Australian Rainfall & Runoff

Revision Projects

PROJECT 6

Loss Models For Catchment Simulation

STAGE 3 REPORT

JULY 2016

Australian Government

ENGINEERS AUSTRALIA
Water Engineering

AUSTRALIAN RAINFALL AND RUNOFF
REVISION PROJECT 6: LOSS MODELS FOR CATCHMENT SIMULATION

STAGE 4A

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FOREWORD

AR&R 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However, many of the practices recommended in the 1987 edition of AR&R now are becoming outdated, and no longer represent the accepted views of professionals, both in terms of technique and approach to water management.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 two 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.

AR&R REVISION PROJECTS

The 22 AR&R 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
22	Benchmarking	

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 were derived in a consistent manner from the analysis of recorded streamflow and rainfall from catchments across Australia. The results were analysed to determine the distribution of loss values, correlation between loss parameters and variation with storm severity, duration and season. Finally, prediction equations were developed that relate the loss values to catchment characteristics.

This report provides an addendum to **Phase 4** reporting, and represents an improved basis for development of the regional prediction equations.

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1. Introduction

ARR Project 6 explored loss rates for design flood estimation in Australia for urban and rural catchments. Phase 4 of the project involved estimating loss parameter values for two conceptual loss models (IL/CL and SWMOD) for a large number of events recorded on 38 catchments across Australia.

A range of physical and hydroclimatic characteristics were examined to see if they could explain the observed variability in median loss values. Although prediction equations were developed for some loss parameters in some regions, the accuracy of the prediction equations in significant areas of Australia were not considered sufficiently accurate for use in design.

Since the completion of ARR Project 6, the Bureau of Meteorology has released modelled data from the Australian Water Resource Assessment – Landscape (AWRA-L) model which runs on daily time step with full spatial coverage over Australia since 1911. One of the main advantages of AWRA-L is that it models the temporal distribution of soil moisture with a consistent approach and inputs across the whole of Australia. This report describes an investigation undertaken to determine whether selected AWRA-L attributes could be used to develop prediction equations more accurate than those developed in Phase 4 of this project (Hill et al, 2014).

The report is structured as follows: Chapter 2 describes the catchments and data used in this study and Chapter 3 explores whether AWRA-L modelled soil moisture explains the variability of loss values for a given catchment. Chapter 4 describes the definition of hydrologic regions defined based upon the magnitude and seasonal variability of soil moisture and then the development and application of prediction equations for IL_s and CL.

2. Data source

2.1. Loss data

Loss values were taken from ARR Project 6 which derived loss values for 38 catchments for the initial loss/continuing loss (IL/CL) model and the SWMOD loss models. Further information on the selection of catchments, identification of events and estimation of loss values is contained in the ARR Project 6 Phase 4 project report (Hill et al., 2014). Loss values were available for the storm initial loss (IL_s) and continual loss (CL) from the IL/CL model; and initial moisture (IM) and capacity factor (CF) from application of the SWMOD model.

For this study, loss data was available for 35 catchments (refer Table 2-1 and Figure 2-1). The 35 catchments are 3 fewer than reported in ARR Project 6 because:

- No AWRA-L data could be obtained for the Tarago catchment;
- Tennant Creek was removed because the median values of losses derived from the analysis of concurrent streamflow and rainfall data consistently presented as outliers;
- Kanjenjie is understood to have unreliable streamflow records and the resulting rainfall-runoff relationships are inconsistent with surrounding catchments (Mark Pearcey Rio Tinto, pers.com).

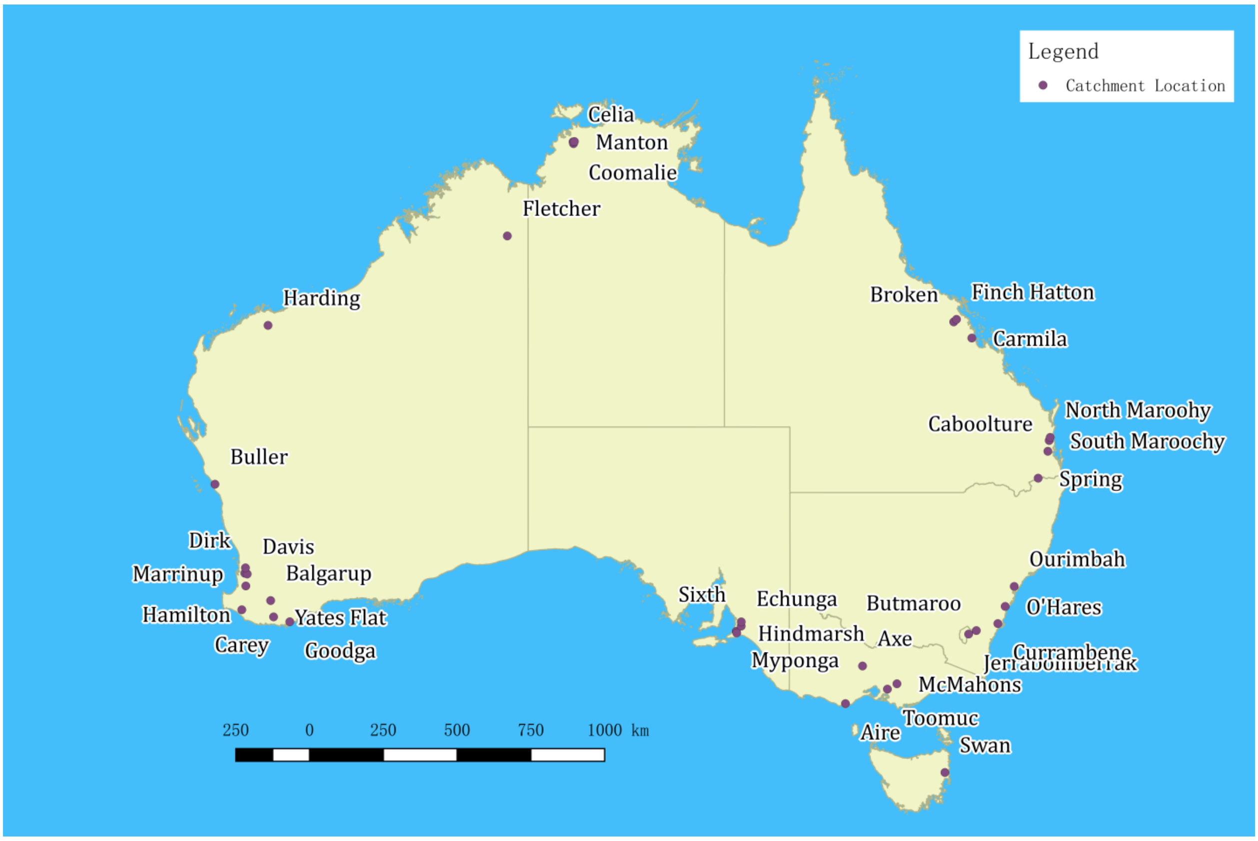

Figure 2-1 Catchment Location

Table 2-1 Study catchments (refer to ARR Project 6)

Gauge	Catchment	State	Area (km²)	Events	Median loss values			
					IL_s (mm)	CL (mm/h)	IM (mm)	CF
211013	Ourimbah	NSW	83	24	40	3.7	45	1.0
411003	Butmaroo	NSW	65	21	40	2.6	-7	0.9
G8170066	Coomalie	NT	82	30	50	8.1	35	4.4
120216A	Broken	QLD	78	34	68	6.2	-20	1.2
126003A	Carmila	QLD	82	19	70	3.1	-25	0.4
141001	South Maroochy	QLD	33	22	38	2.7	10	0.7
142001A	Caboolture	QLD	94	20	50	1.4	2.5	0.4
602199	Goodga	WA	49	27	30	4.8	10	2.7
608002	Carey	WA	30	19	20	3.8	50	2.7
609005	Balgarup	WA	82	13	25	2.5	5	0.9
612004	Hamilton	WA	32	13	47	3.3	50	4.2
614003	Marrinup	WA	46	19	16	7.3	60	2.7
614047	Davis	WA	66	18	25	8.1	40	7.4
701006	Buller	WA	34	14	32	3.8	0	0.6
709007	Harding	WA	49	17	60	8.3	-10	2.6
809312	Fletcher	WA	31	19	30	10.4	40	1.7
213200	O'Hares	NSW	73	22	60	1.6	7.5	0.6
216004	Currambene	NSW	95	17	35	3.9	0	1.3
235219	Aire	VIC	90	30	17	3.1	25	1.6
406216	Axe	VIC	34	12	28	6.0	5	1.0
229106	McMahons	VIC	40	21	20	3.7	45	2.8
AW502502	Myponga	SA	77	15	23	2.6	5	0.6
AW501500	Hindmarsh	SA	56	33	15	3.2	55	1.5
AW503506	Echunga	SA	34	13	25	2.2	40	0.7
G8150151	Celia	NT	52	15	25	5.4	60	2.2
G8170075	Manton	NT	29	32	42	1.6	15	1.3
125006	Finch Hatton	QLD	36	30	23	5.2	70	0.8
A5040523	Sixth	SA	44	24	15	3.3	45	1.3
410743	Jerrabomberra	NSW	52	20	22	2.1	6.5	0.6
614005	Dirk	WA	36	20	14	6.7	60	4.5
2219	Swan	TAS	38	19	40	0.5	-35	0.3
603190	Yates Flat	WA	53	17	27	0.8	15	0.4
228217	Toomuc	VIC	42	25	24	2.5	0	1.6
141009	North Maroochy	QLD	41	23	20	2.2	10	1.1
422321	Spring	QLD	32	27	30	5.1	0	4.5

2.2. AWRA-L data

The Australian Water Resource Assessment – Landscape (AWRA-L) model system was developed by CSIRO and the Bureau of Meteorology in support of the National Water Accounts and Water Resources Assessments reports (Frost et al., 2015).

