Australian Rainfall & Runoff

Revision Projects

PROJECT 6

Loss Models for Catchment Simulation – Rural Catchments

STAGE 3 REPORT

P6/S3/016B

OCTOBER 2014

Australian Government

ENGINEERS AUSTRALIA
Water Engineering

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

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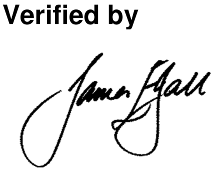
Authors Peter Hill Zuzanna Graszkiewicz Melanie Taylor Dr Rory Nathan	**Verified by** 

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ENGINEERS
AUSTRALIA
Water Engineering

Contractor Details

Jacobs SKM
PO Box 312 Flinders Lane
MELBOURNE VIC 8009

Tel: (03) 8668 3000
Fax: (03) 8668 3001
Web: www.JacobsSKM.com

JACOBS

EnviroWater Sydney Pty Ltd

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However, many of the practices recommended in the 1987 edition of ARR now are becoming outdated, and no longer represent the accepted views of professionals, both in terms of technique and approach to water management.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

Project Team Members:

- Dr Rory Nathan (AR&R TC and Jacobs SKM)
- Peter Hill (Jacobs SKM)
- Zuzanna Graszkiewicz (Jacobs SKM)
- Matthew Scorah (Jacobs SKM)
- David Stephens (Jacobs SKM)
- Clayton Johnson (Jacobs SKM)
- Stephen Impey (Jacobs SKM)
- Dr Ataur Rahman (EnviroWater Sydney)
- Melanie Loveridge (EnviroWater Sydney)
- Leanne Pearce (WA Water Corporation)

This report was independently reviewed by:

- Erwin Weinmann

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**.

AR&R Technical Committee:

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.

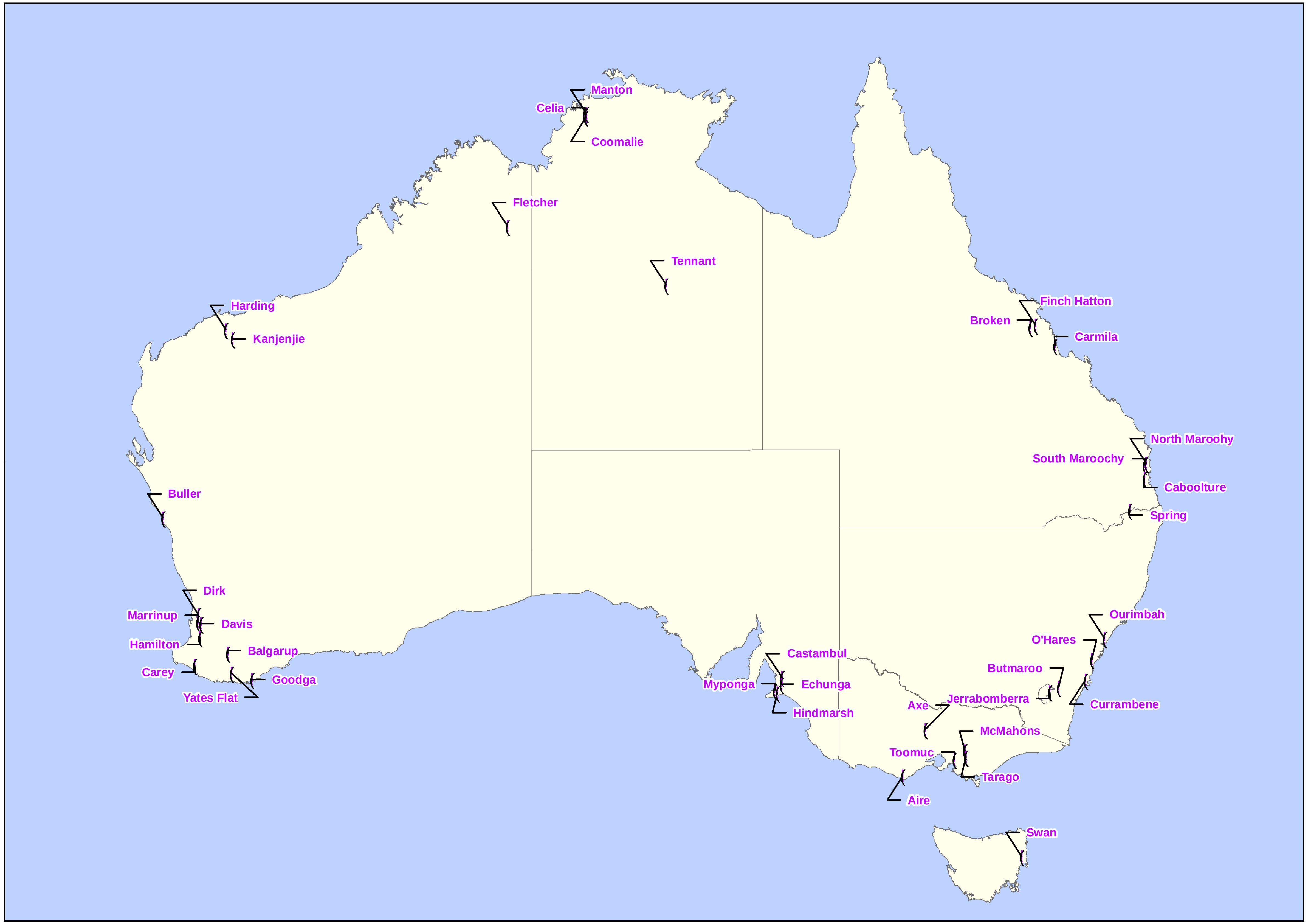
The investigation of the loss values described in Section 6 showed the influence of different hydroclimatic regions across Australia. From preliminary analysis of the data, the regions defined by the BoM in the development of the generalised PMP estimates were adopted as they are based upon the prevalent 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

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Kilometres

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

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.

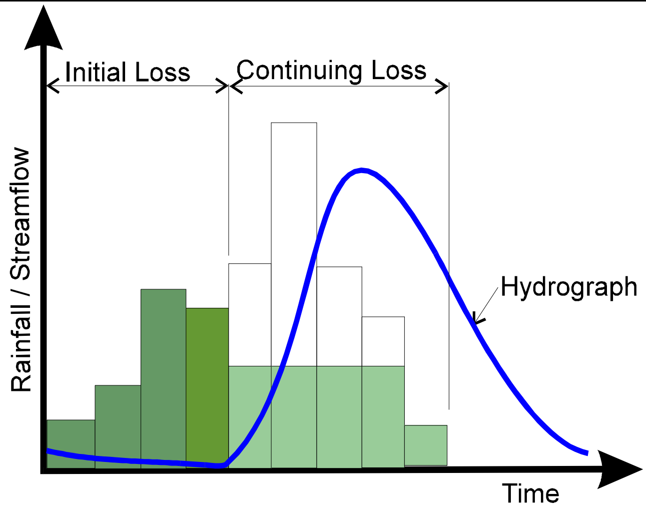

Figure 3-1 Initial Loss – Continuing Loss model

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).

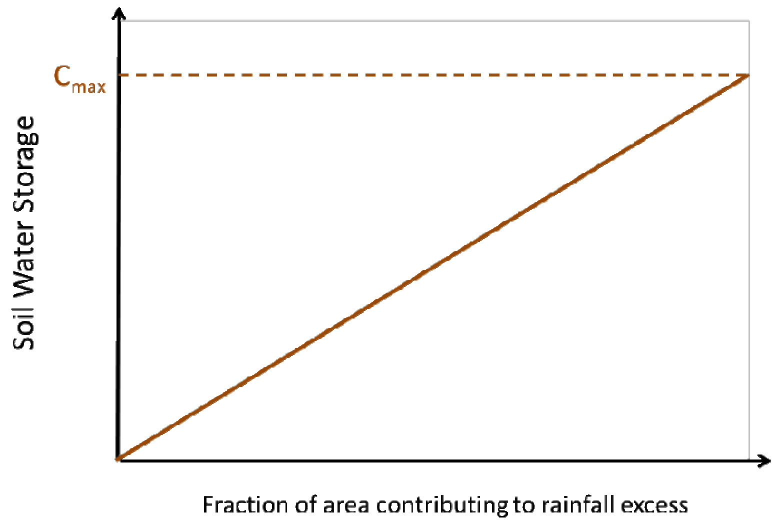

Figure 3-2 PDM distribution of catchment storage elements of different depths

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:

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

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.

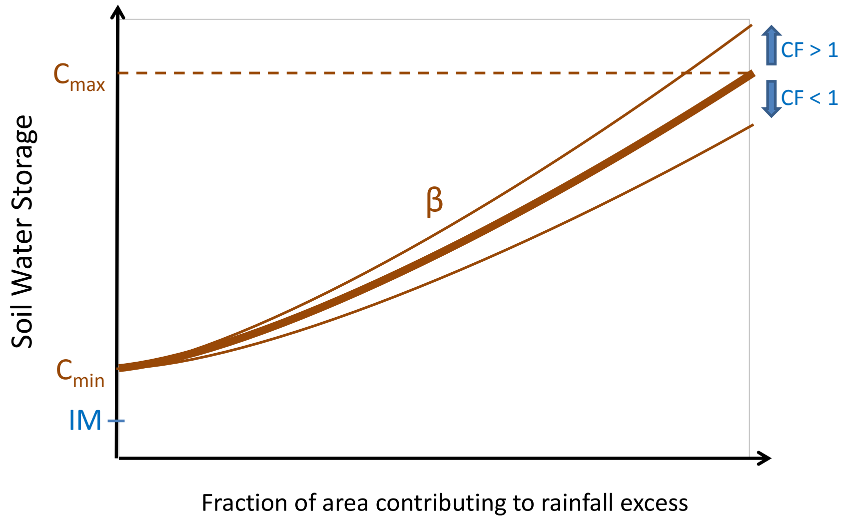

Figure 3-3 Conceptualisation of 2 parameter SWMOD model

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.

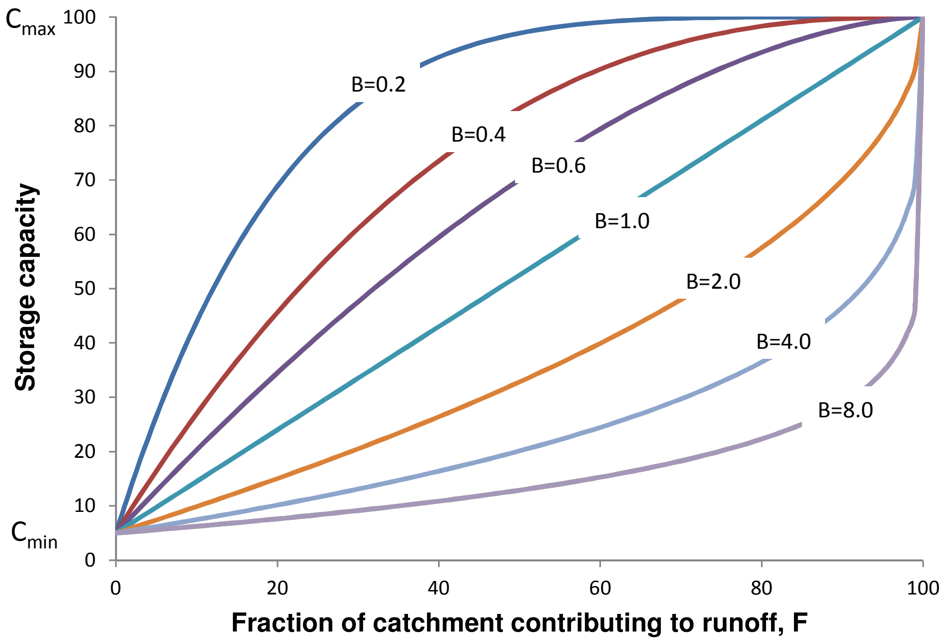

Figure 3-4 Influence of SWMOD shape parameter in defining storage capacity relationships

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.

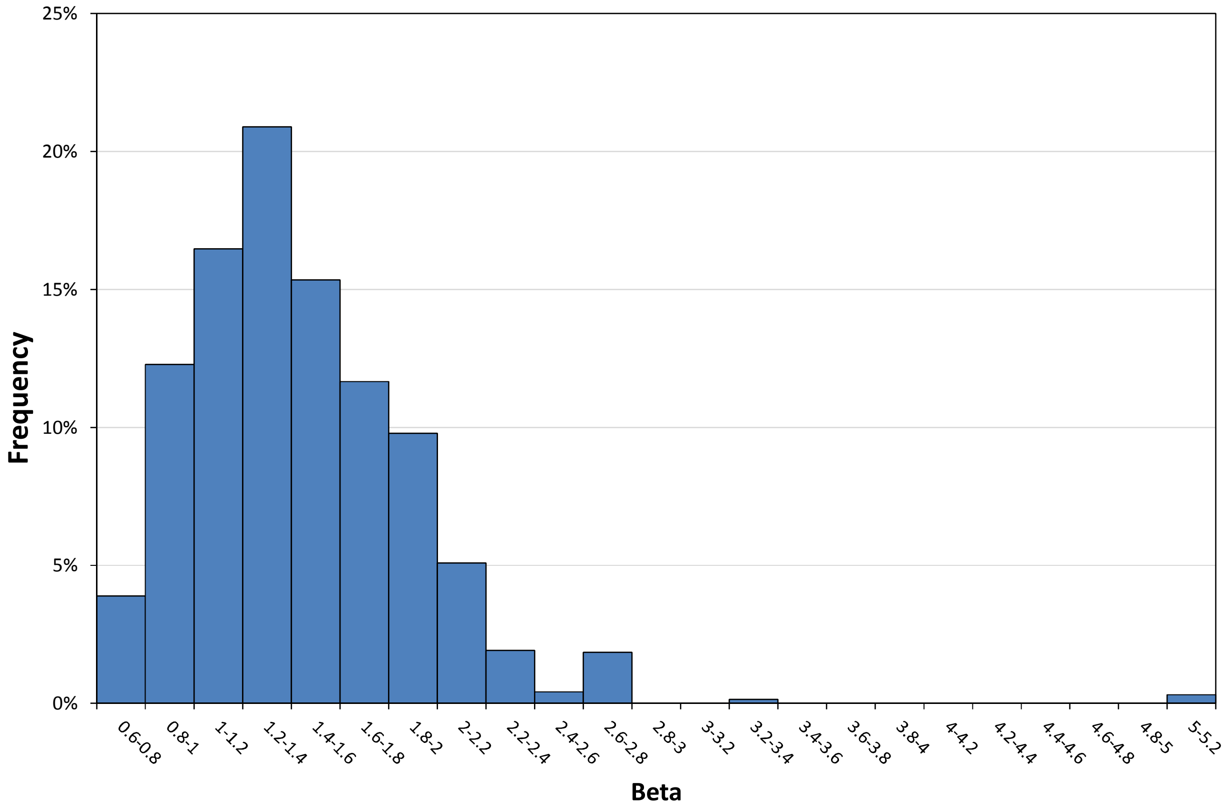

Figure 3-5 Frequency of shape parameter from fitting to Australian soils

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.

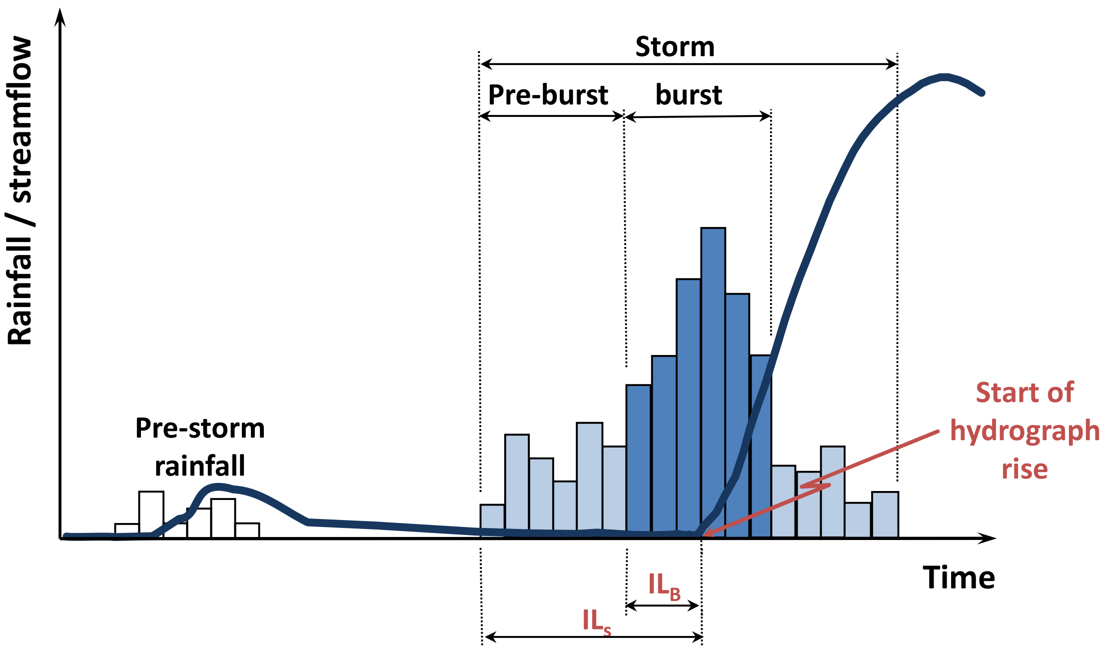

Figure 4-1 Initial Loss for an embedded rainfall burst

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.

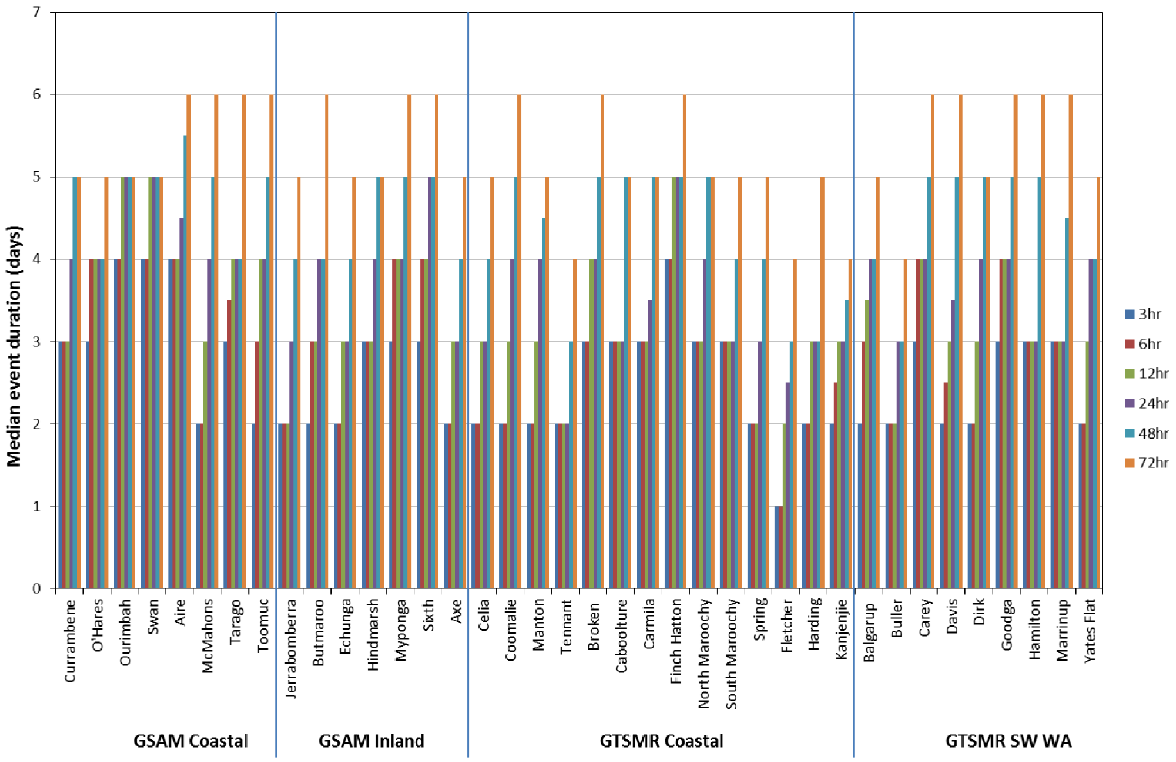

Figure 4-2 Median storm duration of events selected for each burst duration

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.

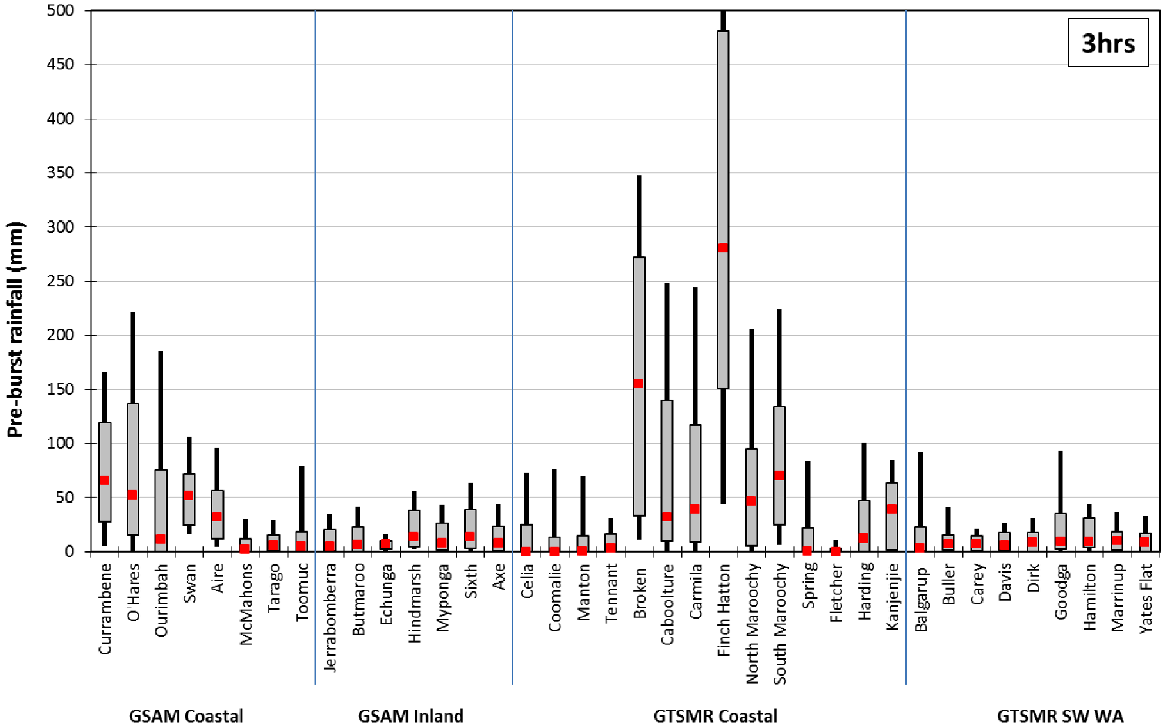

Figure 4-3 Range of pre-burst rainfall for 3-hour bursts (box indicates quartiles and line shows 10th and 90th percentile values)

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.

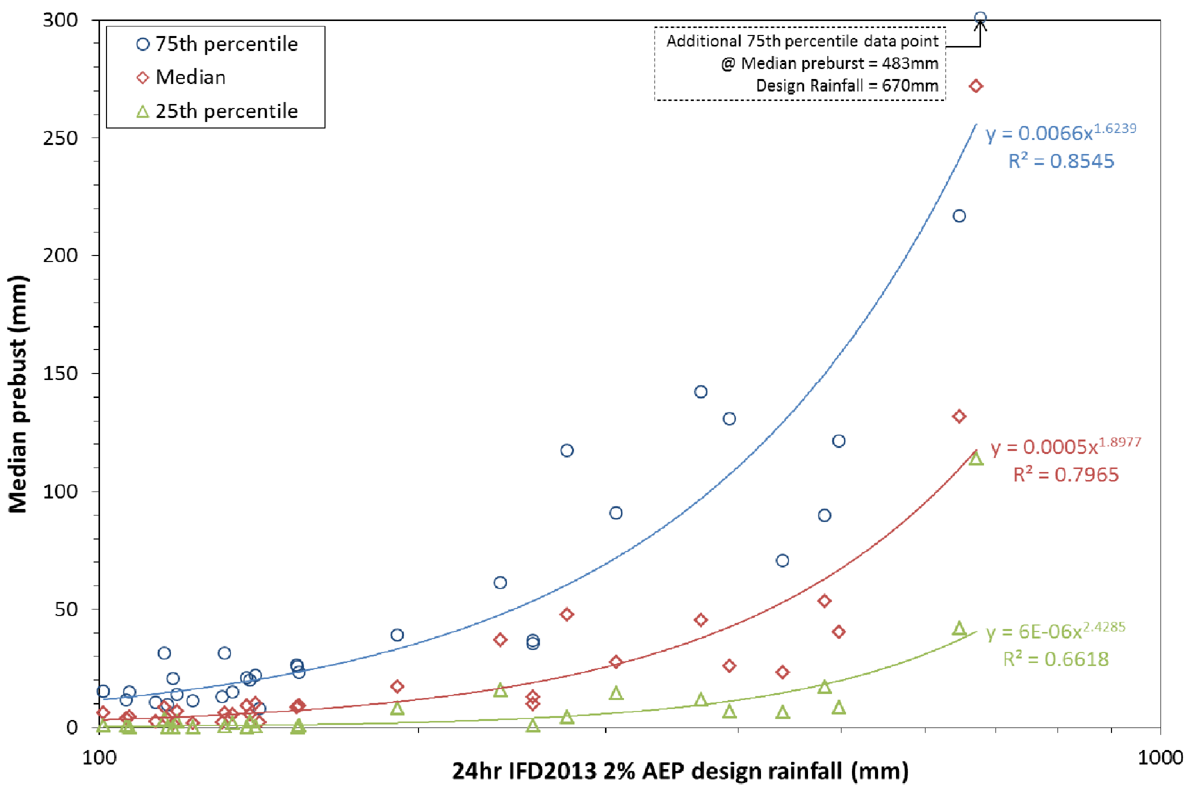

Figure 4-4 Relationship between pre-burst for 6 hour bursts and 2% 24 hour design rainfall

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.

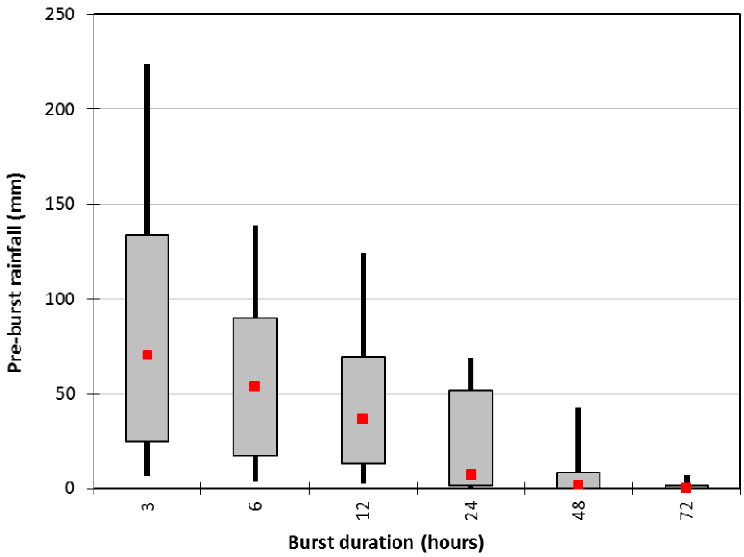

Figure 4-5 Range of pre-burst rainfall for South Maroochy for each duration (box indicates quartiles and line show 10th and 90th percentile values)

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.

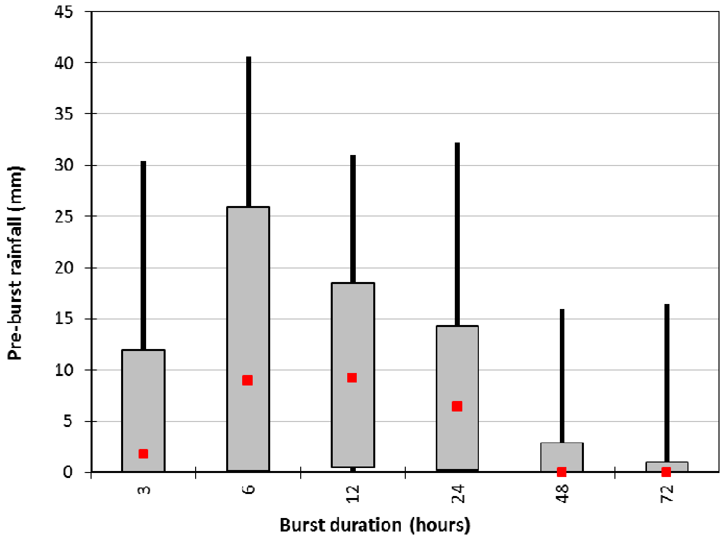

Figure 4-6 Range of pre-burst rainfall for McMahons for each duration (box indicates quartiles and line show 10th and 90th percentile values)

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.

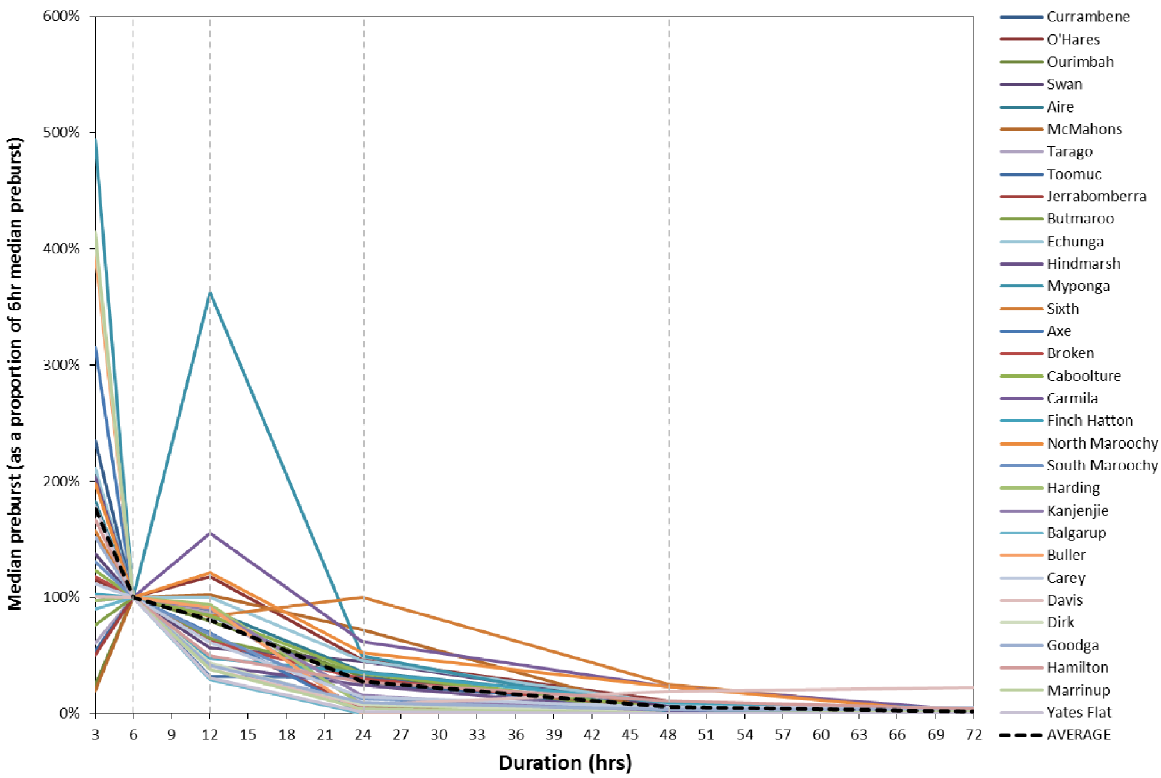

Figure 4-7 Variation of median pre-burst (normalized against 6hour value) with duration for each site

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.

