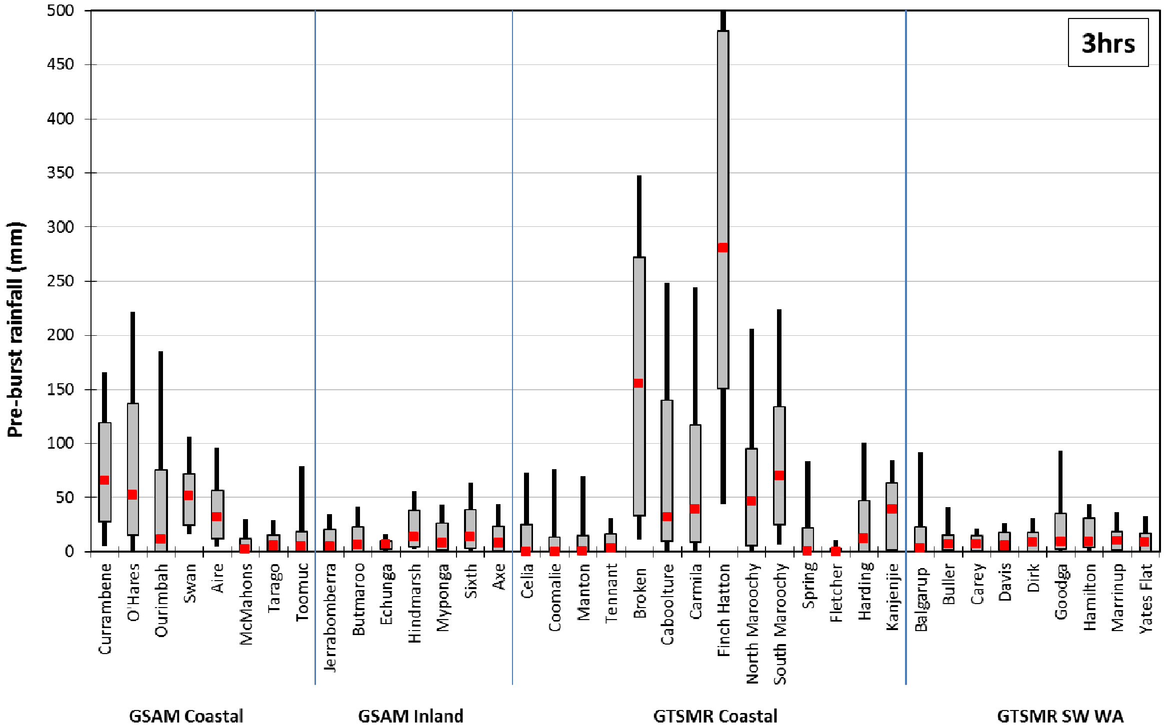


Figure 4-3 Range of pre-burst rainfall for 3-hour bursts (box indicates quartiles and line shows 10th and 90th percentile values)

4.4. Variation of pre-burst rainfall

The median pre-burst values for all sites were compared to a range of rainfall characteristics to explain the observed variability. The characteristics considered included duration, mean annual rainfall, design rainfall depths (from IFD2013) and different measures of antecedent precipitation index (API). Further information on these rainfall characteristics and how they were estimated is provided in Section 7.1.

The pre-burst values were observed to vary with:

- *Design rainfall intensities* - The values are lower for the GSAM Inland and GTSMR SW WA region and for the GSAM Coastal and GTSMR Coastal regions the values vary considerably between sites. There appears to be a trend for wetter sites to have higher pre-burst values and this is further explored in Section 4.4.1.
- *Burst duration* – as expected, the majority of sites demonstrated a reduction in pre-bust depth with burst duration which reflects that for the longer durations the bursts represent a higher proportion of the total storm depth. This is explored in Section 4.4.2.

4.4.1. Pre-burst variation with design rainfall

The median pre-burst rainfall was found to be highly correlated to the design rainfall depths from IFD2013. For 3 hour bursts the median pre-burst was observed to be more highly variable and for long duration events there were some sites with zero median pre-burst which confounded the correlations. Hence, medium length durations were found to have the strongest correlation and 6 hours was adopted as a representative duration.

No increase in regression performance was achieved through separation of data into GSAM and GTMSR region. However, six sites exhibited a median 6-hour pre-burst of zero in spite of relatively high design rainfall (refer **Error! Reference source not found.**). Five of these were the 4 sites from the Northern Territory and Fletcher Creek which is close to the NT border in WA. The remaining site that had zero median 6-hour pre-burst was Spring Creek in south-east Queensland. For this site nearly half of the values were non-zero and the surrounding sites had non-zero median pre-burst. This site was therefore excluded as an outlier.

As a result, the following prediction equations were developed covering the whole of Australia except the Northern Territory:

$$\text{25th Percentile Pre-burst}_{6h} = (5.56 \times 10^{-6}) \times {P_{24}^{2\%}}^{2.4285}$$ r^2=0.66, SEE = 139%, Equation 4-1

$$\text{Median Pre-burst}_{6h} = (5.09 \times 10^{-4}) \times {P_{24}^{2\%}}^{1.8977}$$ r^2=0.80, SEE 22%, Equation 4-2

$$\text{75th Percentile Pre-burst}_{6h} = (6.58 \times 10^{-3}) \times {P_{24}^{2\%}}^{1.6239}$$ r^2=0.86, SEE 10%, Equation 4-3

Where: $P_{24}^{2\%}$ is the 2% 24 hour design rainfall depth from IFD2013

The fit of these relationships is shown in Figure 4-4.

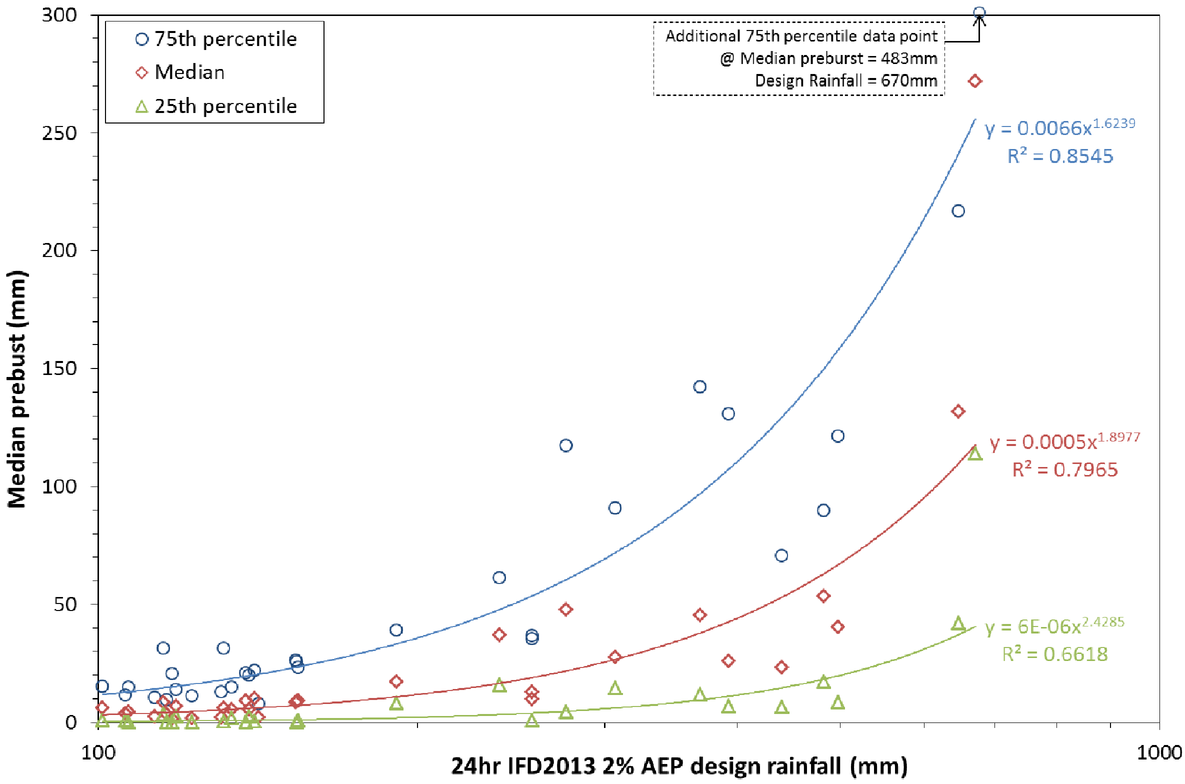


Figure 4-4 Relationship between pre-burst for 6 hour bursts and 2% 24 hour design rainfall

4.4.2. Pre-burst variation with burst duration

The majority of sites demonstrated a reduction in pre-bust depth with burst duration. This is consistent with the longer duration bursts representing a larger proportion of complete storms, whereas short duration bursts are more likely to be embedded within longer duration storms.

The variation of pre-burst depth with burst duration is plotted for each site in Appendix E. An example of the pre-burst rainfall for South Maroochy in Queensland is presented in Figure 4-5. This is typical of most sites and demonstrates the consistent reduction in median pre-burst rainfall with burst duration.

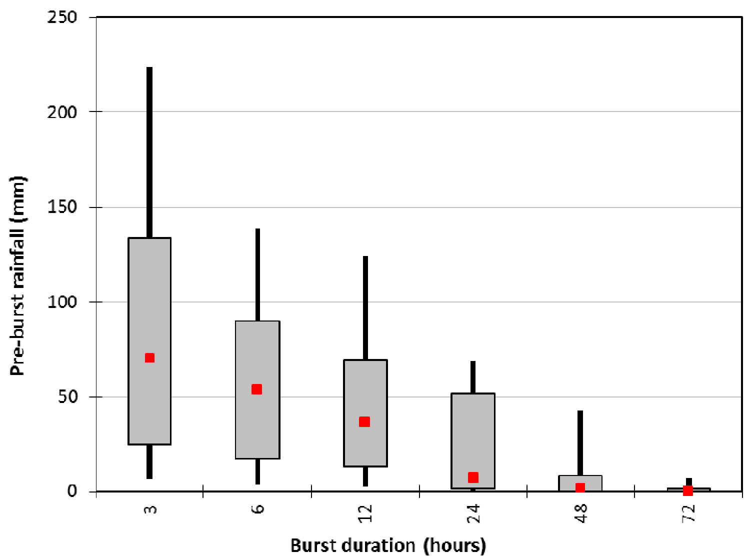


Figure 4-5 Range of pre-burst rainfall for South Maroochy for each duration (box indicates quartiles and line show 10th and 90th percentile values)

However, there is more variability in the pre-burst for 3-hour bursts. For 8 sites the pre-burst for the 3-hours is lower than the pre-burst associated with the 6-hour events. An example of this is shown in Figure 4-6 for McMahons in Victoria.

The variability in the pre-burst depths for 3 hour bursts is likely to be caused by different mixes of storm mechanisms contributing to the rainfall with some 3-hour rainfalls being generated by isolated thunderstorms (associated with zero or very small pre-burst depths) whereas others are intense cells within much longer duration storms.

To explore this variability the ratio of median 3-hour pre-burst to median 6-hour pre-burst was compared to the rainfall characteristics defined in Section 7.1 (see Appendix D); however, none of these characteristics could explain the observed variability. Similarly, there was no obvious variation across regions. It is recommended that this be investigated with a larger dataset.

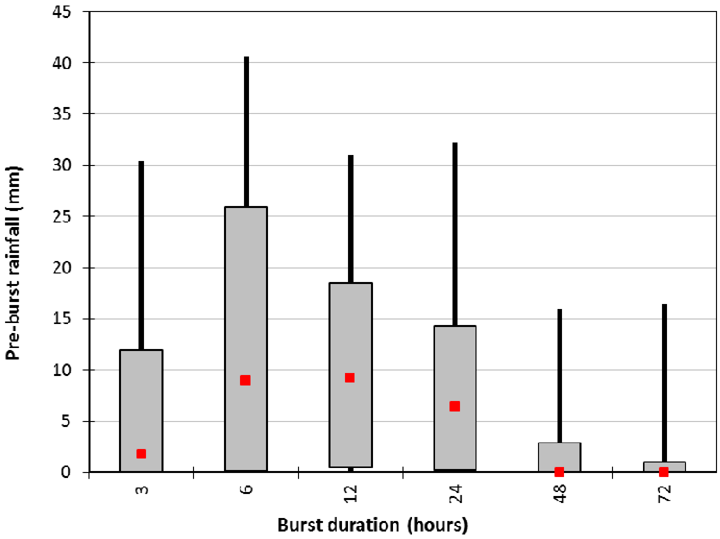


Figure 4-6 Range of pre-burst rainfall for McMahons for each duration (box indicates quartiles and line show 10th and 90th percentile values)

In order to explain the variation of pre-burst with duration, the pre-burst values were standardised by the median value for each site. Because of the noted variability in the pre-burst values for 3-hours, the values were standardised using the 6-hour values. As described in Section 4.4.1 six sites have been excluded from this analysis. The resulting standardised values of pre-burst are shown in Figure 4-7.

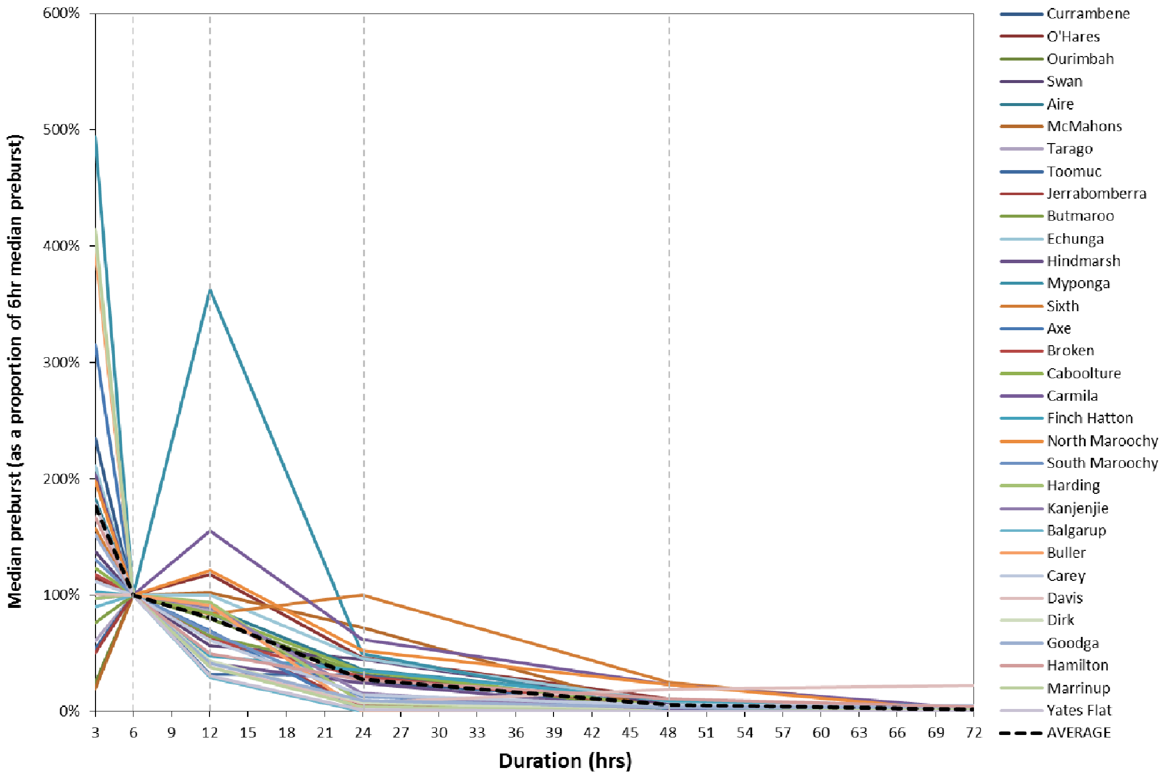


Figure 4-7 Variation of median pre-burst (normalized against 6hour value) with duration for each site

Using the average of each site's curve of representative pre-burst a prediction equation relating duration and pre-burst was defined:

$$\text{Pre-burst}_{\text{duration}} = \text{Pre-burst}_{6\text{h}} \times e^{-0.0648(\text{duration}-6)}$$ r^2=0.99, SEE 18%, Equation 4-4

Where: *duration* is the duration of the burst in hours

Pre-burst$_{6h}$ is the median pre-burst depth in mm for a 6 hour burst

For an ungauged catchment this relationship can be used in conjunction with the regionalization in Section 4.4.1 to estimate pre-burst for each duration.

4.4.3. Pre-burst as a proportion of burst depth

In the previous sections the pre-burst has been expressed as an absolute value. In this section the pre-burst rainfall is considered as a proportion of the burst rainfall. The median values of the ratio for all events in a particular region are summarised in Figure 4-8.

This shows that the ratio of pre-burst to burst rainfall reduces with increasing burst duration. Additionally, pre-burst is larger relative to burst rainfall for the GTMSR coastal and GSAM coastal sites. This is consistent with pre-burst being larger for wetter catchments, as seen in Figure 4-3. The negligible pre-burst for the Northern Territory sites as described in Section 4.4.1 is further illustrated here.