The AWRA-L model simulates the water balance on a continental scale with a spatial resolution of ~5km×5km and daily temporal resolution from 1911 to present (Smith et al., 2016). Conceptualised as a small catchment, each cell is modelled in two hydrological response units (HRU) representing deep rooted vegetation (trees) and shallow rooted vegetation (grass). Model outputs mainly include soil moisture, runoff, actual and potential evapotranspiration (ET), deep drainage and leaf area index (LAI) (Smith et al., 2016).

AWRA-L was identified to explain the variability of loss for its consistency, continuity and availability on the national scale. The data has a temporal coverage for more than 100 years (1911-2015) which covers the period of flood events analysed in all 35 gauged catchments. The dataset is available all over Australia which makes it potentially suited for the development of prediction equations across the entire nation.

A range of input and modelled output variables of AWRA-L have been used in this report and are listed in Table 2-2.

Two separate AWRA-L datasets were provided by the Bureau of Meteorology:

- The first dataset was catchment average values for the 35 study catchments. The time series inputs and modelled outputs were provided from 1950 to 2015 which spans all of the events analysed in ARR Project 6. This data was used to investigate the relationship between loss values and initial moisture for each catchment and to develop prediction equations for the median loss.
- The second dataset was gridded values for the whole of Australia for the period from 1911 to 2015. This data was used in the application of the prediction equations. To maintain consistency with the data used in the deviation of the prediction equations, the median values were calculated over the period 1950 to 2015.

Table 2-2 Input and output variables from AWRA-L used in this study

N	Source	Variable	Unit	Definition
1	AWRA-L Input	slope	Radians	Average slope of catchment
2		f_tree	Dimensionless	Fraction of tree cover within each grid cell
3		meanP	mm/d	Mean annual rainfall (used for prediction equations production)
4		meanPET	mm/d	Mean annual Potential ET
5		K0_sat	mm/d	Saturated hydraulic conductivity of surface soil layer
6		KS_sat	mm/d	Saturated hydraulic conductivity of shallow soil layer
7		S0max	mm	Maximum storage of the surface soil layer
8		Ssmax	mm	Maximum storage of the shallow soil layer
9	AWRA-L Output	I	mm	Infiltration
10		s0	mm	Soil moisture in the surface store
11		sm	mm	Soil moisture in the surface store and the shallow soil layer
12		Etot	mm/d	Evapotranspiration
13		Ei	mm/d	Evaporation of intercepted rainfall
14		E0	mm/d	Soil evaporation (surface soil store)

2.3. Other data sources used in prediction equations

In addition to the AWRA-L inputs and modelled outputs, a range of other catchment characteristics from ARR Project 6 were also considered in the development and application of the prediction equations. These are summarised in Table 2-3.

Prior to application of the prediction equations across Australia, each of the spatial data sets were resampled to a grid size of 15km×15km which was considered a reasonable resolution given the spatial resolution of the inputs, the uncertainty in the prediction equations and the desire to avoid sharp discontinuities between adjacent grid cells.

Table 2-3 other data sources from ARR Project 6

N	Source	Variable	Unit	Definition
15	ARR Project 6	DES_RAIN_24HR	mm	Design Rain Intensity (I24,50)
16		AnnRain_ActEvap	mm/yr	Annual ratio: rain & actual evaporation
17		SOLPAWHC	mm	Average plant available water holding capacity across catchment
18		A_PAWHC	mm	Top soil layer average plant available water holding capacity across catchment
19		ARR_PeakFactor	Dimensionless	ARR P7 peak factor
20		ARR_VolumeFactor	Dimensionless	ARR P7 volume factor
21	BOM website	meanP	mm/d	Average annual rainfall from BOM (1961-1990) (used to apply prediction equation)

3. Loss variation with antecedent conditions

The first application of the AWRA-L data was to investigate whether the soil moisture could explain the variability of loss values for a given catchment. The performance of the soil moisture from AWRA-L was compared to that of the antecedent precipitation index (API) which had previously been applied in ARR Project 6. For this analysis the API was calculated using a fixed decay factor of 0.9 for all catchment throughout the year.

Different depth and temporal measures of soil moisture were considered:

- Three different layers of soil moisture: surface layer (0-0.1m), shallow root zone layer (0.1-1m) and combined layer (0-1m).
- Three temporal measurements: soil moisture on the event starting day (SM_{t0}), soil moisture one day prior to the start of the event (SM_{t0-1}), and average soil moisture over three days prior to event starting day ($avg(SM_{t0-1}+SM_{t0-2}+SM_{t0-3})$).

Preliminary results showed that soil moisture conditions in the combined layer over the upper 1m explains the most variation in loss values in most catchments. Accordingly, soil moisture conditions over this depth were adopted for all subsequent analyses.

For each catchment, the proportion of variance between the loss parameter and soil moisture were investigated and compared with API. For consistency with the previous ARR Project 6 work, the results for each catchment were grouped by the PMP zones defined by the Bureau of Meteorology.

The results for IL are shown in Figure 3-1 and demonstrate that soil moisture has a higher correlation with IL than API for the majority of the catchments, with the maximum R^2 up to 0.72. There are still, however, some catchments for which the initial loss is relatively independent of both the API and AWRA-L soil moisture. The results obtained from this initial comparison were considered sufficiently encouraging to justify further investigation into the efficacy of other AWRA-L characteristics.

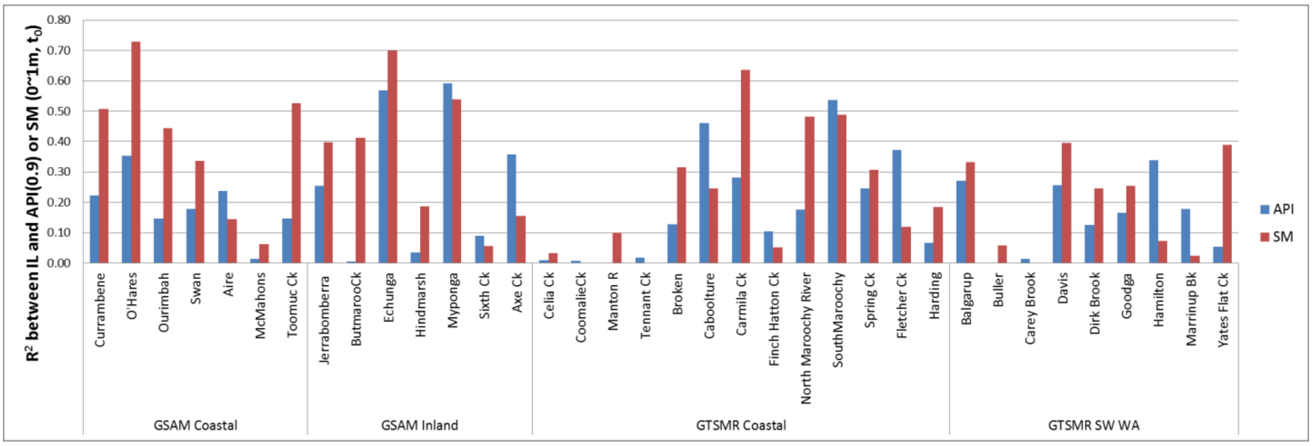

Figure 3-1 Proportion of variance in storm initial loss (IL_s) explained by antecedent precipitation index (API) and soil moisture (SM).

The results for IM are shown in Figure 3-2. These also demonstrate that soil moisture over the upper 1m of the soil profile is more highly correlated with losses than API in most catchments, especially in the GSAM Coastal region.