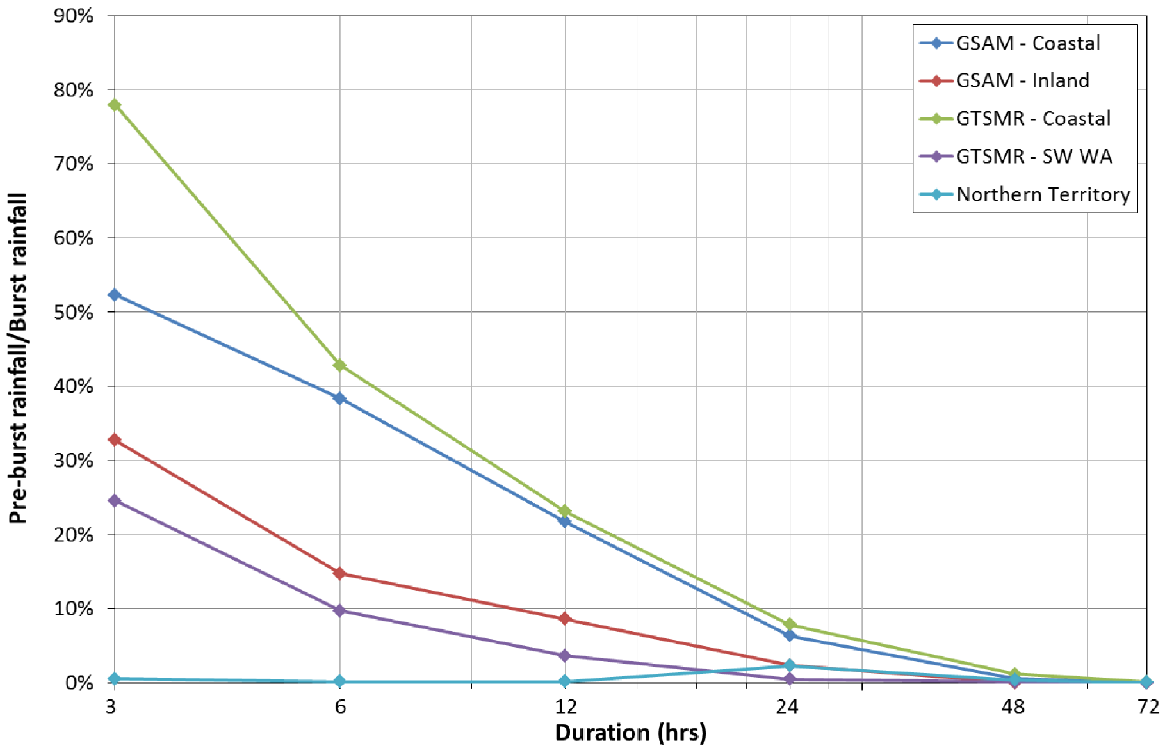

Figure 4-8 Change in Pre-burst/burst rainfall ratio with duration for each region (NT sites and Fletcher Creek separated from GTSMR coastal sites, and Spring Creek excluded)

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.

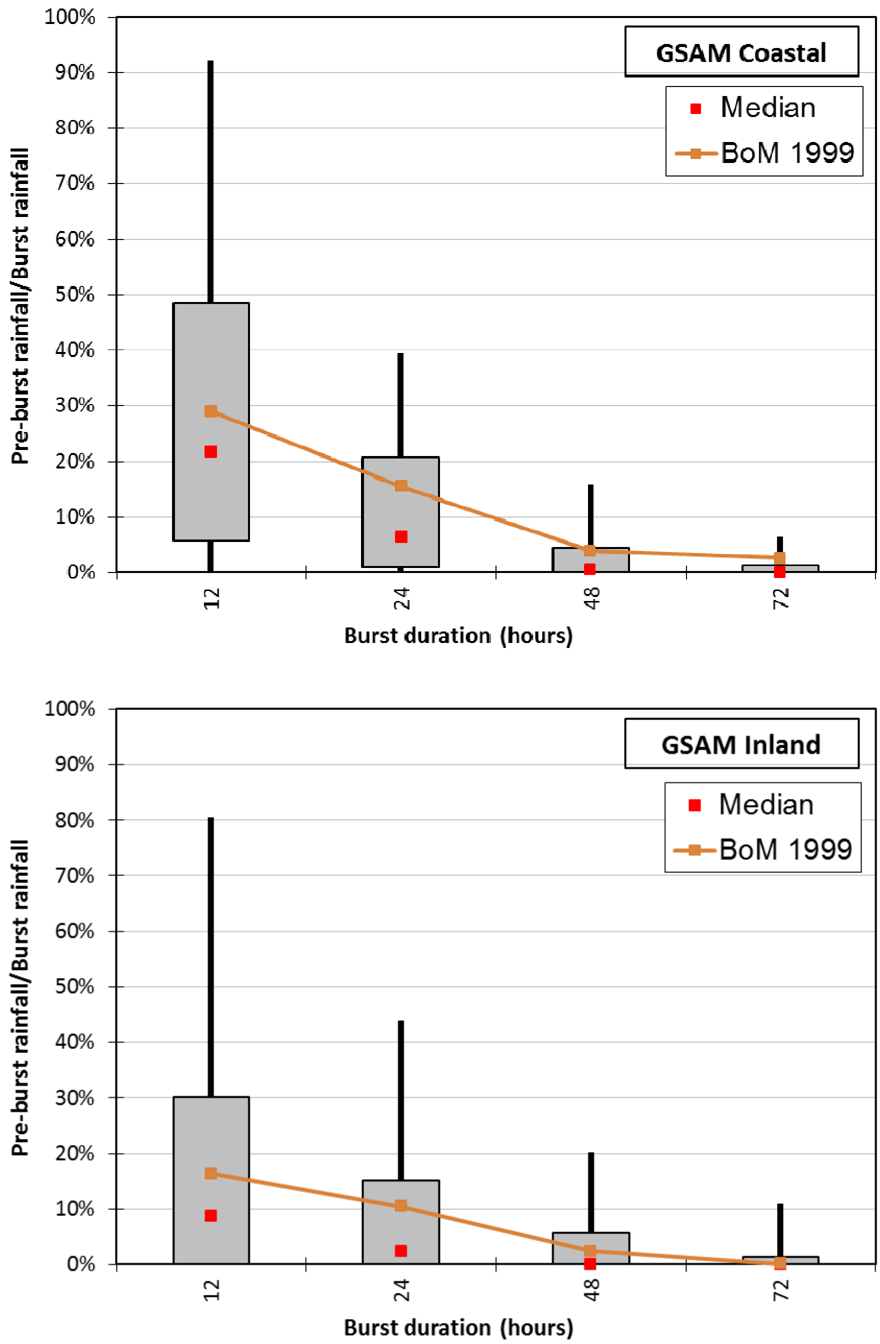

Figure 4-9 Comparison of pre-burst values with median values from BoM (1999) (box indicates quartiles and line show 10th and 90th percentile values)

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.

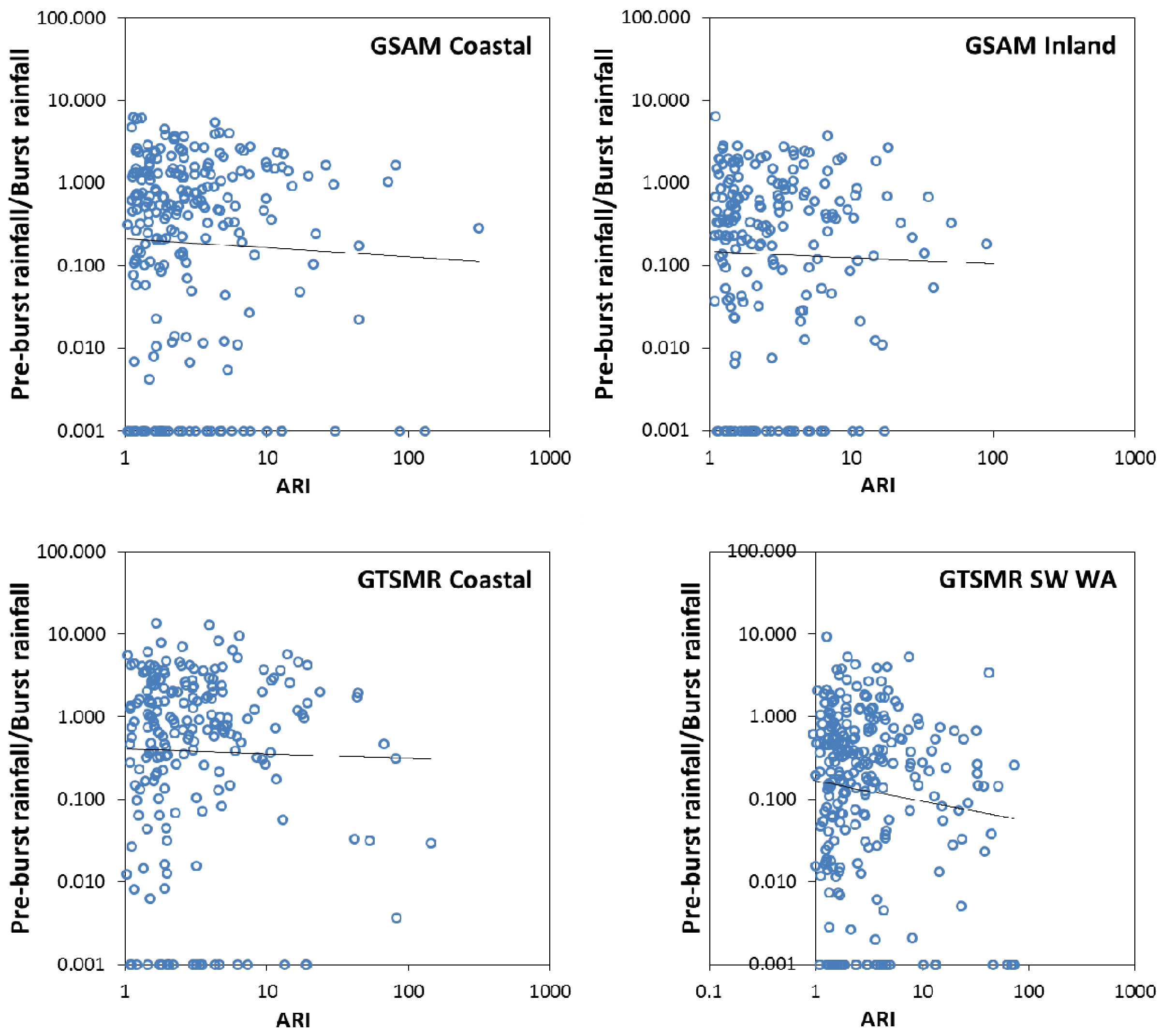

Figure 4-10 Relationship between ratio of pre-burst rainfall and burst rainfall to ARI for 3-hour bursts. (Northern Territory catchments and Fletcher Creek separated from GTSMR coastal catchments, and Spring Creek excluded)

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 1.0m^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.

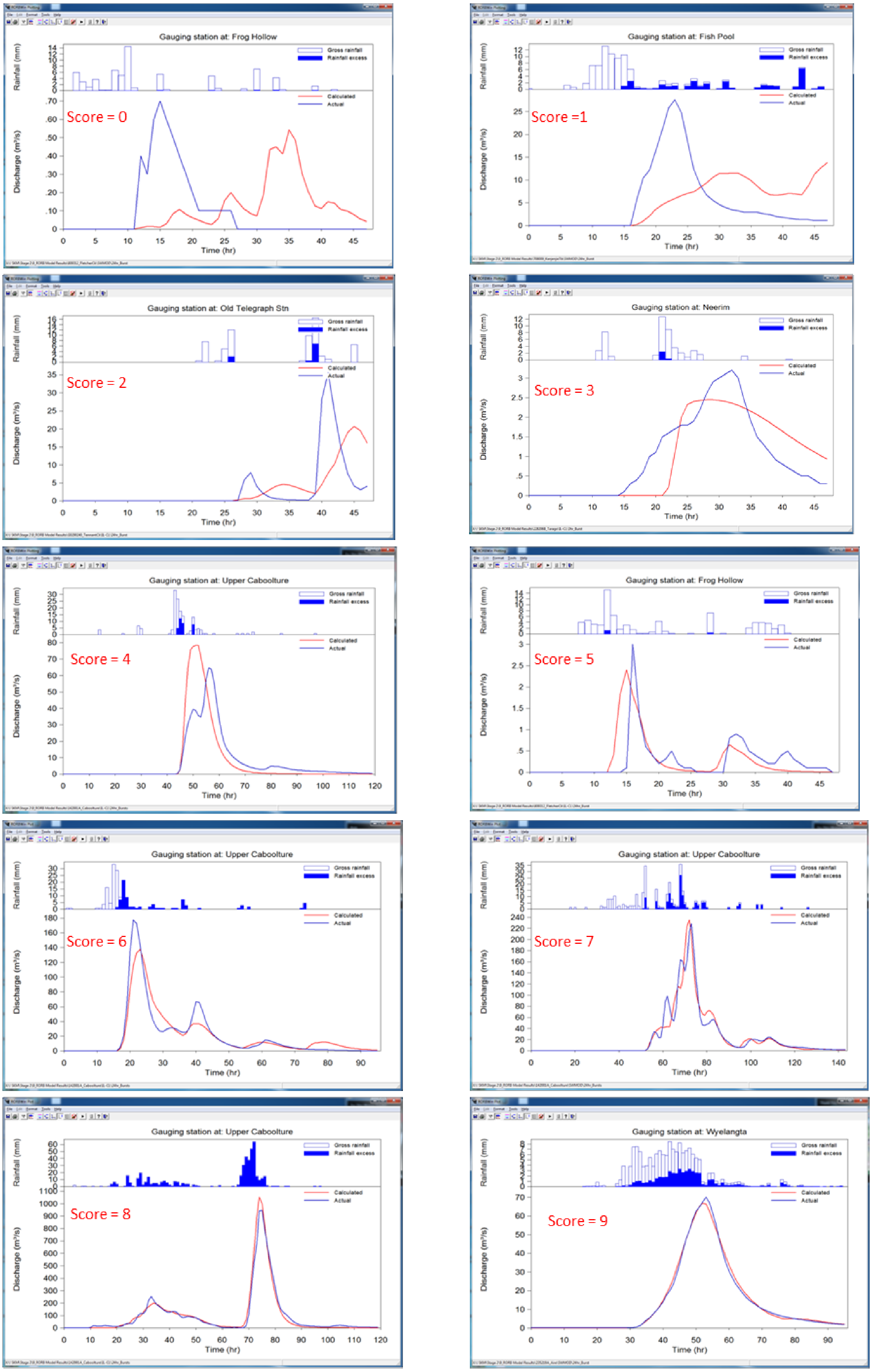

Figure 5-1 Example skill scores used to assess goodness of fit between calculated and recorded hydrographs

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.

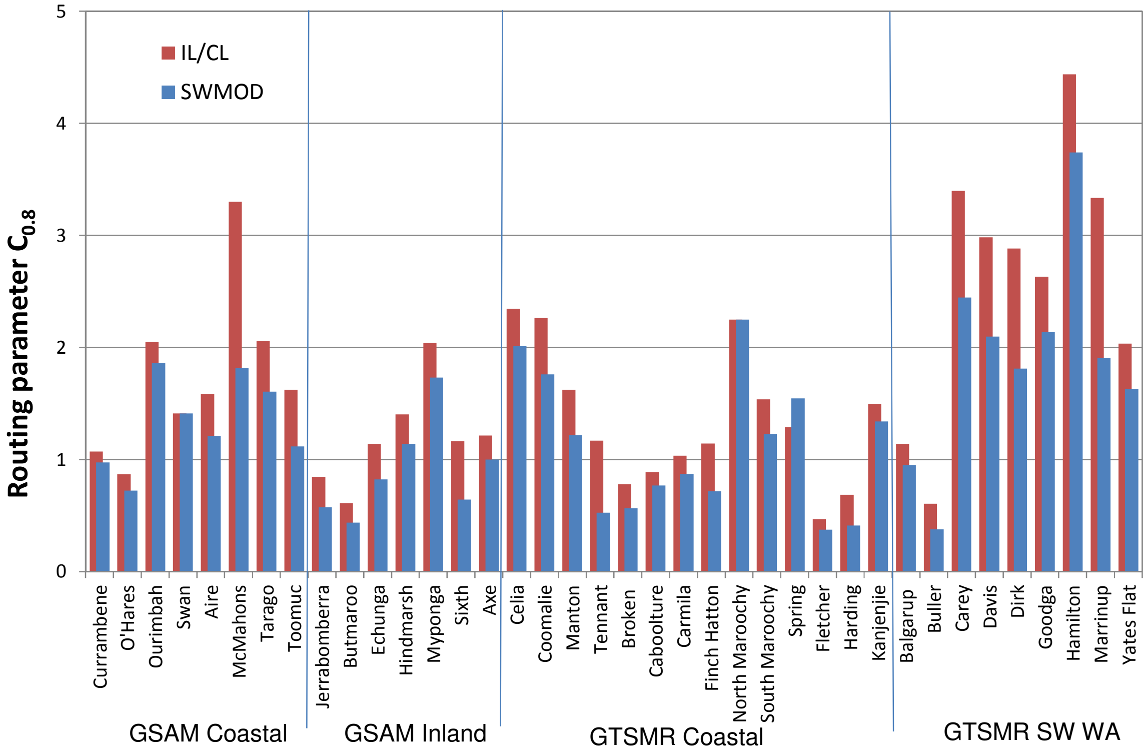

Figure 5-2 Adopted routing parameters

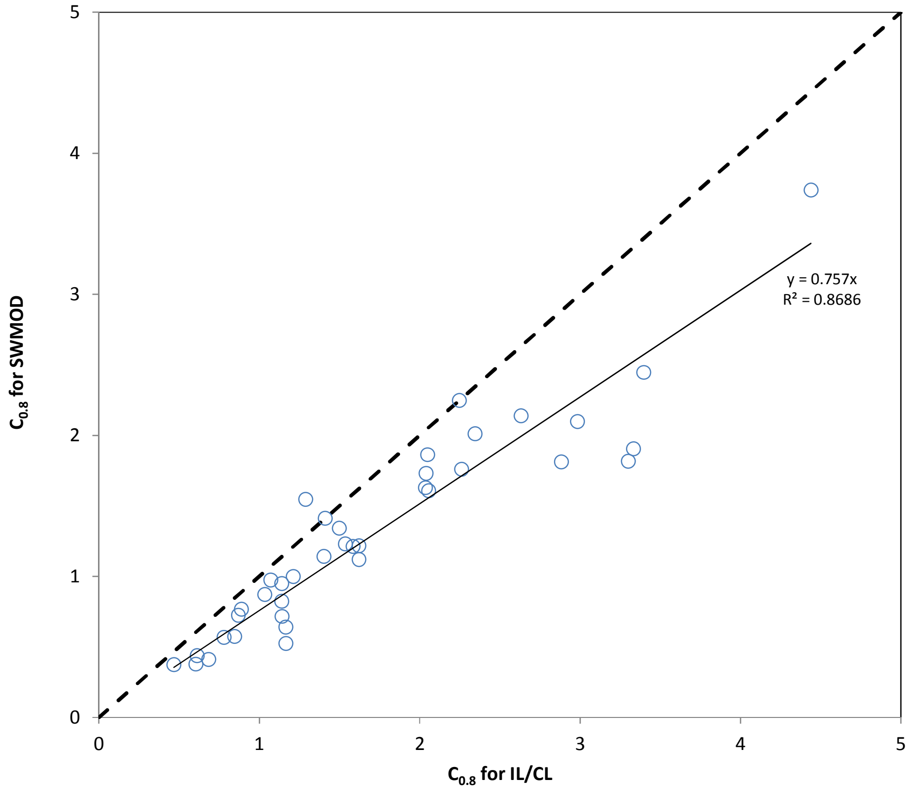

Figure 5-3 Comparison of adopted routing parameters for IL/CL and SWMOD

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

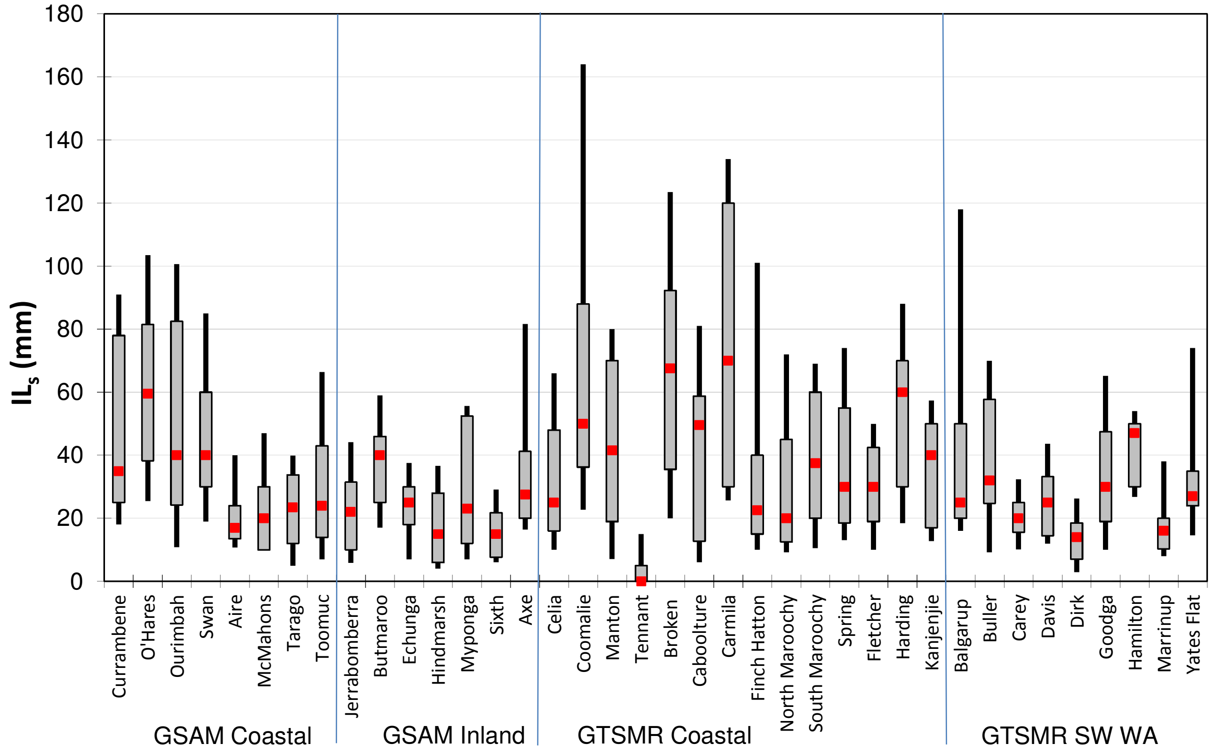

Figure 6-1 Range of storm Initial Loss values for events selected by 24-hour bursts (box indicates quartiles and line shows 10th and 90th percentile values)

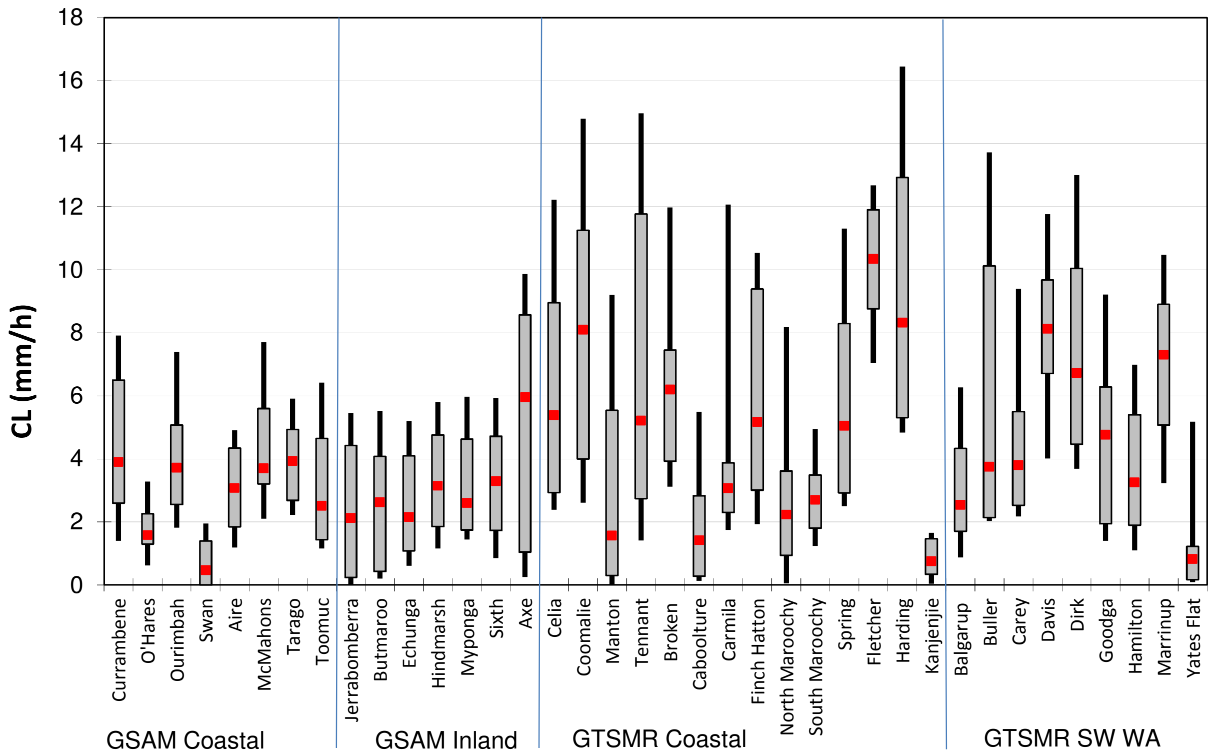

Figure 6-2 Range of Continuing Loss values for events selected by 24-hour bursts (box indicates quartiles and line show 10th and 90th percentile values)

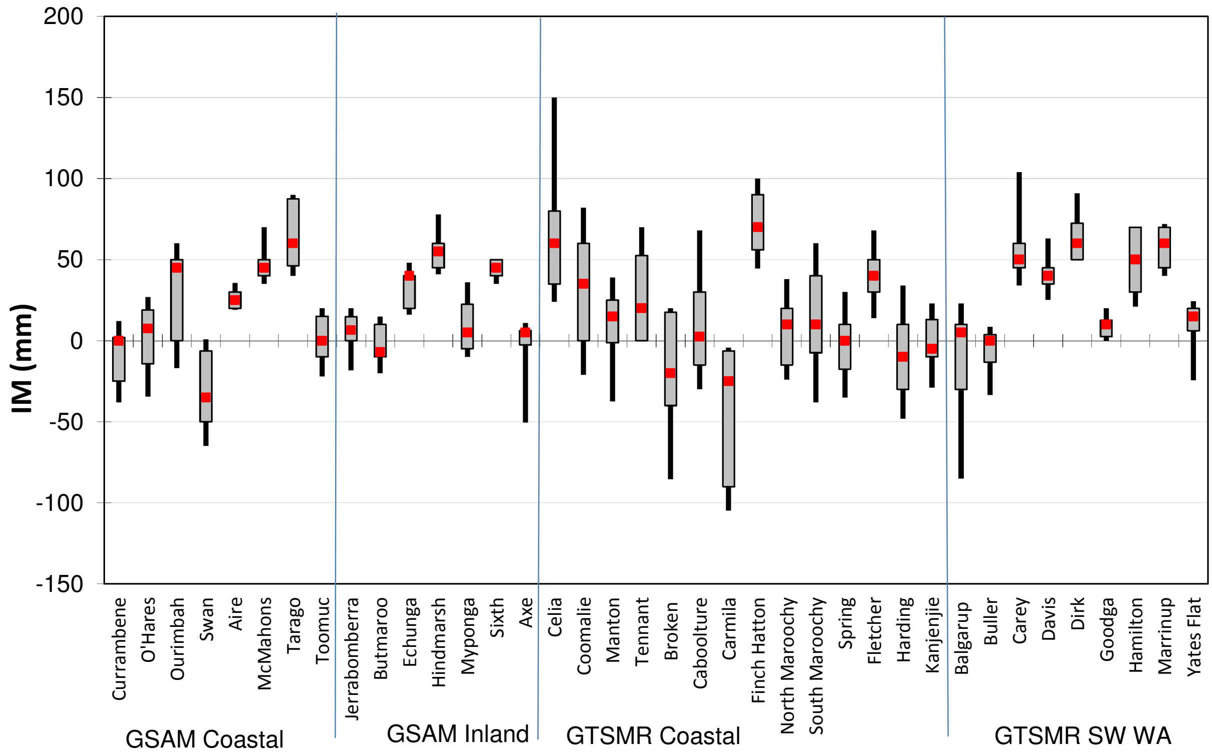

Figure 6-3 Range of Initial Moisture values for events selected by 24-hour bursts (box indicates quartiles and line show 10th and 90th percentile values)

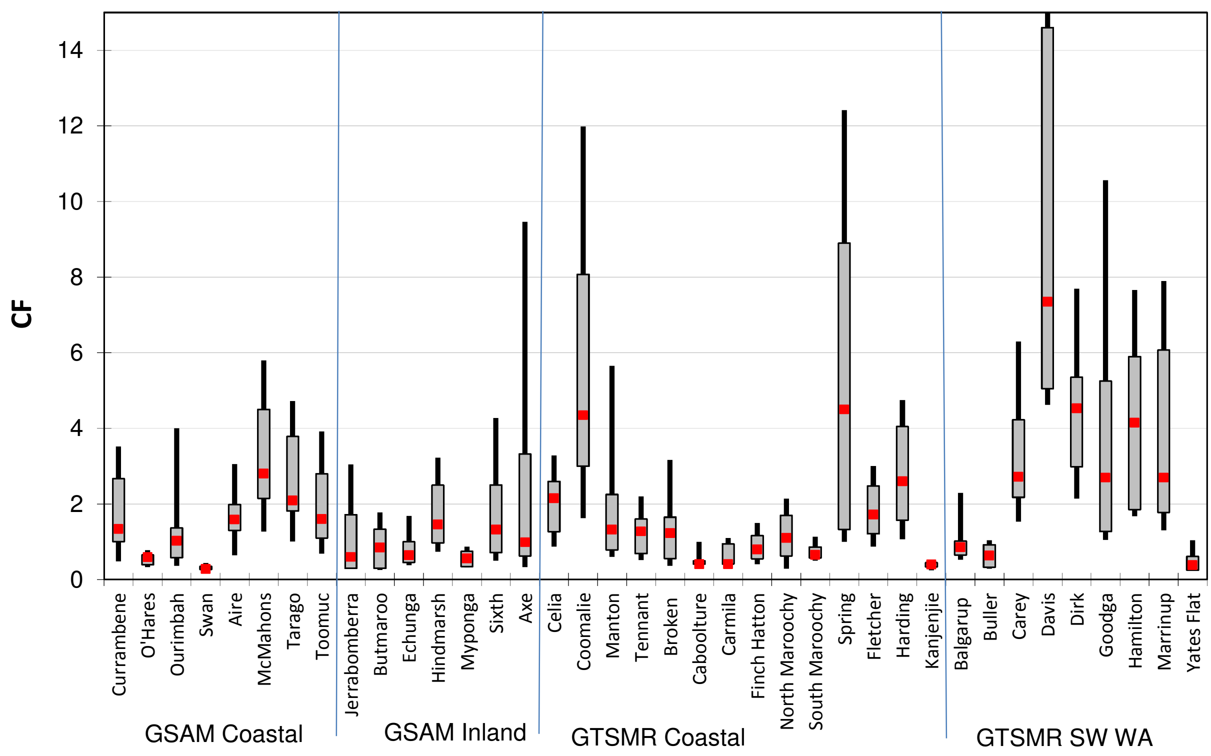

Figure 6-4 Range of Capacity Factor values for events selected by 24-hour bursts (box indicates quartiles and line show 10th and 90th percentile values)

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.