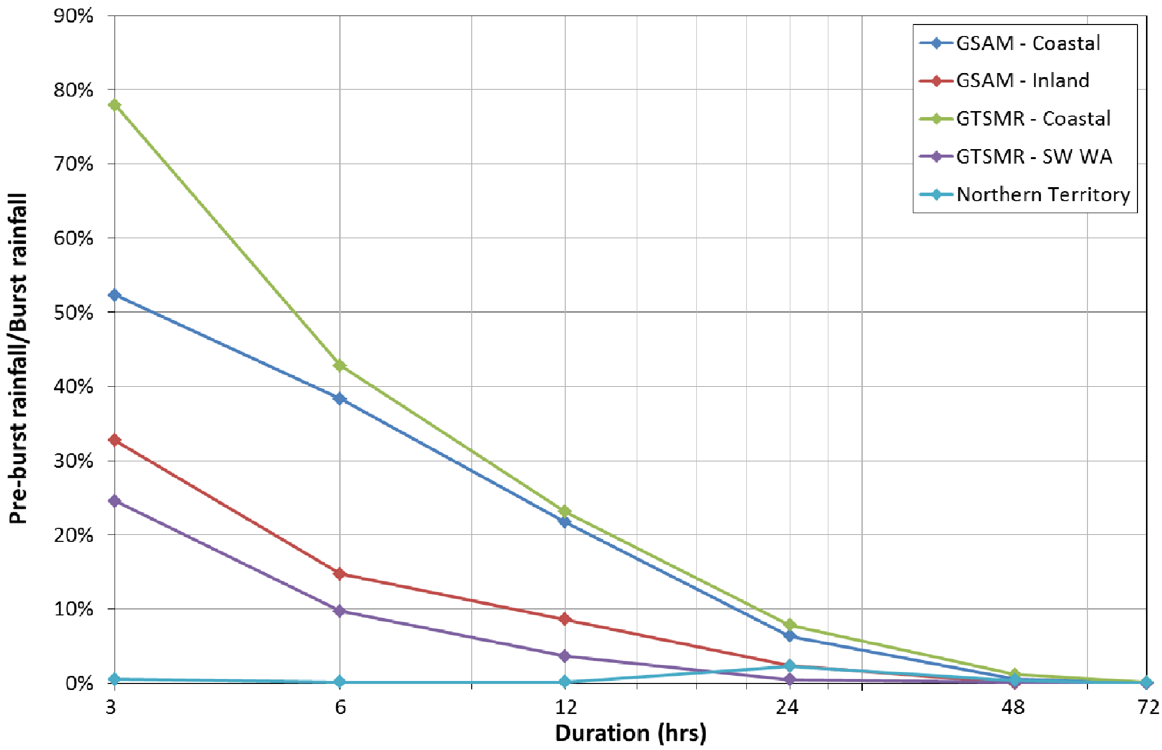
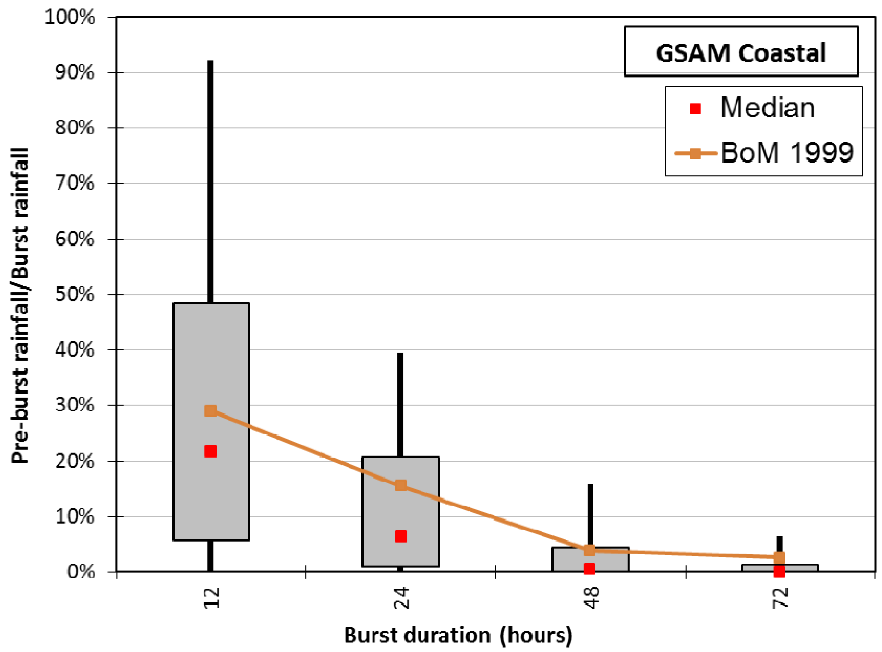


Figure 4-8 Change in Pre-burst/burst rainfall ratio with duration for each region (NT sites and Fletcher Creek separated from GTSMR coastal sites, and Spring Creek excluded)

Distribution summaries of pre-burst normalized against burst rainfall for each region can be found in Appendix F.

The BoM analysed the antecedent rainfall depths for the storms used in the development of the GSAM PMP method (Bureau of Meteorology, 1999). The median results from the BoM (1999) study are compared to the values from this study in Figure 4-9. The BoM (1999) values are slightly higher, but consistent with those from this study.



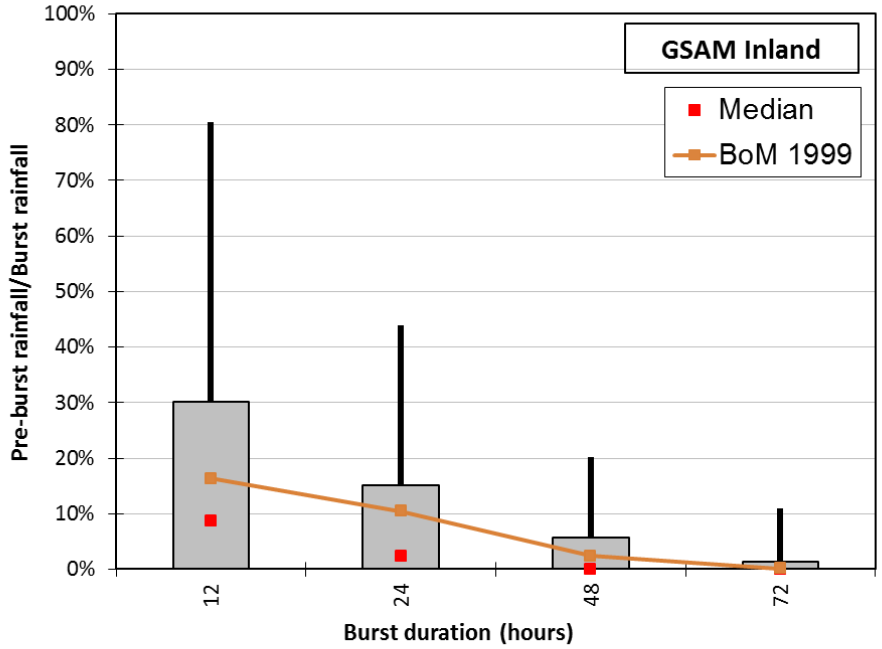


Figure 4-9 Comparison of pre-burst values with median values from BoM (1999) (box indicates quartiles and line show 10th and 90th percentile values)

4.4.4. Pre-burst variation with burst severity

The ratio of pre-burst to burst rainfall is plotted against the Average Recurrence Interval (ARI) of the burst for the 3 hour events in Figure 4-10. It is shown that there is no significant trend for the ratio to vary with the severity of the burst, which implies that the pre-burst rainfall is a fixed proportion of the burst depth.

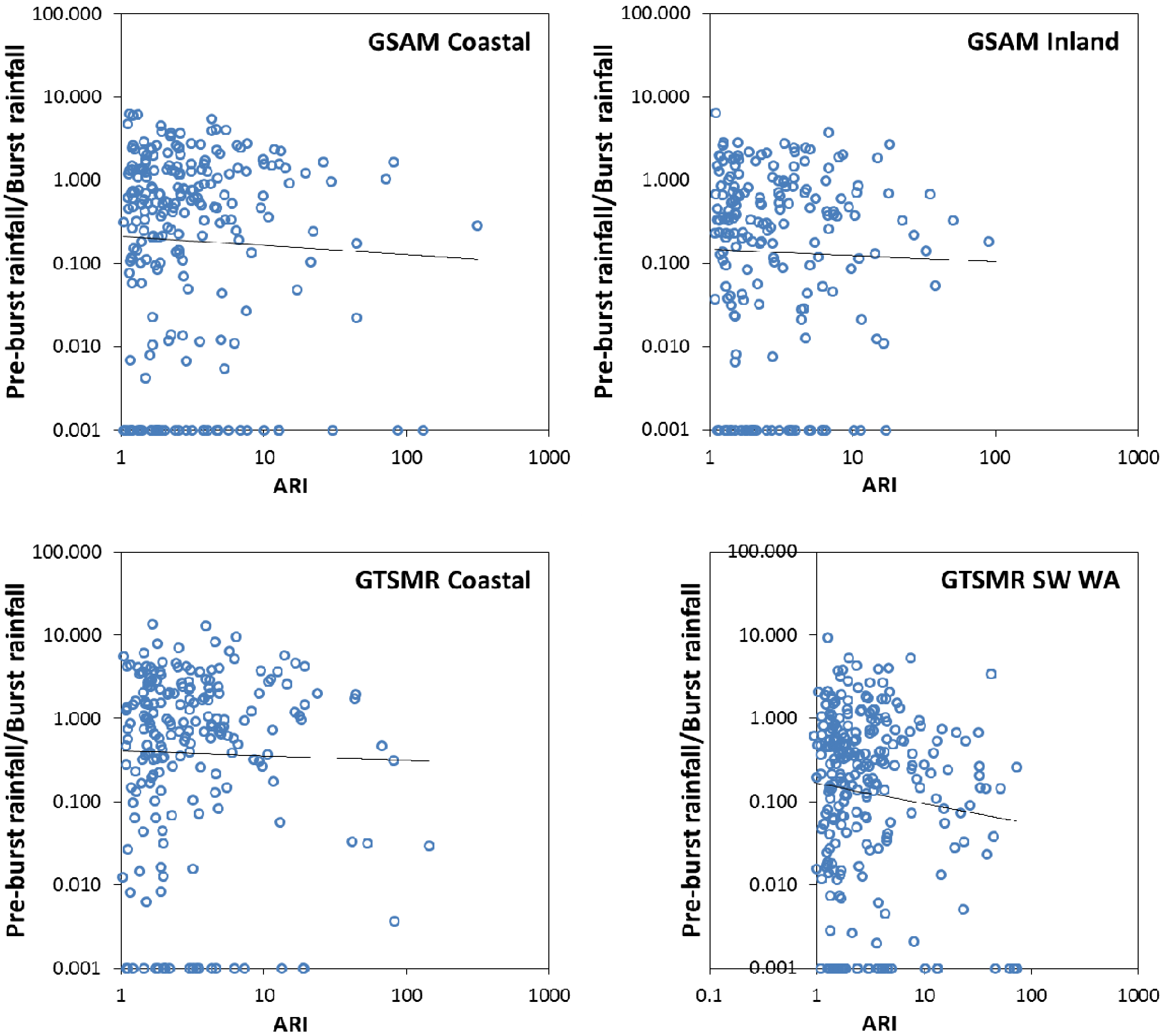


Figure 4-10 Relationship between ratio of pre-burst rainfall and burst rainfall to ARI for 3-hour bursts. (Northern Territory catchments and Fletcher Creek separated from GTSMR coastal catchments, and Spring Creek excluded)

5. Estimation of loss values

This section describes the approach used to estimate loss values. The overall approach was developed and trailed during Stage 1 of ARR Project #6 (SKM, 2012b). Some of the details were further refined as part of a sensitivity analysis undertaken after Stage 1 and these results are documented in Appendix G. This work highlighted the importance of ensuring that the volume of surface runoff is maintained when estimating the loss values and hence the overall shaper and volume was given more weight than the peak as outlined in Section 5.2.

5.1. Baseflow separation

Recorded streamflow is made up of baseflow, which is sourced from groundwater aquifers, and quickflow, which is sourced from surface runoff. The usual method to remove baseflow involves a subjective process of looking at the surface runoff and extracting baseflow based on descriptions such as Nathan and McMahon (1990) and Brodie and Hostetler (2005). Manual baseflow extraction for a large number of events for each of the catchments would be time consuming, and so this process was automated by using a recursive digital filter. Further information on the approach is contained in the ARR Project #7 report (SKM, 2011). The filter parameter was fixed at 0.925 and the number of passes was set to 7 or 9 to provide a realistic separation of baseflow. A summary of the adopted baseflow parameters is contained in Appendix H.

5.2. Method

As part of the Phase 1 Pilot Study a preliminary attempt was made to develop lag relationships which could be applied to the recorded streamflow data to directly estimate the losses. This involved defining a threshold flow above which IL was deemed to be satisfied and then the CL or PL was calculated from a water balance. Such an approach (without the allowance for lag) has previously been applied by Hill et al (1996) and Ilahee (2005) to derive loss values for South-East Australia and Queensland respectively. However, the investigation demonstrated the difficulty in defining a single threshold that reproduces the loss values estimated using flood models.

This reinforced the complexity of identifying the loss from the analysis of rainfall and surface runoff and the importance of utilising a rainfall-runoff model. Therefore, loss values were derived for the large number of events using a simplified calibration procedure which utilised a flood event model.

The RORB rainfall-runoff model was selected as regional prediction equations for its parameterisation are readily available for most regions in Australia. RORB is a general runoff and streamflow routing program that is used to calculate flood hydrographs from rainfall and other catchment and channel inputs. The model subtracts losses from rainfall to determine rainfall excess and routes this through catchment storages represented by the stream length to produce streamflow hydrographs at points of interest. The model can account for both temporal and spatial distribution of rainfall and losses.

The model is based on catchment geometry and topographic data, and the two principal parameters are k_c and m. The parameter m describes the degree of non-linearity of the catchment's response to rainfall excess and was set to 0.8 based upon the recommendations in ARR. The parameter k_c describes the delay in the catchment's response to rainfall excess.

The RORB catchment file requires information about the catchment layout, which is obtained by delineating the catchment into smaller sub-areas that are joined by reaches. The 1 to 25,000 spatial information from the Bureau of Meteorology geofabric was used as a basis for delineating the catchments. The geofabric network information and cartographic layers were used to assist in developing sub-area boundaries and reaches. When delineating the catchment, care was taken to include at least 5 sub-areas upstream of the catchment outlet, and to make the sub-areas a similar size. The catchment boundaries derived using the geofabric information was checked against those reported by the relevant agencies.

As part of scoping the work for Phase 4 a sensitivity analysis was undertaken to test whether the loss values are sensitive to the adopted structure of the routing model. For 5 catchments, losses were estimated using RORB and also an URBS model with separate routing parameters for channel and overland routing (α and β). The results are included in Appendix G4 and demonstrate that the results are not sensitive to the selection of routing model.

The following simplifications were incorporated:

- Spatial patterns – the spatial distribution of rainfall for each event was derived from inverse-distance weighting of nearby daily rainfall stations rather than manually deriving isohyets.
- Fixed routing parameter – for each loss model the routing parameter k_c was kept fixed for every event on a catchment.
- Timing – the temporal distribution of rainfall and streamflow was adopted without adjustment.
- Baseflow separation – the contribution of baseflow to each event was estimated using the recursive digital filter and the parameters summarised in Appendix H rather than manually estimate the baseflow.

Based upon the above simplifications, RORB was used to estimate the values of IL/CL and SWMOD for each of the events identified in Section 4.2.1. The estimation of loss values required subjective fitting of the modelled hydrograph with the surface runoff estimated from subtracting the baseflow from the recorded total streamflow.

In reviewing the results from the Phase 1 Pilot Study it was noted that undue weight was given to fitting the peaks at the expense of the volume and there was a tendency to underestimate the flood volume (refer Appendix G). Hence in Phase 4 greater emphasis was placed on the volume and the following criteria (from most to least important) were adopted:

- Overall shape
- Volume
- Timing
- Peak

In many cases, the fit could have been improved by adjusting the routing parameter but the fits were deemed to be appropriate for estimating the loss values for the event.

5.3. Review of loss values

Because the events were selected on the basis of rainfall, some events yielded little or no surface runoff and this confounded the estimation of loss parameters. Where no surface runoff was generated the event was excluded as it was not possible to estimate the IL value; all that could be determined was that the value was at least the depth of rainfall. For events which yielded a small surface runoff (typically less than a few m^3/s) it was often difficult to obtain a good match between the modelled and surface runoff estimated from the recorded flow data. In these cases the event was discarded as they were subject to considerable uncertainty.

For each event a subjective score from 0 to 9 was assigned based upon the goodness of fits giving consideration to the criteria listed above. An example of the fits is provided in Figure 5-1.

For each catchment, the sample of events was reviewed and outliers or events considered to be highly uncertain were removed. Events were excluded if::

- Volume errors were large (as indicated by zero CL and significant underestimation of volume, typically 20%)
- Runoffs were very low (typically $1.0 m^3/s$ but this threshold was increased for some catchments)
- There was a mismatch in timing between rainfall and runoff
- the fit between calculated and recorded hydrographs was very poor
- The fitted value of CL was abnormally high (typically > 20 mm/h)
- The fitted value of CF was abnormally high (typically > 10)
- The complete period of rainfall was very short (typically less than 3 hours) which made the identification of loss values problematic given the 1 hour time step.

Typically more events were removed from the sample selected by 3-hour rather than 24-hour bursts. Therefore unless otherwise indicated, the analysis and presentation of results in the following sections has focussed on the sample selected from 24-hour bursts.

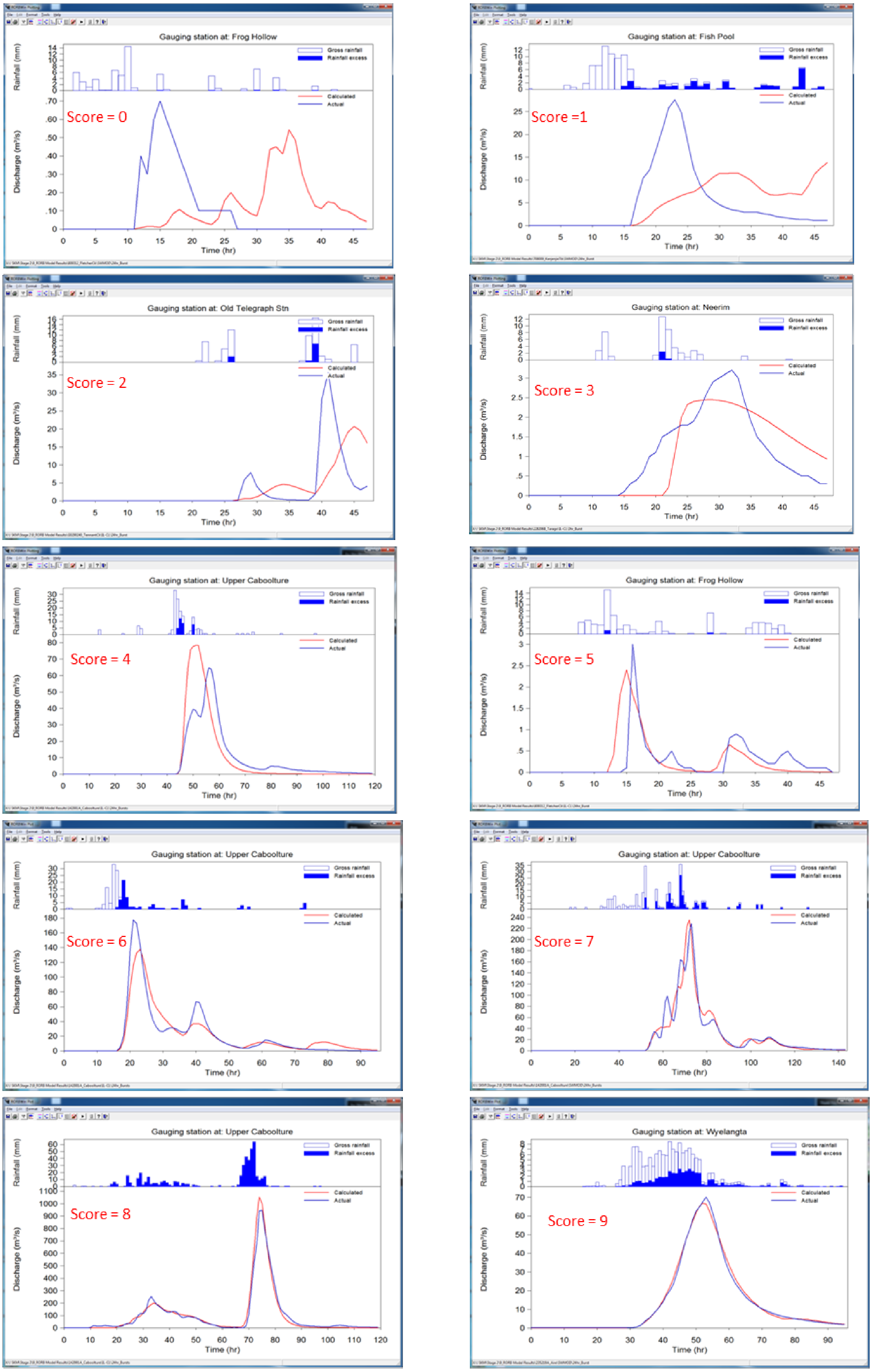


Figure 5-1 Example skill scores used to assess goodness of fit between calculated and recorded hydrographs

5.4. Routing parameters

The RORB routing parameter k_c is a function of the scale of the catchment and therefore it was divided by the average flow distance to the catchment outlet (d_{av}). The resulting value of $C_{0.8}$ allowed the routing parameter to be compared across a range of catchment sizes.