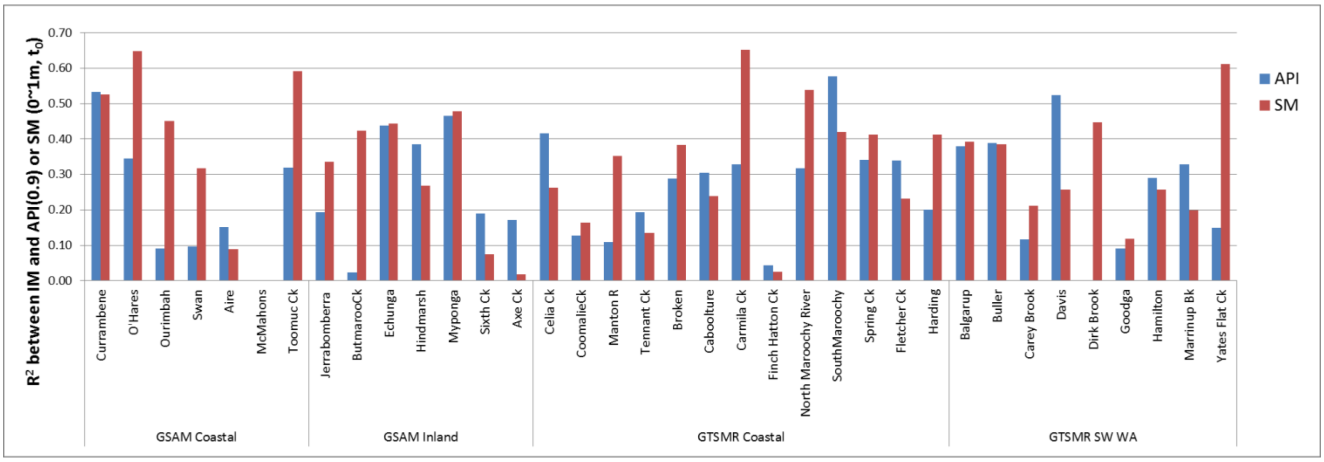

Figure 3-2 Proportion of variance in initial moisture (IM) explained by antecedent precipitation index (API) and soil moisture (SM).

It was expected that the soil moisture would be most useful in predicting IL and IM, however the correlation with CL was also investigated. The results are shown in Figure 3-3, and again the soil moisture was found to explain a large proportion of the variability in CL values for some catchments. (The relationship between CL and API was not considered in ARR Project 6 and therefore no values for API are presented in Figure 3-3.

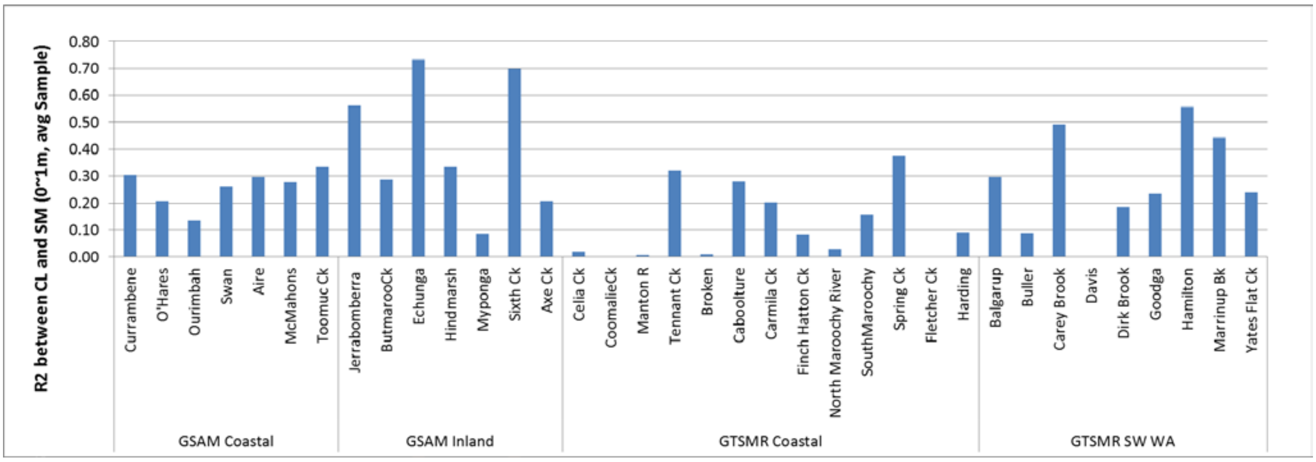

Figure 3-3 Proportion of variance in continuing loss (CL) explained by antecedent precipitation index (API) and soil moisture (SM).

4. Prediction equations

This section describes the development and application of prediction equations for the median IL_s and CL. These were developed with the objective of developing recommended median values of IL and CL for design flood estimation across Australia. This aspect of the project concentrated on the IL/CL model, rather than SWMOD, as this is typically the most suitable loss model for design flood estimation

4.1. Region definition

Initial attempts to derive prediction equation using all 35 catchment across Australia resulted in considerable uncertainty in the estimated loss values and therefore an investigation was undertaken to determine whether developing separate equations for different regions could yield more accurate equations. The regions adopted for the prediction of losses in the original study by Hill et al (2014) were based on the similarity of storm mechanisms associated with extreme rainfalls. While there is some basis for developing regions based on storm type, such an approach ignores the seasonal hydroclimatic factors which influence antecedent conditions, which are in turn directly linked to catchment losses. Assessing regions on the basis of differences soil moisture characteristics provides a more logical basis for regionalisation than rainfall alone, as changes in soil moisture reflect the combined influence of climate regime and catchment storage. The degree of correlation between AWRA-L soil moisture estimates and losses (presented in the previous section) provides some confidence that variation in soil moisture characteristics represents a reasonable basis for regionalisation of losses.

A number of different approaches were trialled to characterise the regional differences in soil moisture regime. The approach adopted was to assess hydrologic similarity on the basis of two measures representing the seasonality ($SeasIndx$) and magnitude ($StdMax$) of variations in soil moisture:

$$SeasIndx = \cos\left(\frac{(I_{max}-3)\pi}{6}\right) \quad \text{Equation 1}$$

$$StdMax = \frac{SM_{std,max}}{\overline{SM}_{std,max}} \quad \text{Equation 2}$$

where:

$I_{max} =$ the month number (1 to 12)in which average soil moisture $\left(SM_{med,i}\right)$is a maximum

$SM_{med,i} =$ median daily soil moisture for month i based on 66 years of simulation (mm)

$SM_{std,i} = SM_{med,i} - \overline{SM}_{med}$; standardised median daily soil moisture for month i

$\overline{\mathrm{SM}}_{\mathrm{med}} =$ average of 12 monthly values of $\mathrm{SM}_{\mathrm{med,i}}$

$SM_{std,max} =$ maximum of the 12 standardised $SM_{std,i}$

$\overline{\mathrm{SM}}_{std,max} =$ average of $\mathrm{SM}_{std,max}$ across all grid cells in Australia

Thus, it is seen that *SeasIndx* varies between -1 and 1, where the maximum value occurs in

March and the minimum in September. Thus, catchments with a *SeasIndx* of 1 are in summer-dominant systems, and those with a *SeasIndx* of -1 are winter-dominant. The standardised amplitude of soil moisture variation (*StdMax*) is the maximum standardised average monthly soil moisture value for the location, divided by the average value across the whole of Australia. Thus, a catchment with a *StdMax* of 2 represents a catchment whose maximum seasonal soil moisture that is twice that of the average across Australia. These concepts are illustrated in Figure 4-1, below.

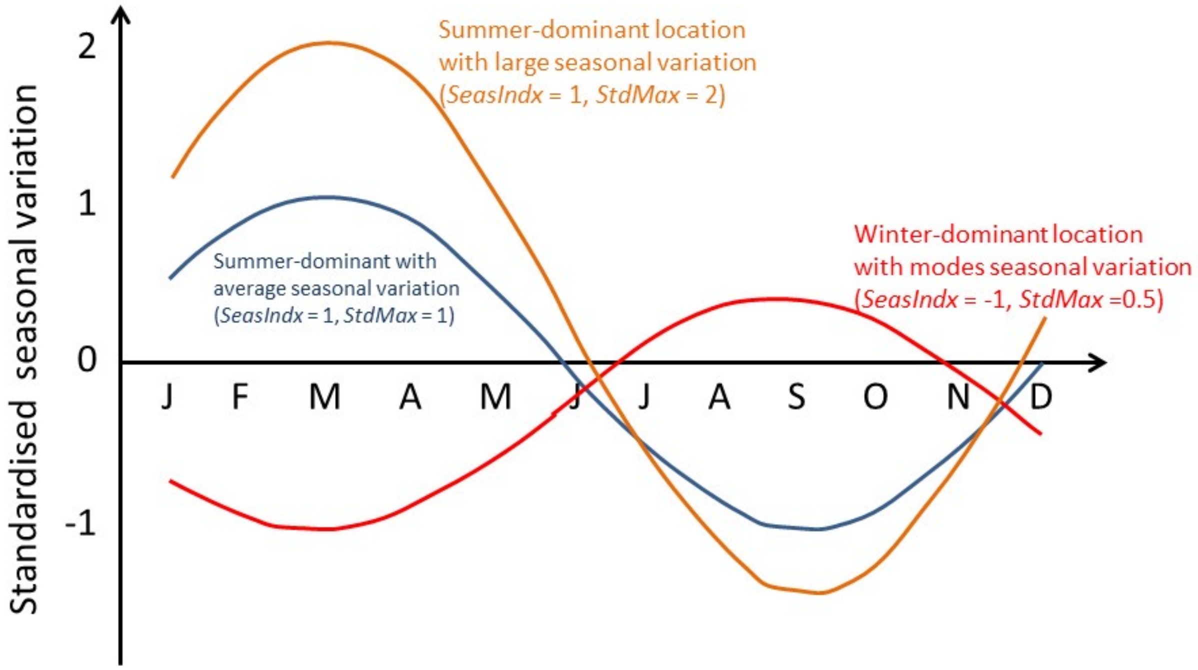

Figure 4-1 Illustration of seasonal indices of soil moisture

Regional differences in soil moisture characteristics was determined using cluster analysis, where the degree of similarity was based on a simple Euclidean distance metric in the two dimensions defined by *SeasIndx* and *StdMax*. The dendrogram of the resulting clusters for the whole of Australia is shown in Figure 4-2. It is seen that there are 4 or 7 major regional groupings. Mapping of these groups revealed that catchments allocated to the same group were located in largely geographically contiguous regions.