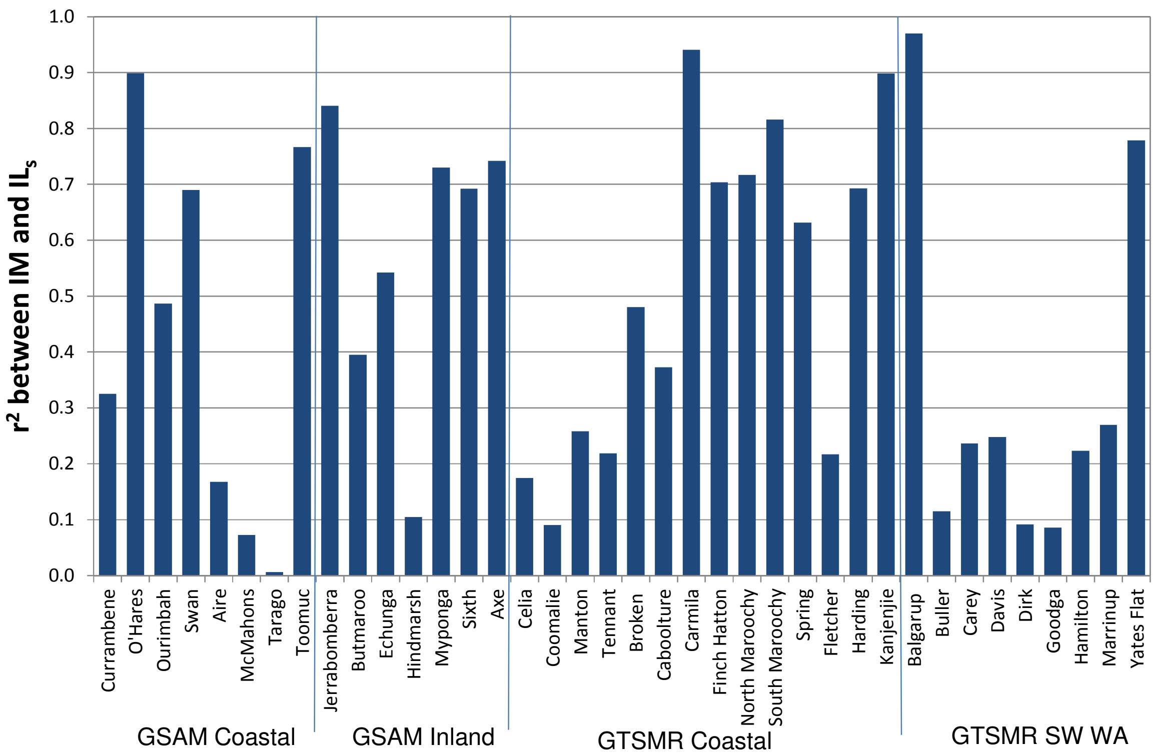

Figure 6-5 Proportion of variance explained (r^2) between IM_s and IL_s

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.

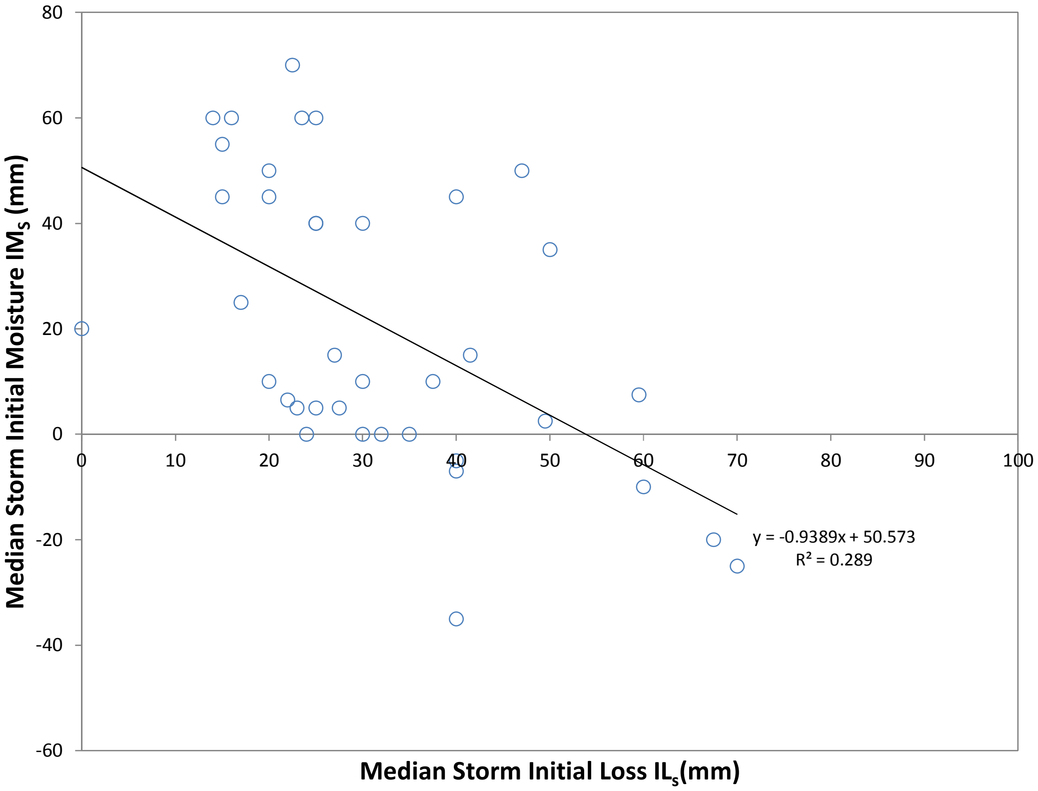

Figure 6-6 Relationship between median Storm Initial Moisture and Storm Initial Loss

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.

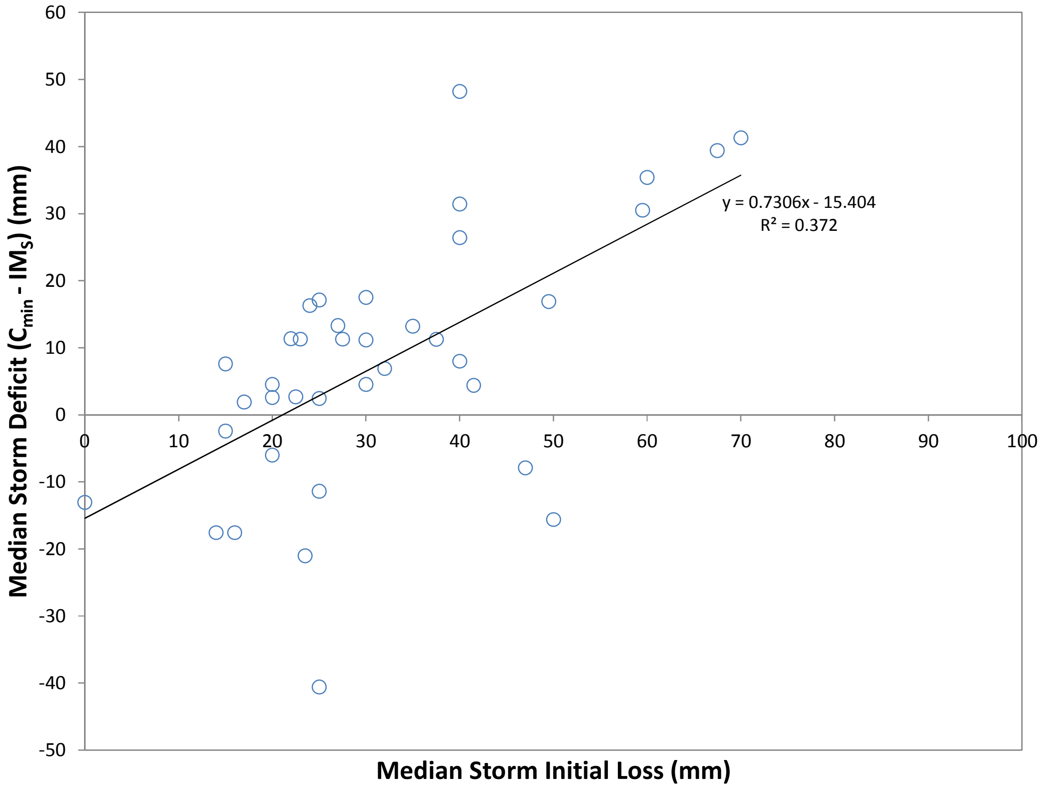

Figure 6-7 Relationship between median Storm Deficit (based upon minimum capacity of soils in the catchment) and Storm Initial Loss

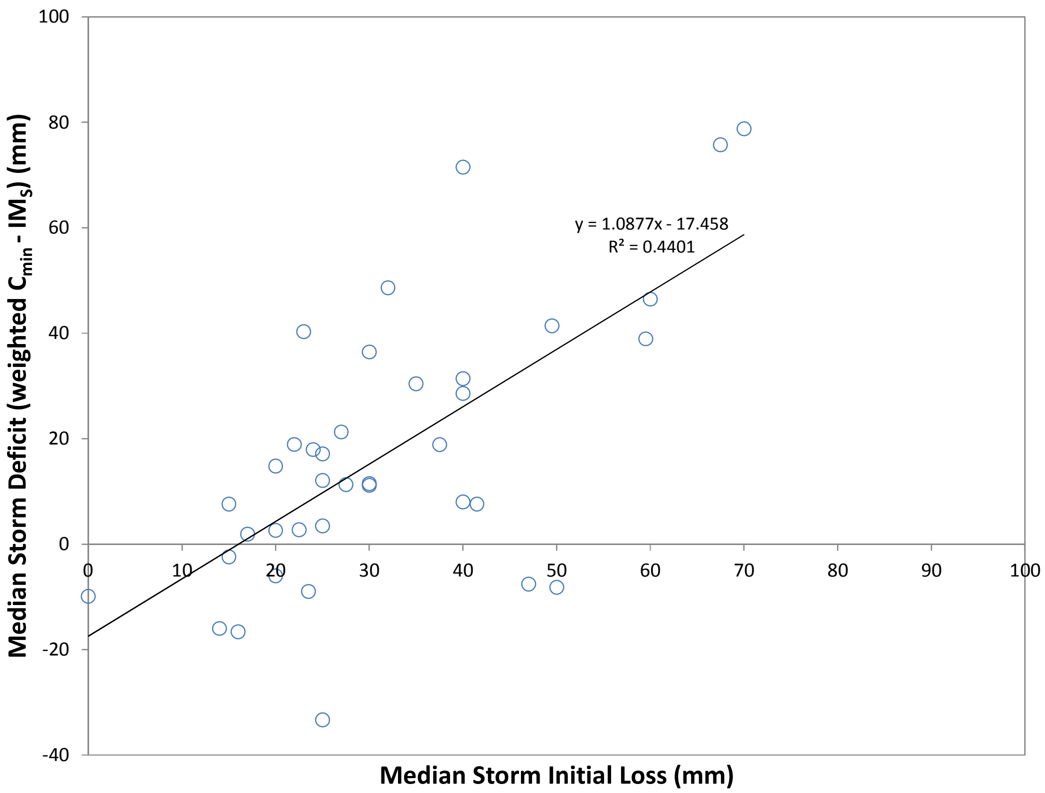

Figure 6-8 Relationship between median Storm Deficit (based upon <u>weighted minimum</u> capacity of soils in the catchment) and Storm Initial Loss

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.

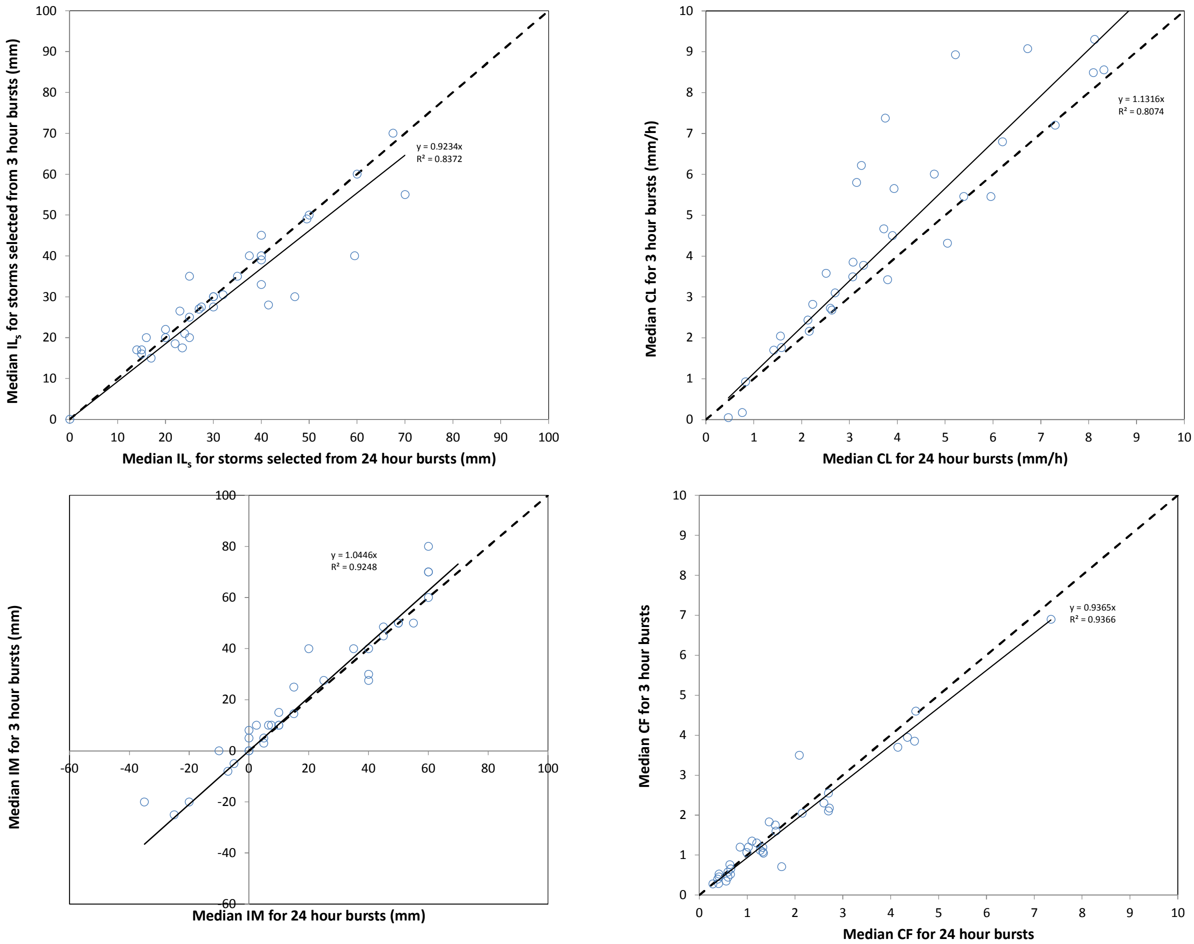

Figure 6-9 Comparison of loss values for events selected by bursts of 3 and 24-hour duration

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.

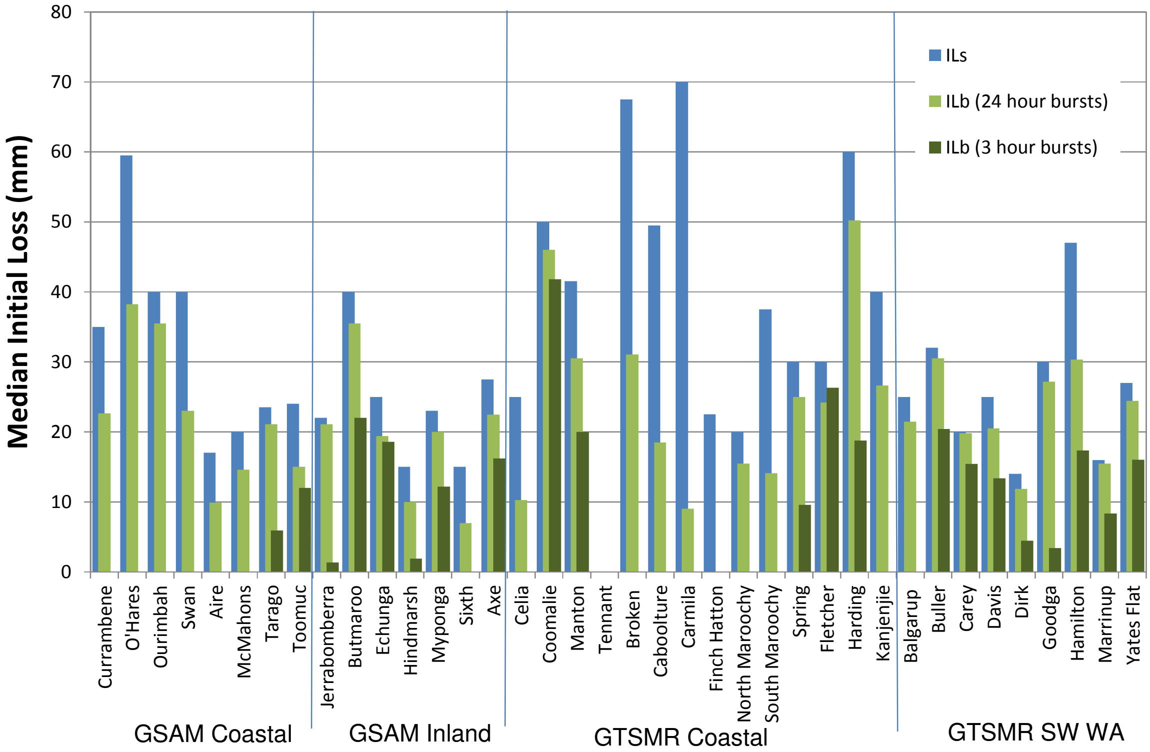

Figure 6-10 Median Initial Loss for different duration bursts

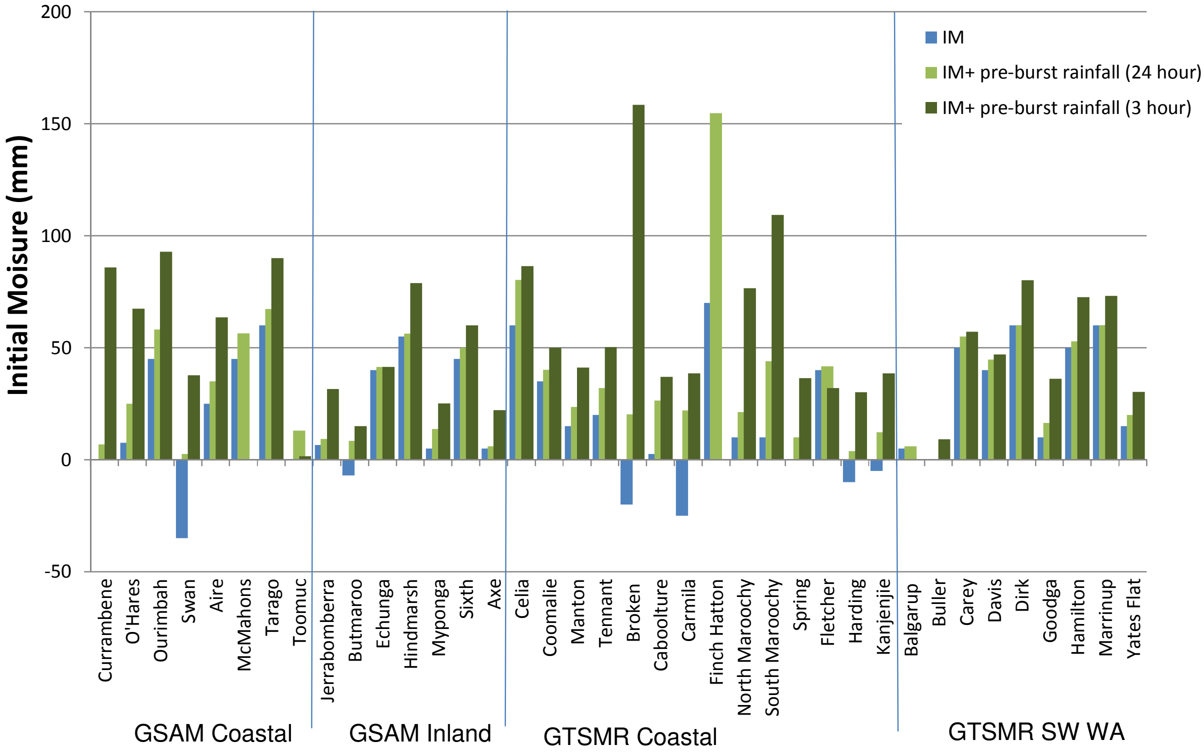

Figure 6-11 Median Initial Moisure for different duration bursts

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.

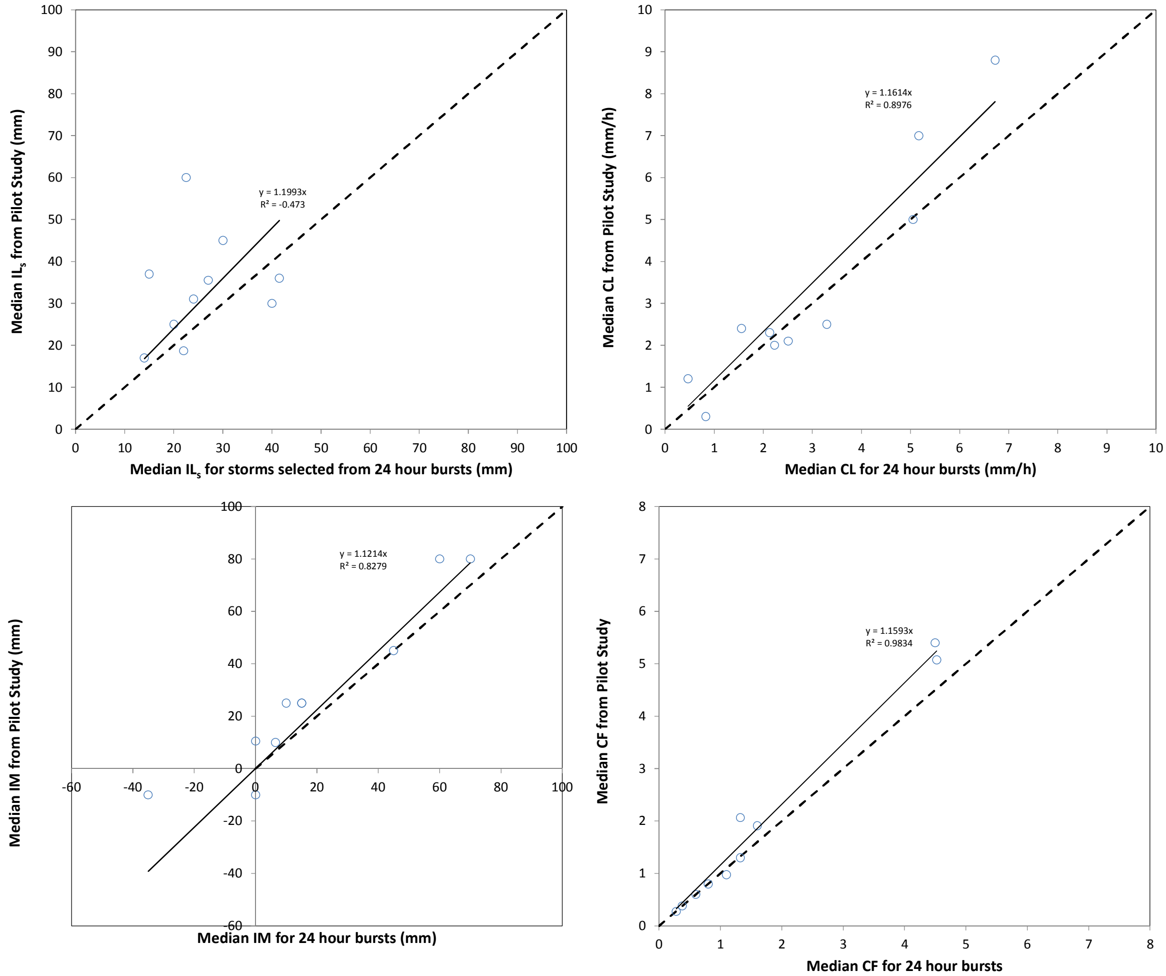

Figure 6-12 Comparison of loss values with Phase 1 Pilot Study

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.

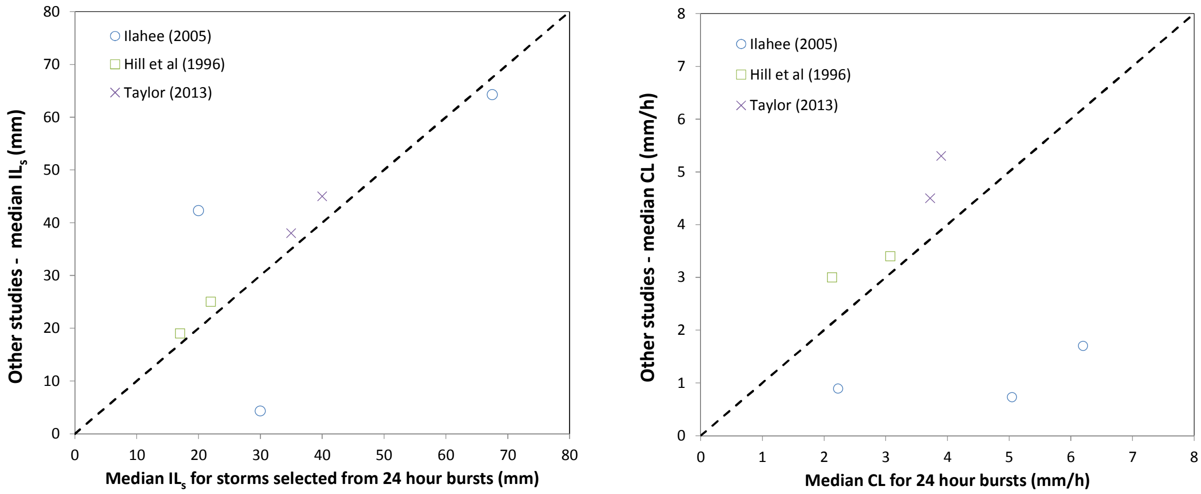

Figure 6-13 Comparison of IL/CL values with other studies

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”.

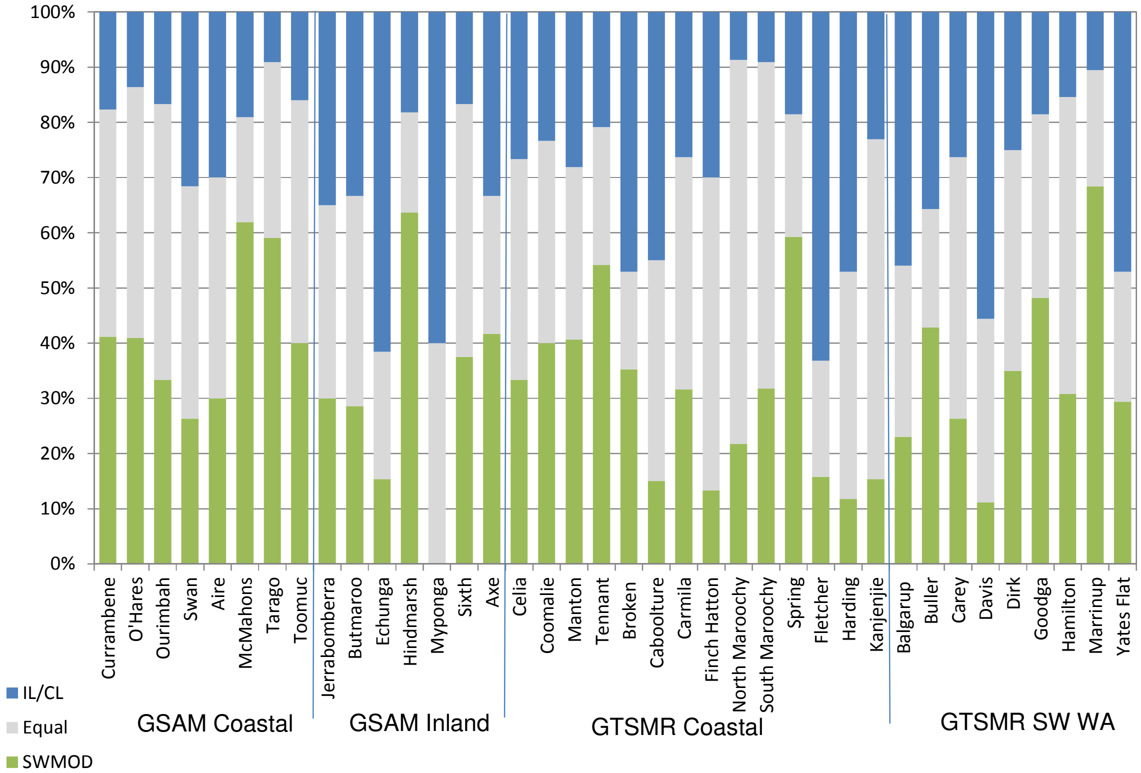

Figure 6-14 Relative performance of IL/CL and SWMOD models

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.