As described above, for each loss model a fixed routing parameter was adopted for each loss catchment. Based upon the work of Pearse et al. (2002) a $C_{0.8}$ values of just over 1.0 was initially trialled on a handful of events for each catchment and varied until a reasonable fit between the estimated and recorded hydrographs was obtained.

The adopted $C_{0.8}$ values for each catchment are listed in Appendix H and summarised in Figure 5-2. The variation of $C_{0.8}$ within each region suggest that factors other than average flow distance to the outlet affect the routing of rainfall excess through the catchment (e.g. slope, drainage network efficiency).

The majority of $C_{0.8}$ values are in the range suggested by Pearse et al. (2002) with the exception of South-west WA where the values were consistently higher. This indicates that the catchment response is different to other regions in Australia and is likely to be characterised by higher levels of interflow.

It was also evident that the $C_{0.8}$ was systematically lower for SWMOD than the IL/CL model (see Figure 5-3). This is likely to be caused by the different time distribution of losses implied by each of the loss models. SWMOD will typically estimate a higher loss (and hence lower rainfall excess) during the most intense portions of the storm when compared to the constant continuing loss model. Thus the time distribution of rainfall excess resulting from the application of SWMOD will tend to be less peaky and hence requires less attenuation from the routing to reproduce the observed hydrograph.

This dependency of the routing parameters on the adopted loss model is not immediately obvious and needs to be considered when selecting parameters for design flood estimation. If the loss model adopted for design differs from that used to calibrate the model then it will be necessary to adjust the routing parameters.

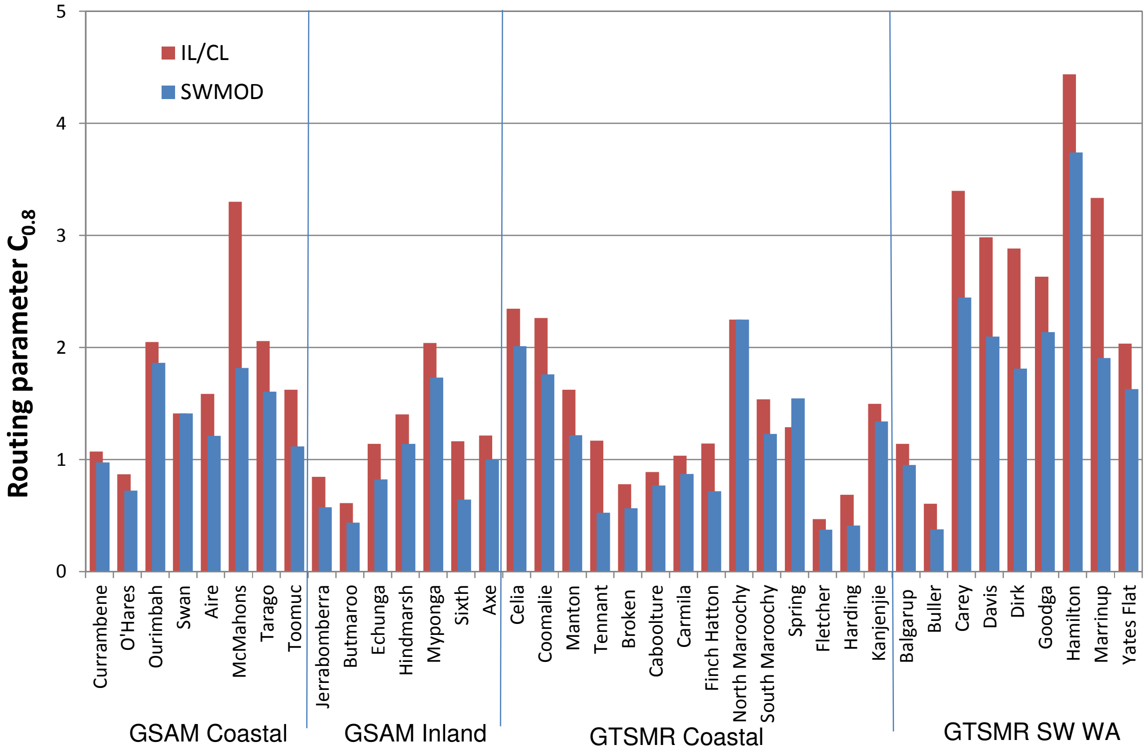


Figure 5-2 Adopted routing parameters

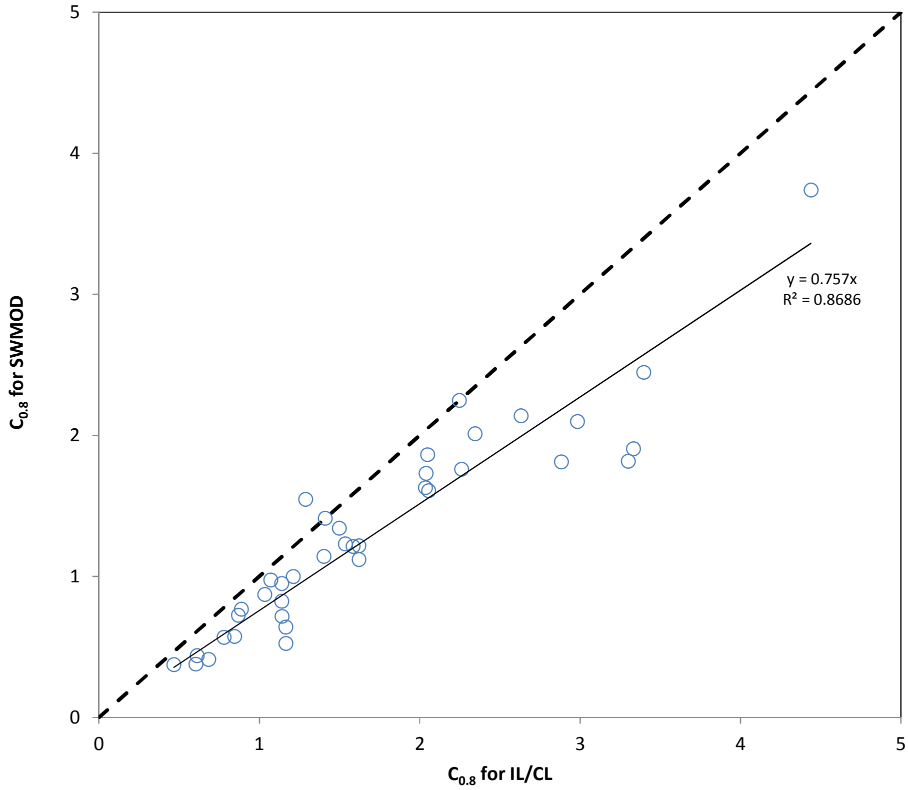


Figure 5-3 Comparison of adopted routing parameters for IL/CL and SWMOD

6. Loss values

6.1. Storm loss values

The approach described in the preceding sections was applied to estimate loss values for each event. Catchment-specific loss summaries are contained in Appendix I and J for events selected from 24-hour and 3-hour bursts respectively. The median loss values are summarised in Table 6-1 and the range of values shown in the following figures. The range of values reflects the influence of antecedent conditions, uncertainties in the inputs (particularly the catchment average rainfall) and data errors.

Table 6-1 Median loss values for events selected by 24-hour bursts

Region	Gauge	Catchment	State	Events	API (mm)	IL_s (mm)	CL (mm/h)	IM_s (mm)	CF
GSAM – Coastal	216004	Currambene	NSW	17	55	35	3.9	0	1.3
	213200	O'Hares	NSW	22	51	60	1.6	7.5	0.6
	211013	Ourimbah	NSW	24	55	40	3.7	45	1.0
	2219	Swan	TAS	19	46	40	0.5	-35	0.3
	235219	Aire	VIC	30	81	17	3.1	25	1.6
	229106	McMahons	VIC	21	62	20	3.7	45	2.8
	228206B	Tarago	VIC	22	70	24	3.9	60	2.1
	228217	Toomuc	VIC	25	52	24	2.5	0	1.6
GSAM – Inland	410743	Jerrabomberra	NSW	20	46	22	2.1	6.5	0.6
	411003	Butmaroo	NSW	21	37	40	2.6	-7	0.9
	AW503506	Echunga	SA	13	49	25	2.2	40	0.7
	AW501500	Hindmarsh	SA	33	52	15	3.2	55	1.5
	AW502502	Myponga	SA	15	46	23	2.6	5	0.6
	A5040523	Sixth	SA	24	72	15	3.3	45	1.3
	406216	Axe	VIC	12	55	28	6.0	5	1.0
GTSMR – Coastal	G8150151	Celia	NT	15	197	25	5.4	60	2.2
	G8170066	Coomalie	NT	30	184	50	8.1	35	4.4
	G8170075	Manton	NT	32	153	42	1.6	15	1.3
	G0290240	Tennant	NT	24	52	0	5.2	20	1.3
	120216A	Broken	QLD	34	201	68	6.2	-20	1.2
	142001A	Caboolture	QLD	20	105	50	1.4	2.5	0.4
	126003A	Carmila	QLD	19	121	70	3.1	-25	0.4
	125006	Finch Hatton	QLD	30	337	23	5.2	70	0.8
	141009	North Maroochy	QLD	23	89	20	2.2	10	1.1
	141001	South Maroochy	QLD	22	94	38	2.7	10	0.7
	422321	Spring	QLD	27	80	30	5.1	0	4.5
	809312	Fletcher	WA	19	121	30	10.4	40	1.7
	709007	Harding	WA	17	60	60	8.3	-10	2.6
	708009	Kanjenjie	WA	13	80	40	0.8	-5	0.4
GTSMR – SW WA	609005	Balgarup	WA	13	27	25	2.5	5	0.9
	701006	Buller	WA	14	40	32	3.8	0	0.6
	608002	Carey	WA	19	152	20	3.8	50	2.7
	614047	Davis	WA	18	140	25	8.1	40	7.4
	614005	Dirk	WA	20	64	14	6.7	60	4.5
	602199	Goodga	WA	27	48	30	4.8	10	2.7
	612004	Hamilton	WA	13	76	47	3.3	50	4.2
	614003	Marrinup	WA	19	84	16	7.3	60	2.7
	603190	Yates Flat	WA	17	43	27	0.8	15	0.4

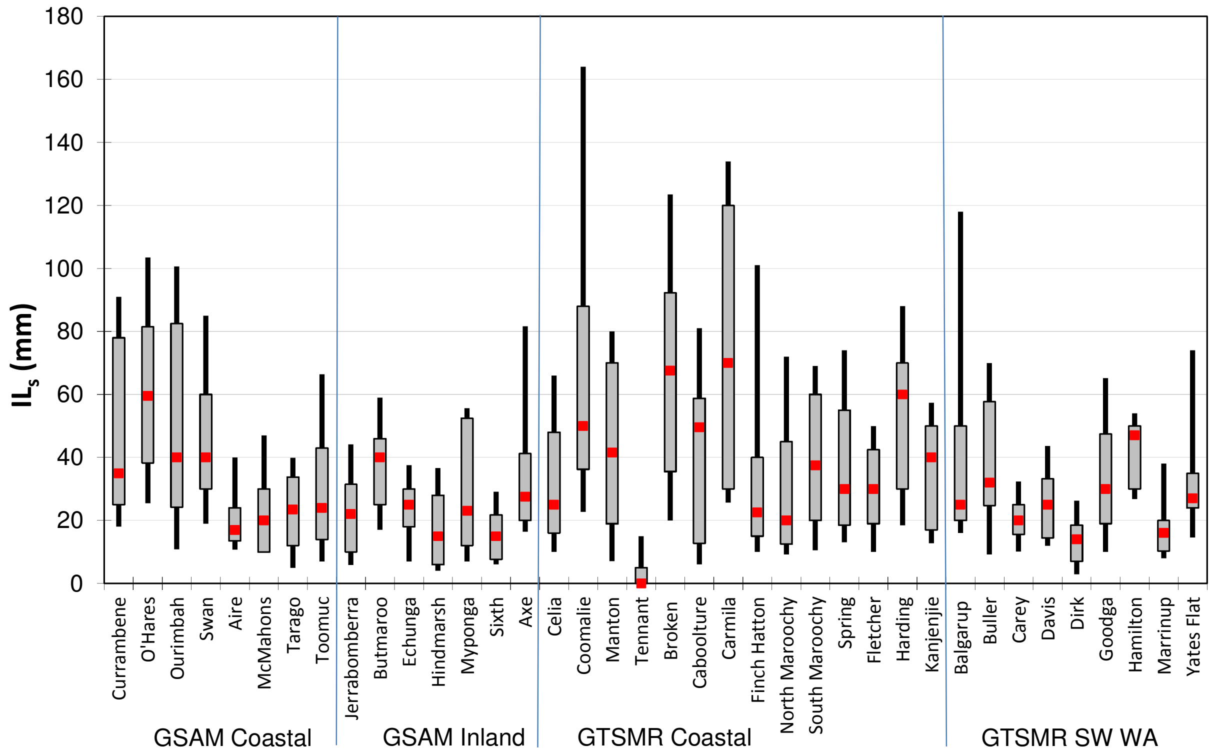


Figure 6-1 Range of storm Initial Loss values for events selected by 24-hour bursts (box indicates quartiles and line shows 10th and 90th percentile values)

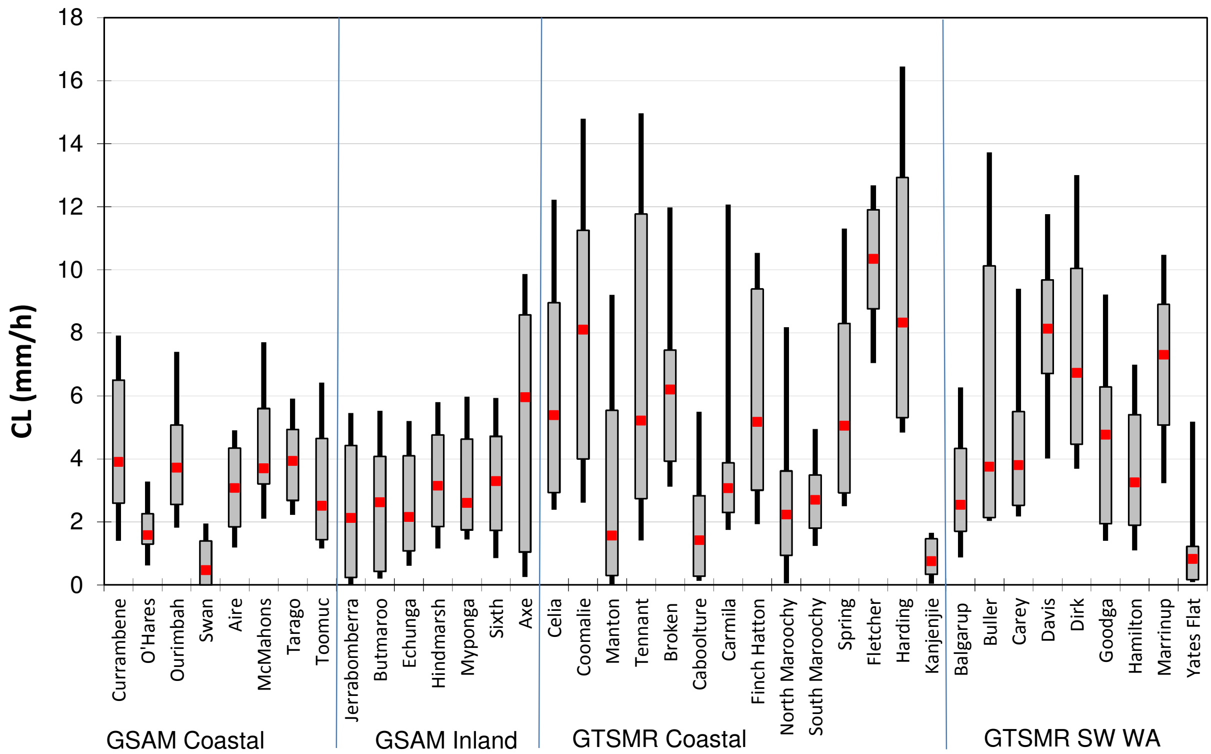


Figure 6-2 Range of Continuing Loss values for events selected by 24-hour bursts (box indicates quartiles and line show 10^{th} and 90^{th} percentile values)