The decision whether to use 4 or 7 groups was based on consideration of the number and distribution of the catchments with information in losses. With 7 groups it was found that there were a number of regions represented by too few catchments, and this would not allow development of robust prediction equations. Accordingly, a few of the regions were combined which resulted in a total of 4 regions being adopted for analysis, and their spatial distribution is shown in Figure 4-3. The adopted grouping of 4 differed slightly from that based solely on soil moisture characteristics as it was found necessary to separately identify catchments in the south-west of Western Australia.

Regions 1 and 3 represent the primary summer- and winter-dominant regions, and region 4 largely represents catchments in the south-west of Western Australia. Region 2 represents a more uniform climate: while the region is very large, information is only available on catchment losses for a small eastern portion of this region. The seasonality of average gridded soil moisture in each of the 4 regions is shown in Figure 4-4.

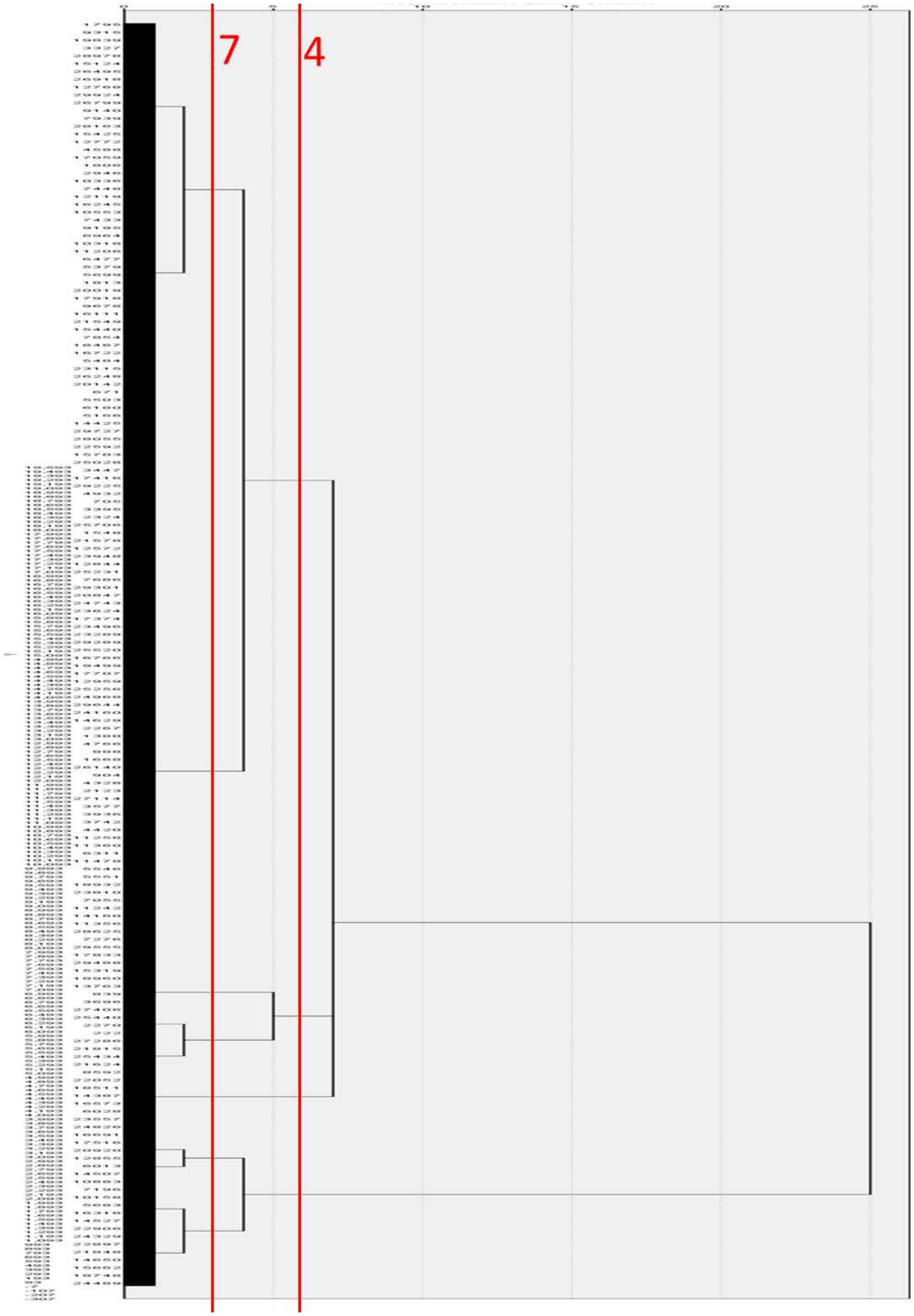

Figure 4-2 Dendrogram of clusters representing regional differences in soil moisture characteristics

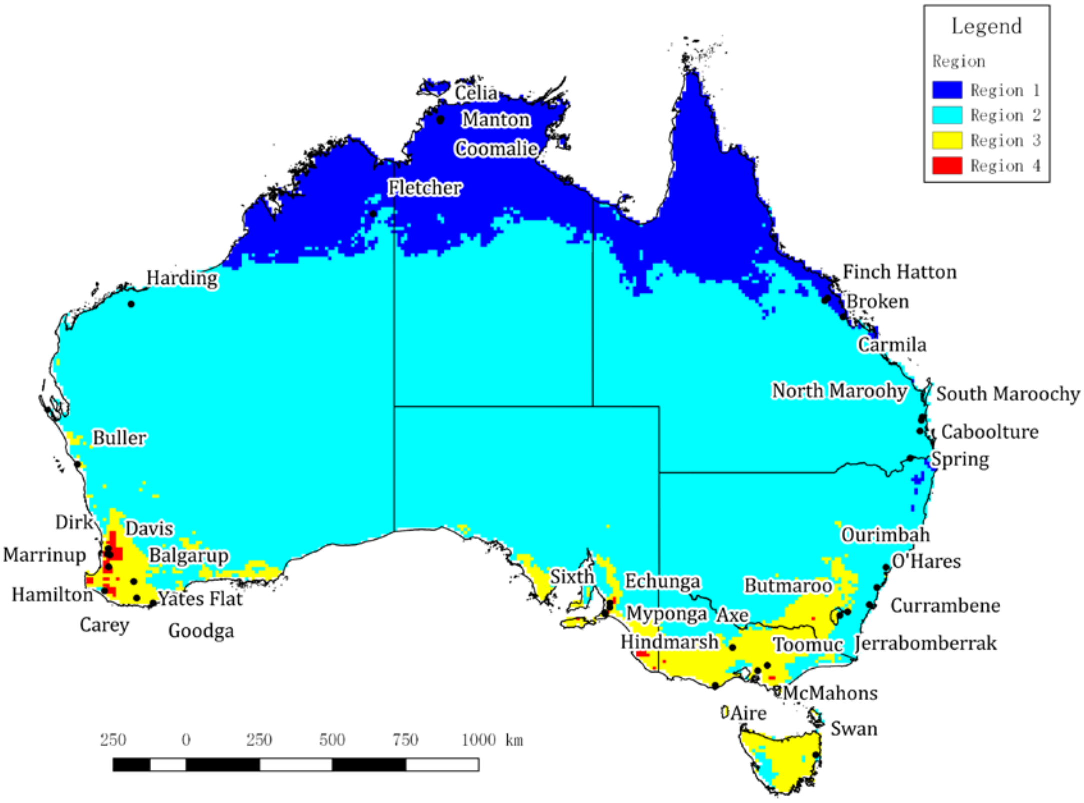

Figure 4-3 Regions defined on the basis of soil moisture for developing loss prediction equations