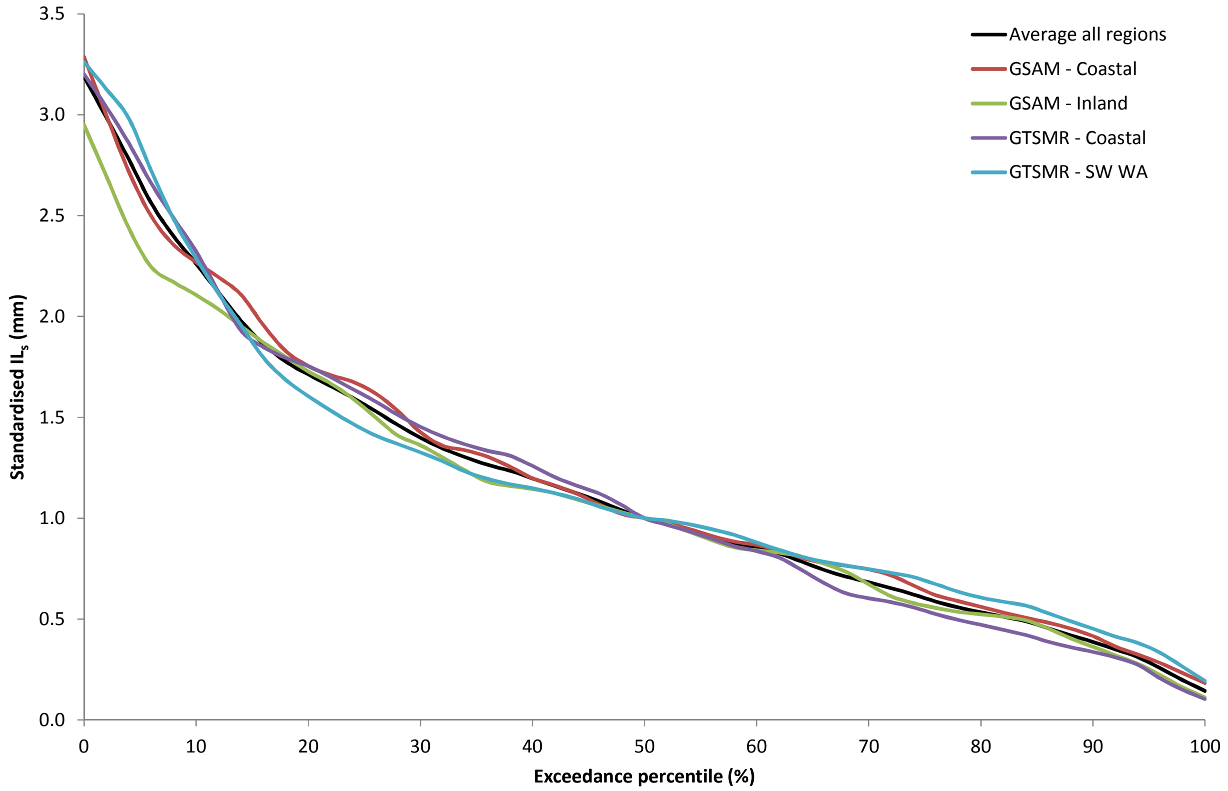

Figure 6-15 Regional average IL_s standardised by the mean value and average across all regions

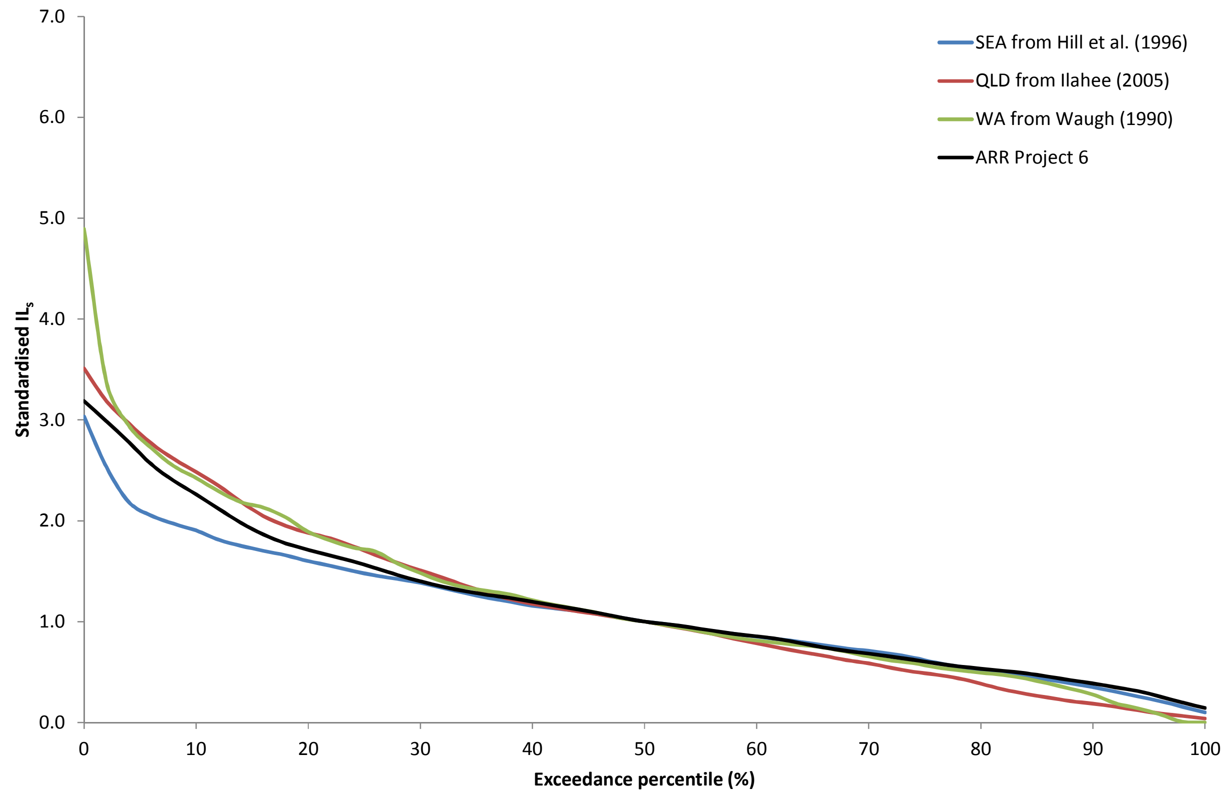

Figure 6-16 Average IL_s standardised by the mean value for Project 6 and standardised Initial Loss distributions from other studies

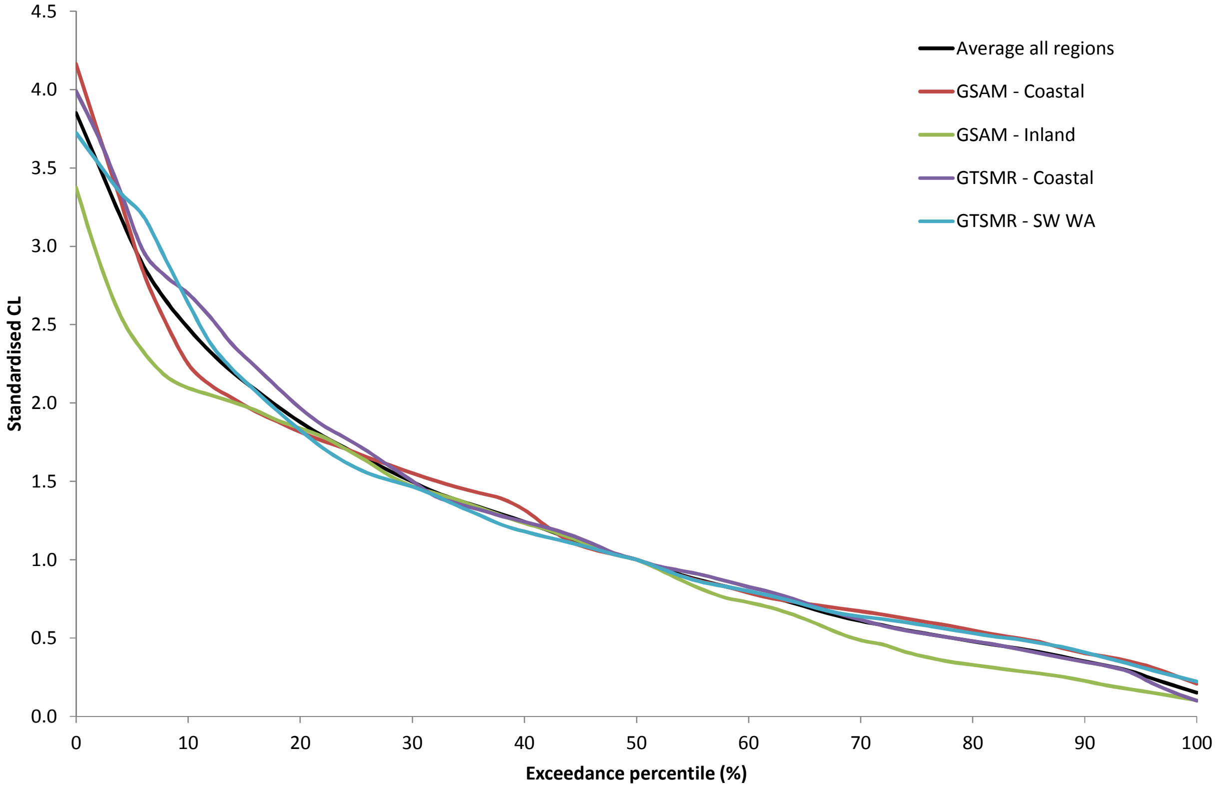

Figure 6-17 Regional average CL standardised by the mean value and average across all regions

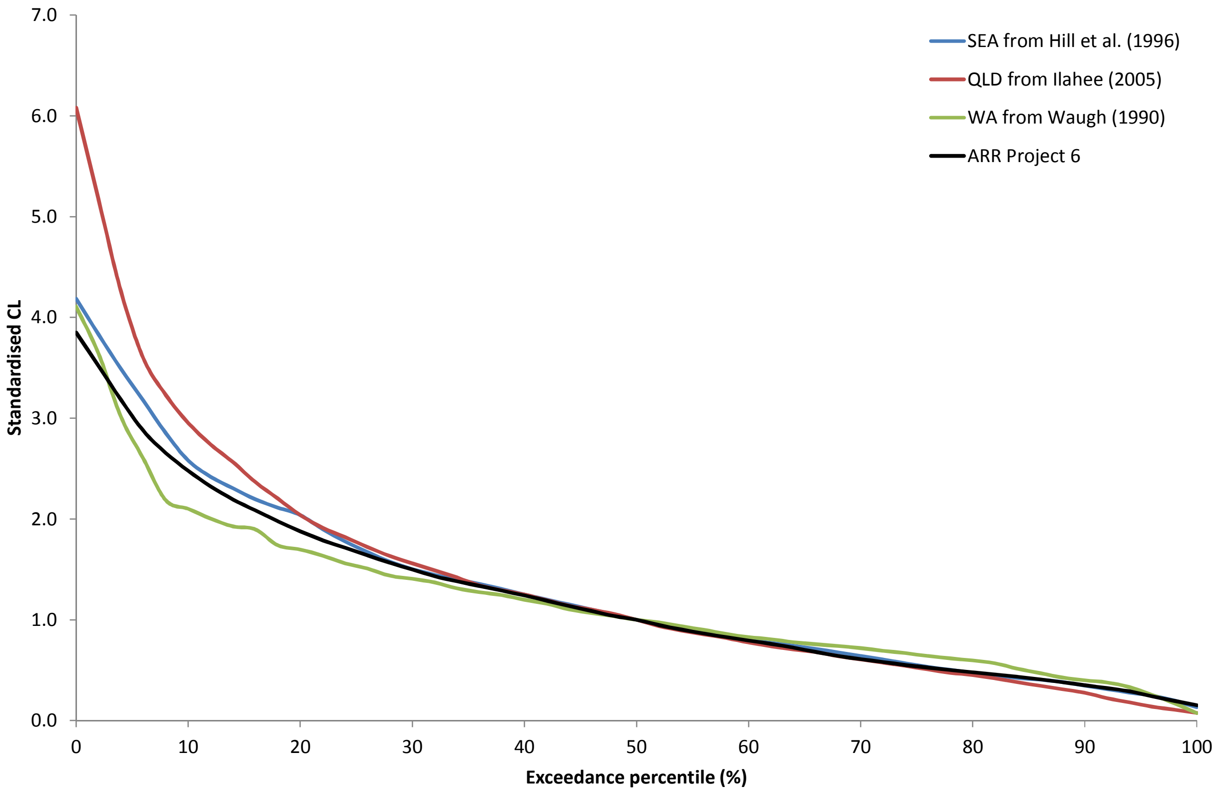

Figure 6-18 Average CL standardised by the mean value for Project 6 and standardised Continuing Loss distributions from other studies

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.

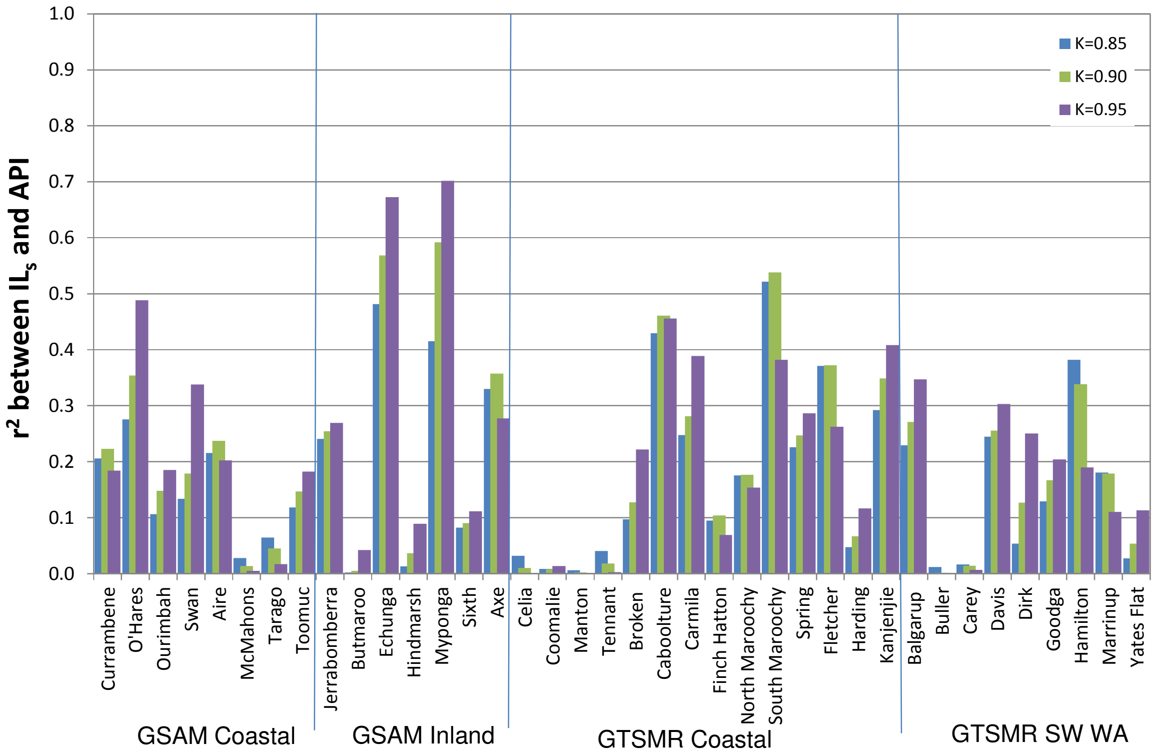

Figure 6-19 Proportion of variance explained (r^2) between Storm Initial Loss and API

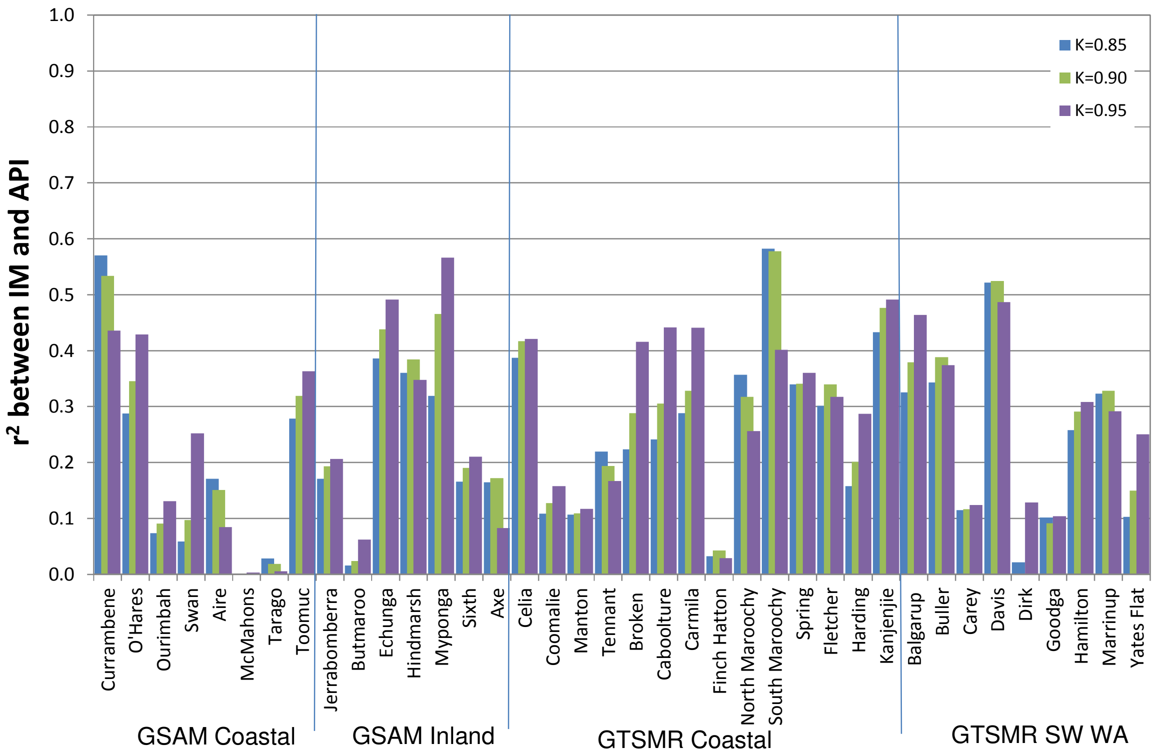

Figure 6-20 Proportion of variance explained (r^2) between Initial Moisture and API

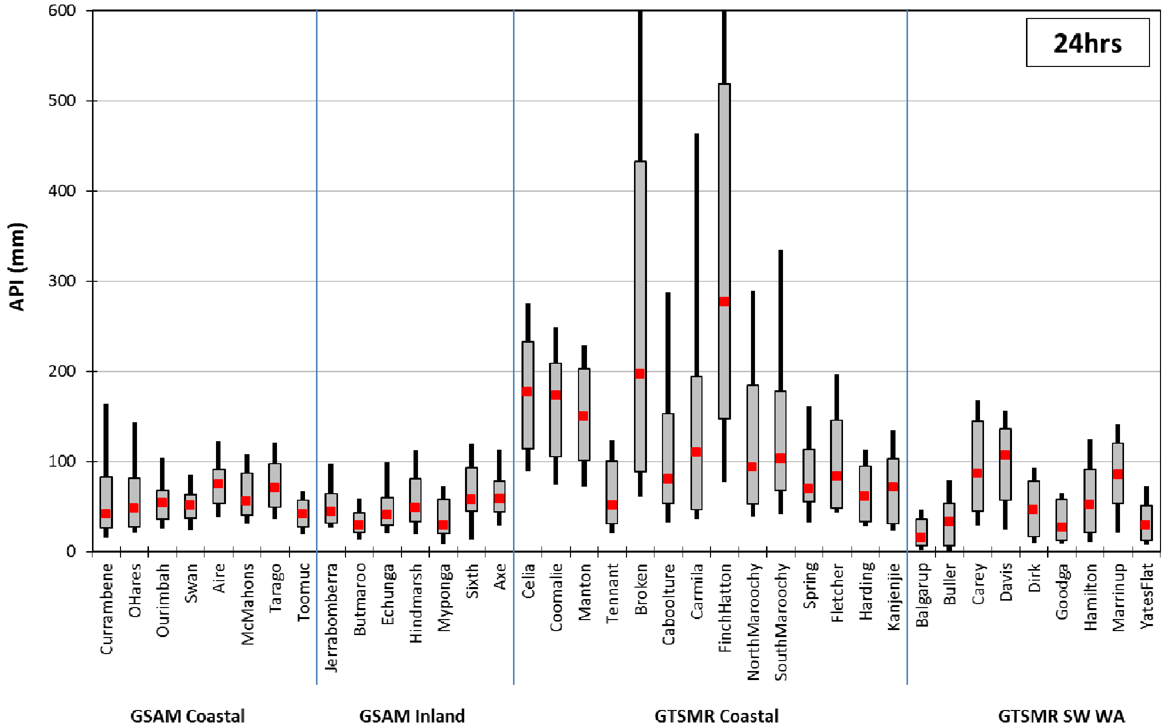

Figure 6-21 Range of API values (*k*=0.95) for storm selected by 24-hour bursts (box indicates quartiles and line shows 10th and 90th percentile values)

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.

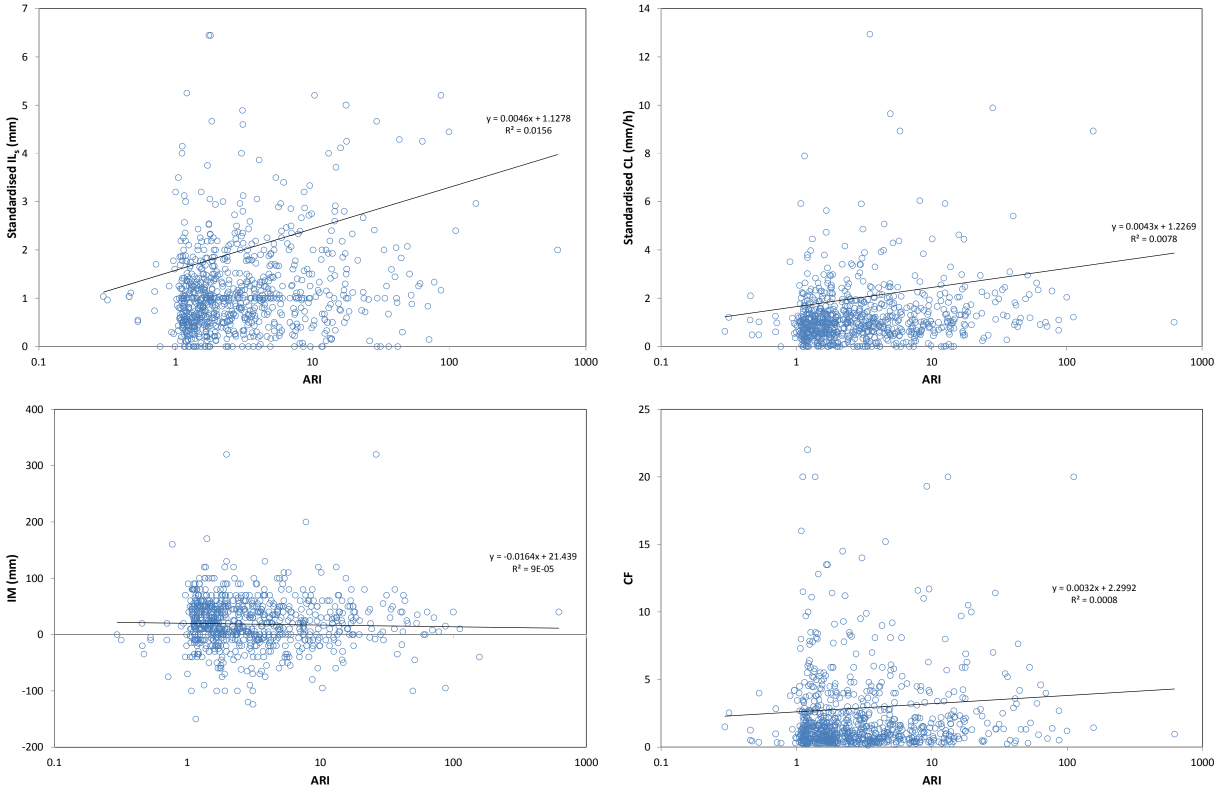

Figure 6-22 Variation of standardised loss values with ARI of the burst rainfall

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

Region	Storm Initial Loss (mm)		Continuing Loss (mm/h)	
	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

Region	Initial Moisture (mm)		Capacity Factor	
	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.

$IL_s = 16.7 + 0.141P_{24h}^{2\%} - 0.291MedianAPI$ 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%

$CF = 0.51 + 0.006A\_k_{sat}$ 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%

$\mathrm{IM_s} = 108.4 + 622Catchment\_Slope - 393.5\mathrm{A\_FCP}$ 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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AUSTRALIAN RAINFALL AND RUNOFF

REVISION PROJECT 6

Loss models for catchment simulation: Phase 4 Analysis of Rural Catchments

APPENDICES A to M

Appendix A Excluded catchments

The table below lists the gauge and pluviograph number of the catchments that were identified but not able to be included in the analysis. Where inclusion criteria was not met, a comment has been included. Other catchments have been excluded because data was not able to be collected or the catchment was located close to other catchments with a better match to inclusion criteria.

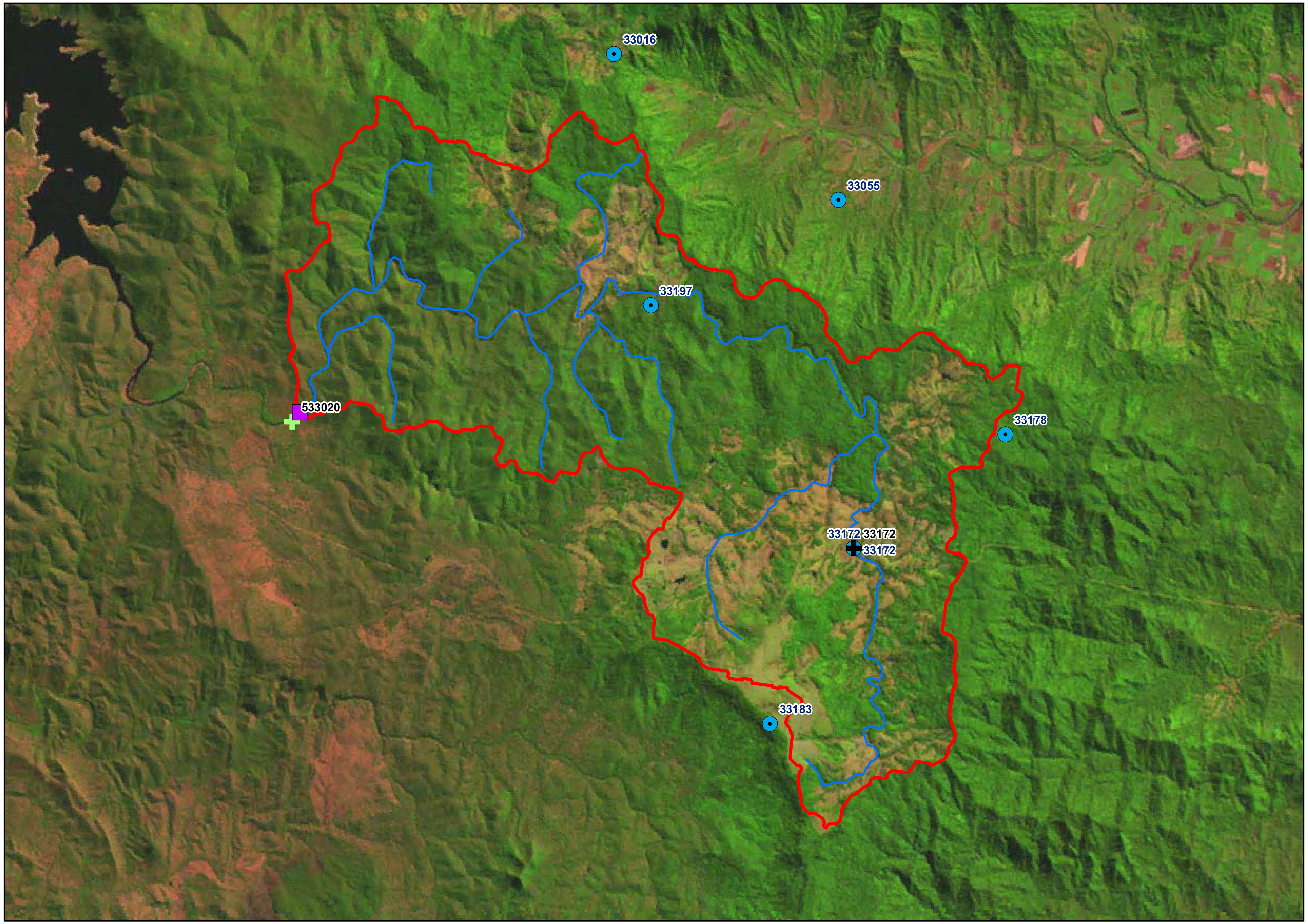
Table A-1 Catchments excluded from analysis

Gauge	Pluvio	State	Comment
410739	570967	ACT	Data not received/available
12001	12002	NSW	No data available
203013	P58072	NSW	15 yrs overlapping data only; 77% missing flow data
203025	P58131	NSW	62% missing flow data
206010	P57104	NSW	11% missing flow data
206026	206026	NSW	Catchment area <20km^2
208002	208002	NSW	11% missing flow data; 43% missing pluvio data
210072	P61325	NSW	No overlapping data; 62% missing flow data
210076	210076	NSW	No useable data
212001	568058	NSW	Affected by transfers
212014	563071	NSW	Data not received/available
214003	568102	NSW	Timing of rainfall and streamflow not matching
219001	219005	NSW	No flow data available
410077	410077	NSW	47% missing flow data; 75% missing pluvio data
410112	410112	NSW	No useable data
418034	418034	NSW	35% missing pluvio data
421034	P63108	NSW	10 years overlapping data only
G8150097	R8150205	NT	Close to other catchments
G8150200	R8150205	NT	18% missing flow data
G8210012	R8210009	NT	No data in file provided
G8260052	P14508	NT	Only equivalent of 16 years overlapping data
G8260054	P14508	NT	Catchment area <20km^2
122004A	122004	QLD	11% missing flow data
122004A	122004	QLD	Insufficient events could be extracted
140002A	P40465	QLD	7 yrs overlapping data only
143032A	P40528	QLD	Also known as 533021; No overlapping data
145018A	540006	QLD	18 years overlapping data only
AW426558	AW426665	SA	3 yrs overlapping data only
AW503503	AW503529	SA	25% missing flow data; 63% missing pluvio data
AW503507	AW503507	SA	14 yrs overlapping data only; 14% missing flow data
AW504528	AW504563	SA	Zero flows from 1993 to end of record
AW505518	AW505537	SA	34% missing flow data
AW507502	AW507506	SA	Equivalent of 17yrs overlapping data; measures the reservoir level & associated storage volumes.
108	122	TAS	No data available
597	597	TAS	Catchment area <20km^2
629	91168	TAS	Lake in catchment

792	321	TAS	No data available
805	97008	TAS	2yrs of pluvio data only
1012	P94153	TAS	<1yr overlapping data only
1061	1024	TAS	No pluvio data available
1435	283	TAS	No flow data available
1457	91186	TAS	No flow data available
2208	P92093	TAS	6 years overlapping data only
6202	94137	TAS	Data not received/available
227225	P85263	VIC	4 years overlapping data only
229652	586021	VIC	27% missing pluvio data
229658	502264A	VIC	37% missing flow data
225020A	585056	VIC	15% missing flow data; 25% missing pluvio data
226017A	585001	VIC	70% missing flow data
226218A	226218A	VIC	16 yrs overlapping data only; 12% missing pluvio data
226410A	P85263	VIC	4 years overlapping data only
228207A	228207A	VIC	No data available
228233A	P86244	VIC	Approx. 1 year pluvio only
229218A	586051	VIC	7 yrs overlapping data only
231218B	P87075	VIC	Only 17 years useable flow data
233214A	233801A	VIC	17 yrs overlapping data only
234209A	234209A	VIC	18 years overlapping data only
235204A	P90083	VIC	Catchment area <20km^2
235216B	233803A	VIC	15 yrs overlapping data only
601005	512250	WA	27% missing flow data
601006	512235	WA	Catchment area <20km^2
609001	509184	WA	56% missing flow data; 21% missing pluvio data
609006	510039	WA	Catchment area <20km^2
610003	509064	WA	Uncertain data
610006	509191	WA	27% missing pluvio data
610007	509354	WA	Catchment area <20km^2
610008	509355	WA	16% missing flow data
610028	509191	WA	7 yrs overlapping data only; 27% missing pluvio data
612003	509177	WA	74% missing flow data
612005	509111	WA	Catchment area <20km^2
612012	509202	WA	Catchment area <20km^2
612016	509321	WA	Catchment area <20km2
612019	509356	WA	19 years overlapping data only
613007	509115	WA	Catchment area <20km^2
613014	509369	WA	21% missing flow data
613018	509368	WA	28% missing flow data; 28% missing pluvio data
613146	509227	WA	Catchment area <20km^2
614028	509135	WA	Dirk Bk already used - 614005
614123	509082	WA	9 years overlapping data only
615011	510038	WA	16 yrs overlapping data only
616007	509154	WA	12 yrs overlapping data only
616009	509159	WA	16% missing flow data; 18% missing pluvio data

616010	509155	WA	16% missing flow data; 17% missing pluvio data
616023	509271	WA	Catchment area <20km2
616041	509269	WA	Difficulties with quality codes/streamflow
617165	509153	WA	17% missing flow data
803003	503006	WA	14% missing pluvio data
806003	501003	WA	11% missing pluvio data
410736	570999	ACT	
210068	P61238	NSW	
401571	P72060	NSW	
410114	410114	NSW	
AW503502	AW503504	SA	
AW504525	AW504563	SA	
232210A	232223A	VIC	
602003	510601	WA	
602005	509353	WA	
603005	509453	WA	
603013	509439	WA	
606002	509413	WA	
609004	509259	WA	
609008	509259	WA	
615017	510048	WA	
616012	509157	WA	

Appendix B Catchment maps



Legend

Gauge Location
Catchment Boundary
Rainfall Gauge

Pluviograph Stations

Bureau of Meteorology
Other Sources
Watercourse
Waterbody
Built-Up Areas

DATA SOURCES
This document incorporates data which is:
Landsat Imagery (2002)
Bureau of Meteorology - Pluviograph Station Locations

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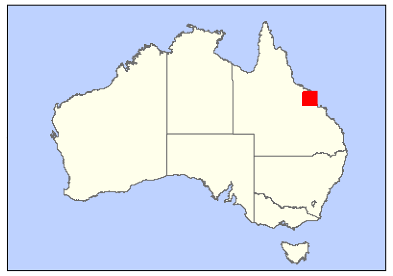
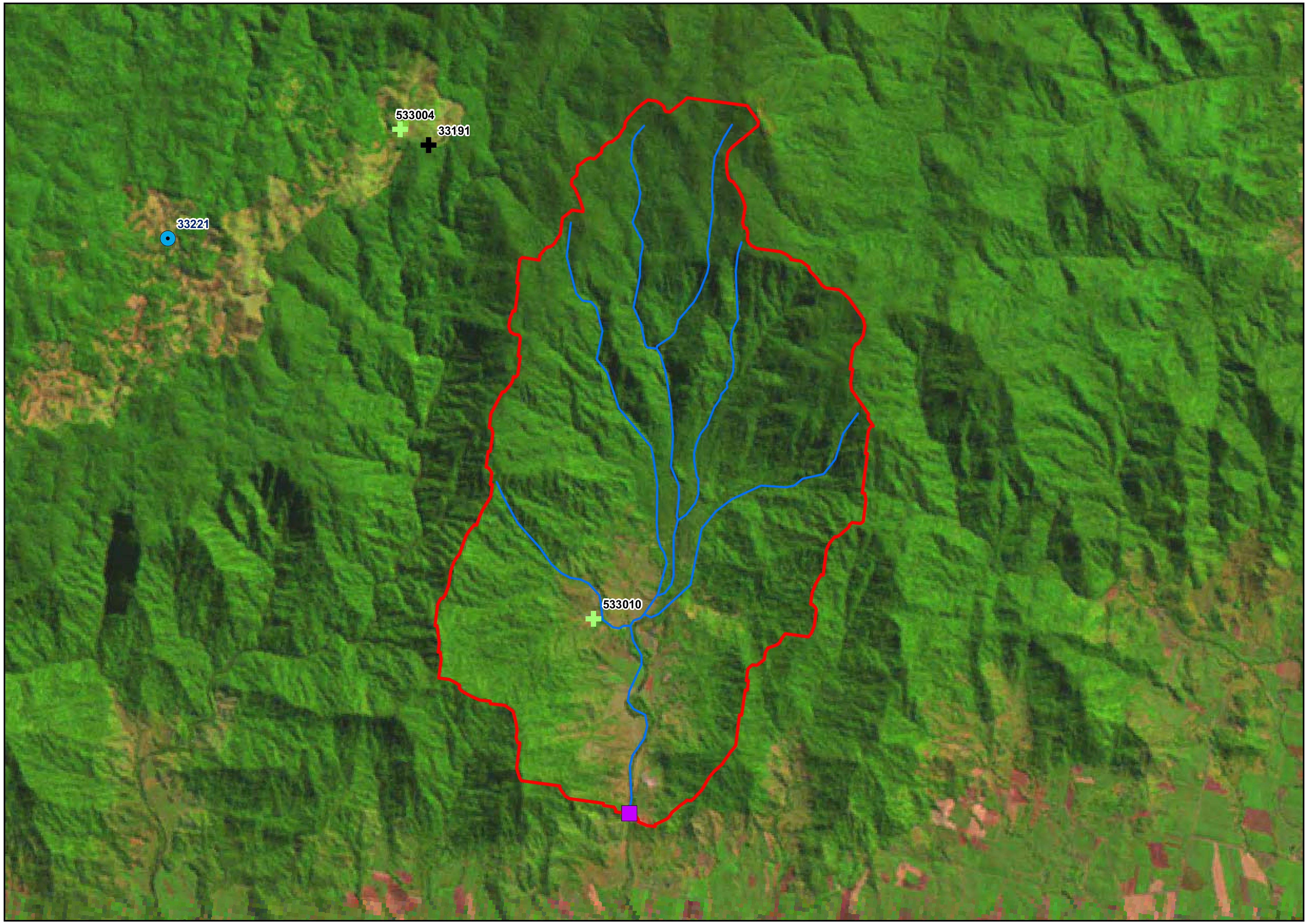