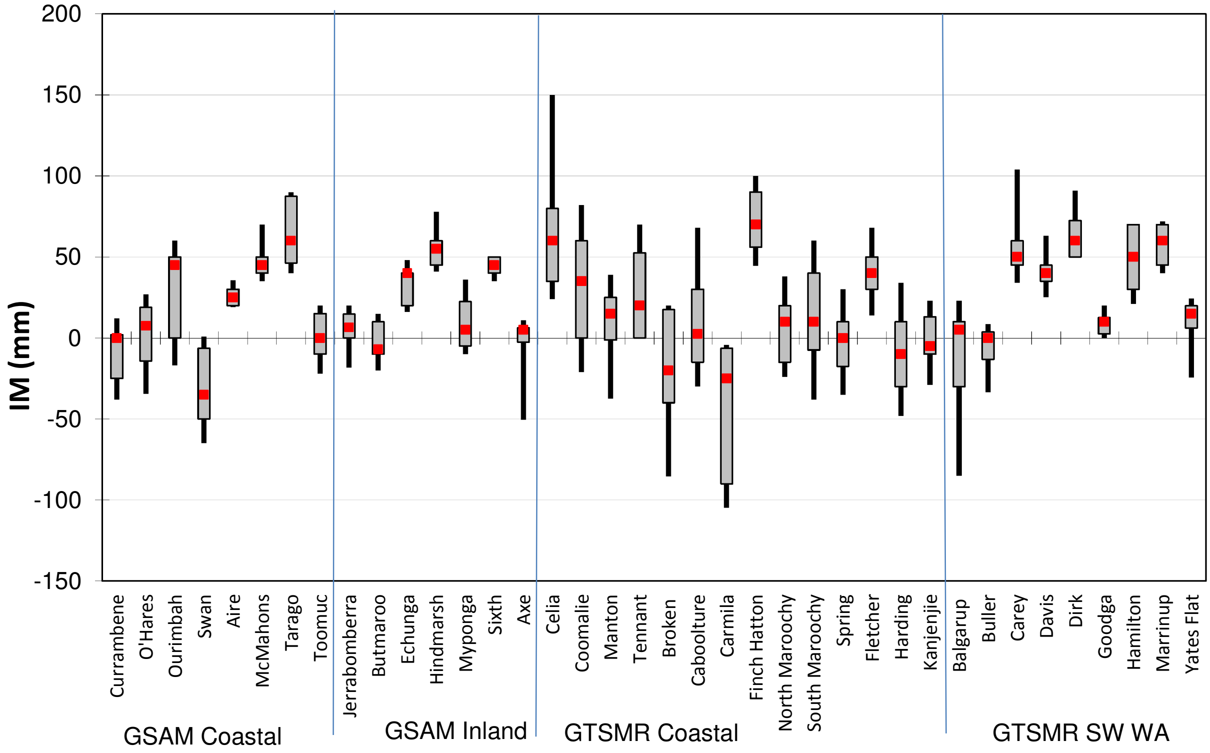


Figure 6-3 Range of Initial Moisture values for events selected by 24-hour bursts (box indicates quartiles and line show 10th and 90th percentile values)

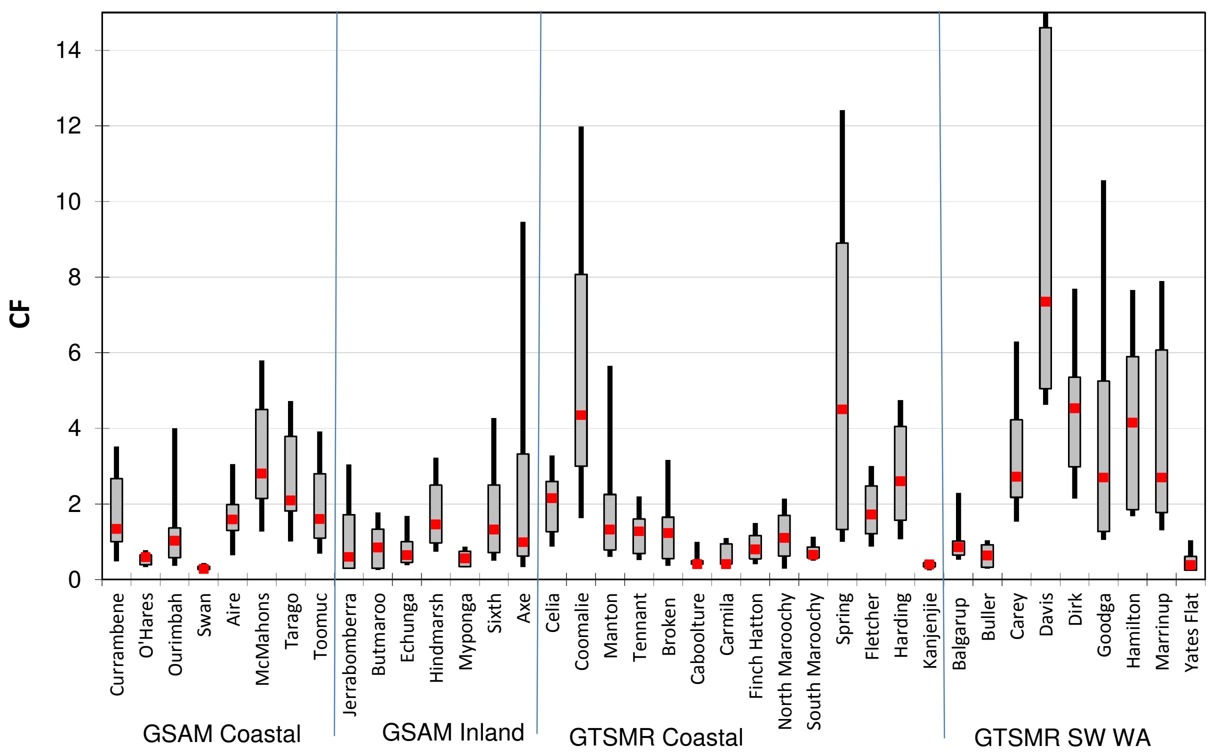


Figure 6-4 Range of Capacity Factor values for events selected by 24-hour bursts (box indicates quartiles and line show 10th and 90th percentile values)

6.2. 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 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 negatively correlated. For each catchment the relationship between the IL_s and IM_s values is shown in Appendices F and G.

The proportion of variance explained (r^2) between the median IL_s and median IM_s values for each catchment is shown in Figure 6-5. 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.

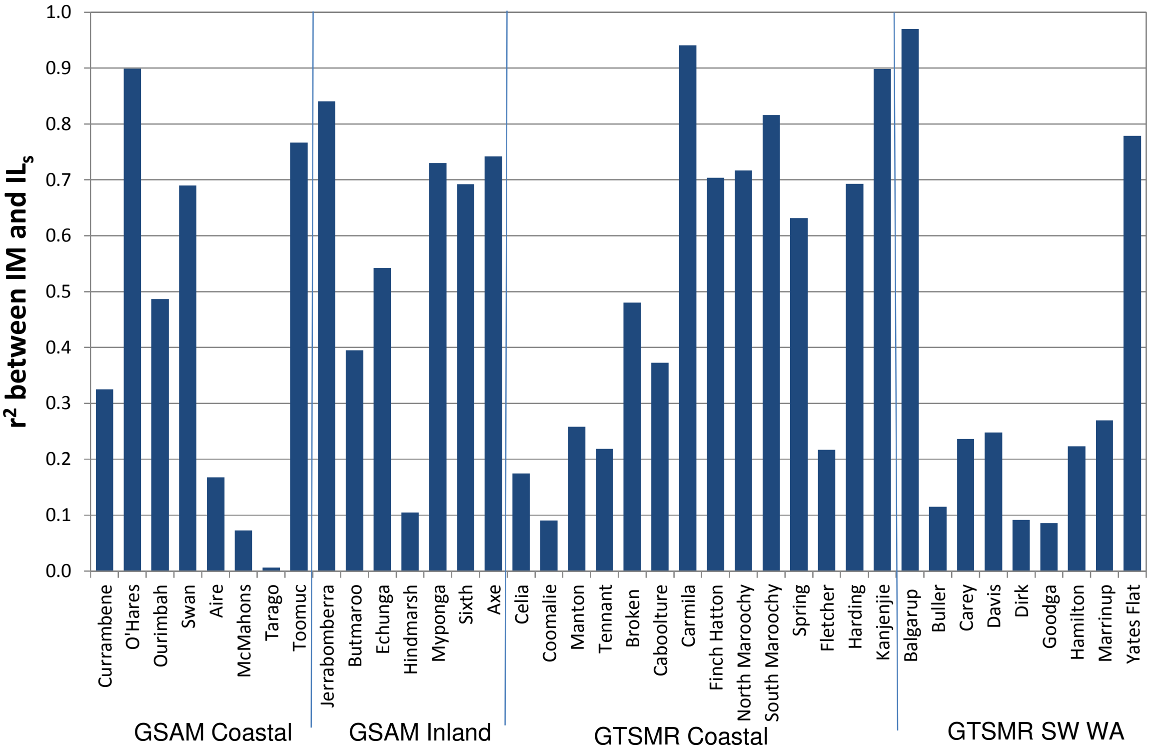


Figure 6-5 Proportion of variance explained (r^2) between IM_s and IL_s

The relationship between the median IM_s and IL_s is shown in Figure 6-6 which shows that, as expected, the values are negatively correlated although there is considerable scatter about the fitted linear relationship.

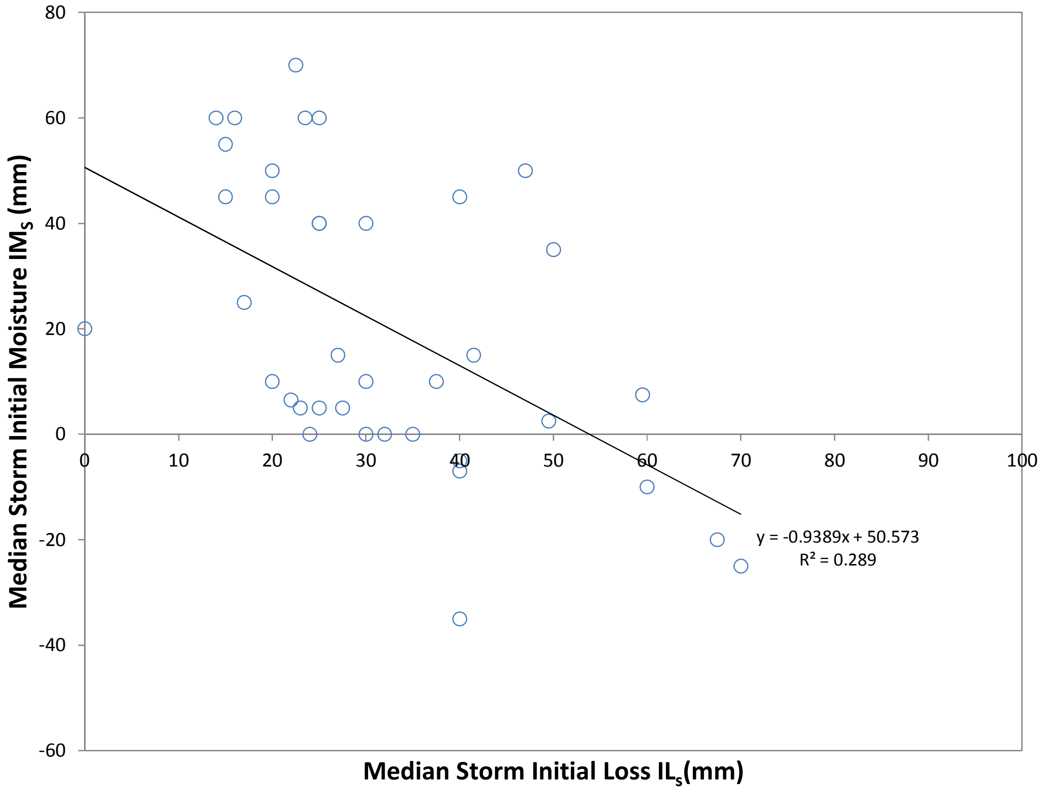


Figure 6-6 Relationship between median Storm Initial Moisture and Storm Initial Loss

The median storm deficit was calculated as the difference between the minimum soil capacity and the IM_s. This reflects the volume that must be satisfied to fill up the smallest store in the catchment and hence is analogous to the IL_s. Given that some catchments had multiple soil types, two different measure of the minimum soil capacity were trialled. The first was simply the minimum soil capacity within the catchment irrespective of what proportion of the catchment was represented and the second was the weighted average minimum soil capacity based upon the relative areas of each soil type.

The relationships between median storm deficit and IL_s are shown in Figure 6-7 and Figure 6-8. The relationship between the 2 parameters is improved when the minimum capacity is weighted by the area.

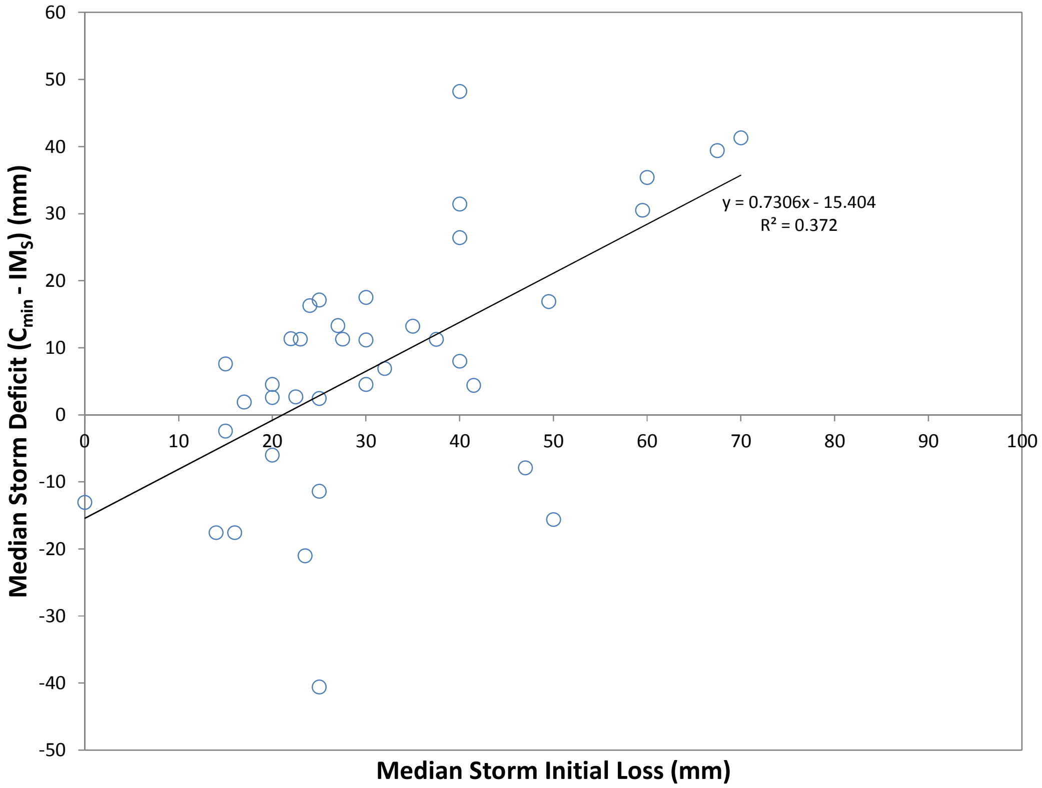


Figure 6-7 Relationship between median Storm Deficit (based upon minimum capacity of soils in the catchment) and Storm Initial Loss

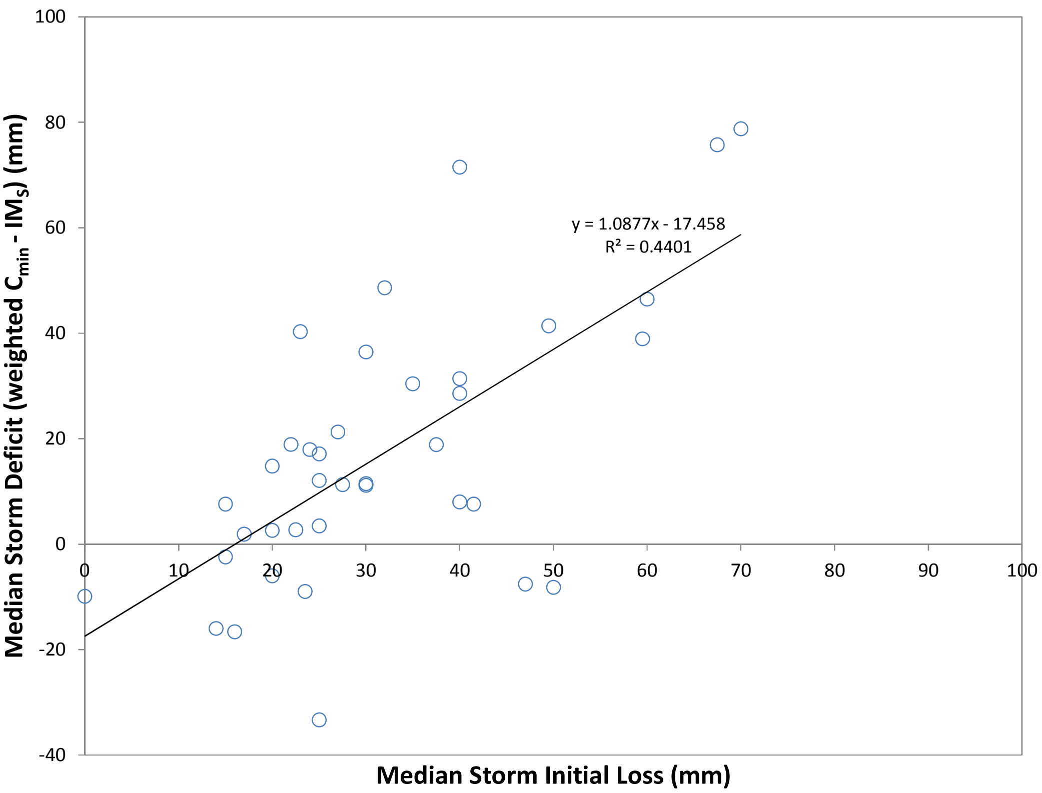


Figure 6-8 Relationship between median Storm Deficit (based upon weighted minimum capacity of soils in the catchment) and Storm Initial Loss

6.3. Sensitivity to burst duration

As discussed in Section 4, for each catchment 2 separate sample of events were selected based upon 3 and 24-hour bursts. For each sample of bursts, complete storms were defined and loss values estimated.