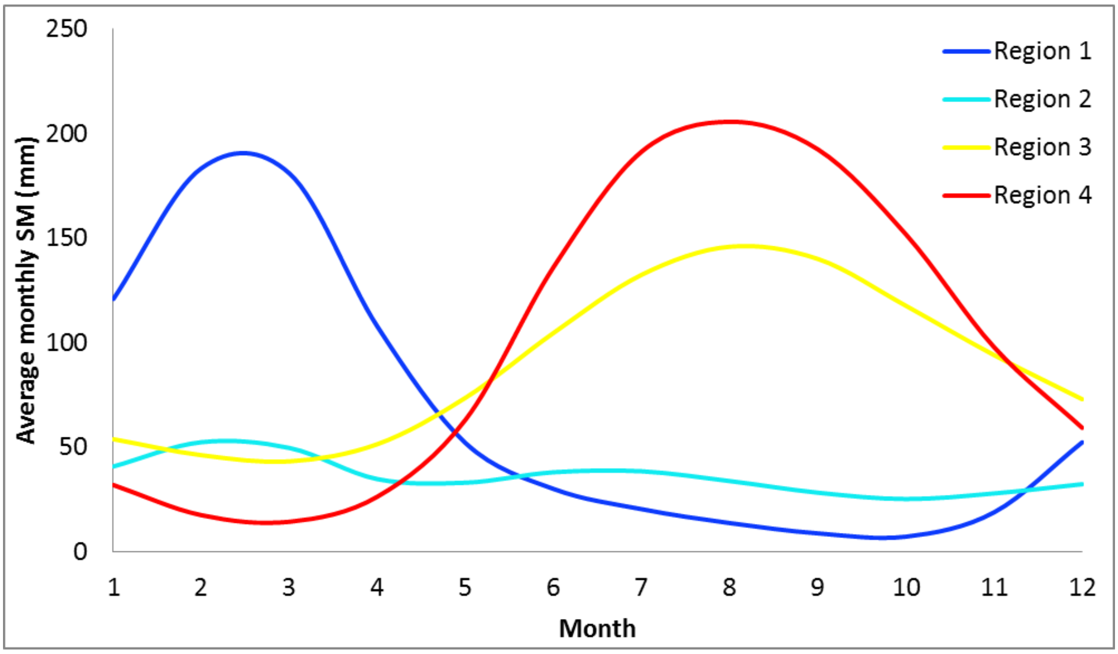

Figure 4-4 Seasonality of average gridded soil moisture in each defined region (using gridded data)

4.1.1. Seasonality in each region

For some parts of Australia, intense bursts of rainfalls are more likely to occur in particular times of the year. For this reason, when selecting representative values of the time series of AWRA-L attributes for use in the prediction equations, values were calculated only for those seasons in which the maximum rainfall events are more likely to occur. For example, for Region 1 in tropical Australia, the median values of the time series were calculated over the summer period rather than across the whole year.

The sample of events selected in ARR Project 6 Phase 4 was used to define the most suitable period over which to define the median values. To this end, median soil moisture values ($SM_{0-1m,t0}$) coincident with the flood events that occurred in the study catchments were extracted from the AWRA-L time series. These "event soil moisture" values were then compared with median soil moisture values calculated over the winter, summer, and annual periods. (For this analysis, summer is defined as the period from December to March and winter is defined as April to September, which is consistent with the seasons used by the Bureau of Meteorology in their analyses of large rainfall events).

Figure 4-5 compares the event soil moisture values with the median values for different seasons. It is seen that the soil moisture conditions coincident with the flood events correspond to median soil moisture conditions over different seasonal periods. Not surprisingly, the seasonality of these correlations varies with the region considered. It is seen that in summer dominant regions (Region 1 and 2) the event losses are more similar to soil moisture conditions in summer, and those for the other two regions are more similar to soil moisture conditions in winter. Accordingly, the seasons adopted for defining representative median values were summer for Region 1 and 2, and winter for Region 3 and 4.

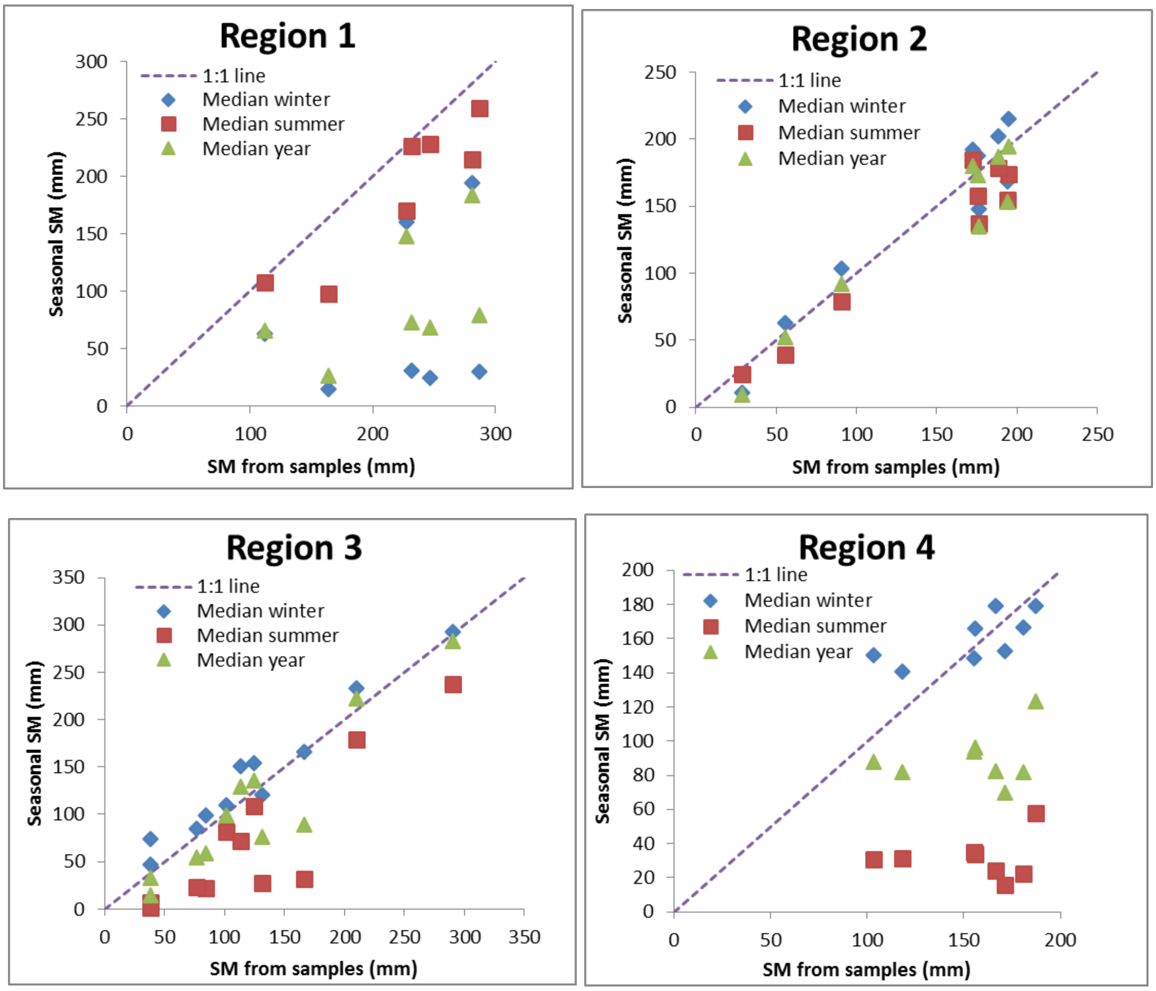

Figure 4-5 Median soil moisture conditions coincident with flood events in comparison with median seasonal soil moisture conditions in different seasons

4.2. Selection of independent variables

A cross-correlation matrix was computed to identify the degree of correlation between candidate independent variates. As shown in Figure 4-6, each value represents a correlation (R) between each pair of variables. Values greater than 0.7 or smaller than -0.7 (in red) were considered highly correlated and therefore not included in the same regression. Note that variables highlighted in blue are time series variables with seasonal values according to regions.