120216A; Broken River @ Old Racecourse



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

DATA SOURCES
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Bureau of Meteorology - Pluviograph Station Locations

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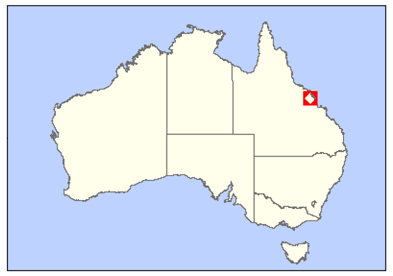
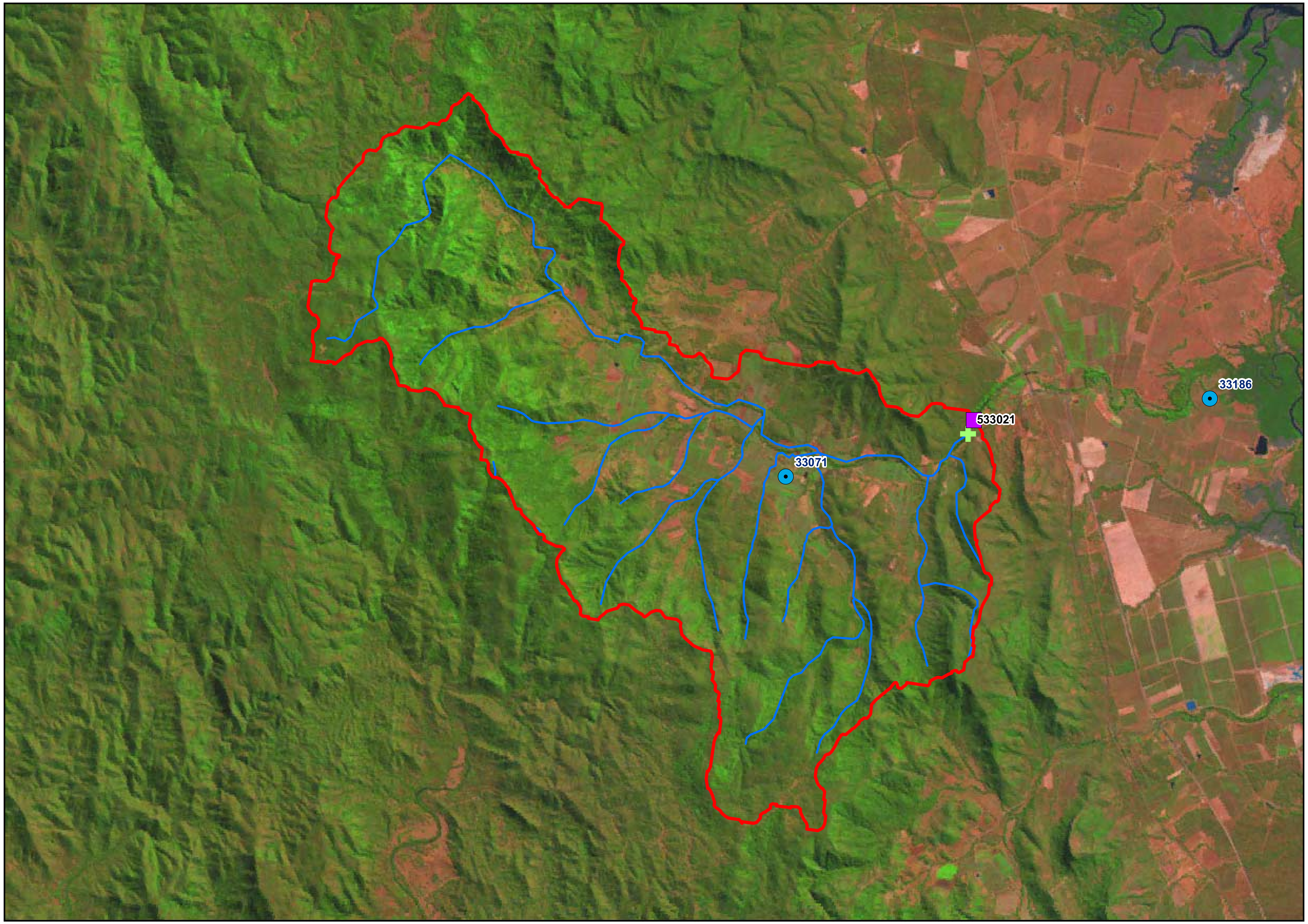


125006; Finch Hatton Creek @ Finch Hatton Creek



Legend
Gauge Location
Catchment Boundary
Rainfall Gauge
Pluviograph Stations
Bureau of Meteorology
Other Sources
Watercourse
Waterbody
Built-Up Areas

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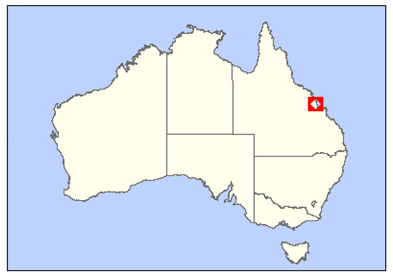
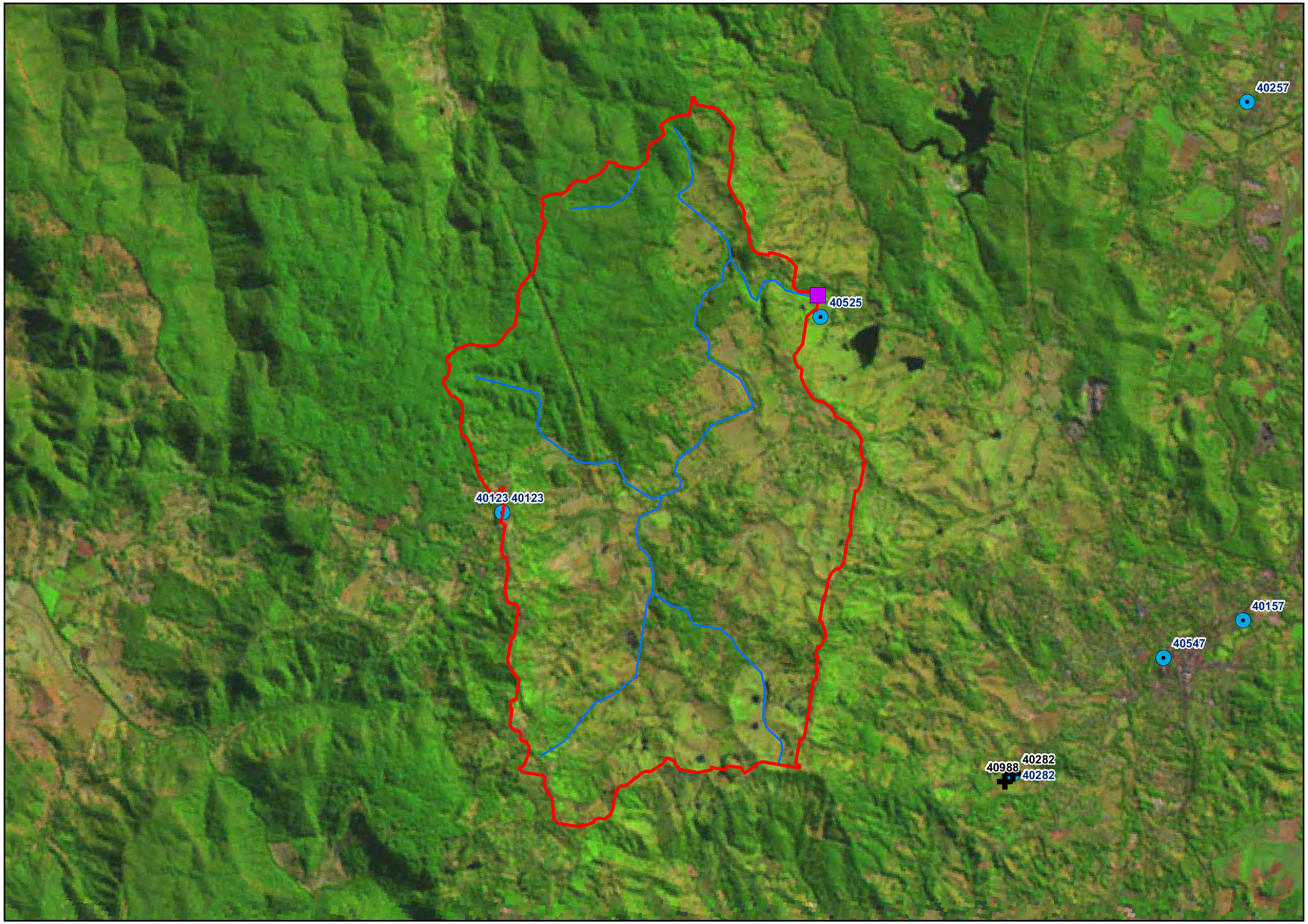


126003A; Carmila Creek @ Carmila



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

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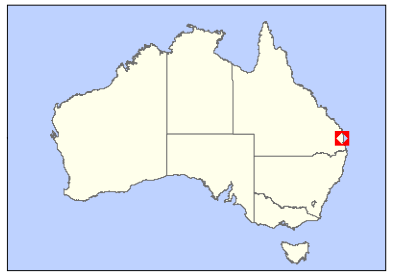
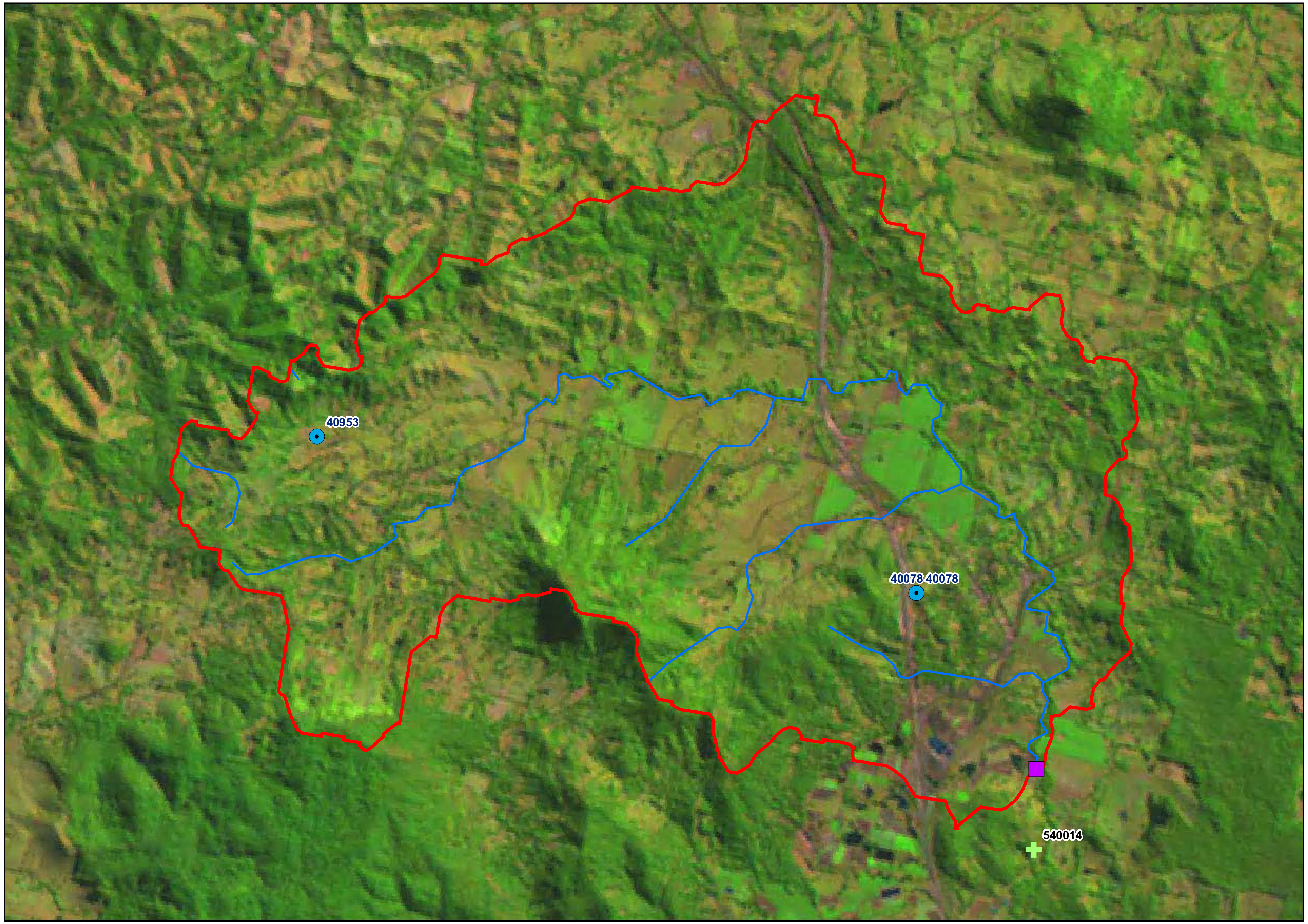


141001B; South Maroochy River @ Kiamba



Legend

- Gauge Location
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- Rainfall Gauge

Pluviograph Stations

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- Built-Up Areas

[GDA94 | MGA55]

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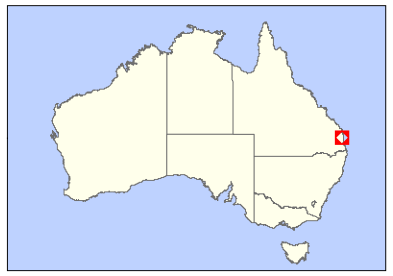
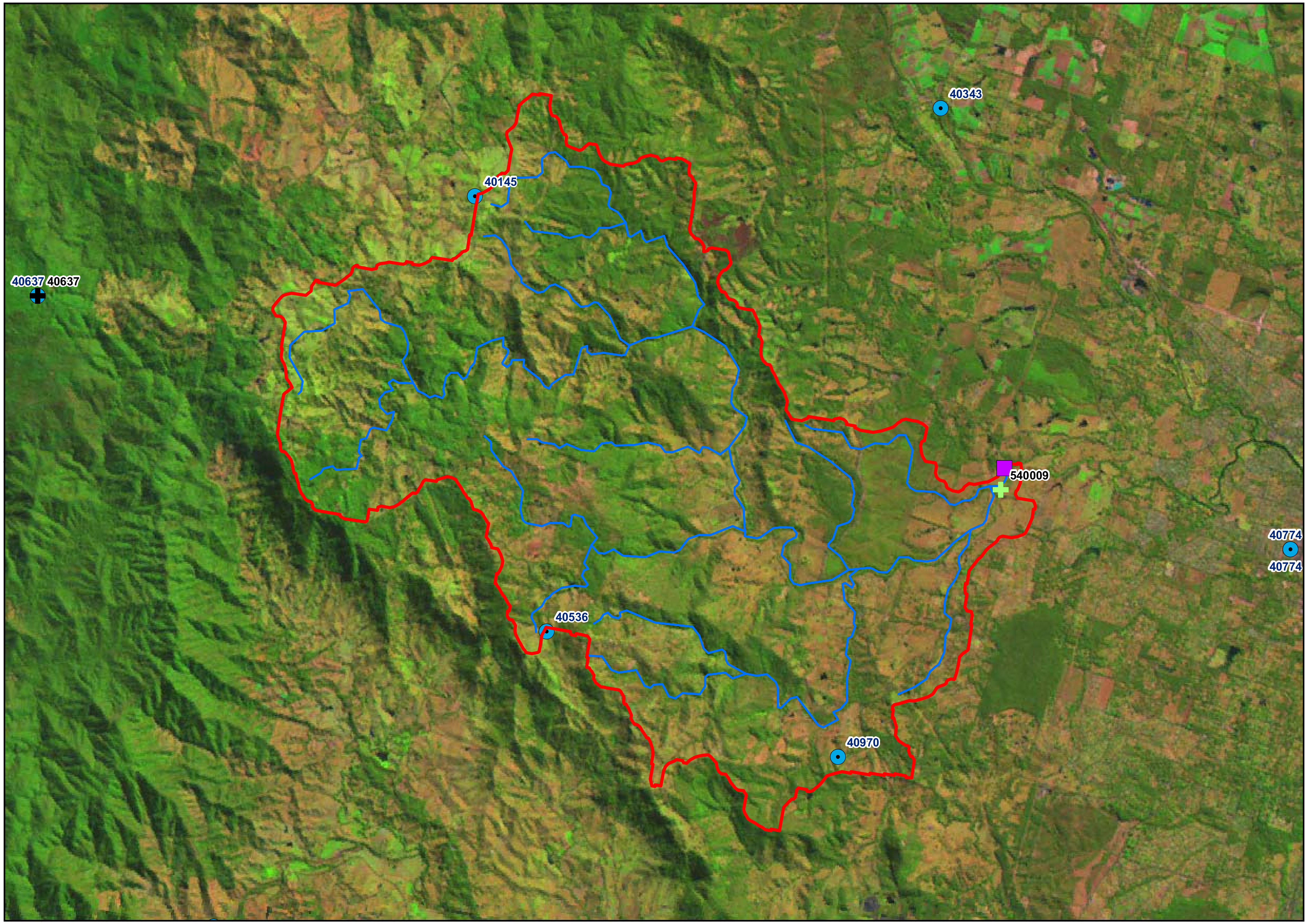


141009; N. Maroohy River @ Eumundi



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
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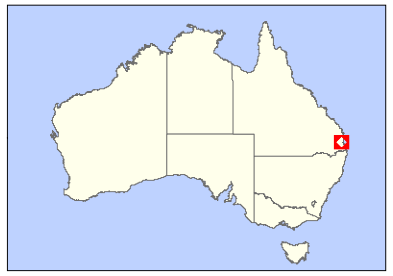
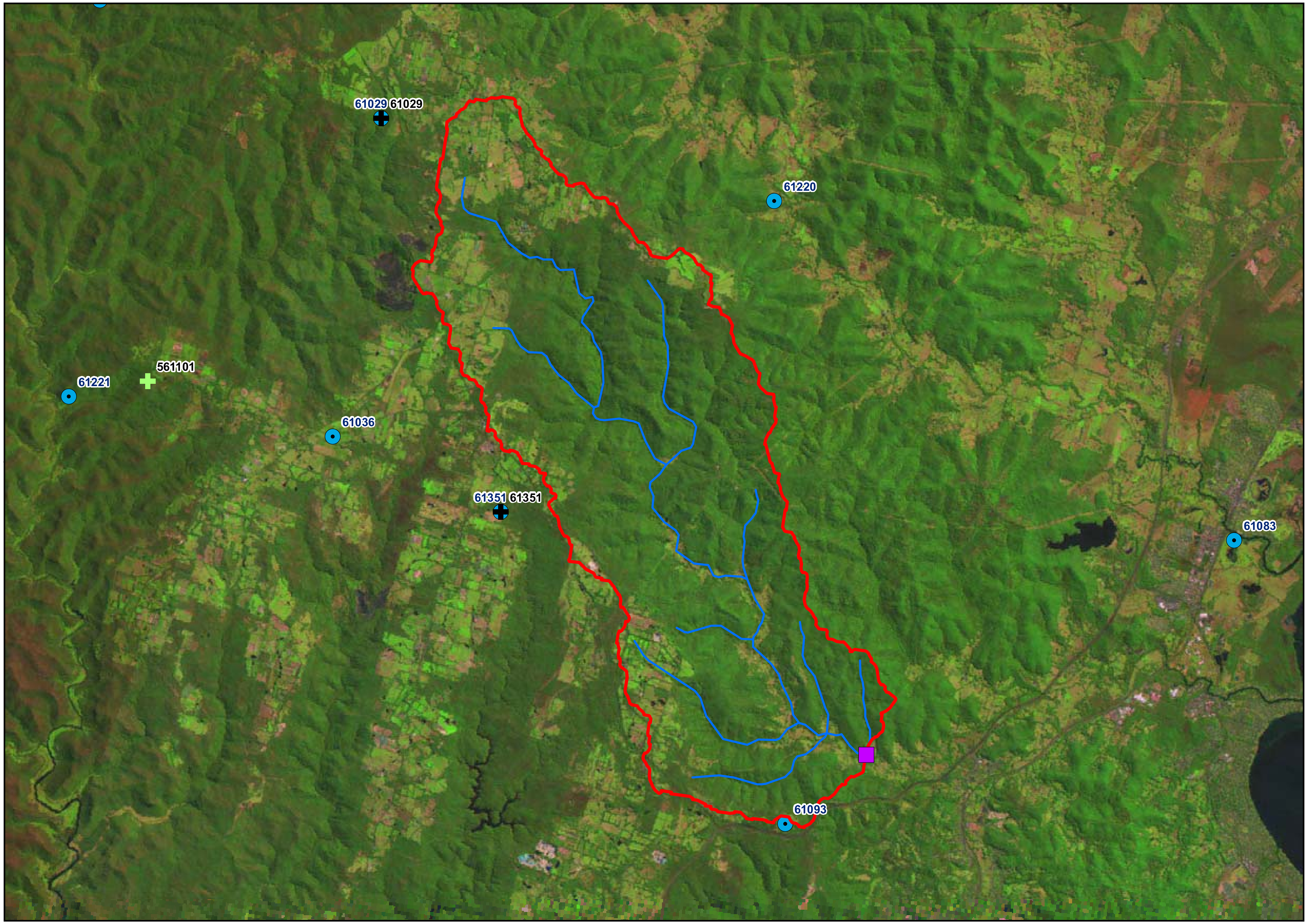


142001A; Caboolture River @ Upper Caboolture

SKM



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

[GDA94 | MGA55]

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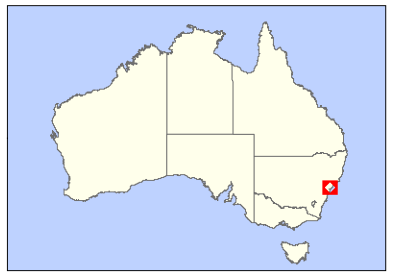
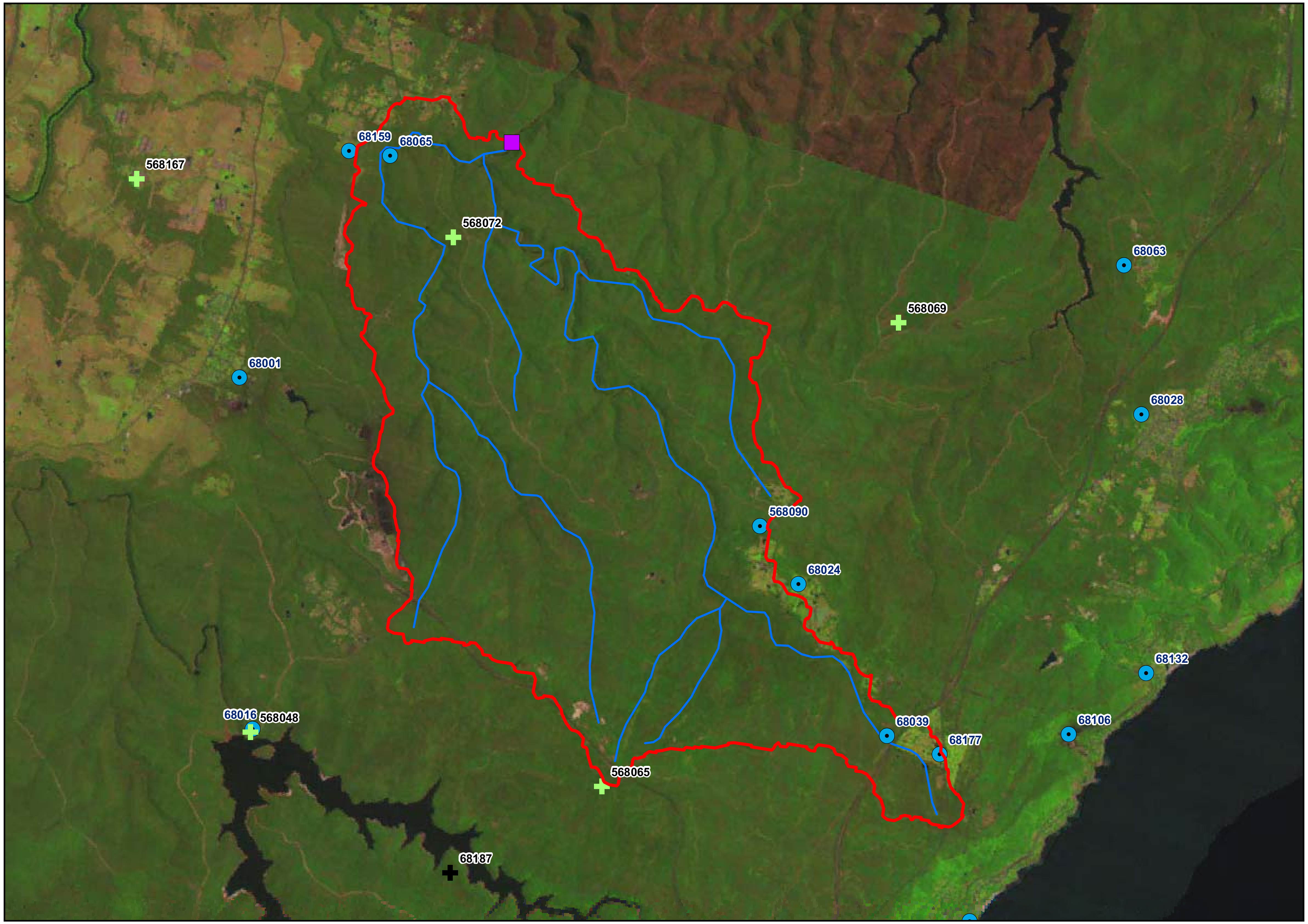


211013; Ourimbah Creek @ U/S Weir

SKM



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

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- Waterbody
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[GDA94 | MGA55]

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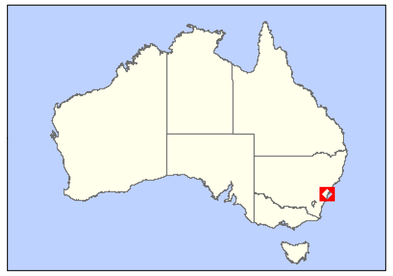
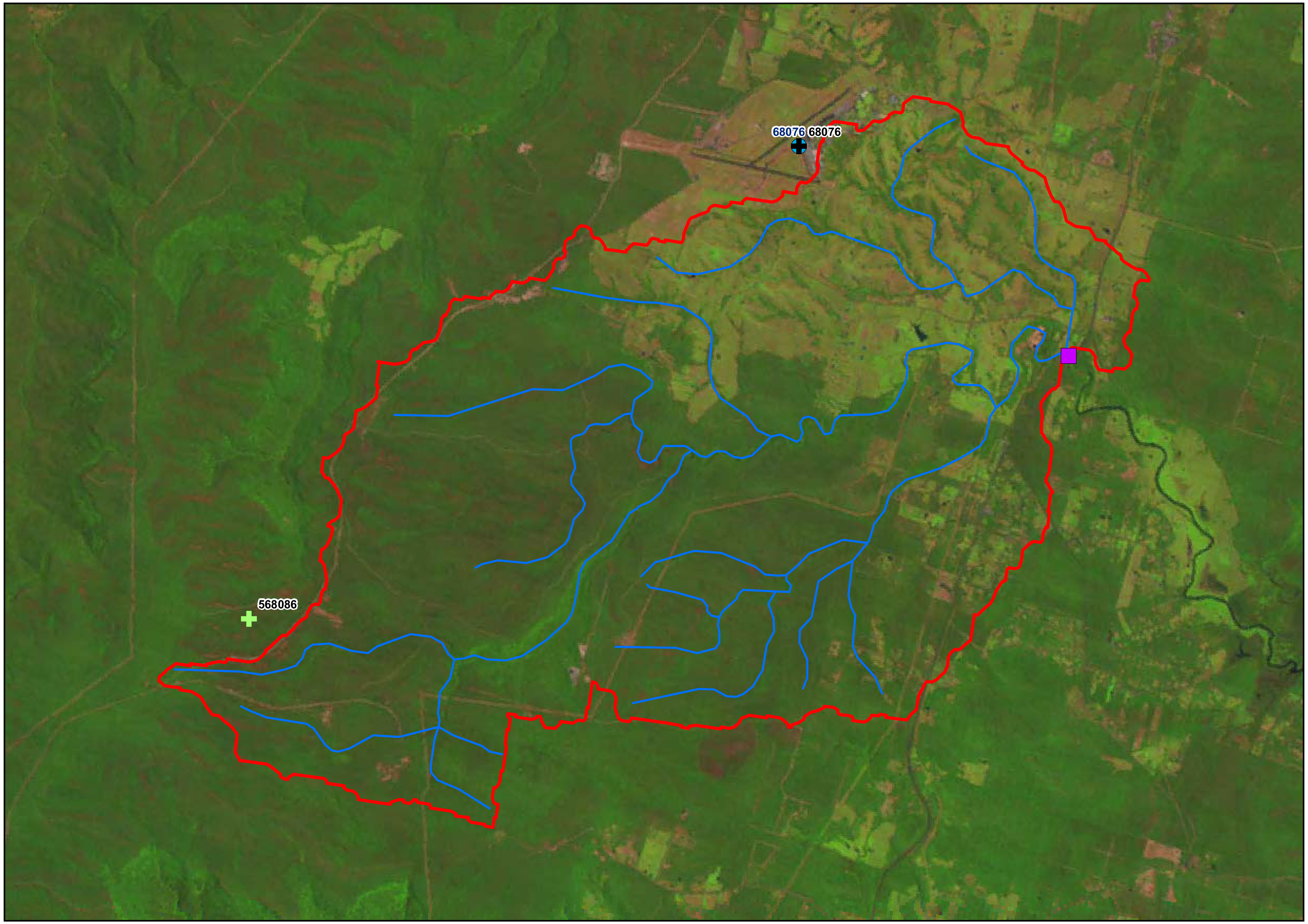


213200; O'Hares Creek @ Wedderburn

SKM



Legend

Gauge Location
Catchment Boundary
Rainfall Gauge

Pluviograph Stations

Bureau of Meteorology
Other Sources
Watercourse
Waterbody
Built-Up Areas

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[GDA94 | MGA55]