Figure 6-9 compares the median loss values for the different sample of events. For three catchments (McMahons, Finch Hatton and Balgarup) the 3-hour median values were not reported as they were not considered to be reliable due to the small number of events and/or the median value was heavily skewed by multiple occurrences of the same event. Thus, the comparison is shown for 35 catchments.

The comparison demonstrates that the median results are generally not sensitive to the duration used to select bursts. This is important as it implies that the loss values relating to the complete storm (IL_s, CL, IM and CF) can be derived from a single sample of events. As discussed in Section 5.3 more events were removed from the sample selected by 3-hour rather than 24-hour bursts. Therefore unless otherwise indicated, the analysis and presentation of results in the following sections focusses on the sample selected from 24-hour bursts. The results presented in Section 4.3 demonstrate that the pre-burst rainfall does vary with duration and hence the losses relevant for design flood estimation need to account for this.

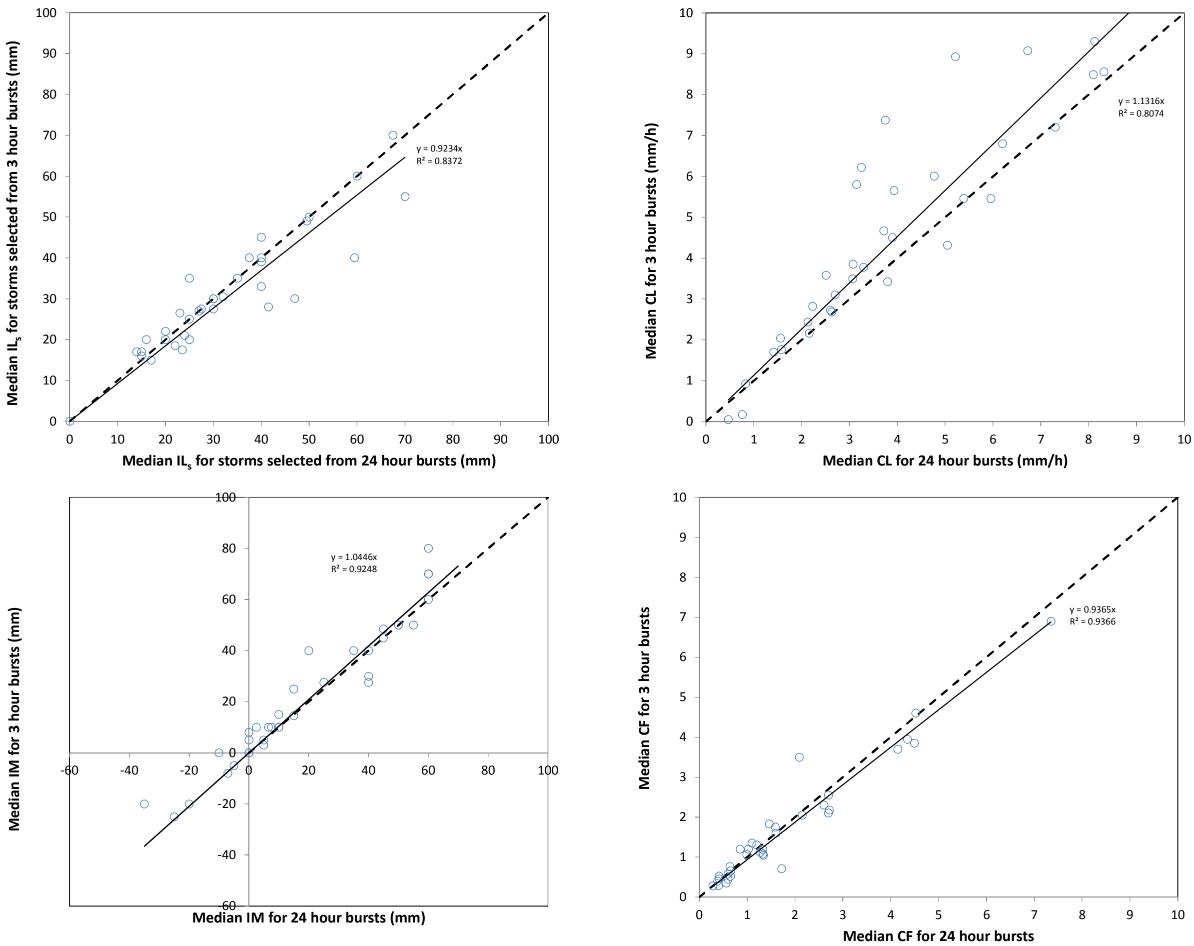


Figure 6-9 Comparison of loss values for events selected by bursts of 3 and 24-hour duration

6.4. Burst loss values

The following figures show the median values of burst loss. As noted in the previous section, for three catchments (McMahons, Finch Hatton and Balgarup) the 3-hour median values were excluded as they were not considered to be reliable.

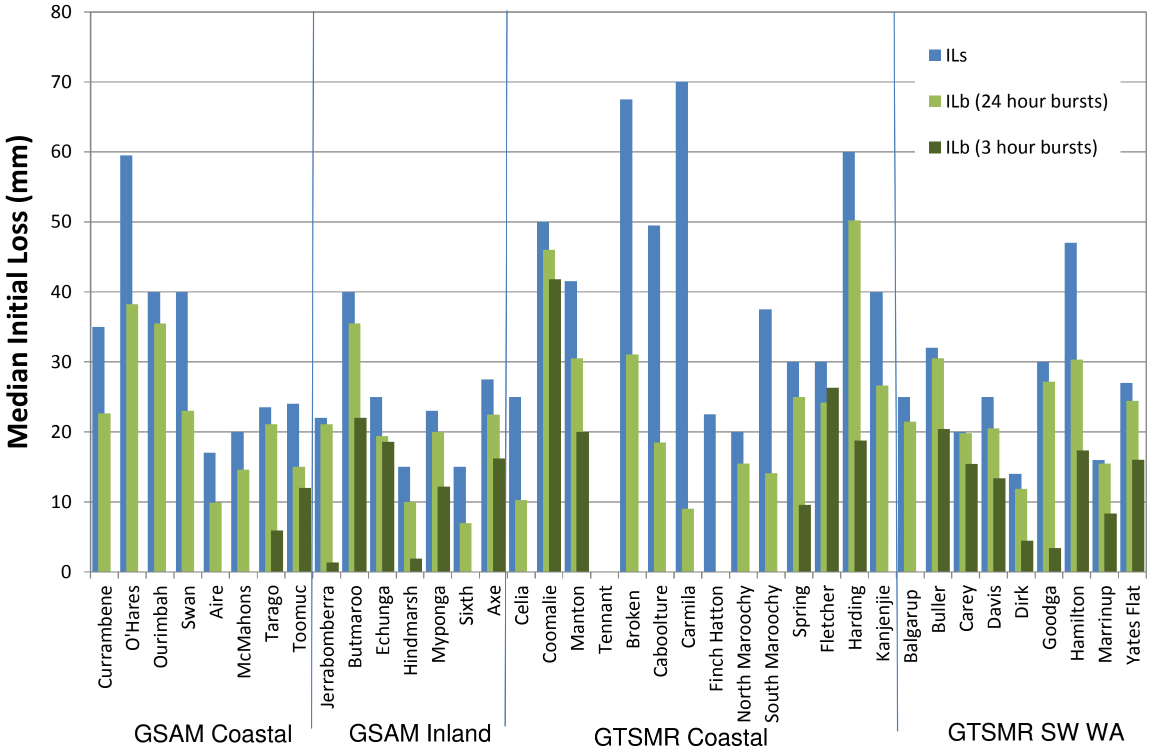


Figure 6-10 Median Initial Loss for different duration bursts

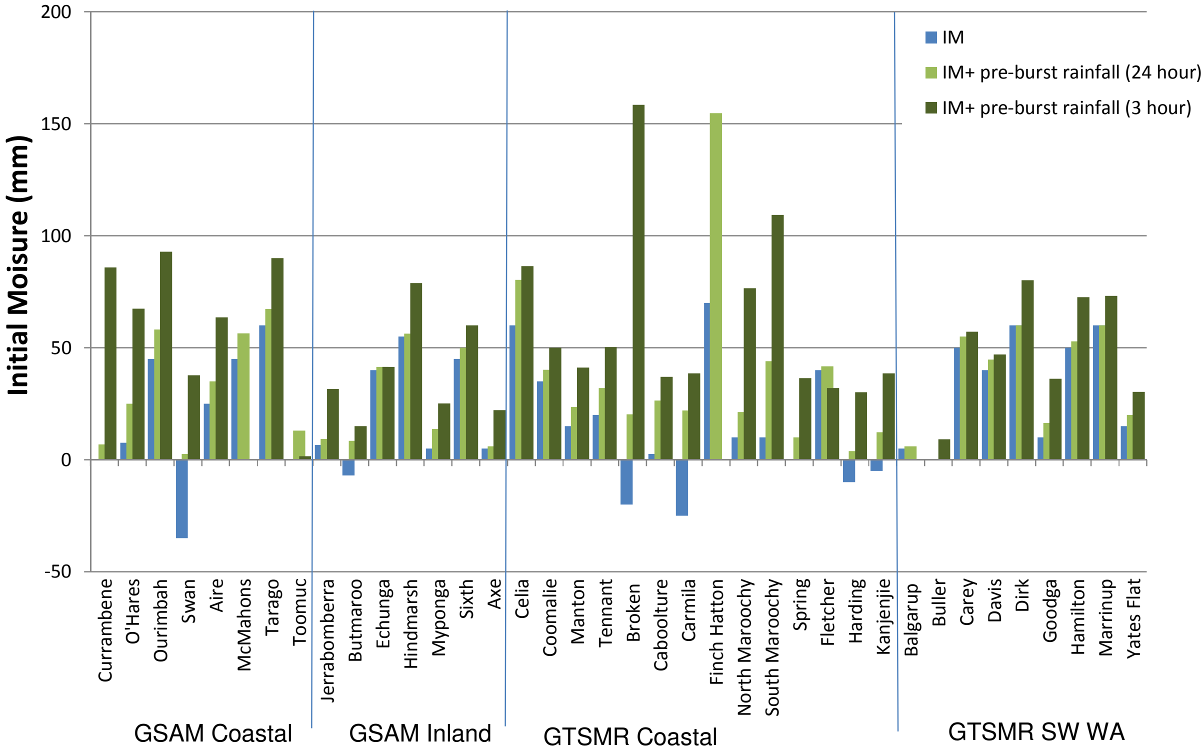


Figure 6-11 Median Initial Moisure for different duration bursts

6.5. Comparison with previous studies

6.5.1. Comparison with Pilot Study

The median loss values are compared to those from the Phase 1 Pilot Study in Figure 6-12. This demonstrates that although the revised approach results in different median values for some catchments, the results are generally consistent. The loss are generally slightly lower than the pilot study and this probably reflects the greater emphasis placed on maintaining the event volume whereas the pilot focussed more on the peak and underestimated the volume.

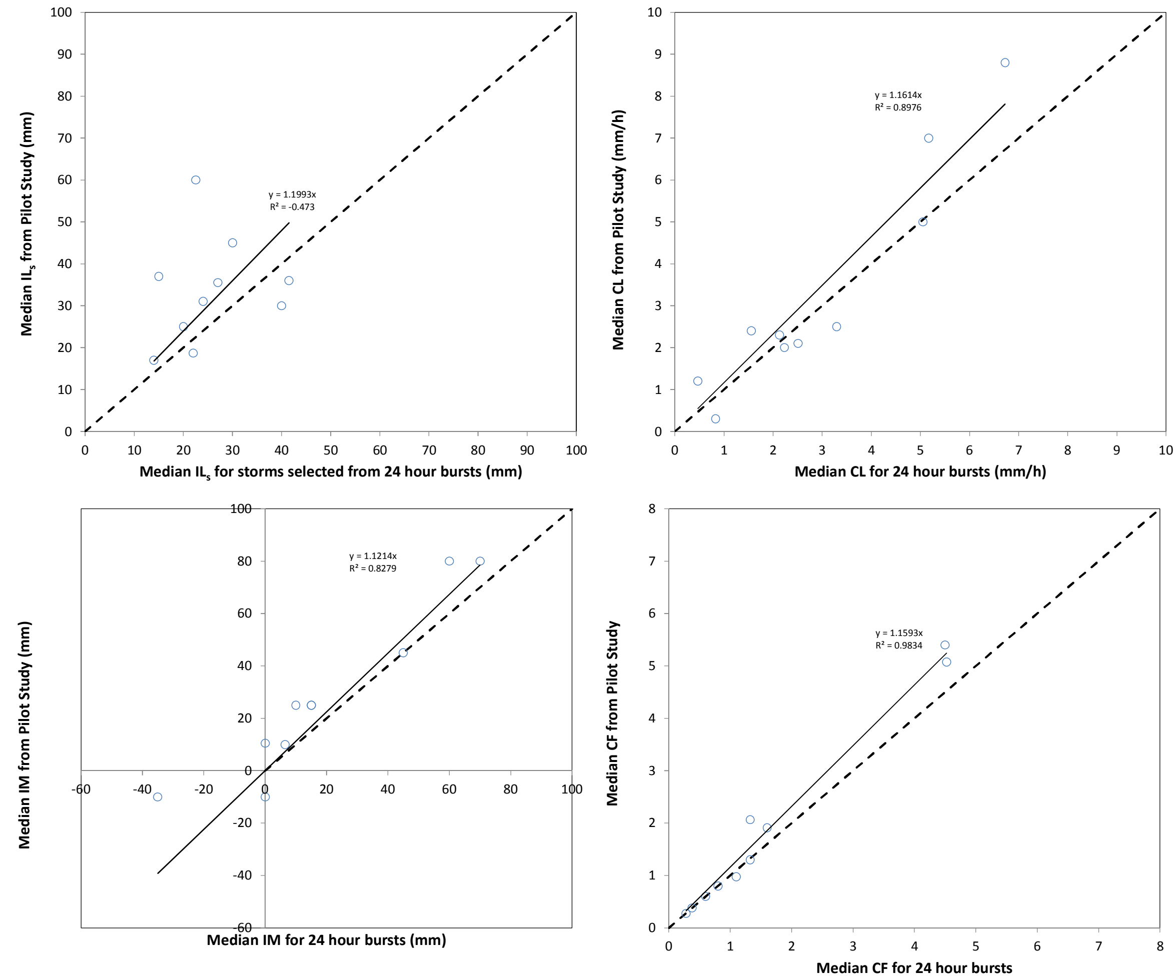


Figure 6-12 Comparison of loss values with Phase 1 Pilot Study

6.5.2. Comparison with other studies

For some of the study catchments, previous studies have analysed recorded data to derive estimates of IL_s and CL. The median IL_s and CL values from this study are compared with these previous estimates in Table 6-2 and Figure 6-13 below.

Table 6-2 Comparison of median loss values with previous studies

Name		Location		This study		Other studies		
Gauge No.	Stream	State	Location	IL_s (mm)	CL (mm/h)	IL_s (mm)	CL (mm/h)	Reference
235219	Aire	VIC	GSAM - Coastal	17	3.1	19	3.40	Hill et al (1996)
410743	Jerrabomberra	NSW	GSAM - Inland	22	2.1	25	3.00	
120216A	Broken	Qld	GTSMR - Coastal	68	6.2	64	1.7	Ilahee (2005)
141009	North Maroochy	Qld	GTSMR - Coastal	20	2.2	42	0.89	
422321	Spring	Qld	GTSMR - Coastal	30	5.1	4	0.73	
216004	Currambene	NSW	GSAM - Coastal	35	3.9	38	5.30	Taylor (2013)
211013	Ourimbah	NSW	GSAM - Coastal	40	3.7	45	4.50	

There is good agreement between the values from this study and those from Hill et al (1996) and Taylor (2013; pers. comm.). However, the values from Ilahee (2005) are different to the current estimates. This is particularly the case for the CL values, where the Ilahee (2005) values are lower than the current estimates. This can be explained by the approach adopted by Ilahee (2005) who estimated the CL as the volume of loss divided by the duration of the event (after IL has been satisfied). Whereas in this study, the CL is calculated as a threshold above which there is rainfall excess. In some timesteps the recorded rainfall is less than the threshold and therefore estimating the loss directly from a volume balance results in a lower CL value.

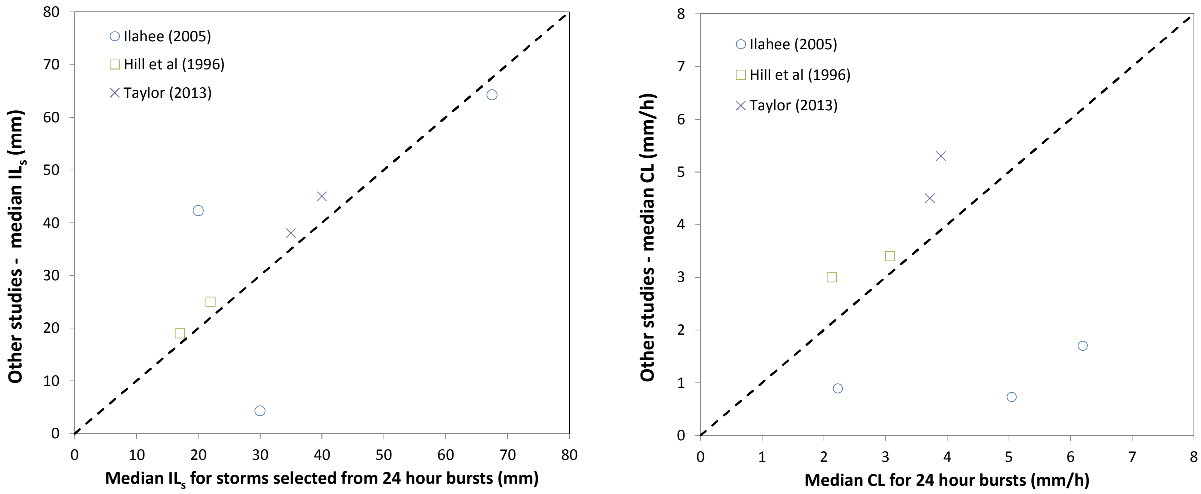


Figure 6-13 Comparison of IL/CL values with other studies

6.6. Relative performance of loss models

As discussed in Section 5.2, for each event, a subjective score between 0 and 9 was assigned to the goodness of fit between the calculated and recorded hydrograph. This score was used to infer the preference of loss model for each event.

The results are shown in Figure 6-14. 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.