Based upon visual inspection of the relationship between the loss values and the independent variables, infiltration (I), ARR P7 peak factor (ARR_PeakFactor) and ARR P7 volume factor (ARR_VolumeFactor) were transformed into the logarithmic domain.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		slope	f_tree	meanP	meanPET	K0_sat	KS_sat	S0max	Ssmax	I	s0	sm	Etot	Ei	E0	DES_RAIN_24HR	AnnRain_ActEvap	SOLPAWHC	A_PAWHC	ARR_PeakFactor	ARR_VolumeFacto
1	slope	1.0																			
2	f_tree	0.4	1.0																		
3	meanP	0.3	0.6	1.0																	
4	meanPET	-0.2	-0.7	-0.1	1.0																
5	K0_sat	-0.4	-0.3	-0.5	0.1	1.0															
6	KS_sat	-0.3	-0.4	-0.5	0.3	0.9	1.0														
7	S0max	0.4	0.3	0.4	0.0	-0.6	-0.5	1.0													
8	Ssmax	0.1	-0.2	0.1	0.3	-0.2	0.0	0.2	1.0												
9	I	-0.3	-0.2	0.5	0.4	-0.1	-0.2	0.2	0.2	1.0											
10	s0	0.3	0.4	0.7	0.0	-0.7	-0.6	0.7	0.1	0.4	1.0										
11	sm	0.2	0.5	0.8	-0.2	-0.3	-0.4	0.4	0.4	0.6	0.6	1.0									
12	Etot	0.0	0.1	0.7	0.4	-0.4	-0.4	0.4	0.2	0.6	0.5	0.4	1.0								
13	Ei	0.3	0.7	0.7	-0.4	-0.3	-0.3	0.3	0.1	0.1	0.5	0.6	0.1	1.0							
14	E0	0.1	-0.1	0.4	0.5	-0.6	-0.4	0.3	0.2	0.4	0.7	0.2	0.7	0.0	1.0						
15	DES_RAIN_24HR	0.3	0.4	0.6	0.2	-0.6	-0.4	0.5	0.0	0.1	0.6	0.2	0.7	0.2	0.6	1.0					
16	AnnRain_ActEvap	0.3	0.6	0.8	-0.1	-0.6	-0.5	0.6	0.2	0.2	0.7	0.5	0.5	0.7	0.4	0.6	1.0				
17	SOLPAWHC	0.2	0.4	0.4	0.0	0.0	0.1	0.0	0.1	-0.2	0.2	0.2	0.3	0.3	0.2	0.5	0.3	1.0			
18	A_PAWHC	-0.3	0.0	-0.1	0.0	0.4	0.3	-0.5	-0.2	0.1	-0.3	0.0	-0.1	-0.1	-0.1	-0.2	-0.3	0.4	1.0		
19	ARR_PeakFactor	-0.2	0.2	0.0	-0.1	0.4	0.3	-0.4	-0.1	0.0	-0.2	0.1	-0.1	0.2	-0.2	-0.2	0.0	0.1	0.2	1.0	
20	ARR_VolumeFactor	-0.3	0.2	0.2	0.0	0.2	0.1	-0.2	0.0	0.2	-0.1	0.2	0.1	0.1	-0.1	0.0	0.0	0.2	0.1	0.6	1.0

Figure 4-6 Cross-correlation matrix

4.3. Prediction equations

Multi-linear regression was used to develop prediction equations for IL_s and CL in each of the four regions. Given the relatively small number of catchments in each region, the number of independent variables was limited to a maximum of two.

Variables listed in Table 2-2 and Table 2-3 in Section 2 were considered and representative values were calculated for each variable in each catchment.

Prediction equations were developed by trial and error giving weight to equations that exhibited:

- high R^2 and low standard error;
- independent variates that are largely uncorrelated, with fitted coefficients that are consistent with physical reasoning;
- predicted loss estimates that remain within reasonable ranges.

4.3.1. Region 1

There are 7 catchments in Region 1 and the prediction equations of loss parameters are displayed below. Initial loss is a function of maximum storage capacity of shallow soil layer while CL is a function of mean annual PET and surface soil hydraulic conductivity.

$$IL_s = -0.37 * Ssmax + 136.0$$ R^2 = 0.77, SE = 23% (Eq5)

$$CL = 2.20 * meanPET - 0.0015 * K0_{sat} - 3.2$$ R^2 = 0.67, SE = 36% (Eq6)

Where:

IL_s is the storm Initial Loss (mm)

CL is the Continuing Loss (mm/h)

$Ssmax$ is the maximum storage of the shallow soil layer (mm)

$meanPET$ is the mean annual potential ET (mm/d)

$K0_{sat}$ is the saturated hydraulic conductivity of surface soil layer (mm/d)

4.3.2. Region 2

9 catchments are in Region 2 and most of them are located near the coast. Prediction equations of this region are as follows.

$$IL_s = 7.89 * meanPET + 0.44 * SOLPAWHC - 47.1$$ R^2 = 0.68, SE = 24% (Eq7)

$$CL = 0.77 * KS_{sat} + 0.29 * S0max - 12.7$$ R^2 = 0.92, SE = 20% (Eq8)

Where:

IL_s is the storm Initial Loss (mm)

CL is the Continuing Loss (mm/h)

$meanPET$ is the mean annual potential ET (mm/d)

$SOLPAWHC$ is the average plant available water holding capacity across catchment (mm)

KS_{sat} is the saturated hydraulic conductivity of shallow soil layer (mm/d)

$S0max$ is the maximum storage of the surface soil layer (mm)

4.3.3. Region 3

There are 11 catchments in Region 3 and their loss parameters were estimated as follows.

$$IL_s = -1.57 * s0\_wtr + 0.14 * DES\_RAIN\_24HR + 18.8$$ R^2 = 0.71, SE = 18.3% (Eq9)

$$CL = -0.03 * DES\_RAIN\_24HR + 0.06 * S0max + 5.1$$ R^2 = 0.38, SE = 45% (Eq10)

Where:

IL_s is the storm Initial Loss (mm)

CL is the Continuing Loss (mm/h)

$s0\_wtr$ is the soil moisture in the surface store in winter season (mm)

DES_RAIN_24HR is the design Rain Intensity (I24,50) (mm)

$S0max$ is the maximum storage of the surface soil layer (mm)

4.3.4. Region 4

There are 8 catchments in this region and the prediction equations are presented as follows.

$$IL_s = -56.2 * slope + 0.28 * S0max + 16.4$$ R^2 = 0.47, SE = 21% (Eq11)

$$CL = 0.088 * SOLPAWHC - 4.9$$ R^2 = 0.88, SE = 19% (Eq12)

Where:

IL_s is the storm Initial Loss (mm)

CL is the Continuing Loss (mm/h)

$slope$ is the average slope of catchment (radians)

$S0max$ is the maximum storage of the surface soil layer (mm)

$SOLPAWHC$ is the average plant available water holding capacity across catchment (mm)

4.3.5. All Regions

Single prediction equations were also developed for the whole of Australia:

$$IL_s = -7.57 * \ meanP + 0.09 * \ DES\_RAIN\_24HR + 34.55$$ R^2 = 0.45, SE = 36% (Eq13)

$$CL = 1.01 * meanPET + 0.03 * A\_PAWHC \ - 1.96$$ R^2 = 0.38, SE = 48% (Eq14)

Where:

IL_s is the storm Initial Loss (mm)

CL is the Continuing Loss (mm/h)

$meanP$ is the mean annual rainfall (mm/d)

DES_RAIN_24HR is the design Rain Intensity (I24,50) (mm)

$meanPET$ is the mean annual potential ET (mm/d)

A_PAWHC is the top soil layer average plant available water holding capacity across catchment

It is clear to see that the prediction equations developed for the 4 individual regions have lower uncertainty than the single one for the whole of Australia.

4.4. Application in Australia

The above equations were applied to the relevant regions in Australia using independent variables derived for a grid size of 15 km x 15 km. The resulting maps of the predicted variables are shown in Figure 4-7 and Figure 4-9. Given the uncertainty in the prediction equations and the desire to have smooth variations in loss across catchment areas, the gridded values were smoothed using a smoothing window of 45 km x 45 km; ie the value of each grid was the average of that value and the adjoining 8 values.

The 35 catchments had mean annual rainfalls between 375 to 1,800 mm. However, much of inland Australia has mean annual rainfalls less than 375 mm and therefore prediction equations was only applied to areas with rainfalls greater than 350 mm. Drier areas are shown in grey shading in the figures.

Based upon the 35 catchments from ARR Project 6 Phase 4, the reasonable range of median IL_s is 0 to 80 mm, and for CL it is 0 to 10 mm/h. Values smaller than 0 were manually set to 0 and values larger than upper limits were set to the maximum values.

Figure 4-8 and Figure 4-10 are histograms illustrating the distribution of IL and CL in each region. The percentage values in each title indicate proportion of values falling outside either the upper or lower limits.

The range of values for the independent variables and the resulting loss values for the 35 catchments and for all grid cells in each region can be found in Table 4-1 and Table 4-2. These tables provide information on how far the prediction equations have been applied outside of the range of values used in their derivation.