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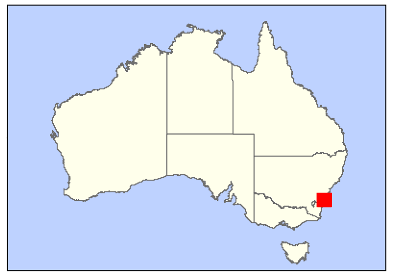
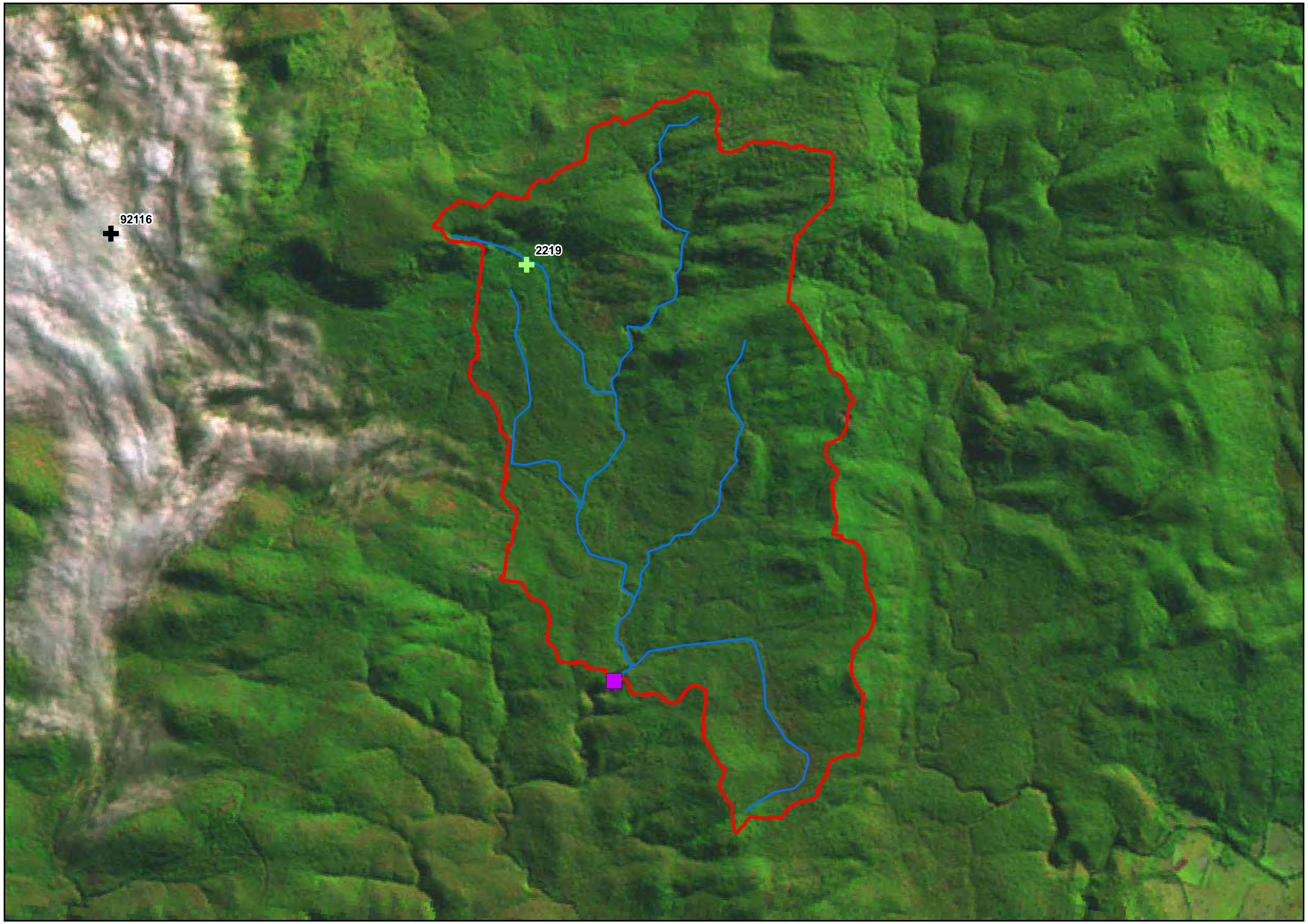


216004; Currambene Creek @ Falls Ck



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

[GDA94 | MGA55]

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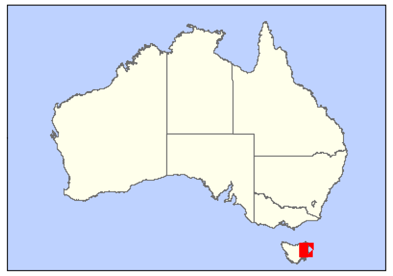
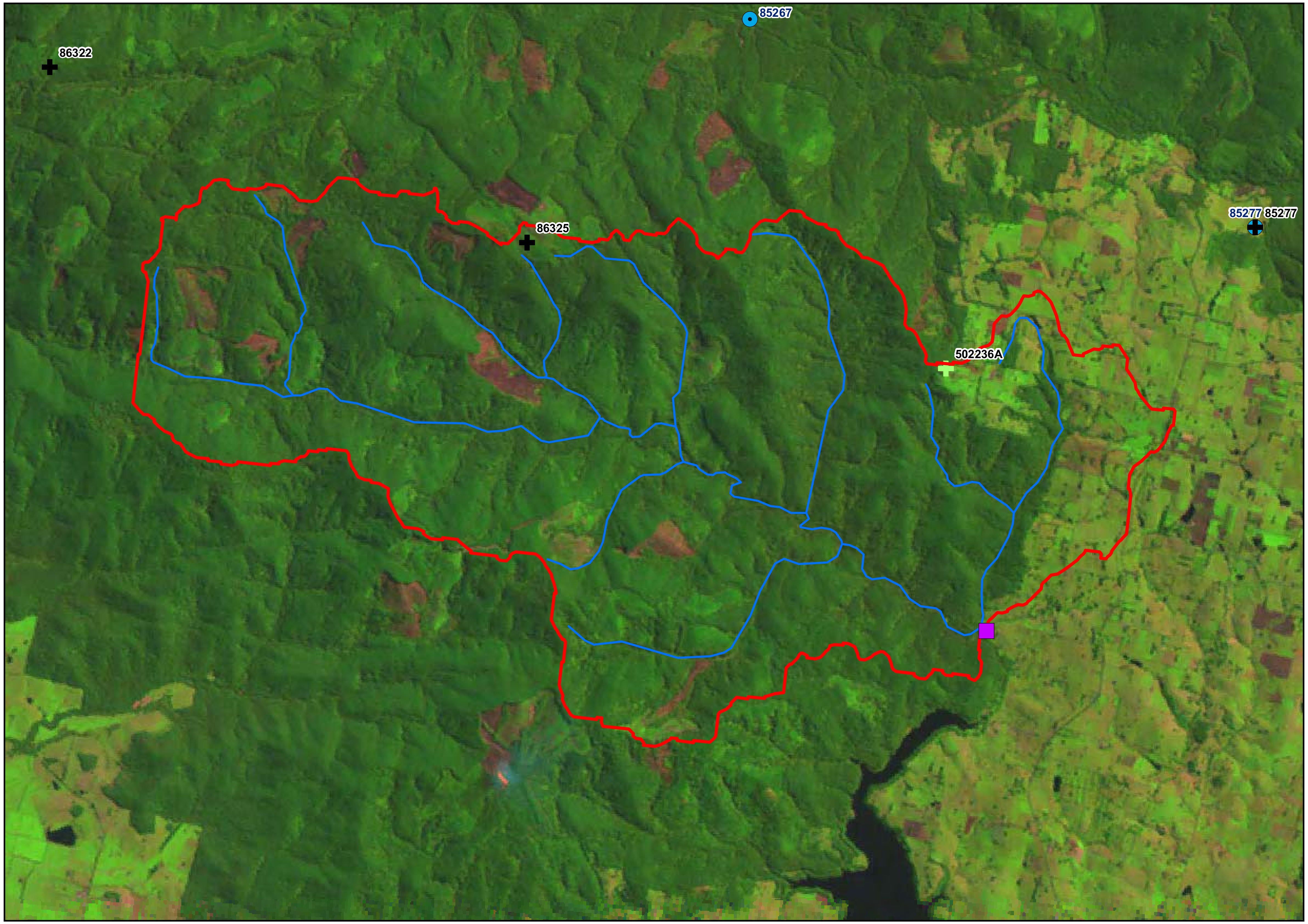


2219; Swan River u/s Hardings Falls



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

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[GDA94 | MGA55]

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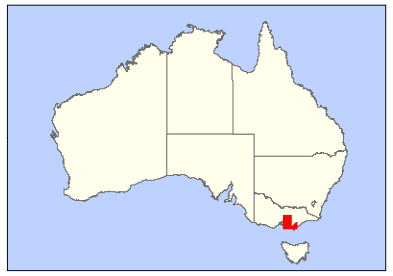
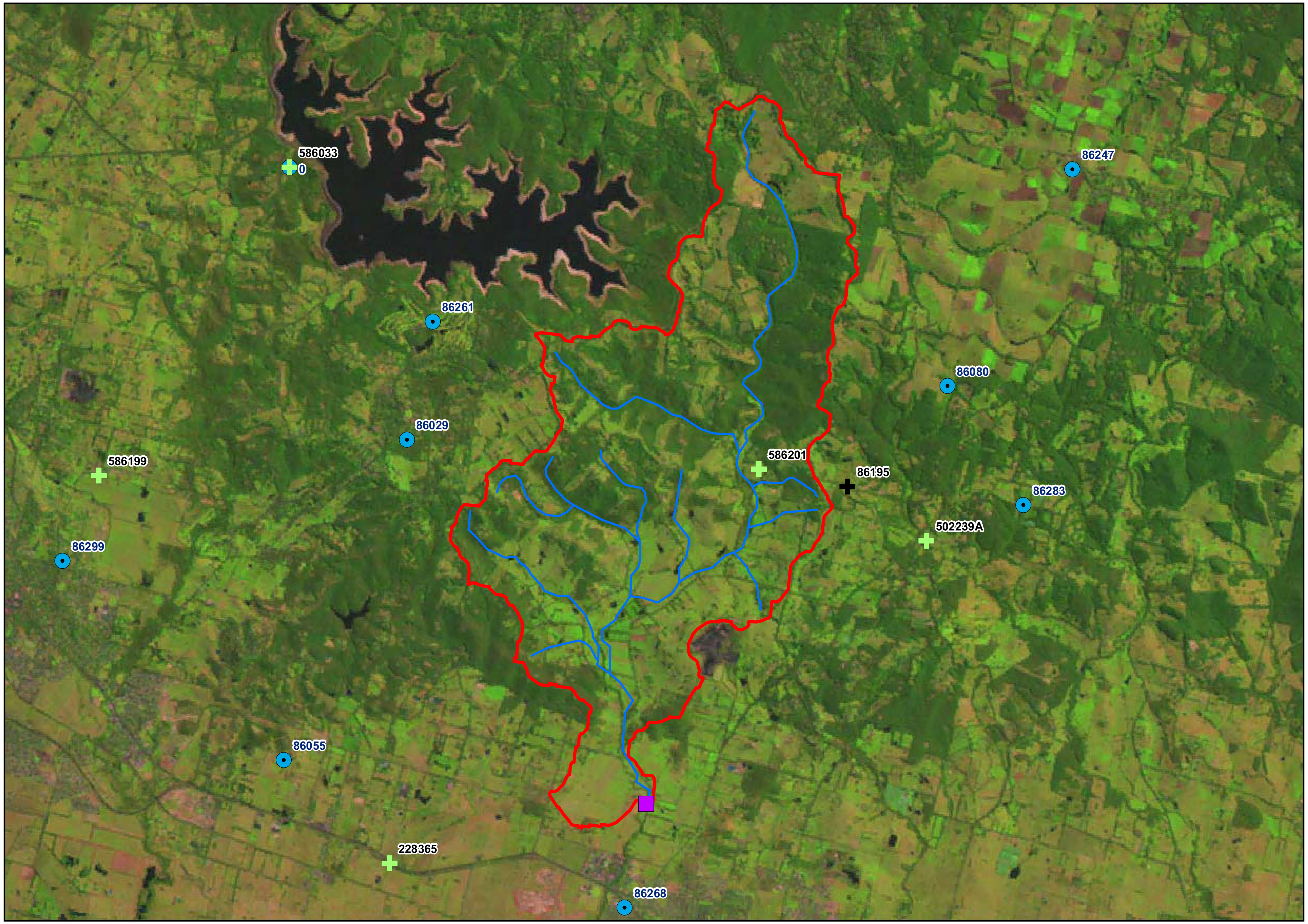


228206B; Tarago River @ Neerim



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

[GDA94 | MGA55]

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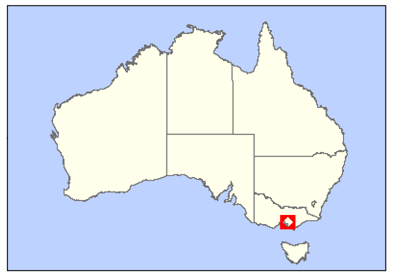
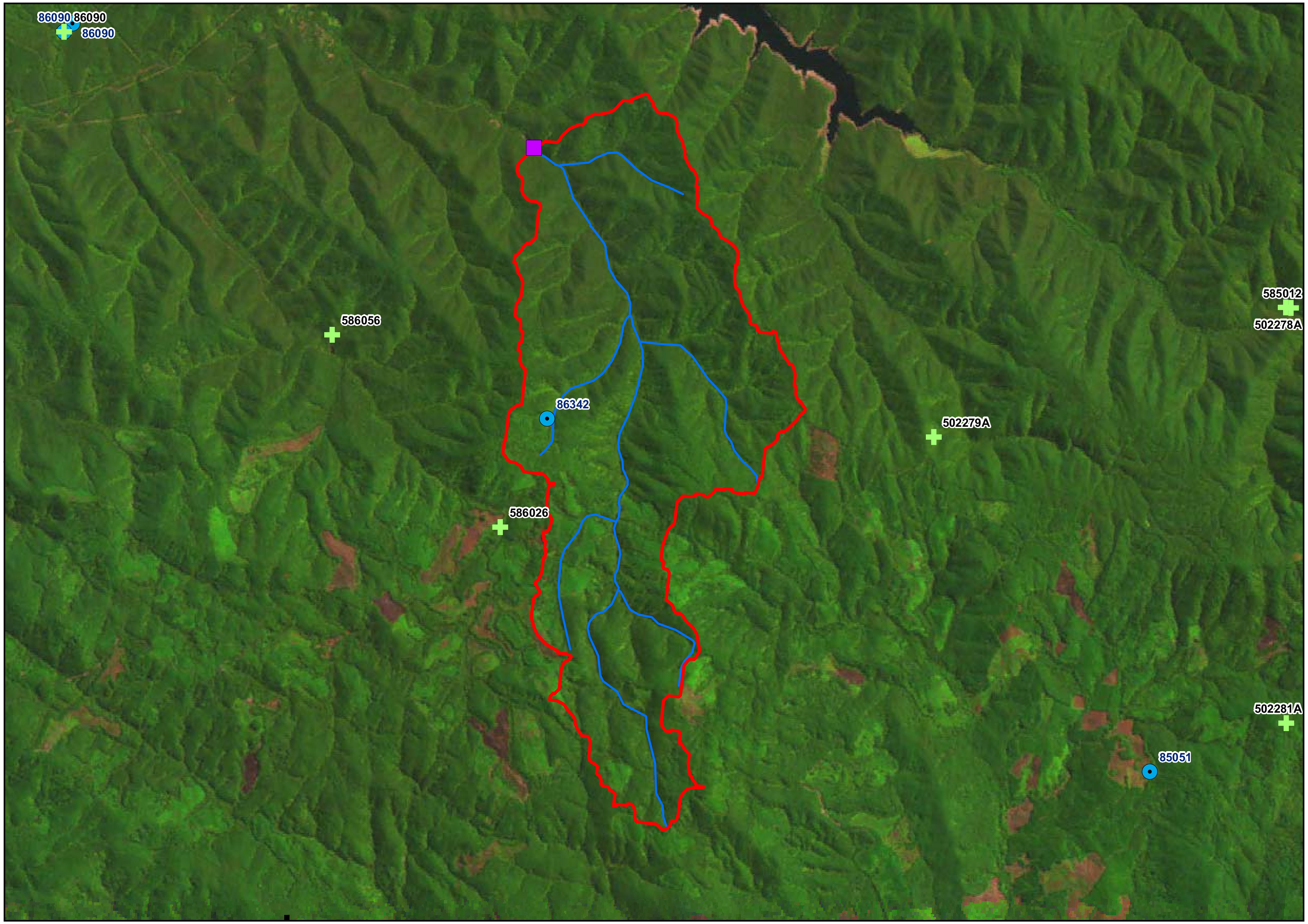


228217; Toomuc Creek @ Pakenham



Legend

Gauge Location
Catchment Boundary
Rainfall Gauge

Pluviograph Stations

Bureau of Meteorology
Other Sources
Watercourse
Waterbody
Built-Up Areas

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[GDA94 | MGA55]

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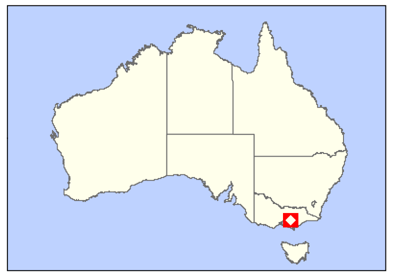
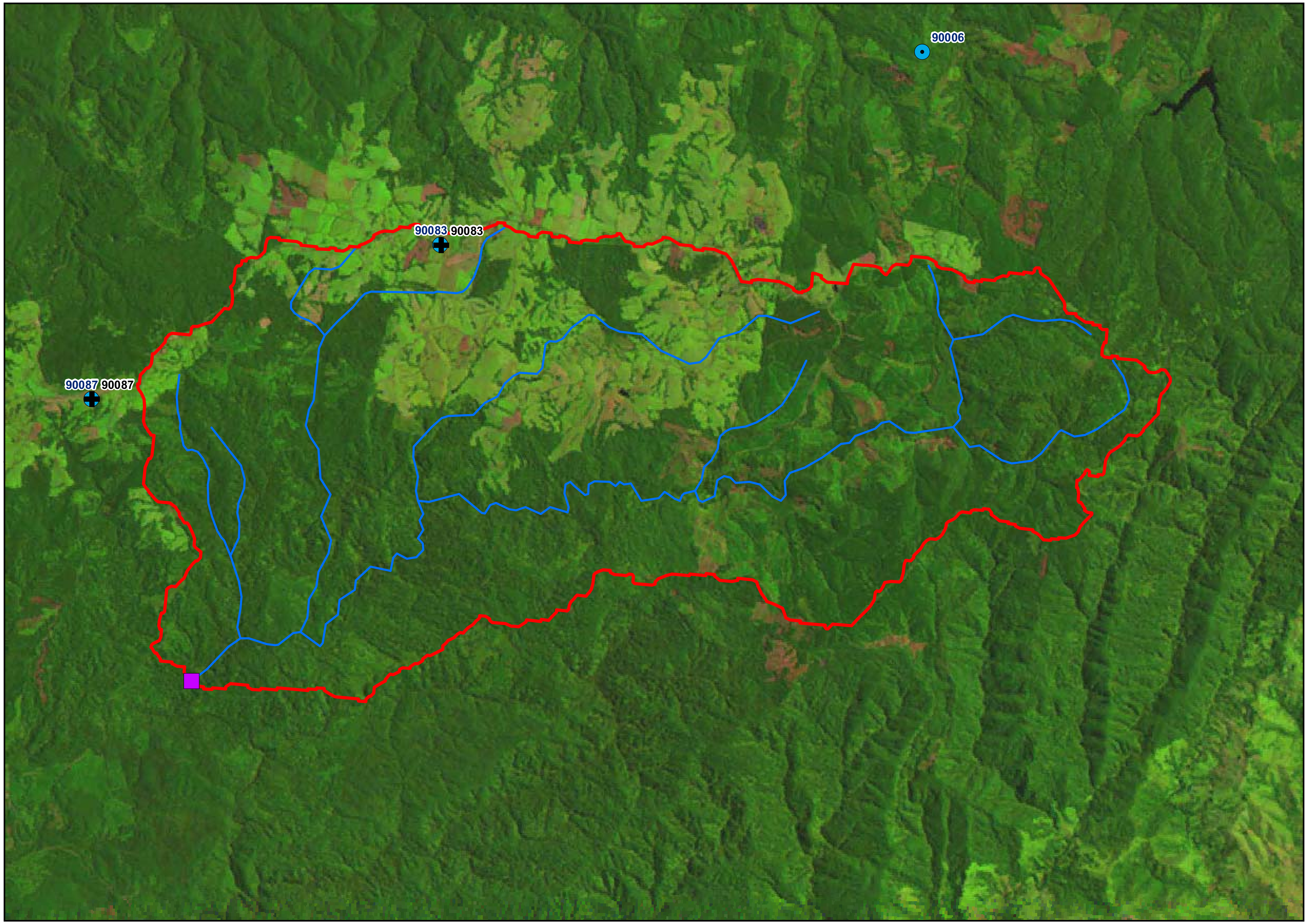


229106; McMahons Creek @ Upstreams Weir



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
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[GDA94 | MGA55]

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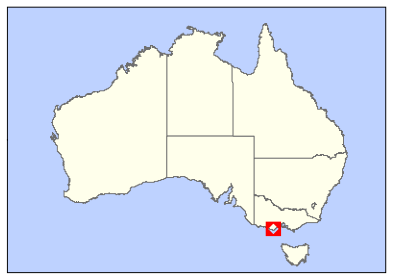
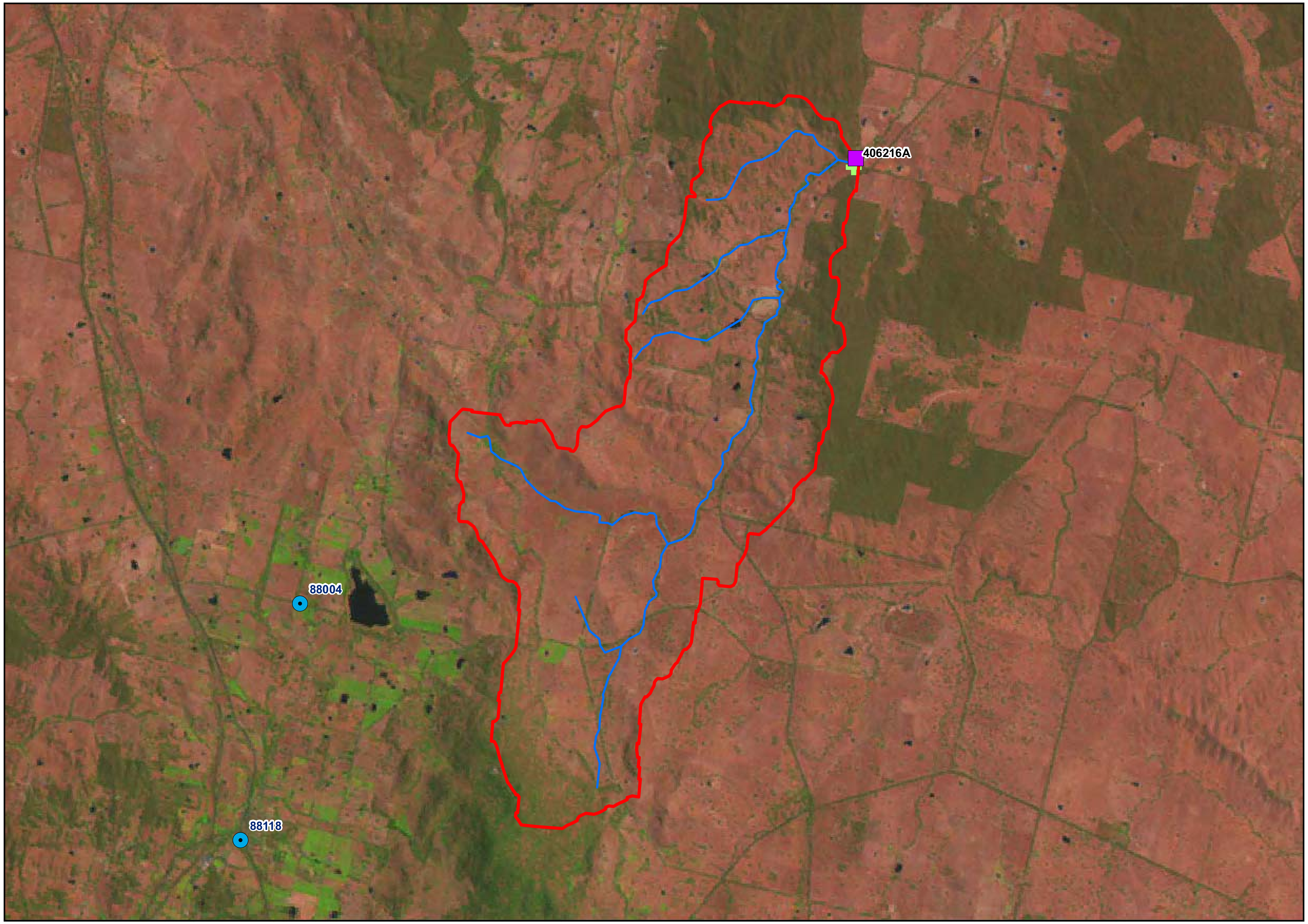


235219A; Aire @ Wyelangta



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

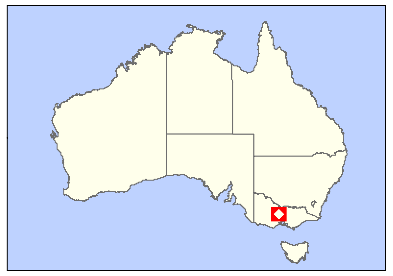
Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

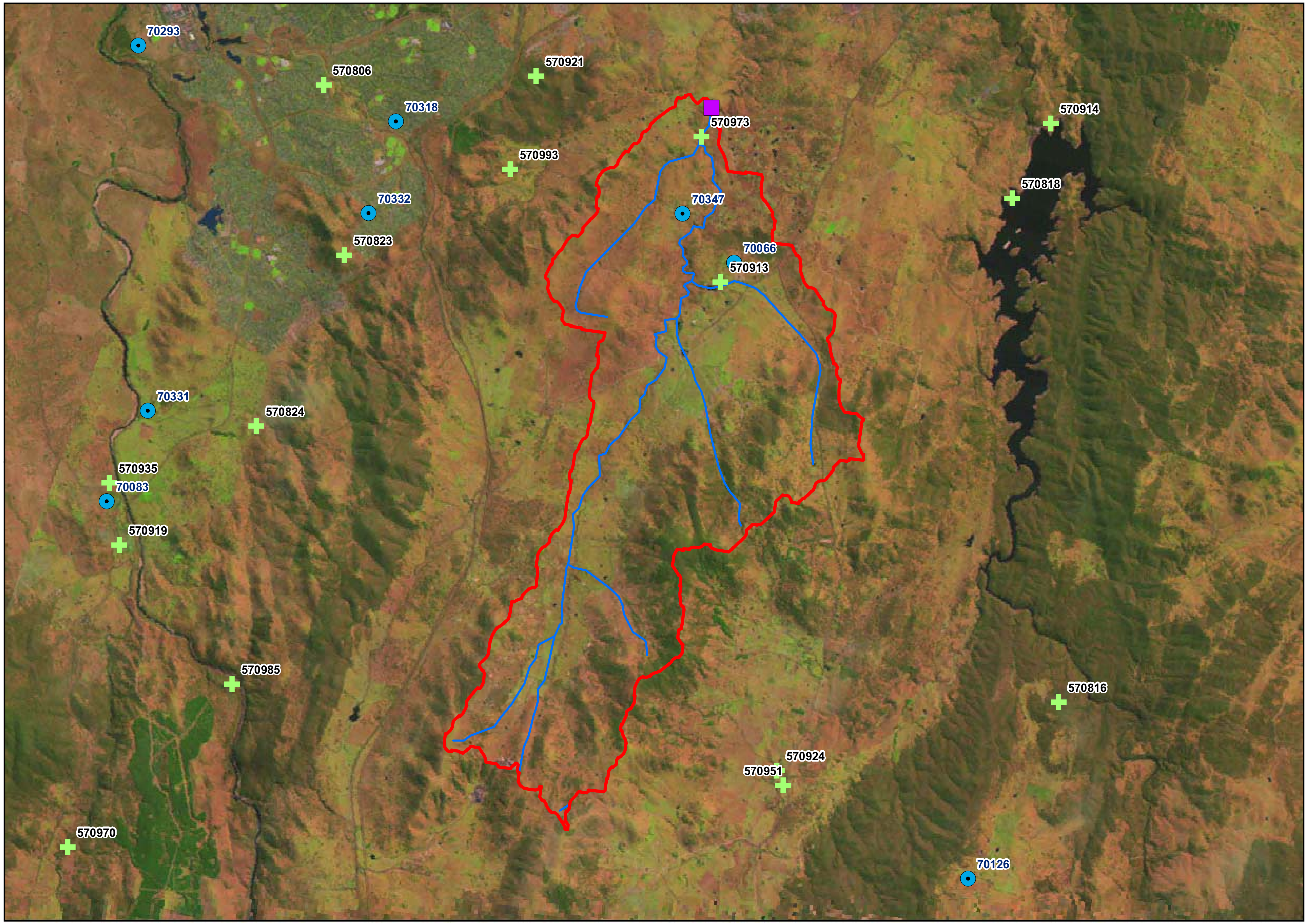
DATA SOURCES
This document incorporates data which is:
Landsat Imagery (2002)
Bureau of Meteorology - Pluviograph Station Locations

[GDA94 | MGA55]

0 1,280
Meters



406216A; Axe Creek @ Sedgewick



Legend

Gauge Location
Catchment Boundary
Rainfall Gauge

Pluviograph Stations

Bureau of Meteorology
Other Sources
Watercourse
Waterbody
Built-Up Areas

[GDA94 | MGA55]

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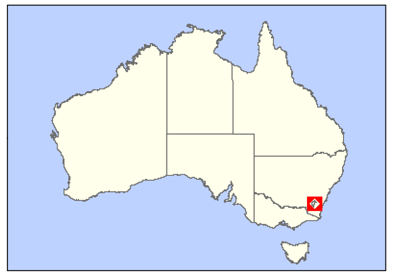
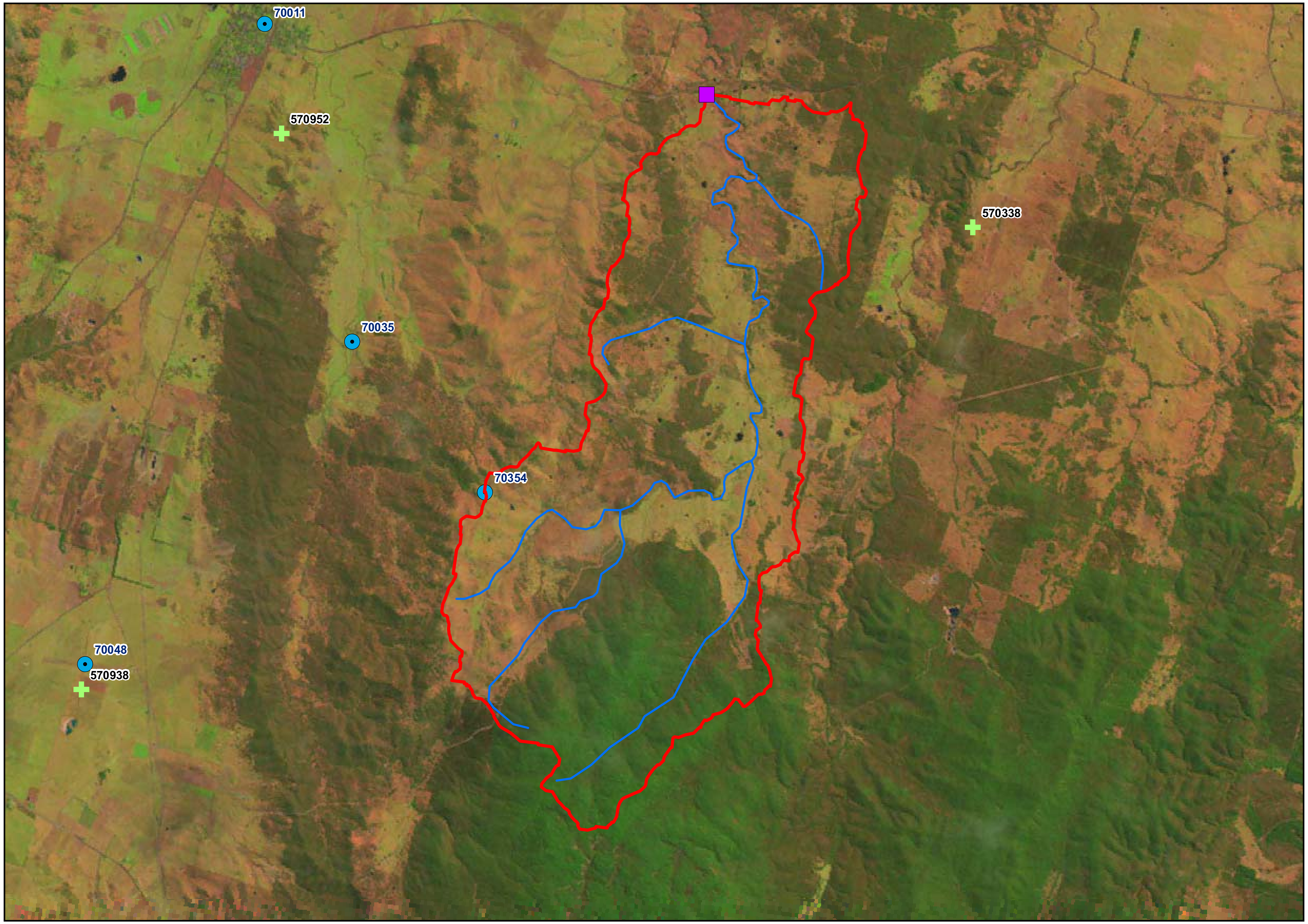