Some catchments a particular loss model was preferred for a majority of events. For example for Fletcher the IL/CL model was preferred for approximately two thirds of the events and for Marrinup the SWMOD model was preferred for approximately two thirds of the events.

However, even for those catchments where there is a preference for one loss model over the other, 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”.

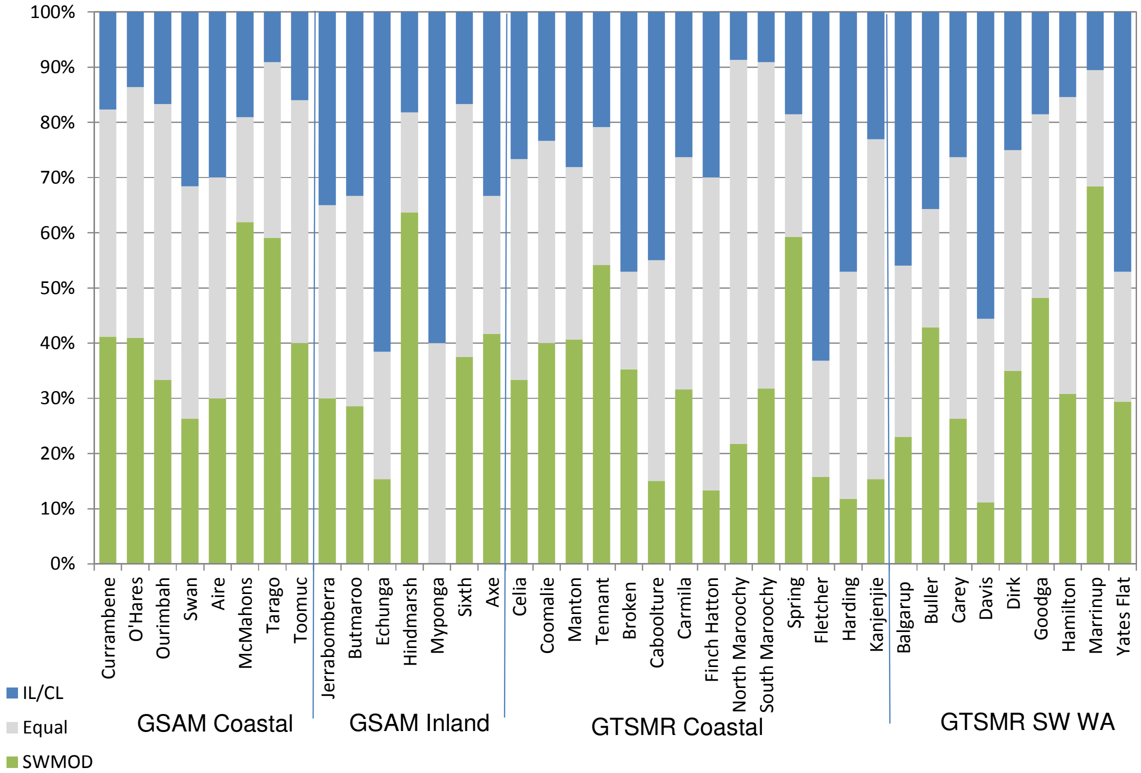


Figure 6-14 Relative performance of IL/CL and SWMOD models

6.7. Non-parametric distribution

The degree of variability in the losses reflects both natural variability in the factors contributing to loss (initial state of catchment wetness, seasonal effects on vegetation) and impacts of error in rainfall and streamflow data. As long as these errors are of a random rather than systematic nature, they should not bias the estimated loss 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 in a region to obtain a single non-dimensional curve. The standardised distributions of losses from the different regions are compared in Figure 6-15 and Figure 6-17 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.

Conceptually, the Continuing Loss represents the losses due to catchment characteristics such as vegetation and soils, and therefore the values are not expected to vary significantly between events, however the distributions shown indicate that it can be up to 4 times the median value.

The distributions of Initial Loss and Continuing Loss were compared to those obtained from previous studies for Western Australia (Waugh, 1990), south-eastern Australia (Hill et al., 1996) and for Queensland (Ilahee, 2005), as shown in Figure 6-16 and Figure 6-18. These comparisons again demonstrate the consistency between the distributions from the different studies.

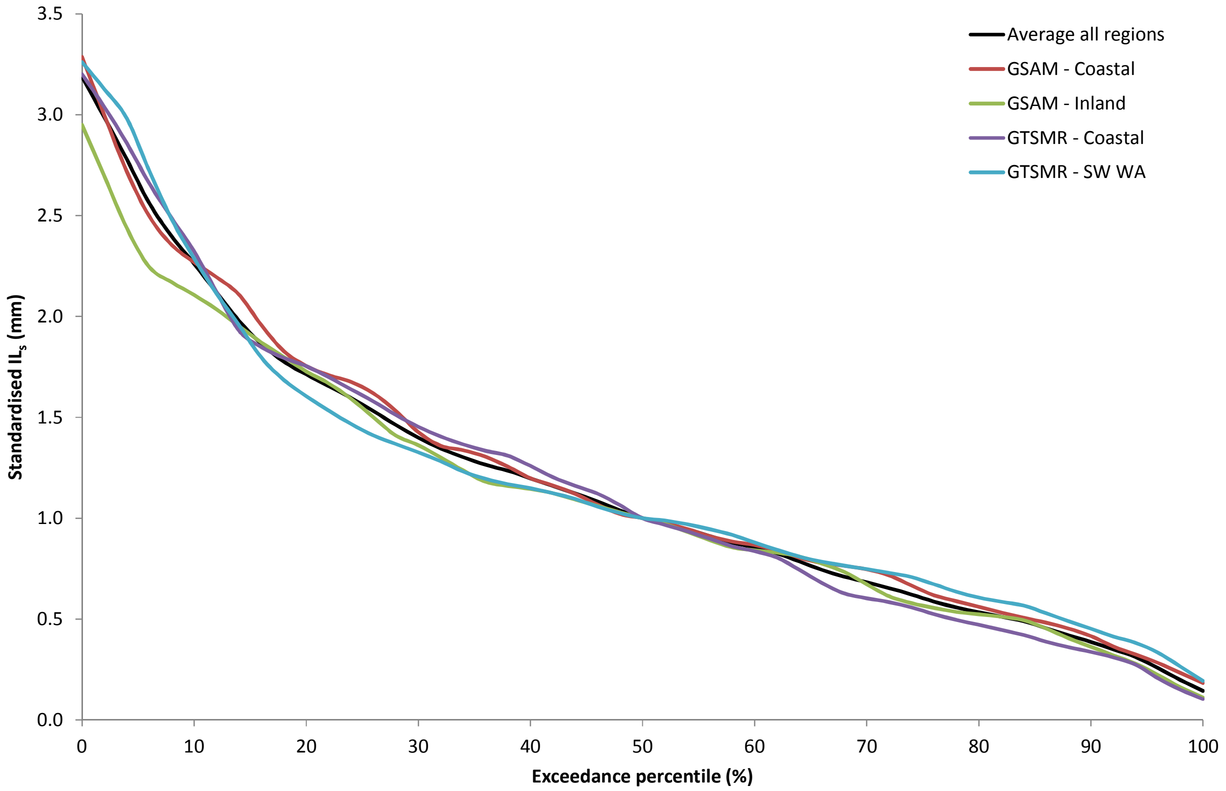


Figure 6-15 Regional average IL$_s$ standardised by the mean value and average across all regions

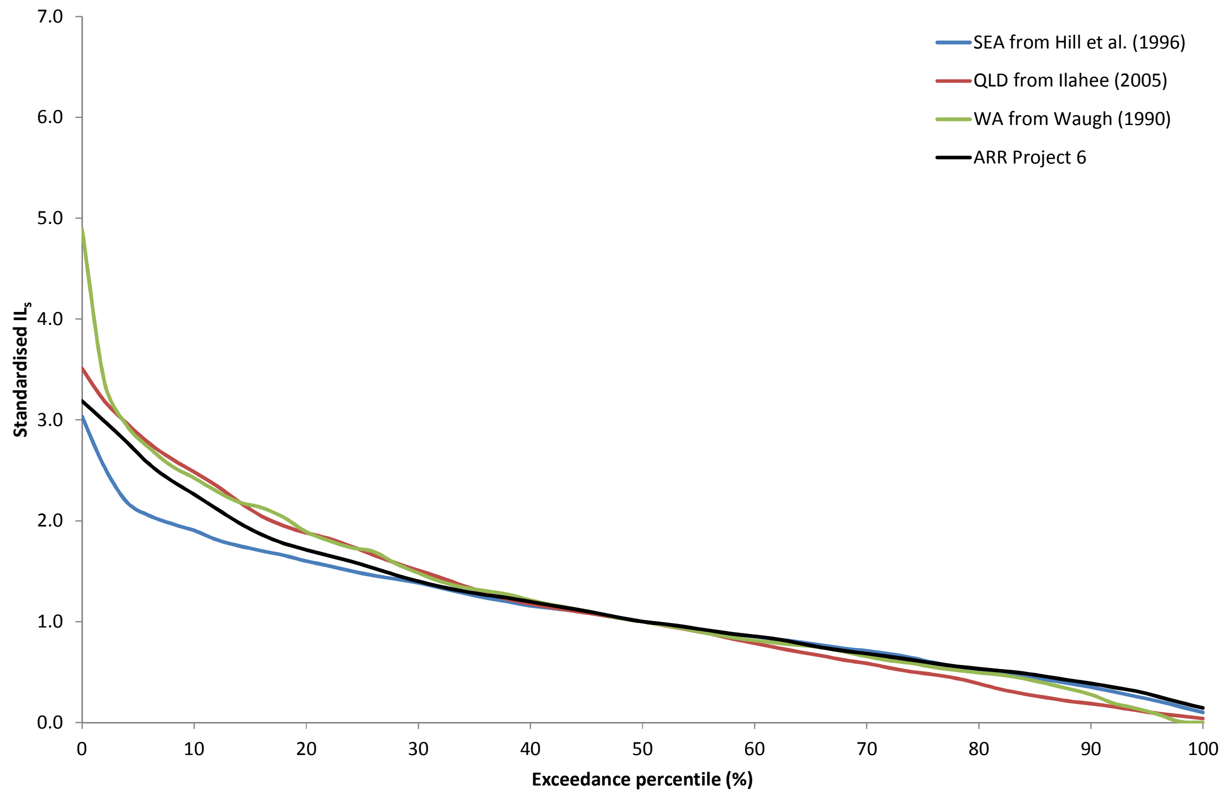


Figure 6-16 Average IL$_s$ standardised by the mean value for Project 6 and standardised Initial Loss distributions from other studies

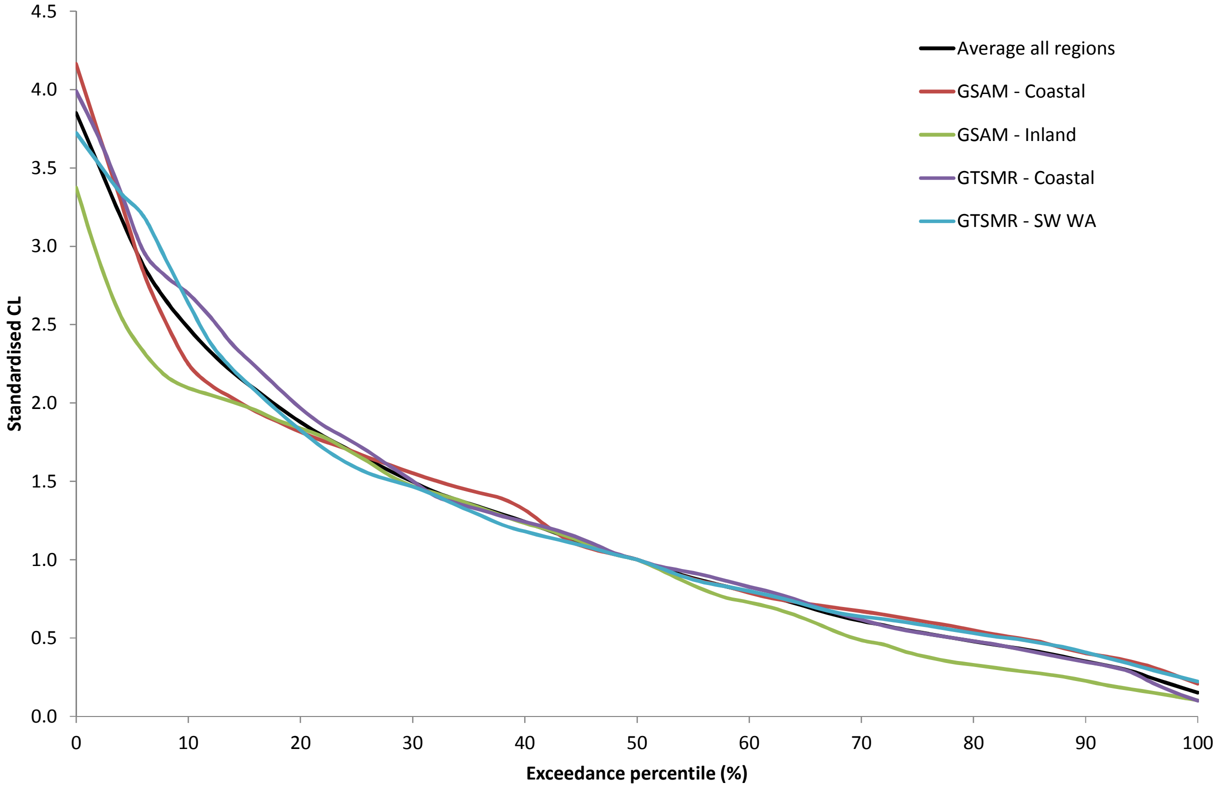


Figure 6-17 Regional average CL standardised by the mean value and average across all regions

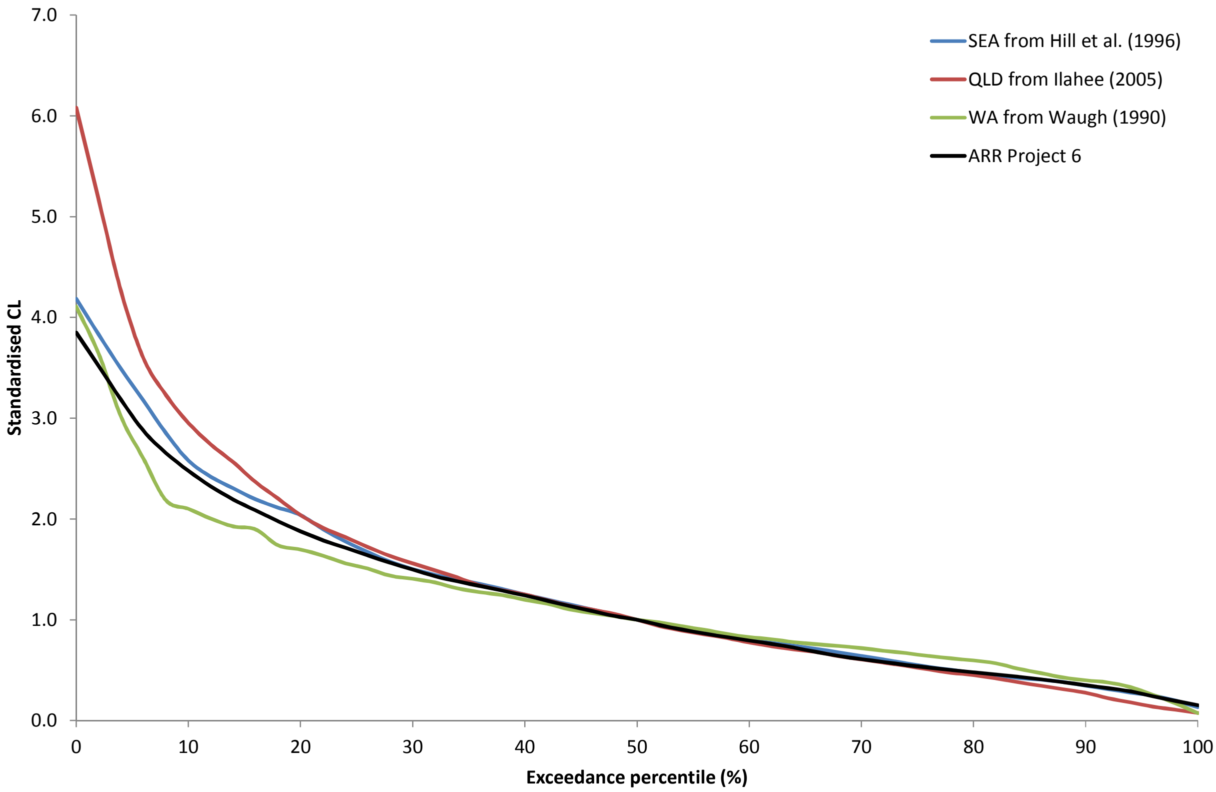


Figure 6-18 Average CL standardised by the mean value for Project 6 and standardised Continuing Loss distributions from other studies

6.8. 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 varies typically in the range of 0.85 to 0.98 (Linsley et al., 1982) and Cordery (1970) found that the average relationship for Australian catchments was 0.92. The value of k is considered to vary seasonally and has been linked to the variation in potential evapotranspiration (Mein et al. 1995).

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 are summarised in Figure 6-19 and Figure 6-20. For both the IL_s and IM_s the highest correlation was obtained with a k of 0.95 and hence this was adopted consistently across all catchments.

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 and it is recommended that this be further investigated.

The ranges of values of API for each catchment are shown in Figure 6-21 for a k of 0.95 for storms selected based upon 24-hour bursts. The range of API values for the sample of events based upon different duration bursts is shown in Appendix E. The API values are not sensitive to the burst duration used to select the events and this is consistent with the findings for IL_s and IM_s noted above.