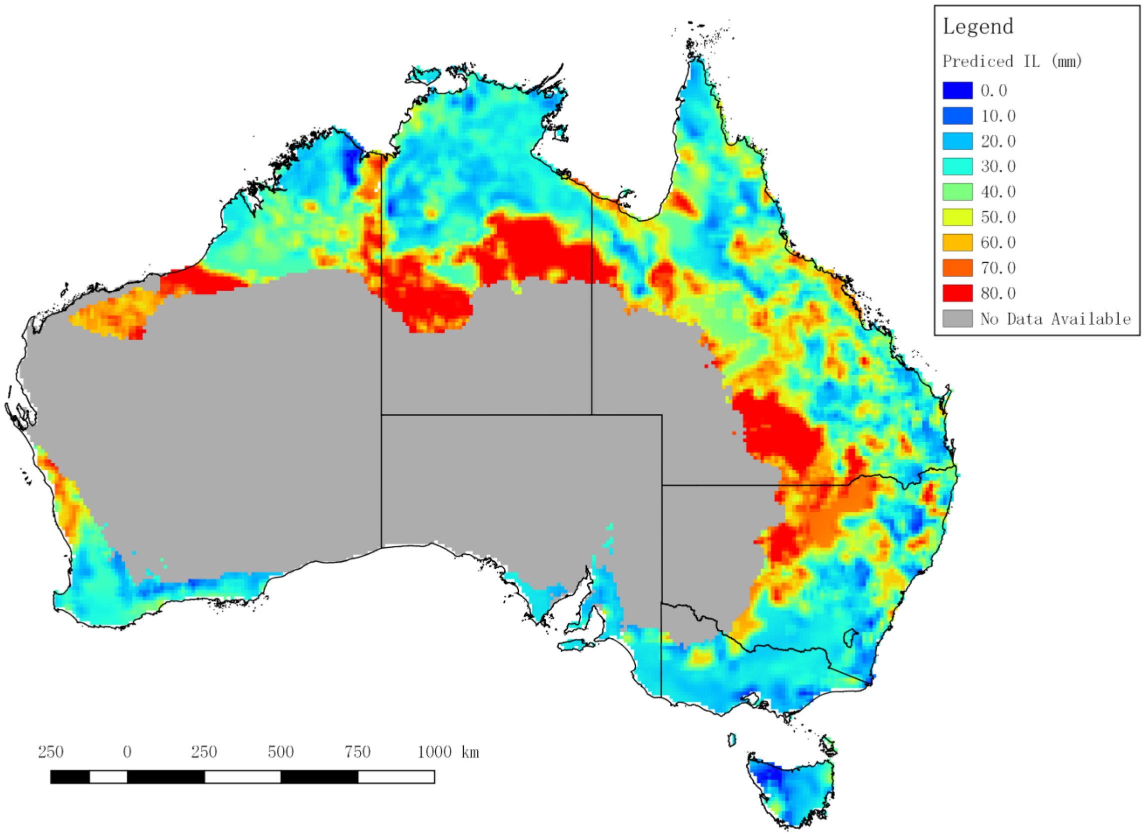

Figure 4-7 Predicted IL_s (mm) in Australia

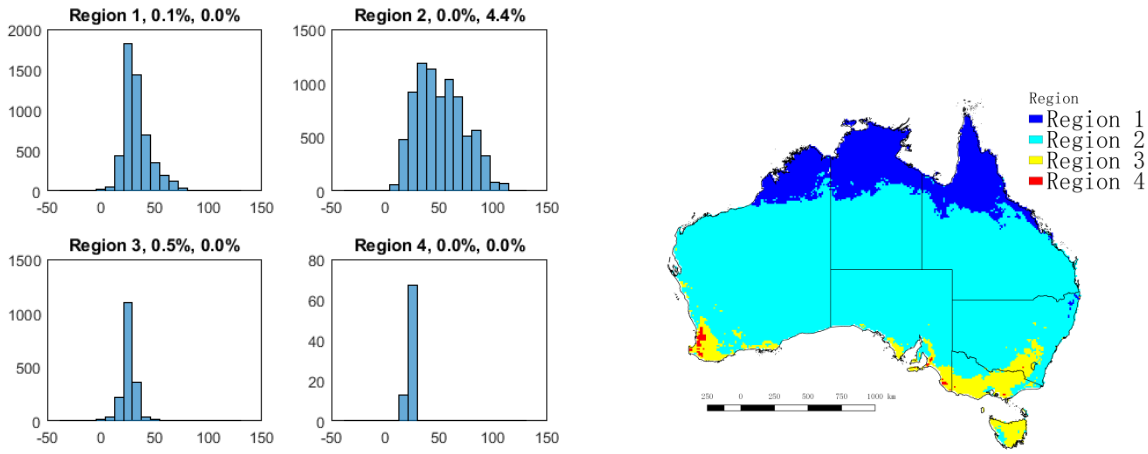

Figure 4-8 Histograms (left) of IL_s corresponding to each region (in each title, the 1st percentage represents proportion of values less than 0 and the 2nd larger than 80); Region map (right)

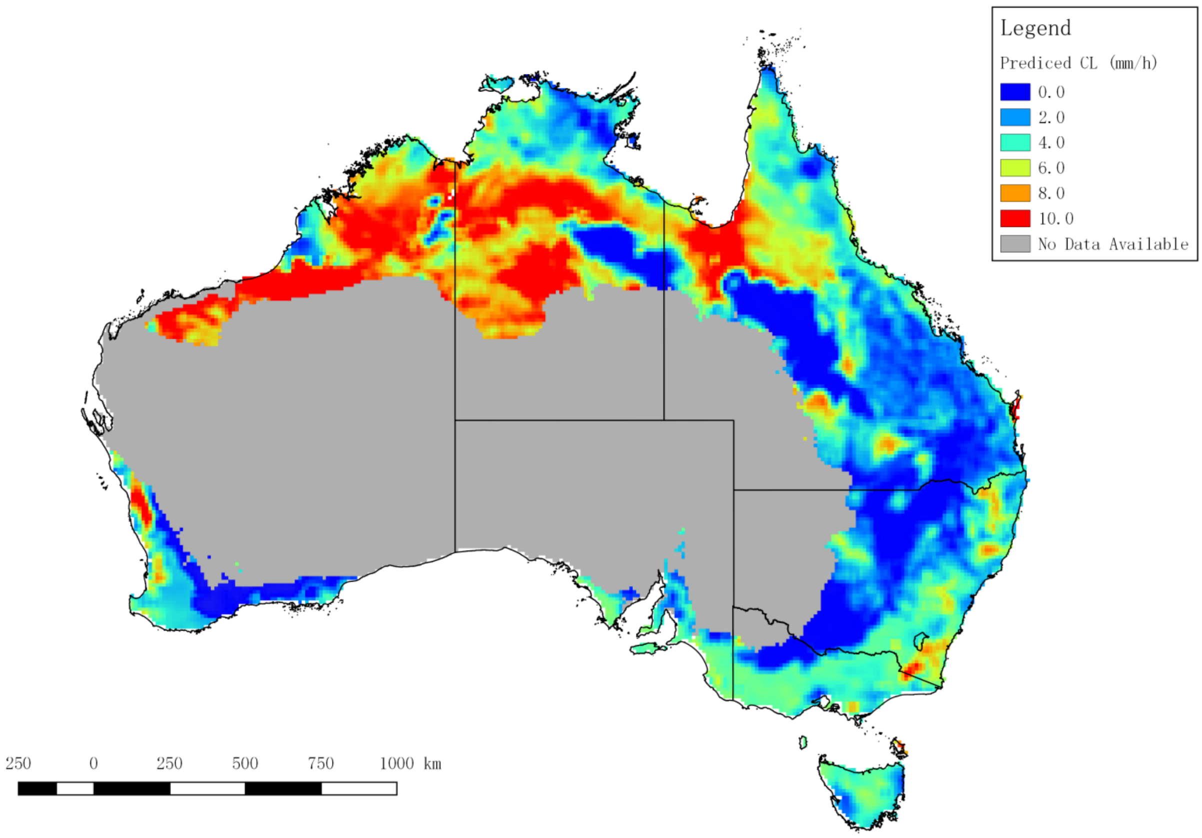

Figure 4-9 Predicted CL (mm/h) in Australia

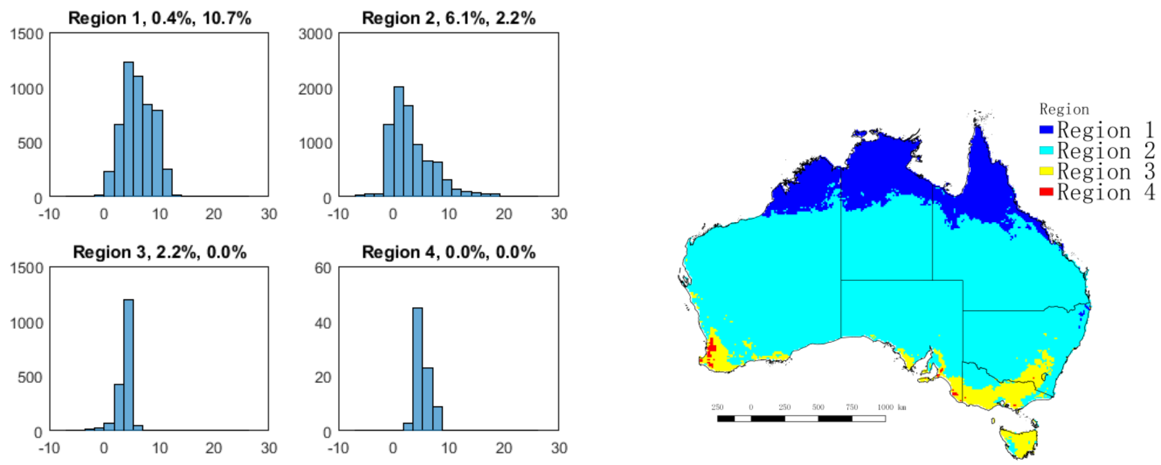

Figure 4-10 Histograms (left) of CL corresponding to each region (in each title, the 1st percentage represents proportion of values less than 0 and the 2nd larger than 10); Region map (right)