410743; Jerrabomberra Creek @ Four Mile Creek



DATA SOURCES
This document incorporates data which is:
Landsat Imagery (2002)
Bureau of Meteorology - Pluviograph Station Locations

[GDA94 | MGA55]

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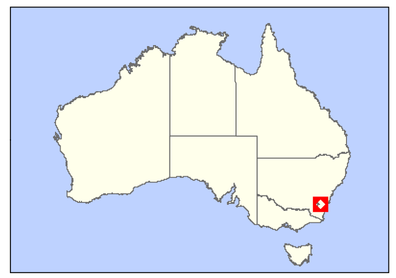
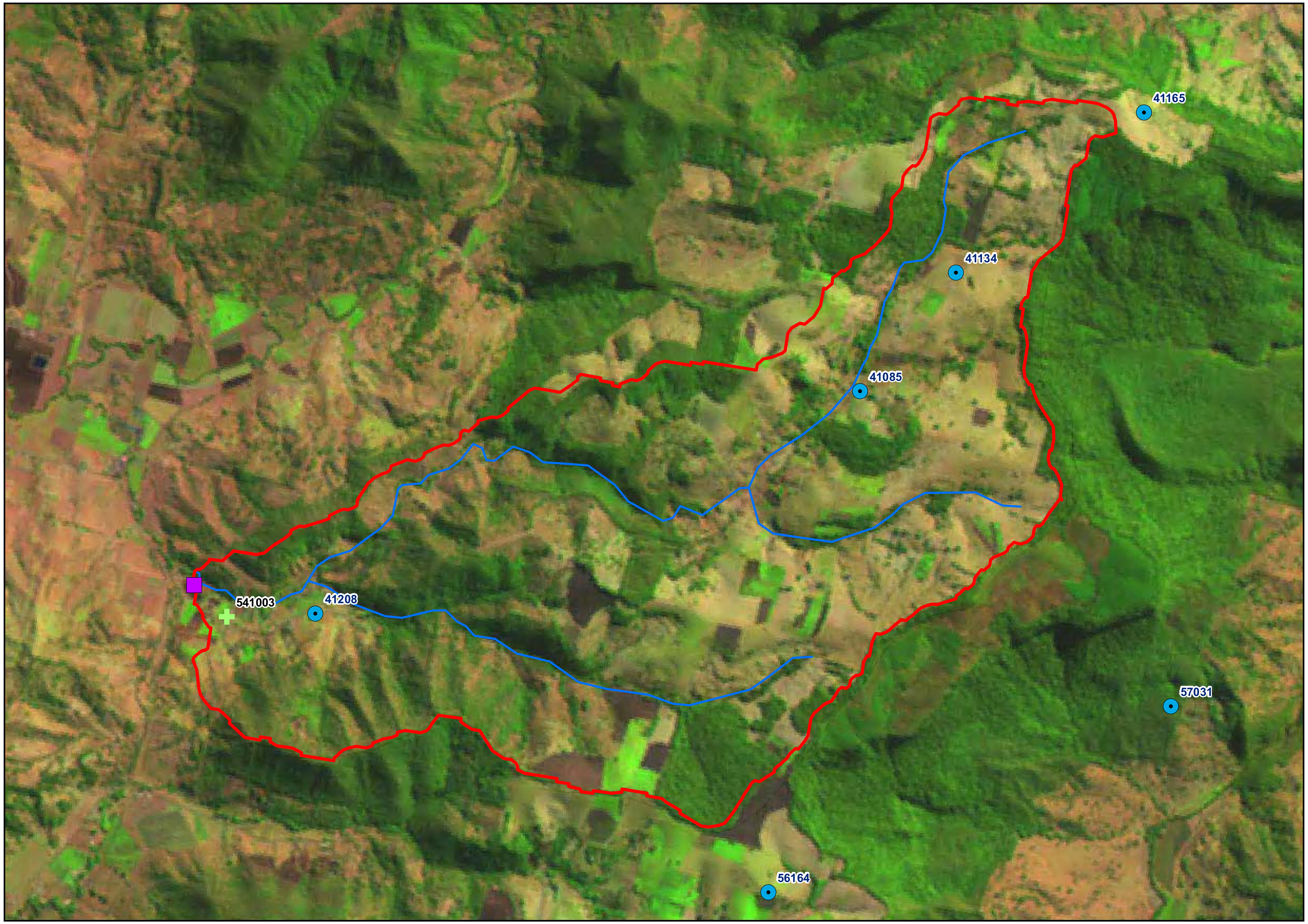
Meters



411003; Butmaroo Creek @ Butmaroo

SKM



Legend

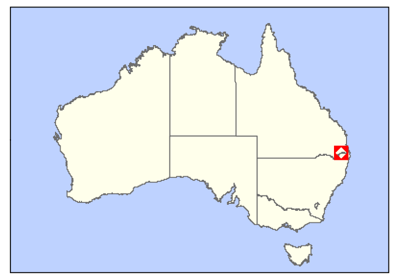
- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

[GDA94 | MGA55]

0 880
Meters



422321; Spring Creek @ Killarney

SKM

Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
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- Built-Up Areas

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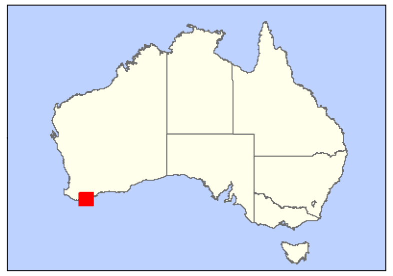
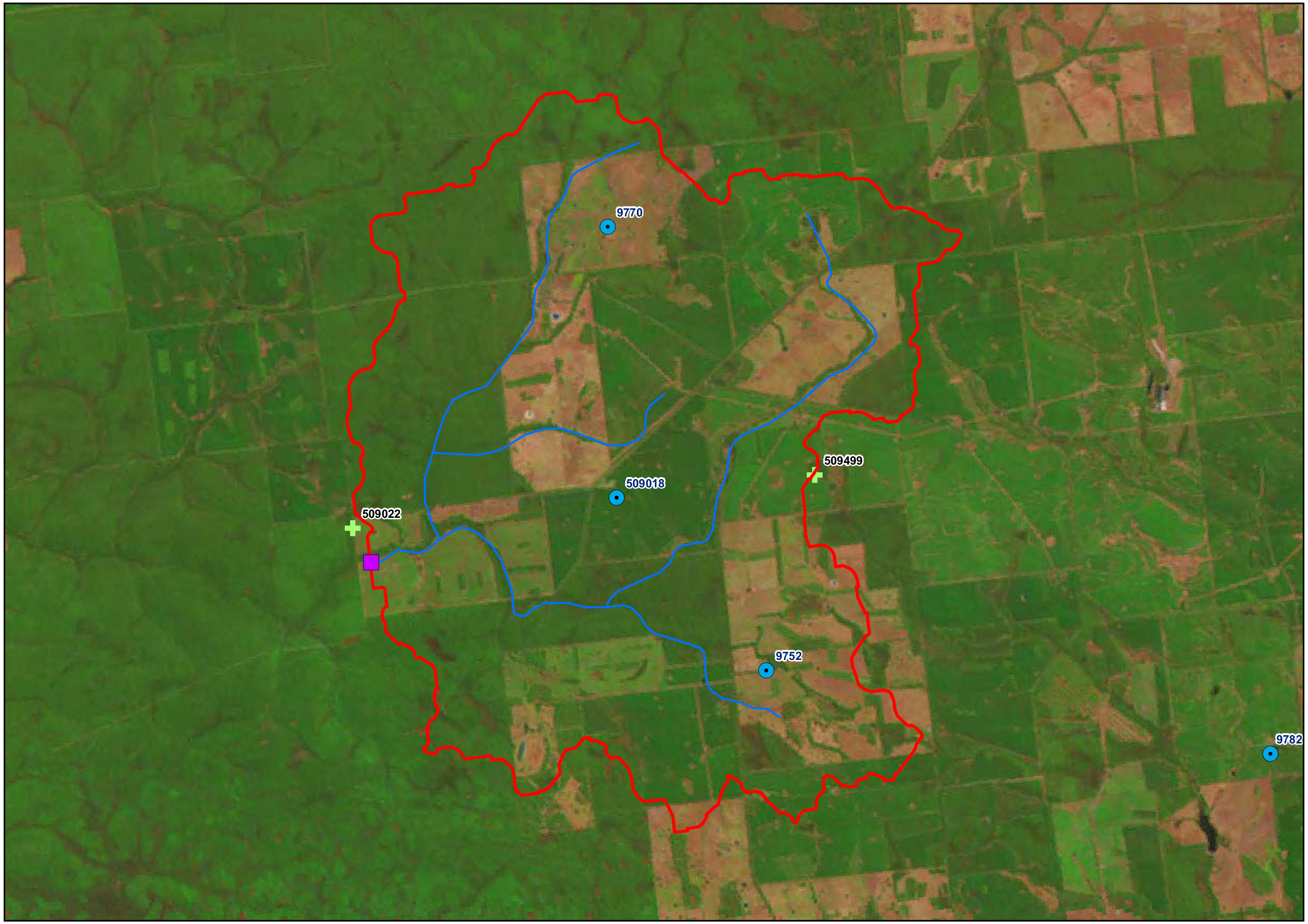
[GDA94 | MGA55]

0 1,040
Meters



602199; Goodga River @ Black Cat



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

DATA SOURCES
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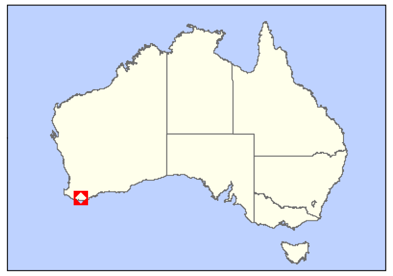
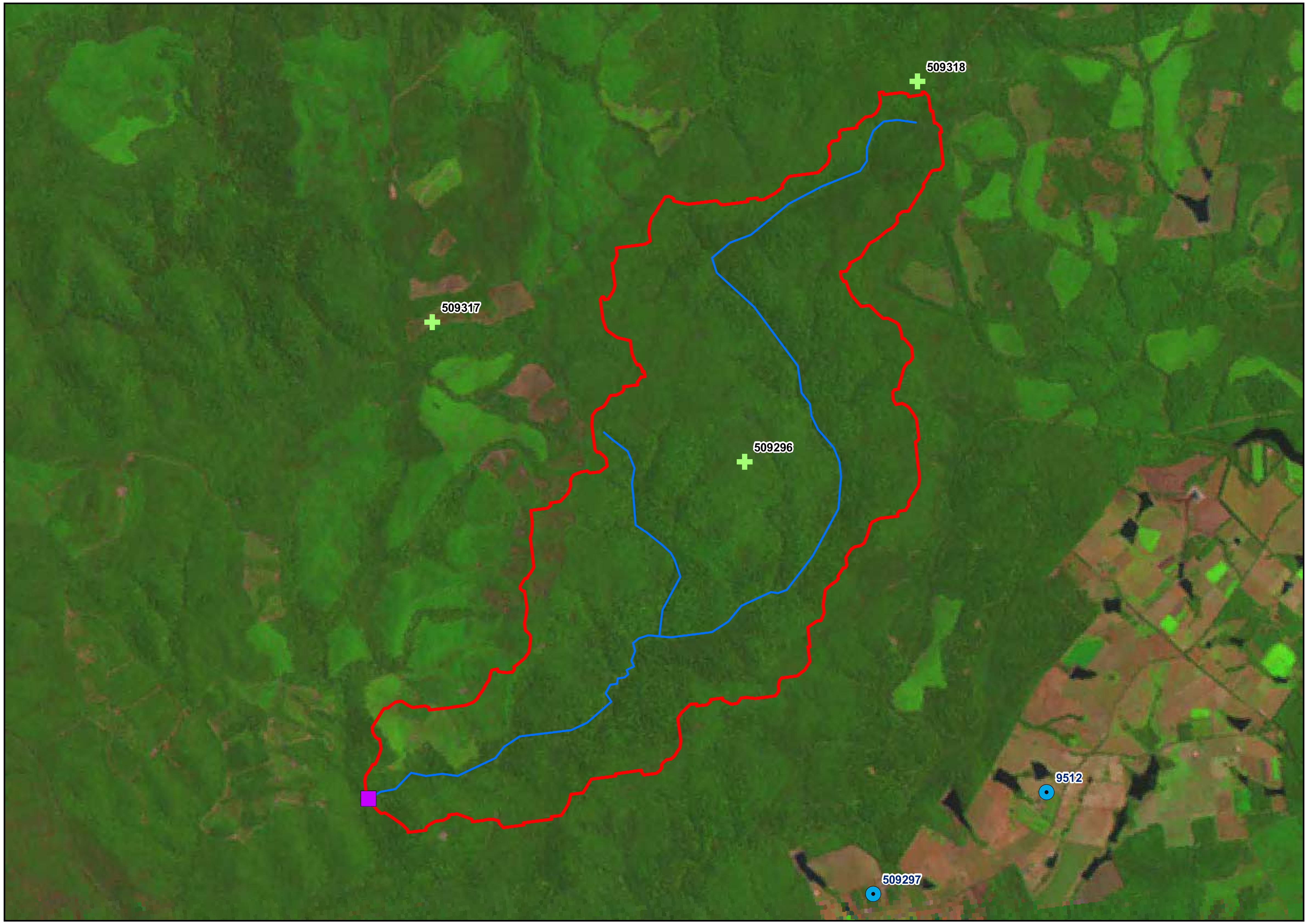
[GDA94 | MGA55]

0 1,100
Meters



603190; Yates Flat Creek @ Yates Flat Creek



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

DATA SOURCES
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Bureau of Meteorology - Pluviograph Station Locations

[GDA94 | MGA55]

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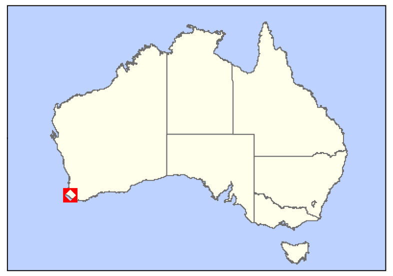
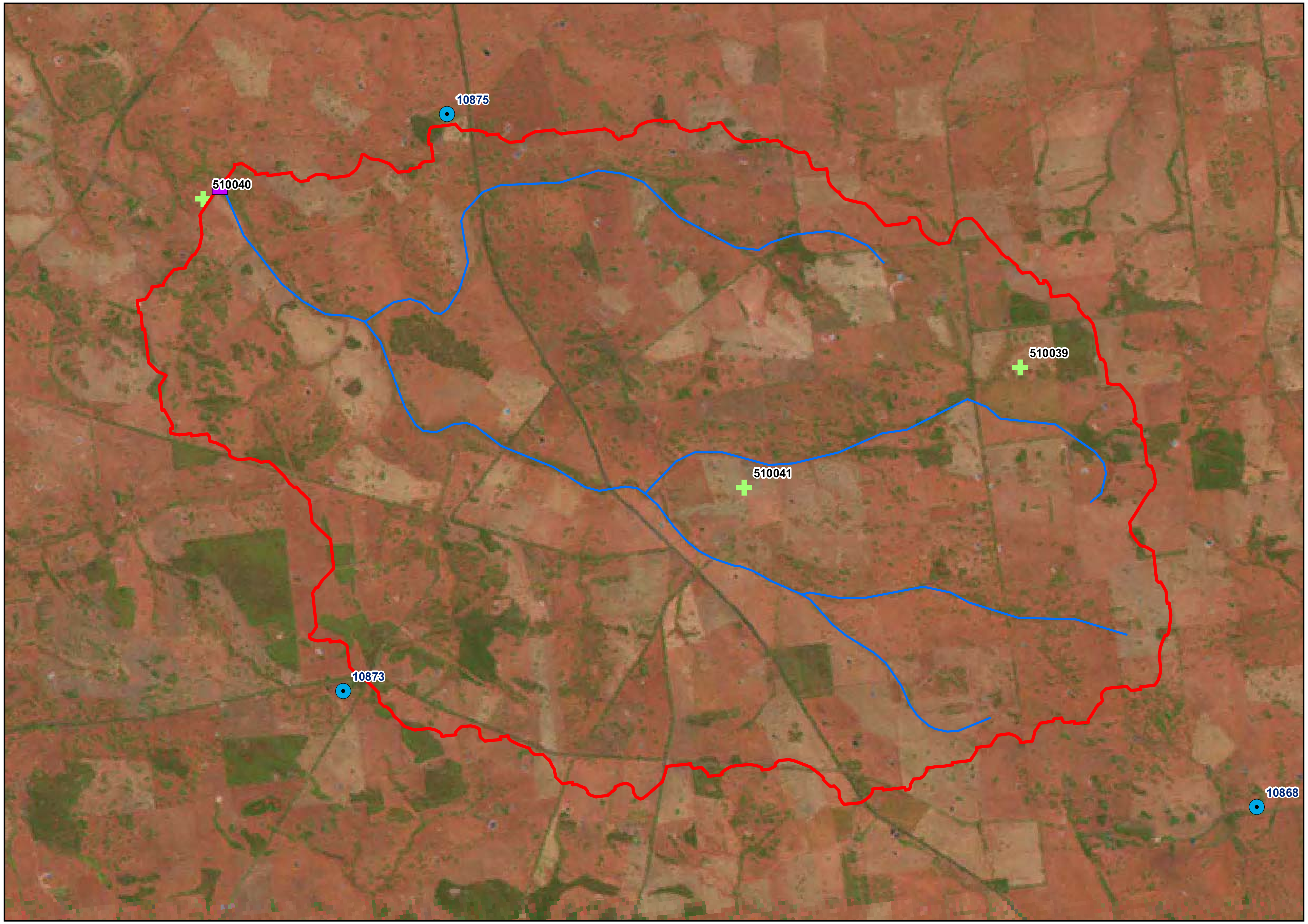
Meters



608002; Carey Brook @ Staircase Rd

SKM



Legend
- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations
- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

DATA SOURCES
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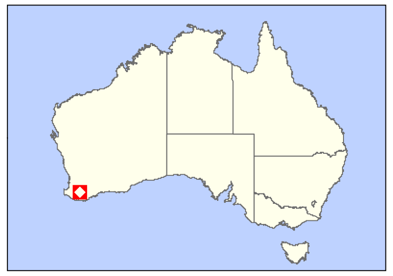
Bureau of Meteorology - Pluviograph Station Locations

[GDA94 | MGA55]

0 1,000
Meters



609005; Balgarup River @ Mandelup Pool

Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

[GDA94 | MGA55]

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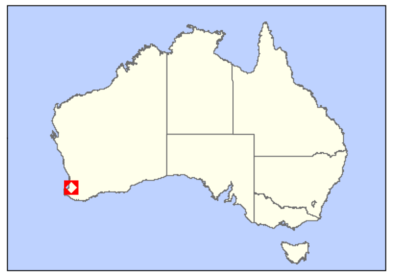
Meters



612004; Hamilton River @ Worsley

SKM

October 22, 2013 | II:\VWES\Projects\VW07245\Technical\Spatial\ArcGIS\VW07245_FinalCatchmentMaps_v2.mxd
Prepared by : SI
Checked by : ZG

Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

DATA SOURCES
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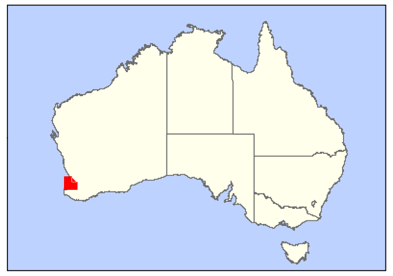
Bureau of Meteorology - Pluviograph Station Locations

[GDA94 | MGA55]

0 1,000
Meters



614003; Marrinup Brook @ Brookdale Siding

Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

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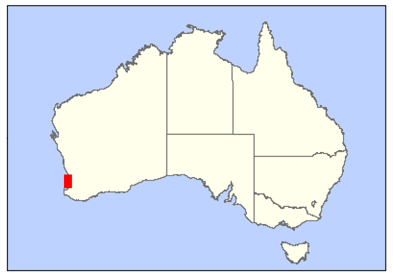
[GDA94 | MGA55]

0 760
Meters



614005; Dirk Brook @ Kentish Farm

SKM

Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

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- Other Sources
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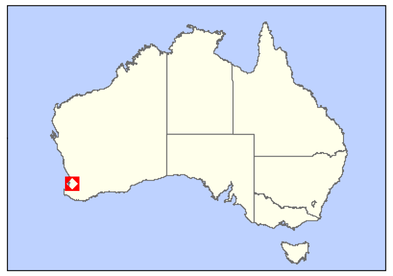
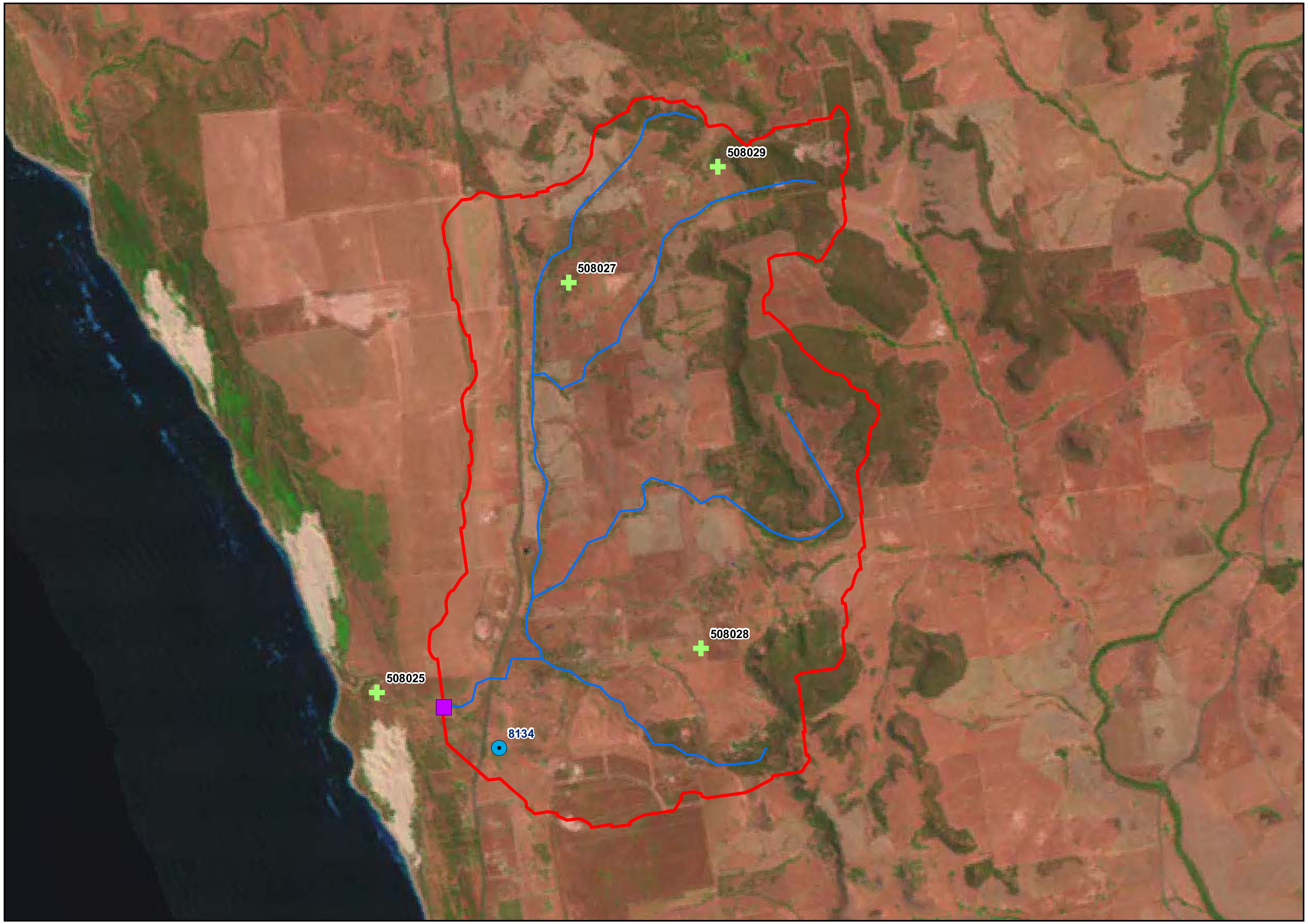
[GDA94 | MGA55]

0 1,000
Meters



614047; Davis Brook @ Murray Valley Plntn

SKM



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

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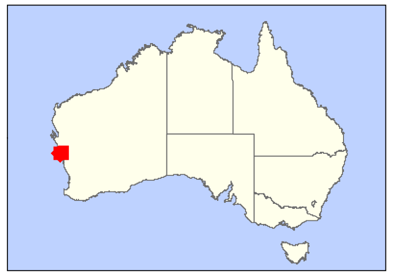
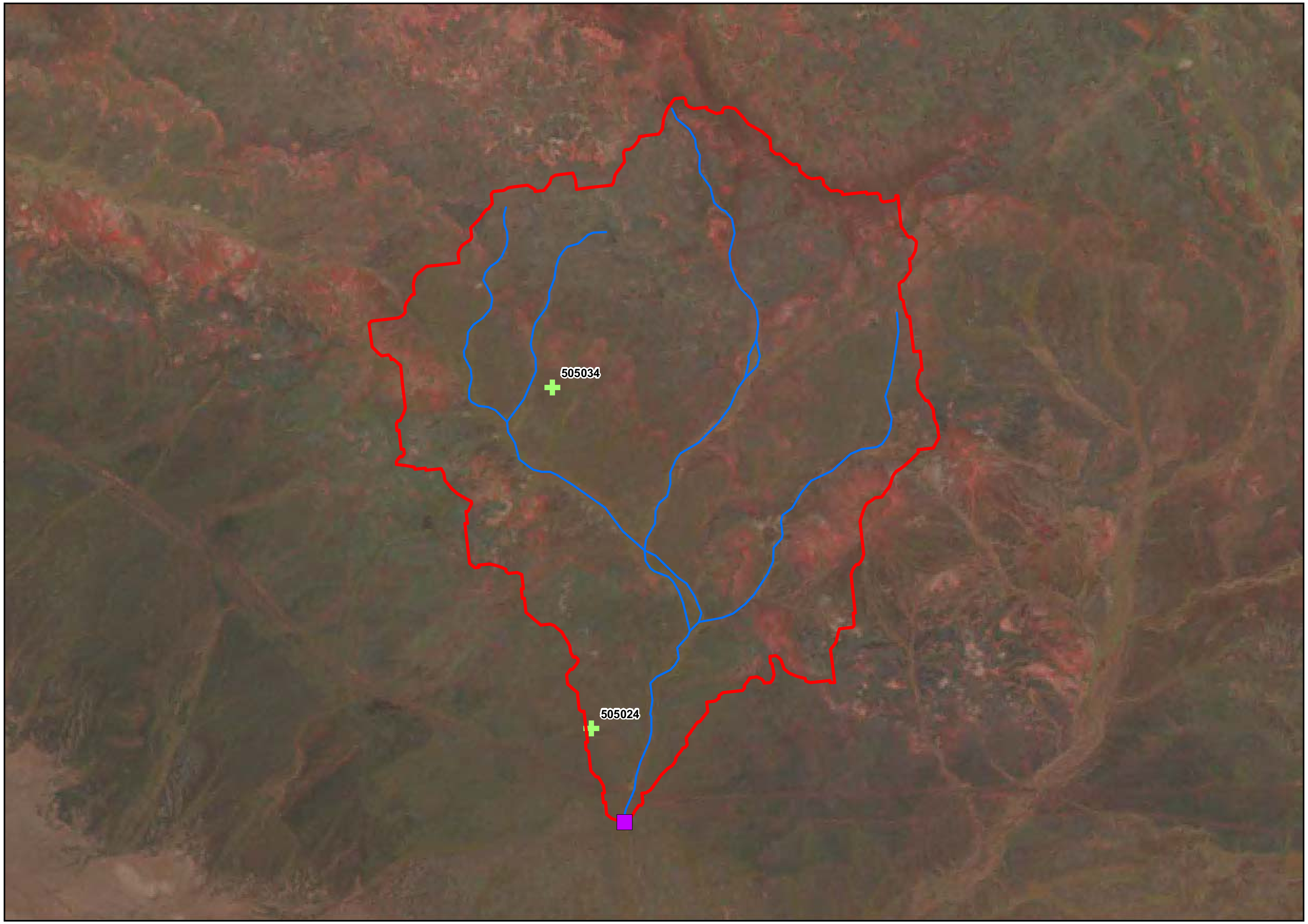
[GDA94 | MGA55]

0 960
Meters



701006; Buller River @ Buller

October 22, 2013 | II:\VWES\Projects\VW07245\Technical\Spatial\ArcGIS\VW07245_FinalCatchmentMaps_v2.mxd
Prepared by : SI
Checked by : ZG



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

DATA SOURCES
This document incorporates data which is:
Landsat Imagery (2002)
Bureau of Meteorology - Pluviograph Station Locations

[GDA94 | MGA55]

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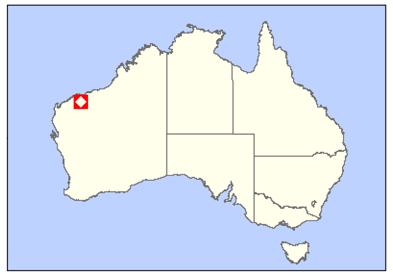
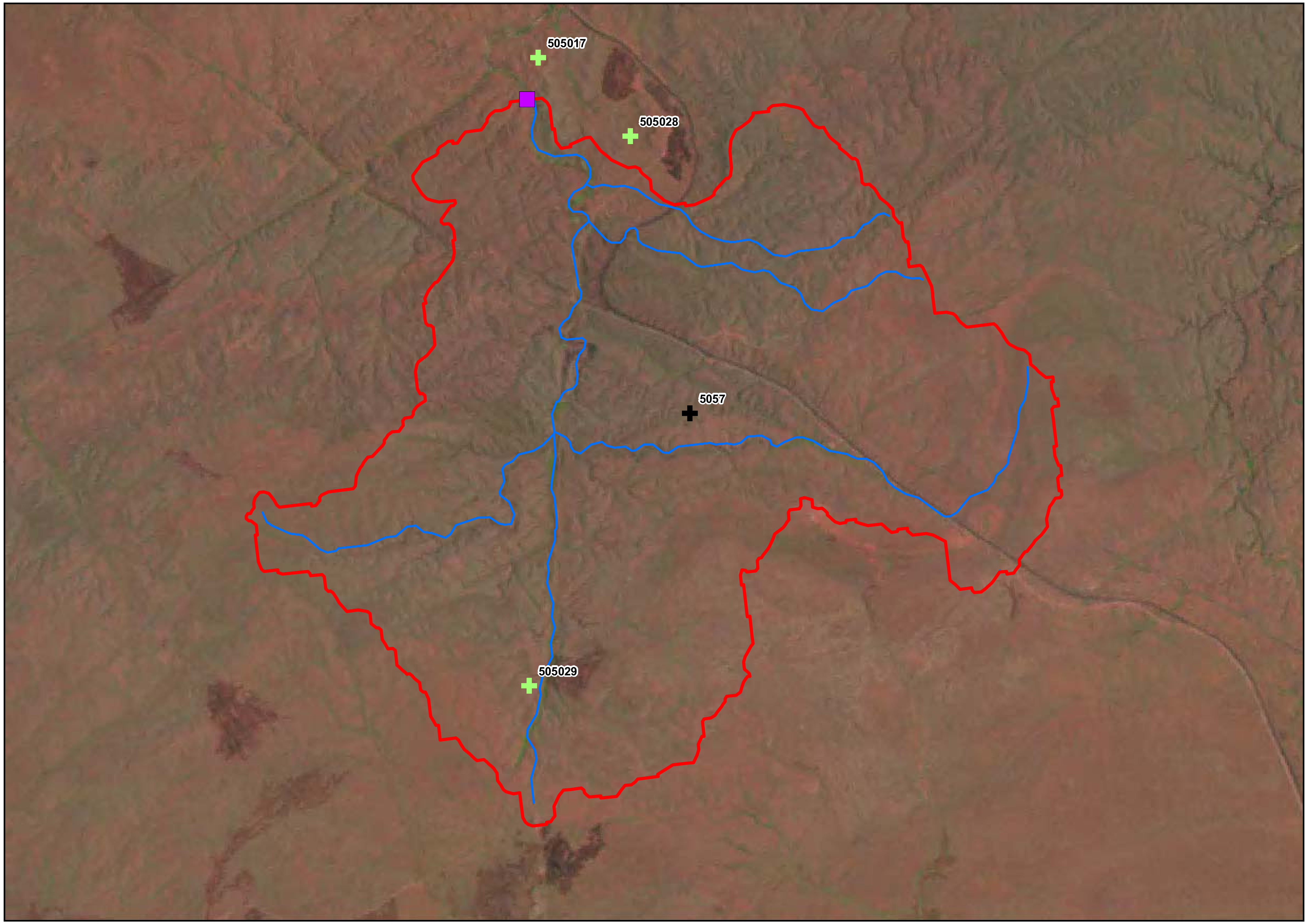
Meters