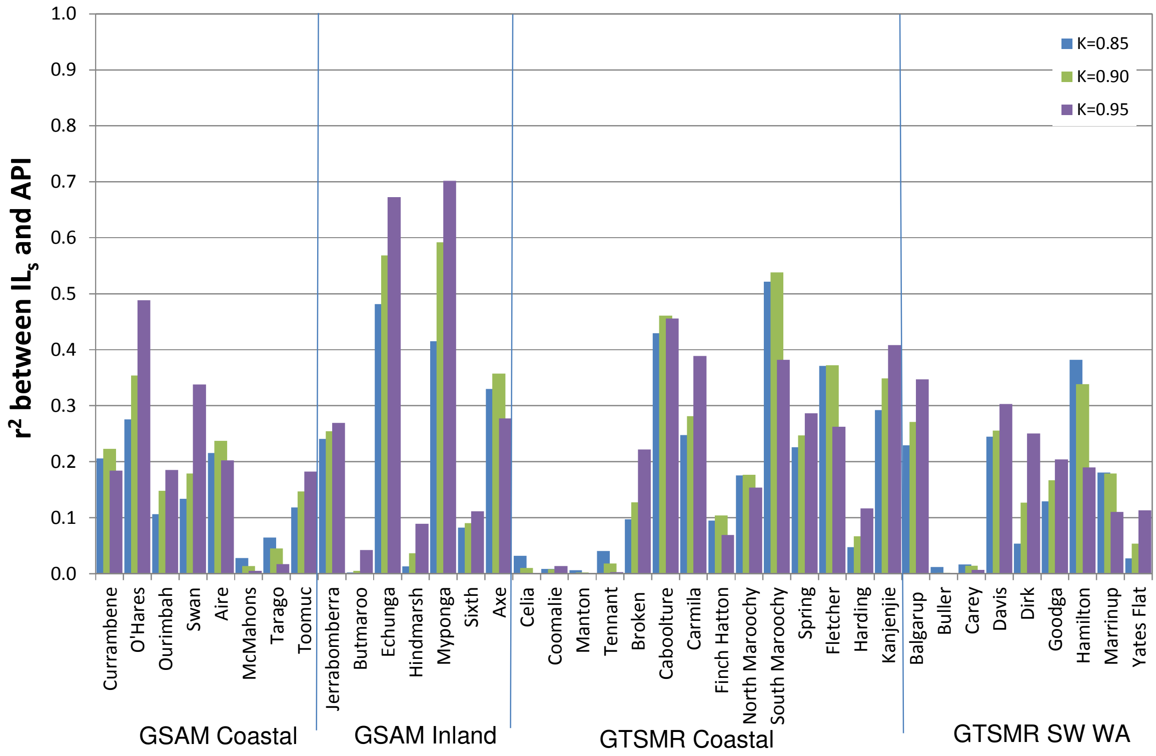


Figure 6-19 Proportion of variance explained (r^2) between Storm Initial Loss and API

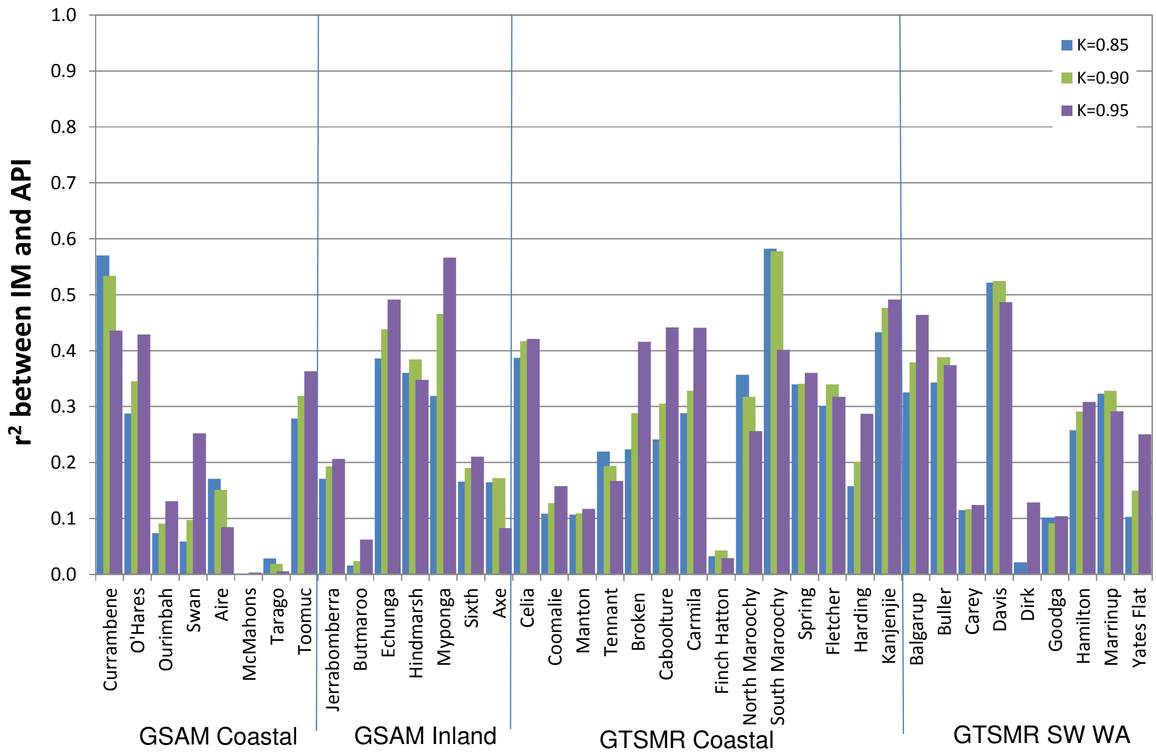


Figure 6-20 Proportion of variance explained (r^2) between Initial Moisture and API

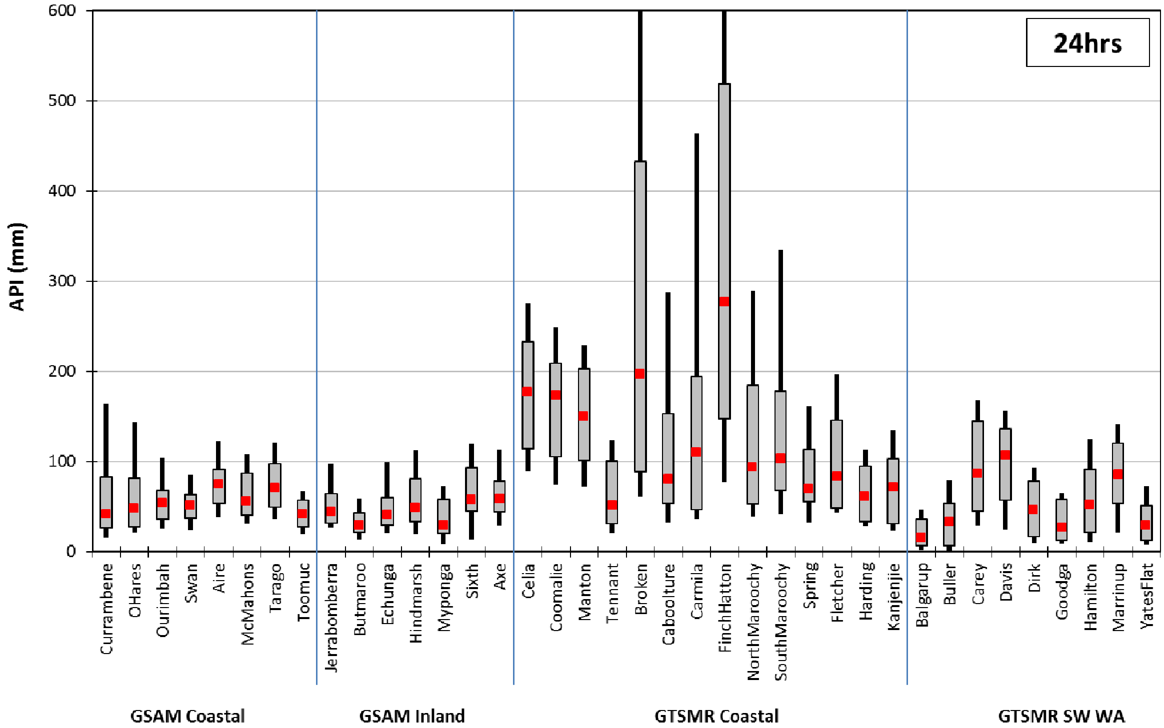


Figure 6-21 Range of API values (*k*=0.95) for storm selected by 24-hour bursts (box indicates quartiles and line shows 10th and 90th percentile values)

6.9. Variation with storm severity

The catchment specific loss summaries provided in Appendix I and J include plots of the loss values versus the storm severity which is characterised as the average recurrence (ARI) of the rainfall burst. It is difficult to infer the variation of loss values with storm severity because of the lack of severe rainfalls recorded for a particular catchment. It should be noted however, that the storm severity is characterised as the ARI of the rainfall burst whereas the loss values relate to the complete storm and this discrepancy further hinders the identification of any trend with storm severity.

The events for all catchments were therefore pooled by standardising by the median values. The variation of standardised loss with ARI is presented in the following figures and shows that there is no systematic variation of loss values with ARI. This is consistent with a range of previous studies that have failed to find a trend with ARI.

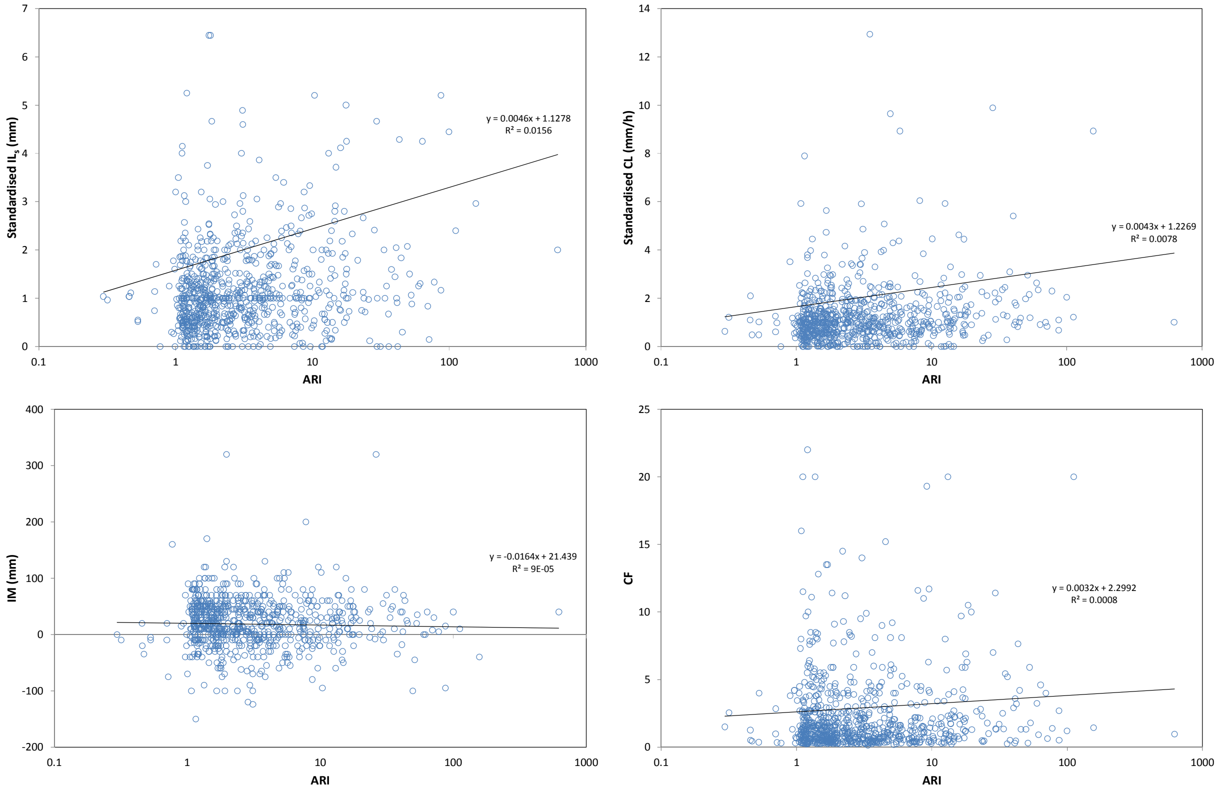


Figure 6-22 Variation of standardised loss values with ARI of the burst rainfall

7. Development of prediction equations

This section investigates catchment and hydroclimatic characteristics that explain the observed variability in the loss values. Where possible, prediction equations are then developed to allow the loss parameters to be estimated for ungauged catchments. This section summarises the techniques used, details of the derived relationships and the accuracy of the relationships.

As noted earlier, the range of loss values reflects the influence of antecedent conditions, uncertainties in the inputs (particularly the catchment average rainfall) and data errors. This confounds attempts to link the derived loss values to catchment characteristics. The IL_s and CL values for Tennant Creek were consistently identified as outliers and were therefore excluded from the analysis.

7.1. Catchment characteristics

A series of catchment characteristics were extracted from a number of sources relevant to development of the predictive model. A list of the catchment characteristics and sources is shown in Table 7-1.

In addition to the characteristics in Table 7-1, design rainfall intensities for 2% AEP 3-hour, 6 hour, 12 hour and 48 hour were included, as well as top 5, 10 and 20 percentile daily APIs. It was determined that the 2% AEP 24-hour design rainfall intensity and the top 2 percentile API was the best or close to the best explanatory variable of these related variables. Therefore, for consistency, these were used in developing the regressions.

The catchment characteristics that were considered as candidate predictive variables for the regression equations are listed in Table 7-1.

Table 7-1 List of variables considered for use in regression equations

	Variable	Unit	Abbreviation	Source
CLIMATE CHARACTERISTICS				
Precipitation	Mean annual rainfall	mm/yr	MEAN_ANN_RAIN	BOM mean annual rainfall data. Climatic Atlas of Australia (BOM, 2012)
	Design rainfall depth (2% AEP, 24hr)	mm	DES_RAIN_24HR	BOM IFD, 2013
	Design rainfall depth (2% AEP, 12hr)	mm	DES_RAIN_12HR	BOM IFD, 2013
	Median API	mm	MED_ API	Calculated from BoM daily rainfall series. Climatic Atlas of Australia (BOM, 2012)
	Top 2 percentile daily API	mm	TOP_2PC_API	
Evapotranspiration	Mean annual point potential evaporation	mm/yr	MN_ANN_PT_POT_E-VAP	BOM mean annual evapotranspiration data. Climatic Atlas of Australia (BOM, 2001).
	Ratio of annual rain to annual actual evaporation		ANN_RAIN_ACT_EV-AP	Calculated BOM mean annual evapotranspiration data. Climatic Atlas of Australia (BOM, 2001).

	Variable	Unit	Abbreviation	Source
	Ratio of rain to actual evaporation for wettest average month		WET_MON_RAIN_ACT_EVAP	Calculated from BOM mean monthly evapotranspiration data. Climatic Atlas of Australia (BOM, 2001).
CATCHMENT CHARACTERISTICS				
Slope	Slope between streamflow line at centroid and catchment outlet across the direct distance	m/m	ELEV_CENT_ELEV_OUT	SRTM DEM V1.0, Geoscience Australia
	Elevation range / square root of catchment area		ELEVRANGE_SQRTCA	
Vegetation	Proportion of catchment with woody vegetation		PROP_WOODVEG	Forest extent and change (v4), Department of Climate Change
	Proportion of forest		PROP_FOREST	Australia - Present Major Vegetation Groups - NVIS Version 4.1, Department of the Environment
	Proportion of forest and woodland		PROP_FOREST_WOOD	
Soil characteristics	Average soil depth across catchment	m	AV_SOLDEPTH	Digital Atlas of Australian Soils, BRS and CRC Catchment Hydrology interpretation. (CRC for Catchment Hydrology, 2004)
	Average plant available water holding capacity across catchment	mm	SOLPAWHC	
	Top soil layer thickness	m	A_THICK	
	Top soil layer hydraulic conductivity	mm/h	A_KSAT	
	Top soil layer catchment average volumetric water content (field capacity)	m	A_FCP	
	Top soil layer plant available water holding capacity across catchment	mm	A_PAWHC	
	Bottom soil layer thickness	m	B_THICK	
	Bottom soil layer hydraulic conductivity	mm/h	B_KSAT	
	Bottom soil layer catchment average volumetric water content (field capacity)	m	B_FCP	
	Bottom soil layer plant available water holding capacity across catchment	mm	B_PAWHC	
Geology	Proportion of catchment: Alluvial - coarse grained (gravels/sands)		PROP_AC	Surface geology of the states of Australia 1:1,000,000 scale, prepared by Geoscience Australia. Geological classifications based on accumulated classes.
	Proportion of catchment: Alluvial - medium grained (fine to med-grained sands)		PROP_AS	
	Proportion of catchment: Alluvial ('general' or undifferentiated- sands, silts, clays or fine-grained)		PROP_AU	
	Proportion of catchment: Alluvial – all		PROP_A	

	Variable	Unit	Abbreviation	Source
	Proportion of catchment: Colluvial		PROP_C	
	Proportion of catchment: Limestone		PROP_L	
	Proportion of catchment: Basalt		PROP_B	
	Proportion of catchment: Sandstone		PROP_SS	
	Proportion of catchment: Igneous & metamorphic rocks, conglomerates, mudstones, siltstones, conglomerate, shale, phyllite, chert, BIF		PROP_IM	
	Weighted average conductivity based on proportion of catchment with each geology classification	mm/h	WEIGHT_AV_COND	
STREAM CHARACTERISTICS				
	ARR Project 7 Peak factor		ARR_PEAKFACTOR	ARRP7 report/maps
	ARR Project 7 Volume factor		ARR_VOLUMEFACTO-R	

7.2. Multiple linear regression approach

Multiple linear regression was used with the variables in Table 7-1 to produce prediction equations for the values of the each of the dependent variables. The multiple linear regression model is of the form:

$$Y = a_0 + a_1X_1 + a_2X_2 + ... + a_nX_n \qquad \text{Equation 7-1}$$

where the dependent variable Y is expressed as a linear function of n independent variables X_1, X_2 , ..., X_n. The regression coefficients a_0, a_1, a_2, ..., a_n are estimated from the sample data using the least squares method. The degree of leverage indicated by the F-statistic was used as the criteria for including independent variables in the regression. Instances of high leverage indicated that the variable was a strong predictor potentially suitable for inclusion in the prediction equation.

A forward step-wise selection method was initially used to select variables for inclusion in the regression. This involved first adding the best explanatory catchment characteristic at each step. Each independent variable in the regression was then cycled out to determine whether a different variable was a better addition given the variables already included.

In some instances, it was necessary to transform some or all of the dependent or independent variables to produce a valid model. Transforming variables aims to improve the model fit and ensure that the model assumptions are satisfied.

The multiple linear regression models were assessed using the coefficient of determination R^2 (which describes the proportion of variance explained by the model) and the standard error of the estimate (SEE). These statistics were used throughout each stage of model development to evaluate the efficacy of the included variates.