Table 4-1 Range of values for IL_s prediction equations

			35 Catchments			All grid cells in Region		
Region	**Equation**	**Parameter**	**Min**	**Max**	**Median**	**Min**	**Max**	**Median**
Region 1	**Eq5**	ssmax	180.6	315.4	258.6	109.5	410.7	289.3
		IL	22.5	70.0	41.5	-14.8	95.8	29.8
Region 2	**Eq6**	meanPET	3.26	8.61	4.09	1.95	9.83	7.98
		SOLPAWHC	86.48	147.00	118.29	0.000	269.4	91.0
		IL	20.00	60.00	37.50	-19.8	130.6	51.3
Region 3	**Eq7**	s0_wtr	0.9	15.9	3.0	0.5	47.6	4.5
		DES_RAIN_24HR	106.1	238.9	137.7	72.8	368.4	109.8
		IL	17.0	47.0	27.5	-38.3	51.5	27.1
Region 4	**Eq8**	slope_rad	0.1	0.2	0.1	0.003	0.215	0.076
		s0max	18.2	45.0	29.5	17.7	65.9	25.3
		IL	14.0	25.0	18.0	14.9	31.6	19.3

Table 4-2 Range of values for CL prediction equations

			35 Catchments			All grid cells in Region		
Region	**Equation**	**Parameter**	**Min**	**Max**	**Median**	**Min**	**Max**	**Median**
Region 1	**Eq9**	meanPET	4.8	7.7	6.2	3.2	8.8	7.0
		K0_sat	476.5	4153.5	3036.2	209.3	9869.5	3578.1
		CL	1.56	10.35	5.39	-1.73	13.65	6.04
Region 2	**Eq10**	KS_sat	1.55	9.27	3.37	0.047	36.4	5.8
		S0max	41.37	56.19	46.03	15.0	65.9	43.4
		CL	1.4	8.3	2.7	-7.2	27.9	4.3
Region 3	**Eq11**	DES_RAIN_24HR	106.1	238.9	137.7	72.8	368.4	109.8
		S0max	17.2	62.8	42.6	15.0	65.9	42.6
		CL	0.5	6.0	3.1	-2.392	5.990	4.374
Region 4	**Eq12**	SOLPAWHC	82.8	136.9	103.4	26.3	269.4	124.7
		CL	2.2	8.1	3.5	-2.6	18.7	6.0

4.5. Verification

To assess the performance of the prediction equations, the predicted IL_s and CL values were compared with estimated values from a number of published studies that derived loss parameters in a similar manner. Only the location of the gauging station, rather than the catchment centroid was available for these other studies, and so this adds some additional uncertainty to the comparison.

Figure 4-11 compares predicted IL_s with observed data. Overall, the data points scatter around the 1 to 1 line between 0 and 80 mm, with data from Waugh slightly overestimated and Loveridge a bit underestimated. For the catchments analysed by Hill et al. the prediction equation results in less variability than estimated by the earlier study and the cause of this is not immediately apparent.

In Figure 4-12, the scatter of CL spread is wider, with predicted results ranging from 2-8 mm/h while observed data from 1-11 mm/h.

Overall it is considered that the results provide reasonable reassurance in the regional estimates. The use of the previous published data sets are expected to introduce additional uncertainty due to methodological differences in how the loss values were estimated from concurrent rainfall and streamflow data, and because catchment average values are being compared to point estimates at the catchment outlet. There is no gross bias or differences in the estimates of initial loss, and the estimates of continuous loss cover a similar range.

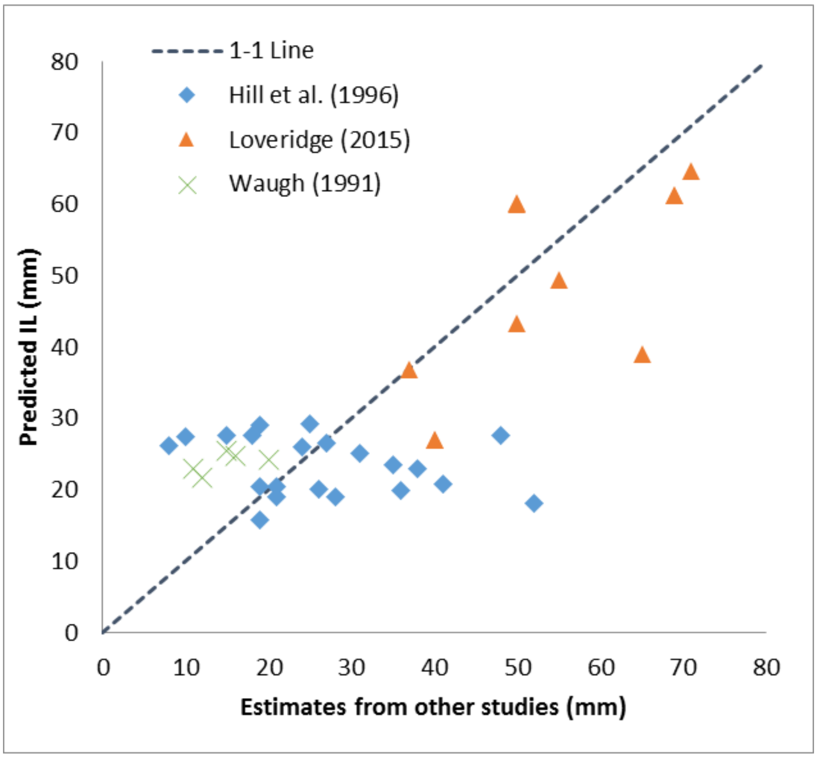

Figure 4-11 Predicted IL_s against ILs from other studies

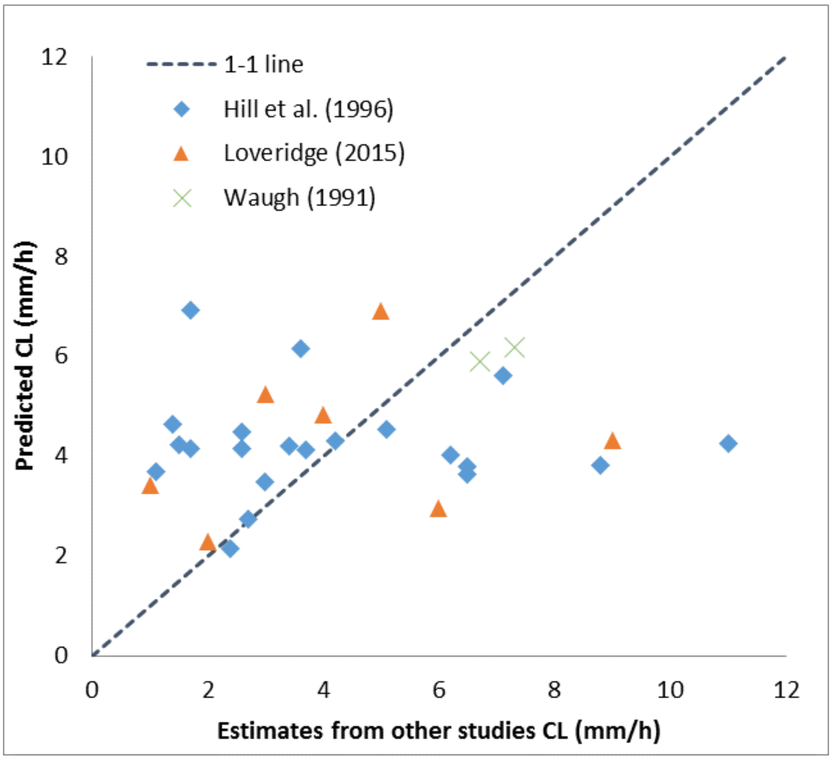

Figure 4-12 Predicted CL against CL from other studies

5. Conclusions

The advantage of AWRA-L is that it models the water balance at a daily timestep over a long period and is derived consistently which makes it amenable to the analysis of soil moisture across Australia. This project has demonstrated that AWRA-L is helpful for explaining the observed variability in losses on a given catchment and the variability of median losses between different catchments.

For the majority of the 35 catchments considered, the AWRA-L modelled soil moisture immediately prior to the event was more highly correlated with the storm initial loss than the antecedent precipitation index (API) estimated in Phase 4 of ARR Project 6. This demonstrates that the soil moisture estimated by AWRA-L has the potential to inform the selection of initial loss values for real-time flood forecasting. Further work is required to identify why the correlation between modelled soil moisture and storm initial loss (and even CL) varies between catchments.

The AWRA-L inputs and modelled outputs were used to define regions for the development of predictions equations for estimating IL and CL across Australia. These prediction equations are based upon catchment and climatic characteristics that would be expected to influence loss, and the resulting equations are more accurate than those presented in Hill et al (2014). The mapped estimates provide an indication of the spatial distribution of different loss values across the whole of Australia, with the exception of the arid interior.

It should be noted that the results were derived based upon only 35 catchments and the standard error of the estimates range between 20% and 50%. Because of the limited number of catchments available, the prediction equations are based upon one or two independent variables. However it is anticipated that a wide range of characteristics combine to influence the loss values for a catchment and therefore judgement will be required when selecting suitable values for use in design.

6. References

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