7.3. Selection of independent variables

It is necessary to ensure variables incorporated into regression relationships are independent. A cross-correlation matrix has been used to show the degree of correlation between pairs of variables. For this study, variables with correlation values greater than 0.7 were considered to exhibit too high a level of dependence and were not included in the same regression relationship. The cross correlation matrix is shown in Figure 7-1, with red shading indicating variables that were highly correlated and orange indicating moderately correlated variables. Note that 2 of the geology classes did not exist in the study catchments and therefore are shown as blanks in the matrix.

Those characteristics with no shading in the matrix were considered independent and were used in the development of the regression relationships.

MEAN_ANN_RAIN	1.0																																		
DES_RAIN_24HR	0.7	1.0																																	
DES_RAIN_12HR	0.7	1.0	1.0																																
MED_ANN_API	0.8	0.4	0.4	1.0																															
TOP_2PC_API	0.8	0.9	0.9	0.5	1.0																														
MN_ANN_PT_POT_EVAP	-0.1	0.2	0.3	-0.6	0.3	1.0																													
ANN_RAIN_ACT_EVAP	0.8	0.6	0.6	0.8	0.6	-0.2	1.0																												
WET_MON_RAIN_ACT_EVAP	0.3	0.0	0.0	0.6	0.0	-0.5	0.6	1.0																											
ELEV_CENT_ELEV_OUT	0.1	-0.1	-0.1	0.4	0.0	-0.3	0.3	0.3	1.0																										
ELEVRANGE_SQRTCA	0.2	0.4	0.4	0.4	0.4	-0.3	0.3	0.1	0.5	1.0																									
PROP_WOODVEG	0.5	0.2	0.2	0.7	0.3	-0.5	0.4	0.4	0.2	0.3	1.0																								
PROP_FOREST	0.4	0.1	0.0	0.7	0.1	-0.8	0.3	0.4	0.3	0.4	0.6	1.0																							
PROP_FOREST_WOOD	0.3	0.0	0.0	0.5	0.1	-0.6	0.1	0.2	0.1	0.2	0.5	0.7	1.0																						
AV_SOLDEPTH	0.6	0.7	0.6	0.6	0.6	-0.3	0.5	0.2	0.1	0.5	0.4	0.4	0.3	1.0																					
SOLPAWHC	0.5	0.5	0.4	0.4	0.5	-0.1	0.4	0.0	0.3	0.4	0.6	0.2	0.2	0.6	1.0																				
A_THICK	-0.2	-0.4	-0.4	-0.1	-0.3	-0.2	-0.4	-0.1	-0.3	-0.3	0.3	0.1	0.3	-0.2	0.1	1.0																			
A_KSAT	0.2	0.1	0.0	0.2	0.2	-0.1	0.0	-0.1	0.3	0.2	0.5	0.2	0.2	0.1	0.7	0.4	1.0																		
A_FCP	0.5	0.7	0.7	0.3	0.6	0.1	0.5	-0.1	0.4	0.6	0.1	0.1	-0.1	0.5	0.5	-0.7	0.2	1.0																	
A_PAWHC	-0.1	-0.2	-0.2	0.0	0.0	-0.1	-0.3	-0.2	-0.2	-0.2	0.4	0.1	0.2	0.0	0.3	0.9	0.5	-0.5	1.0																
B_THICK	0.6	0.8	0.7	0.4	0.7	0.0	0.5	0.0	0.3	0.5	0.2	0.2	0.1	0.8	0.6	-0.6	0.1	0.8	-0.4	1.0															
B_KSAT	-0.1	-0.2	-0.2	-0.1	0.0	0.1	-0.3	-0.2	0.1	-0.1	0.3	0.0	0.1	-0.4	0.4	0.5	0.8	-0.2	0.5	-0.2	1.0														
B_FCP	0.4	0.5	0.5	0.3	0.4	0.0	0.5	0.2	0.3	0.5	-0.2	0.1	-0.1	0.5	0.0	-0.8	-0.4	0.8	-0.7	0.7	-0.7	1.0													
B_PAWHC	0.5	0.6	0.6	0.4	0.6	0.0	0.5	0.0	0.4	0.5	0.4	0.2	0.1	0.6	0.9	-0.2	0.6	0.7	0.0	0.8	0.2	0.3	1.0												
PROP_AC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-											
PROP_AS	-0.2	-0.2	-0.2	-0.1	-0.2	-0.1	-0.3	-0.2	-0.2	-0.2	0.0	0.0	0.1	-0.1	0.1	0.6	0.2	-0.2	0.6	-0.3	0.2	-0.3	-0.1	-	1.0										
PROP_AU	0.1	0.1	0.1	0.1	0.1	-0.2	0.1	0.1	0.0	0.0	0.0	0.2	0.2	0.1	0.0	-0.1	0.0	0.0	0.0	0.1	-0.1	0.1	0.0	-	-0.1	1.0									
PROP_A	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.1	-0.1	-0.2	0.0	0.2	0.2	0.0	0.0	0.4	0.2	-0.2	0.4	-0.2	0.1	-0.2	-0.1	-	0.7	0.6	1.0								
PROP_C	0.1	0.1	0.1	-0.1	0.1	0.2	0.0	-0.2	-0.2	-0.1	-0.2	-0.3	0.0	0.0	-0.1	0.1	-0.2	-0.1	0.1	-0.1	-0.2	0.0	-0.1	-	-0.1	-0.1	-0.1	1.0							
PROP_L	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-						
PROP_B	0.3	0.2	0.2	0.2	0.1	0.0	0.4	0.0	0.4	0.2	-0.1	0.1	0.0	0.1	0.2	-0.5	0.0	0.6	-0.4	0.4	-0.1	0.5	0.4	-	-0.1	-0.1	-0.2	-0.1	-	1.0					
PROP_SS	0.0	-0.1	-0.1	0.3	-0.1	-0.3	0.3	0.6	-0.1	0.0	0.2	0.2	0.2	0.0	-0.2	0.1	-0.3	-0.4	0.0	-0.2	-0.3	-0.1	-0.2	-	-0.2	-0.1	-0.2	-0.1	-	-0.2	1.0				
PROP_IM	-0.2	0.0	0.0	-0.3	0.1	0.3	-0.4	-0.5	-0.1	0.0	-0.1	-0.1	-0.2	-0.1	0.1	0.0	0.3	0.1	0.1	0.0	0.4	-0.1	0.0	-	0.0	0.0	0.0	-0.2	-	-0.3	-0.8	1.0			
WEIGHT_AV_COND	0.2	0.1	0.1	0.1	0.1	0.1	0.2	-0.1	0.1	0.0	-0.2	-0.2	0.1	0.1	0.0	-0.1	-0.2	0.2	-0.1	0.1	-0.2	0.2	0.1	-	0.1	-0.1	0.0	0.8	-	0.5	-0.1	-0.4	1.0		
ARR Project 7 Peak factor	0.1	-0.2	-0.2	0.1	0.0	-0.1	0.0	0.1	-0.1	-0.1	0.3	0.1	0.1	-0.1	0.1	0.3	0.2	-0.2	0.2	-0.2	0.3	-0.2	0.0	-	0.0	0.2	0.1	-0.1	-	-0.1	-0.2	0.2	-0.1	1.0	
ARR Project 7 Volume factor	0.2	0.0	0.0	0.1	0.1	0.0	0.1	-0.1	0.0	-0.1	0.3	0.2	0.2	0.0	0.2	0.1	0.3	0.0	0.1	0.0	0.3	-0.1	0.2	-	0.0	0.0	0.0	-0.1	-	-0.1	-0.3	0.3	-0.2	0.6	1.0

Figure 7-1 Variable correlation matrix

7.4. Prediction equations

Prediction equations were developed for each of the 4 loss parameters separately for each of three hydroclimatic regions defined by the BoM:

- GSAM Coastal and Inland
- GTSMR Coastal
- GTSMR Southwest WA

In developing the prediction equations, a check was made that the variables and the sign of their coefficients were consistent with the dominant physical processes. For some loss parameters in some regions, it was not possible to develop prediction equations with physically meaningful parameters and therefore the mean value is simply adopted. The mean values for each region are summarised in the following tables:

Table 7-2 Mean IL/CL values

	Storm Initial Loss (mm)		Continuing Loss (mm/h)	
Region	Mean	Standard Error	Mean	Standard Error
All	33	46%	4.0	60%
GSAM Coastal & Inland	28	43%	3.0	42%
GTSMR	42	40%	4.6	65%
GTSMR SW WA	26	38%	4.6	52%

Table 7-3 Mean SWMOD values

	Initial Moisture (mm)		Capacity Factor	
Region	Mean	Standard Error	Mean	Standard Error
All	20.8	131%	1.8	87%
GSAM Coastal & Inland	19.8	138%	1.2	56%
GTSMR	14.5	195%	1.6	83%
GTSMR SW WA	32.2	76%	2.9	77%

The range of variable used in the development of the prediction equations is summarised in Section 7.4.4.

7.4.1. GSAM Coastal and Inland Region

For the GSAM Coastal and Inland Region there are 15 catchments and the prediction equations are shown below. The IL_s is estimated as function of the design rainfall intensity and the median API. No physically meaningful variables could be identified to explain the variability in the CL and therefore a mean value of 3.0 mm/h was adopted, where two thirds of the values lie between $\pm$40% of this value, as represented by its standard deviation (SD). The SWMOD parameters are a function of the hydraulic conductivity of the top soil layer.

$IL_s = 16.7 + 0.141 P_{24h}^{2\%} - 0.291 MedianAPI$ r^2=0.78, SE = 22%

CL = 3.0 mm/h SD = 40%

$\mathrm{IM_s} = -4.5 + 0.229 \mathrm{A\_k_{sat}}$ r^2=0.43, SE = 108%

$CF = 0.51 + 0.006 A\_k_{sat}$ r^2=0.58, SE = 38%

Where:

IL_s is the storm Initial Loss (mm)
CL is the Continuing Loss (mm/h)
IM_s is the storm Initial Moisture (mm)
CF is the Capacity Factor
$P_{24h}^{2\%}$ is the 2% AEP 24-hour design rainfall depth from IFD2013 (mm)
MedianAPI is the median API calculated with a K=0.95 (mm)
A_ksat is the hydraulic conductivity of the top soil layer (mm/h)

7.4.2. GTSMR Coastal

For the GTSMR Region there were 14 catchments and the prediction equations are shown below. The IM was expressed as a function of the catchment slope (expressed as the elevation range within the catchment divided by the square root of the catchment area) and the top soil layer catchment average volumetric water content (field capacity). No physically plausible variables could be identified to explain the variability in the IL_s, CL or CF and therefore mean values were adopted.

IL_s = 42 SD = 40%

CL = 4.6 SD = 65%

$\mathrm{IM_s} = 108.4 + 622 Catchment\_Slope - 393.5 \mathrm{A\_FCP}$ r^2=0.66, SE = 124%

CF = 1.6 SD = 83%

Where:

IL_s is the storm Initial Loss (mm)
CL is the Continuing Loss (mm/h)
IM_s is the storm Initial Moisture (mm)
CF is the Capacity Factor
Catchment Slope is the elevation range (difference between the maximum and minimum elevation in the catchment) divided by the square root of the catchment area
A_FCP is top soil layer catchment average volumetric water content (m)

7.4.3. GTSMR SW WA

For the GTSMR Southwest WA Region there were 9 catchments and the prediction equations are shown below. No physically plausible variables could be identified to explain the variability in the IL_s and therefore a mean value was adopted. The CL, IM_s and CF are expressed as functions of the design rainfall, API and hydraulic conductivity, respectively.

$IL_s = 26$ SD = 38%

$$\mathrm{CL} = -10.7 + 0.159\mathrm{P}_{12\mathrm{h}}^{2\%}$$ r^2=0.54, SE = 38%

$$\mathrm{IM_s} = -36 + 0.472\mathrm{Top\_2\%\_API}$$ r^2=0.89, SE = 26%

$$\mathrm{CF} = 0.88 + 0.012\mathrm{B\_}k_{\mathrm{sat}}$$ r^2=0.49, SE = 59%

Where:

IL_s is the storm Initial Loss (mm)
CL is the Continuing Loss (mm/h)
IM_s is the storm Initial Moisture (mm)
CF is the Capacity Factor
$P_{12h}^{2\%}$ is the 2% AEP 12 hour design rainfall depth from IFD2013 (mm)
Top_2%_API is the top 2% of API values calculated with a K=0.95 (mm)
B_k_{sat} is the hydraulic conductivity of the top soil layer (mm/h)

7.4.4. Range of applicability

The range of variable used in the development of the prediction equations in the preceding sections is summarised in the table below.

Table 7-4 Range of values used in development of prediction equations

Parameter	Units	GSAM Inland & Coastal		GTSMR		GTSMR SW WA	
		Min	Max	Min	Max	Min	Max
$P_{24h}^{2\%}$	mm	113	369	-	-	-	-
$P_{12h}^{2\%}$	mm	-	-	-	-	80	109
MedianAPI	mm	30	91	-	-	-	-
TOP_2%_API	mm	-	-	-	-	78	202
Catchment Slope	m/m	-	-	0.007	0.192	-	-
A_FCP	m	-	-	0.22	0.42	-	-
A_k_{SAT}	mm/h	30	300	-	-	-	-
B_k_{SAT}	mm/h	-	-	-	-	10	298

8. Conclusions and recommendations

A total of 38 rural catchments from around Australia were selected for analysis in this study. The major constraint on the identification of catchments was the availability of long term pluviograph records within close proximity to the centroid of the catchment.

Although the Bureau of Meteorology has greatly advanced the collection of data at the national level, the collation, formatting and checking of streamflow and pluviograph data in a form suitable for this project still required significant effort. Moves to increase the consistency and accessibility of these data are strongly supported and will assist future hydrologic research.

A number of additional potential catchments were identified for south-west WA which were not included to ensure that the study catchments reflected a reasonable mix across Australia. There is the potential to extend the current study utilising this additional data. The analysis of additional catchments would shed additional insights on the drivers of the variation of loss values in this region.

The Phase 1 Pilot Study reviewed a number of lumped conceptual loss models and recommended that the initial loss/continuing loss (IL/CL) and SWMOD loss models be applied in Phase 4.

SWMOD is a distributed storage capacity model and accounts for the spatial variability in runoff generated across a catchment. The structure of a distributed model such as SWMOD addresses the limitations of the initial loss/proportional loss (IL/PL) model for design flood estimation as the updating of the soil moisture content during the event results in a reducing proportional loss (increasing proportion of runoff) as the event progresses.

For the SWMOD an additional parameter, the capacity factor, was introduced to allow additional flexibility in calibrating the results to recorded flood hydrographs. Both the IL/CL and SWMOD have two parameters (after the soil profile is defined in SWMOD) and their relatively simple structures make them suitable for design flood estimation.

In this study, the distribution of profile water holding capacity was estimated using hydrologic interpretation of the Atlas of Australian Soils. For the majority of catchments, the SWMOD capacity factor was greater than 1.0 which is consistent with the findings of other studies such as Ladson et al. (2006) which found that the values from the Atlas of Australian Soils typically underestimate the hydrologic capacity. Based upon the estimated capacity factors and investigations by the WA Water Corporation, this underestimation is most pronounced in south-west WA.

The application of a probability loss model such as SWMOD is hampered by the lack of consistent and reliable estimates of the hydrologic properties of soils across Australia (with the exception of south-west WA). Further research on the definition of hydrologic properties would greatly assist the application of these models and has the potential to reduce the current uncertainty in estimating loss values for ungauged catchments.

The events used to estimate the loss values were selected on the basis of rainfall, rather than flow, to ensure that they weren't 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.

Although not the focus of the study, the definition of complete storms for events selected on the basis of rainfall bursts allowed the pre-burst rainfall to be investigated. The analysis was undertaken for burst durations between 3 and 72 hours which showed that the pre-burst rainfall varies both with location and duration. It is important that this pre-burst rainfall is accounted for when applying loss values derived from the analysis of complete storms with design rainfalls derived from the analysis of rainfall bursts (such as IFD2013).

The pre-burst rainfall was shown to be correlated with design rainfall depths, and a prediction equation was developed for the pre-burst rainfall for 6 hour bursts as a function of the 24 hr 2% IFD2013. There was a consistent trend for the pre-burst values to reduce for longer durations and a prediction equation was developed that relates the pre-burst depth for any duration as a function of the value for 6 hours. For 3 hour bursts there was significant variability which could not be explained by simple rainfall characteristics.

It is recommended that the analysis of pre-burst rainfall be extended to a larger number of sites and the variability of the values for the 3 hour bursts be investigated. The value of pre-burst has been presented in both absolute terms and also as a function of the depth of the burst. It is recommended that the implications of either approach on design flood estimation for rare and extreme floods be further explored before design guidance is provided.

No correlation was evident in the ratio of pre-burst rainfall to burst rainfall with the severity of the burst, which implies that the pre-burst rainfall is a fixed proportion of the burst depth. This has important implications for design flood estimation and it is recommended that this is further investigated.

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 and hence guidance will be required for different routing parameters based upon the loss model. 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.

Loss values were derived for each event and a subjective score was assigned to each result based upon the goodness of fit between the calculated and recorded hydrographs. This score was used to assess which of the loss models was preferred. This assessment did not include any clear “winner”, where the proportion of cases where one or either of the loss models was approximately uniform. Even for catchments where one of the loss models was preferred for a majority of events, there were still some events for which the alternate model was preferred. Similarly there was no obvious relationship between the preference for a particular model and hydroclimatic or catchment characteristics which could explain the preference for a particular approach.

For a given catchment the calculated loss values varied over a wide range which reflects the importance of antecedent conditions and the uncertainty associated with the values.

A non-parametric distribution of IL and CL values was derived by standardising by the median value for each catchment. The distributions from different catchments and regions were remarkable similar and consistent with the results from a number of studies. This implies that having identified the median value, the likelihood that the loss value is proportionally more or less than this value (i.e. the likelihood that the catchment is likely to be drier or wetter than average) is similar for any of the study catchments. Accordingly, these distributions are well suited to incorporation in a Monte-Carlo framework for design flood estimation.

The variation of the loss values with event severity was investigated by plotting the (standardised) values against the Average Recurrence Interval (ARI) of the burst depth. There was no evidence of any variation with ARI. 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.

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.

In this study 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 the proportion of the variance explained by the prediction equation varies for the different parameters and different regions, these relationships represent some of the first defensible relationships between loss values and catchment characteristics in Australia. It would be desirable as part of future work to assess the sensitivity of design flood estimates to variations of loss parameters within the range of the standard errors.

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.

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