708009; Kanjenjie Creek Trib. @ Fish Pool



Legend
- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations
- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

DATA SOURCES
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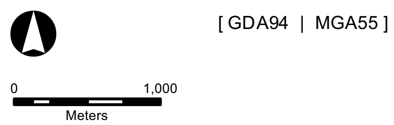
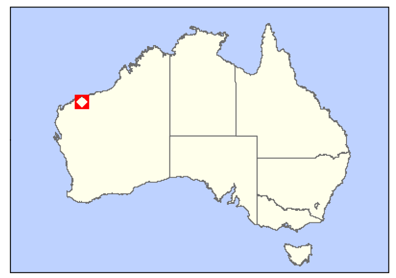
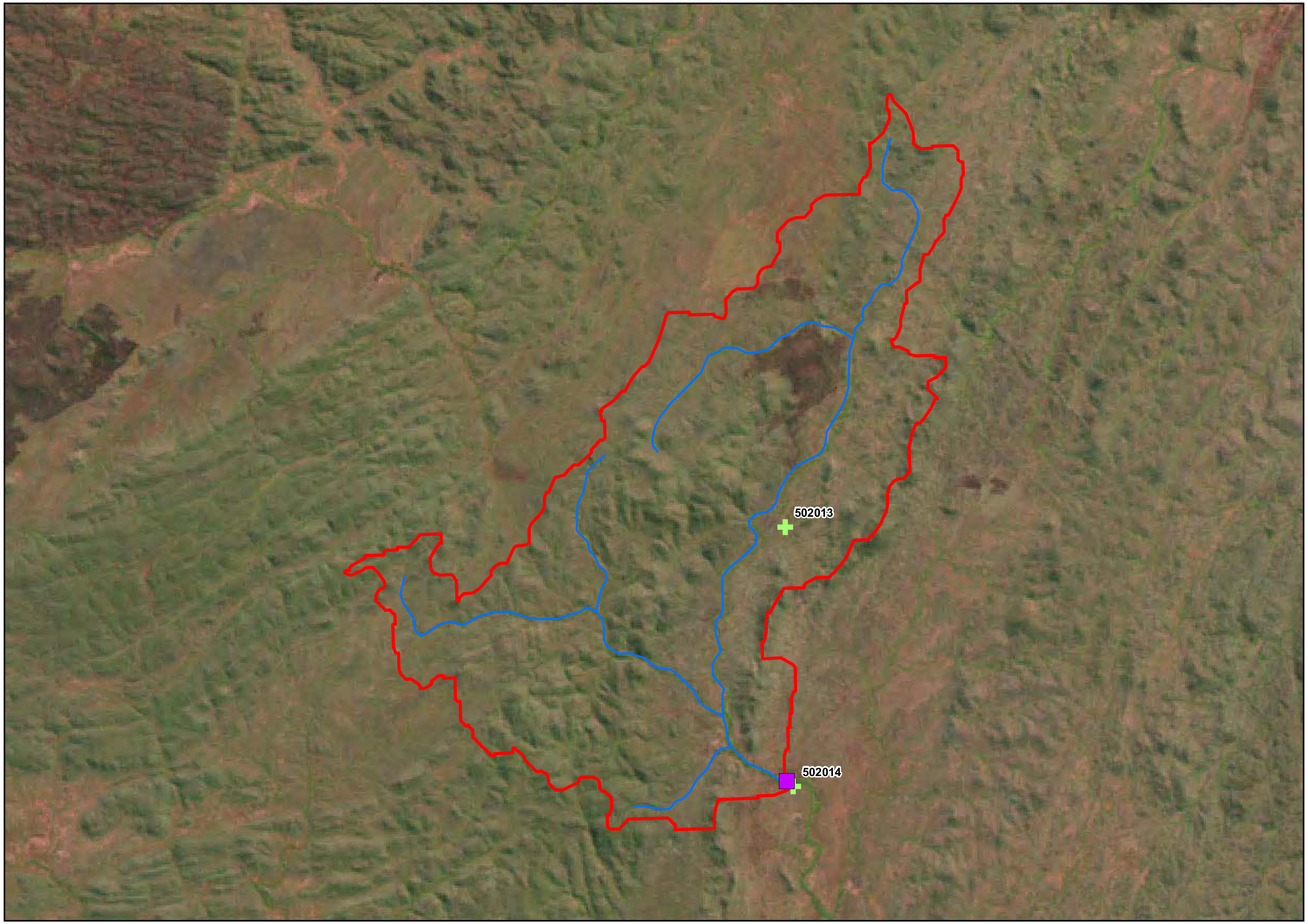
Bureau of Meteorology - Pluviograph Station Locations





709007; Harding River @ Marmurrina Pool U-South



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

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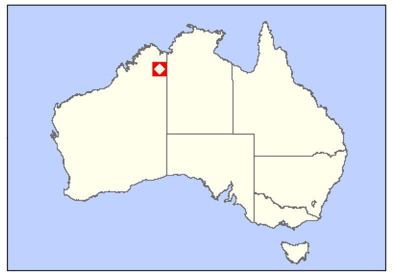
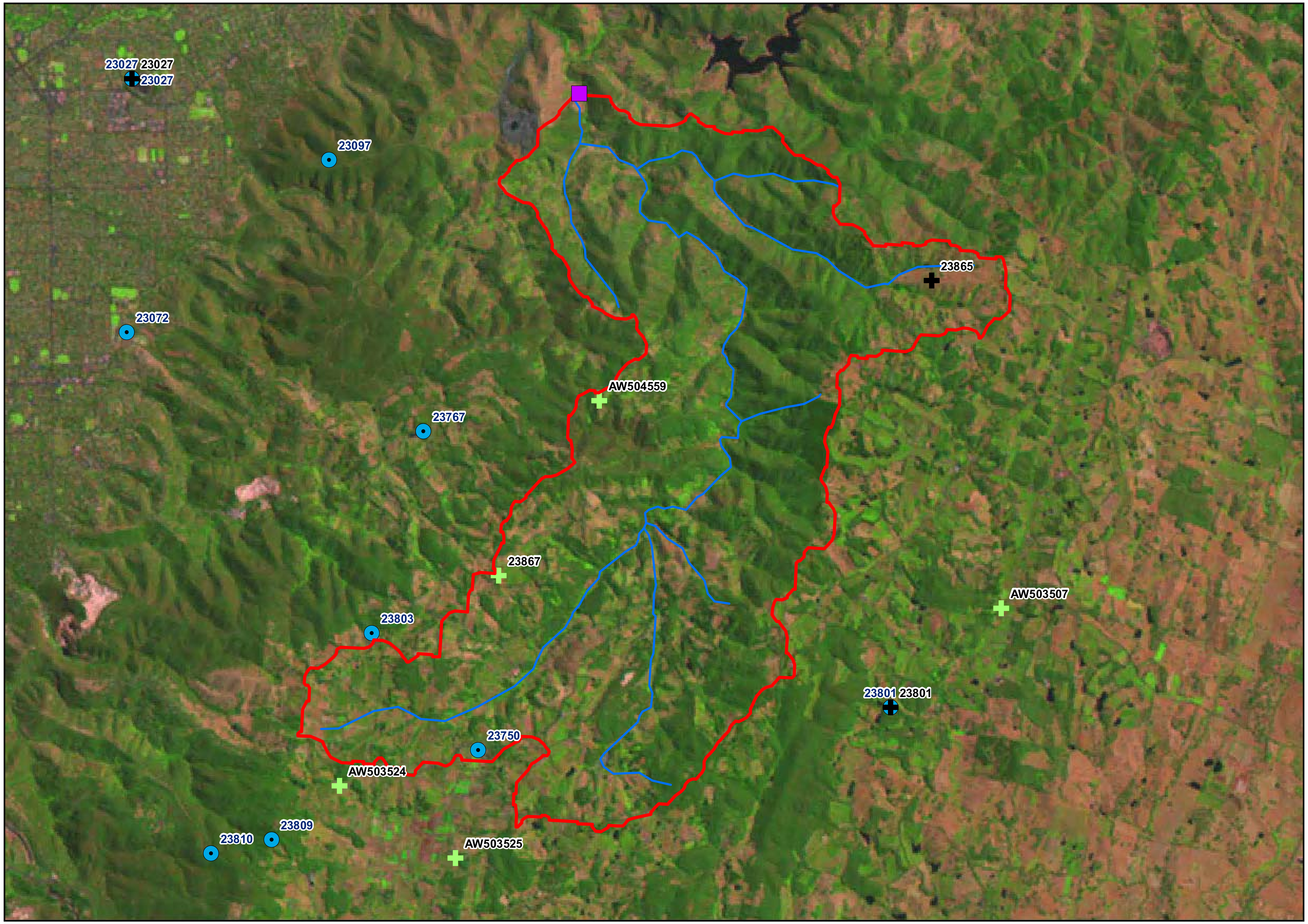
[GDA94 | MGA55]

0 1,000
Meters



809312; Fletcher Creek Trib @ Frog Hollow

SKM



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

DATA SOURCES
This document incorporates data which is:
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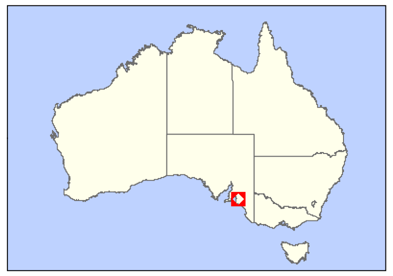
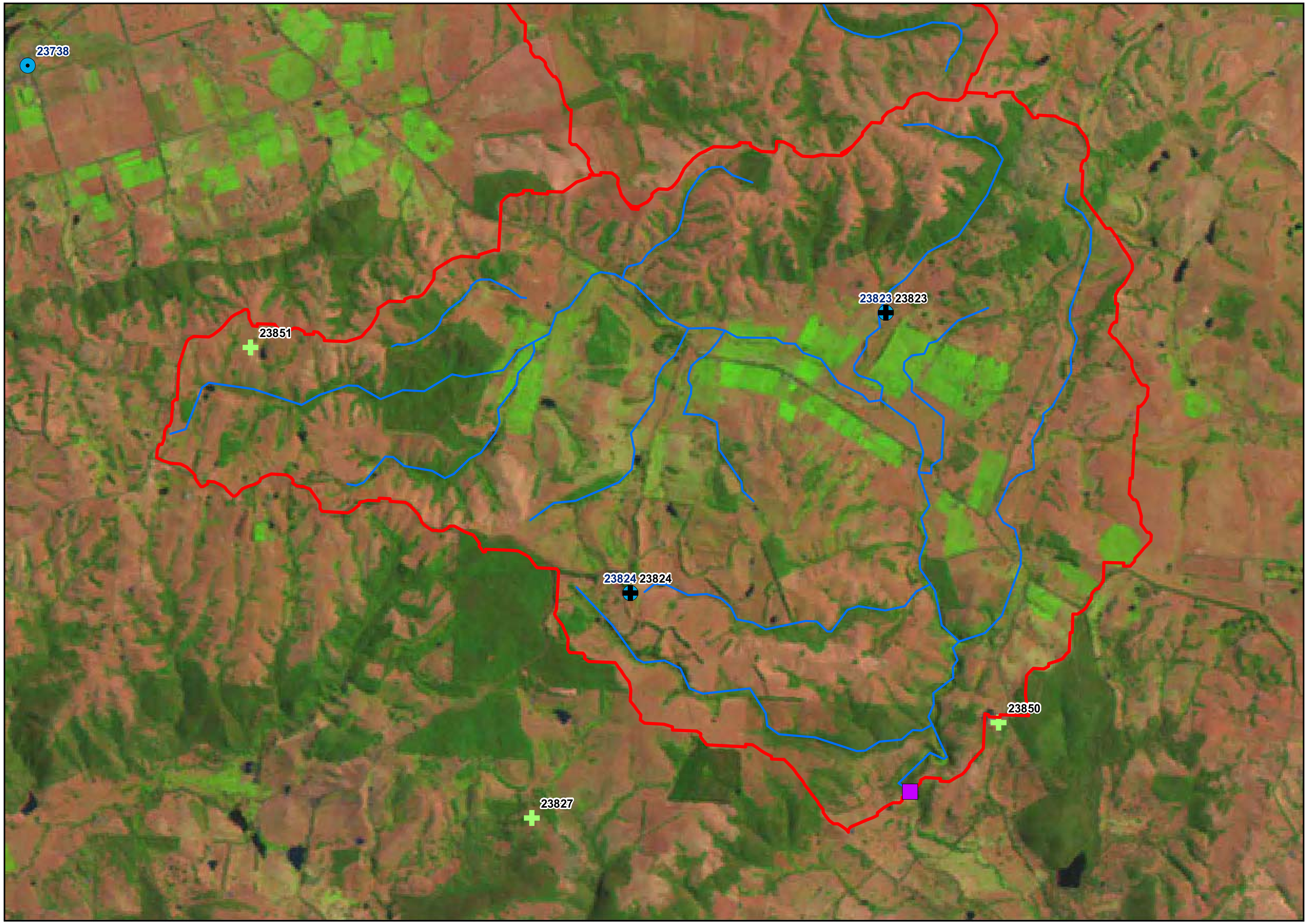
Bureau of Meteorology - Pluviograph Station Locations

[GDA94 | MGA55]

0 1,120
Meters



A5040523; Castambul @ Sixth Creek



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
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- Waterbody
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DATA SOURCES
This document incorporates data which is:
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Bureau of Meteorology - Pluviograph Station Locations

[GDA94 | MGA55]

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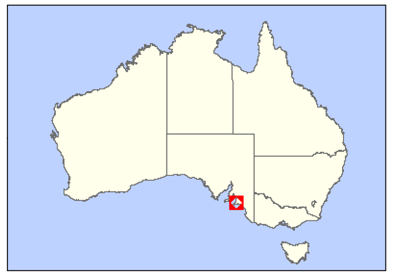
Meters



AW501500; Hindmarsh @ Hindmarsh Vy Res Offtake W

SKM

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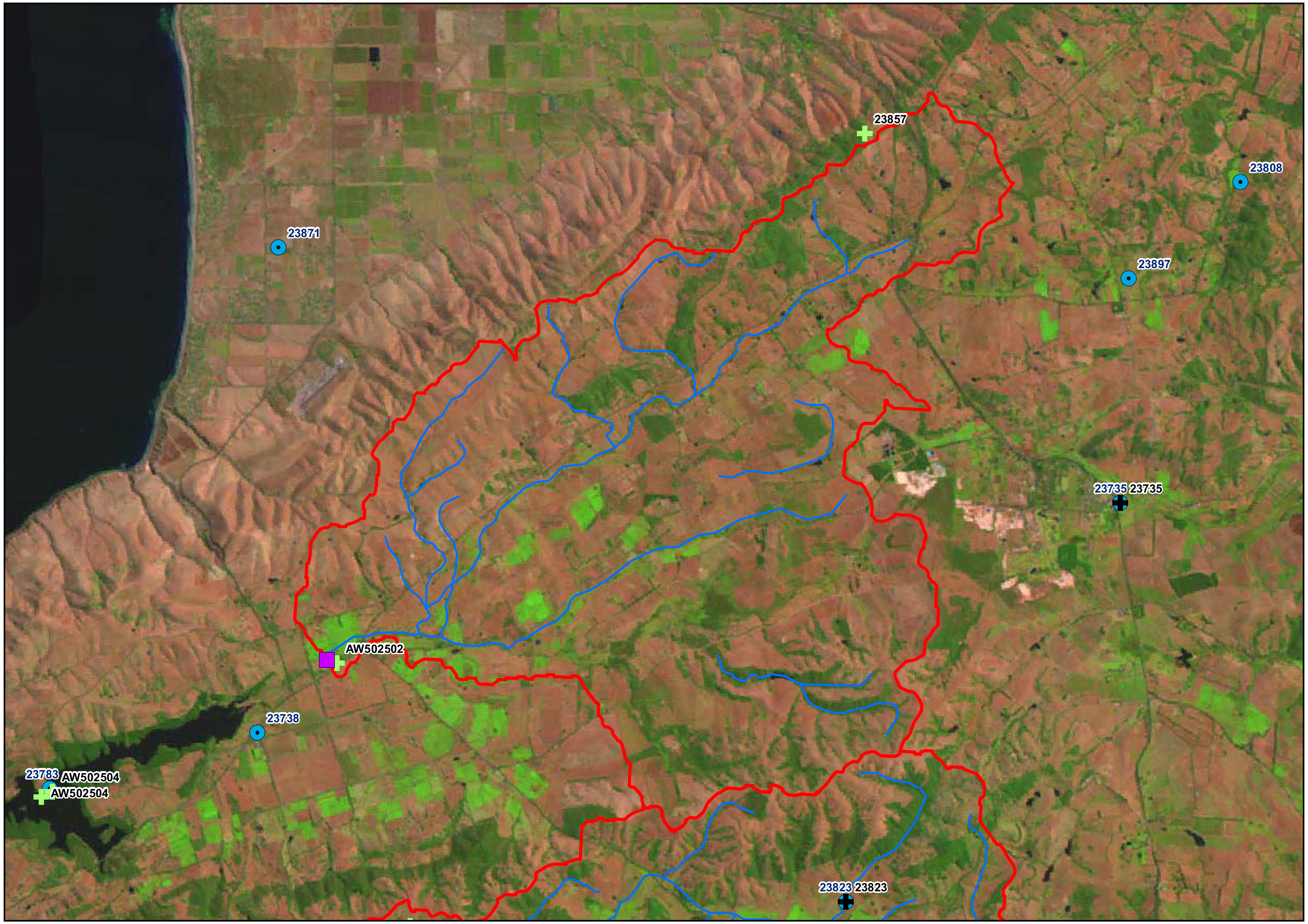
Prepared by : SI
Checked by : ZG



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

[GDA94 | MGA55]

0 1,360
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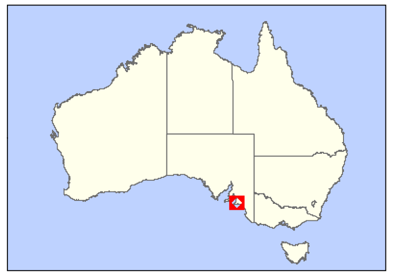

AW502502; Myponga River u/s Dam and Rd Br

Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

- Bureau of Meteorology
- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

DATA SOURCES
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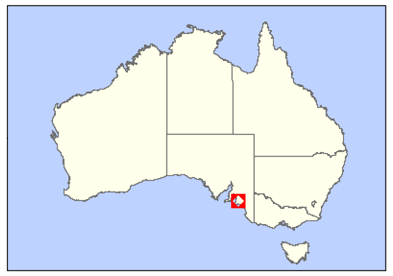
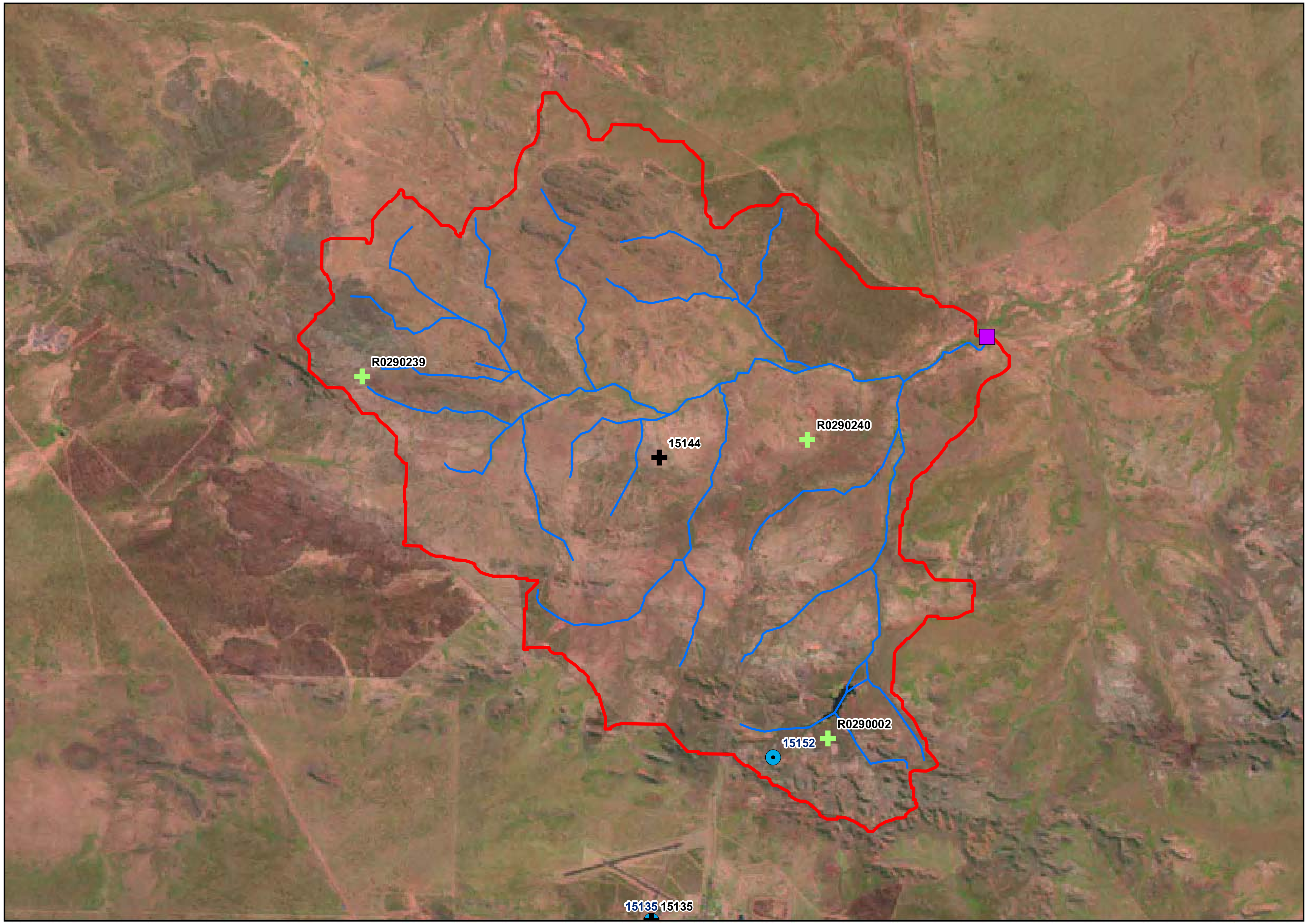
Bureau of Meteorology - Pluviograph Station Locations

[GDA94 | MGA55]

0 800
Meters



AW503506; Echunga Creek u/s Mt Bold Reserve



Legend

Gauge Location
Catchment Boundary
Rainfall Gauge

Pluviograph Stations

Bureau of Meteorology
Other Sources
Watercourse
Waterbody
Built-Up Areas

DATA SOURCES
This document incorporates data which is:
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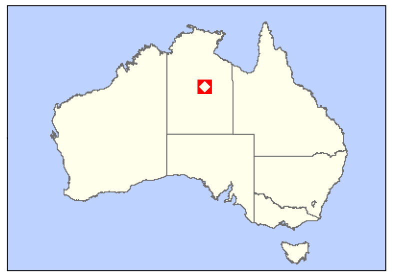
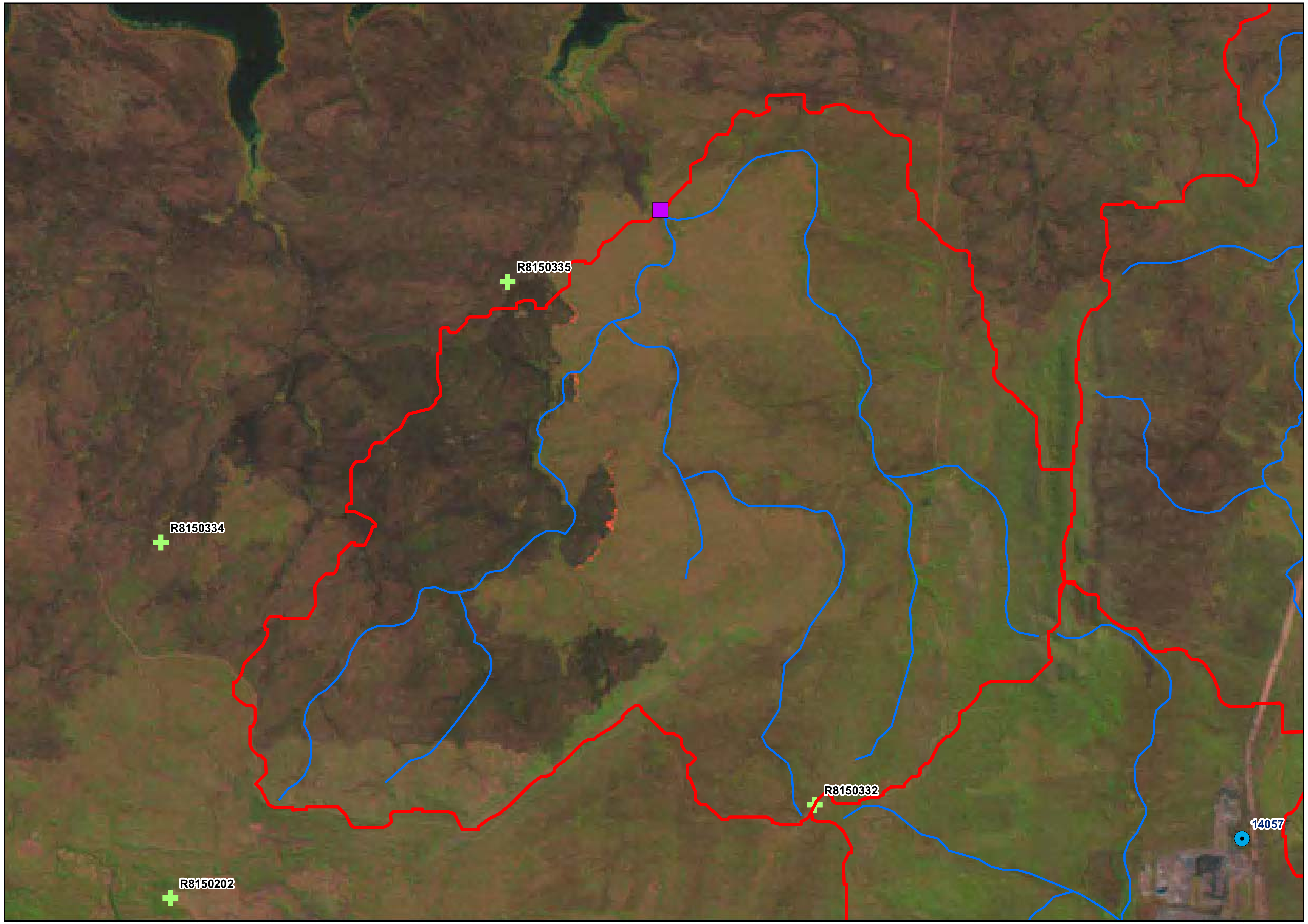
Bureau of Meteorology - Pluviograph Station Locations

[GDA94 | MGA55]

0 1,300
Meters



G0290240; Tennant Creek @ Old Telegraph Station



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

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- Other Sources
- Watercourse
- Waterbody
- Built-Up Areas

DATA SOURCES
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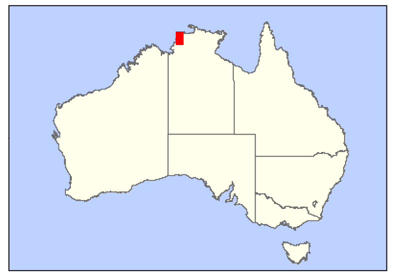
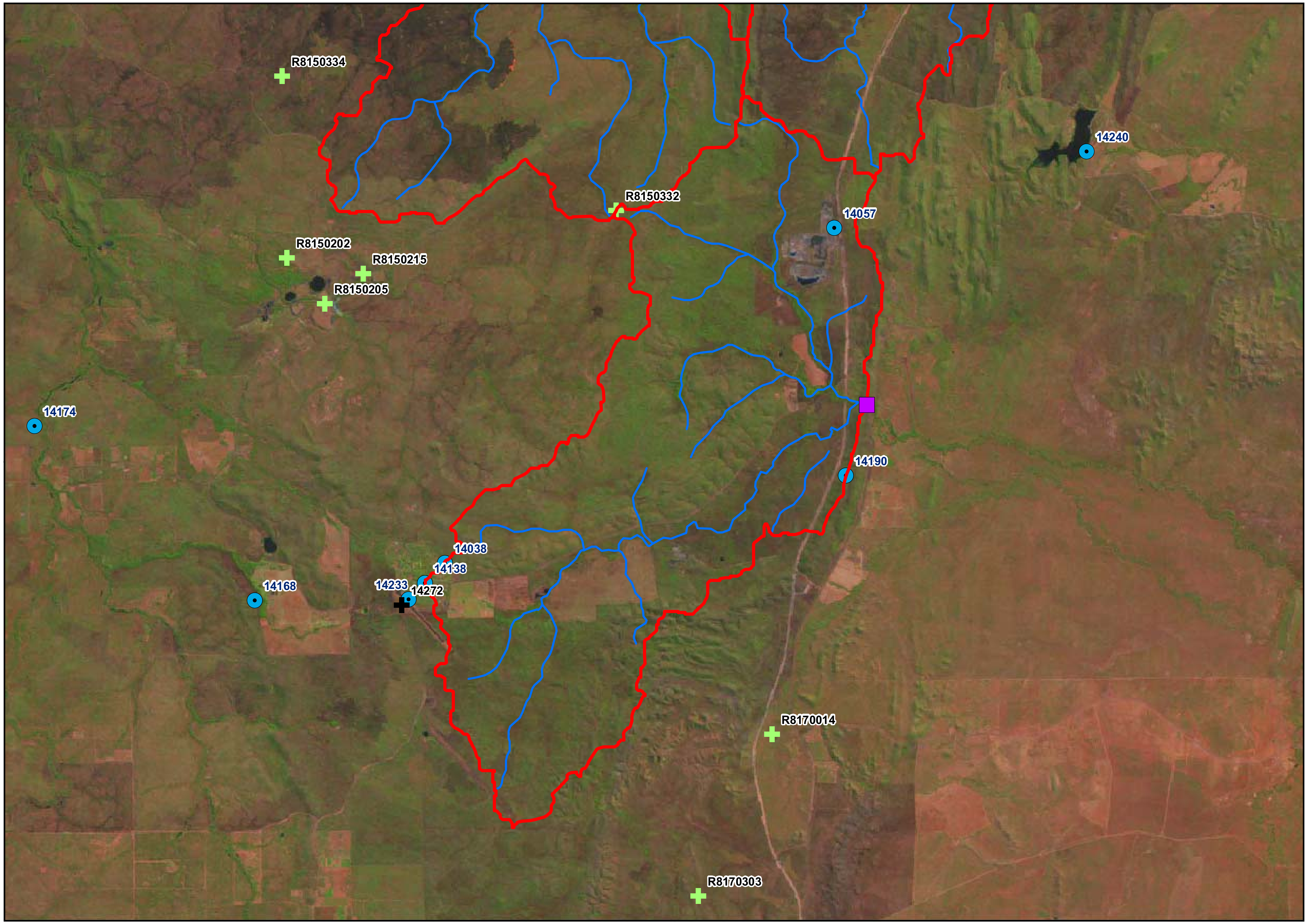
Bureau of Meteorology - Pluviograph Station Locations

[GDA94 | MGA55]

0 920
Meters



G8150151; Celia Creek u/s Darwin River Dam



Legend

- Gauge Location
- Catchment Boundary
- Rainfall Gauge

Pluviograph Stations

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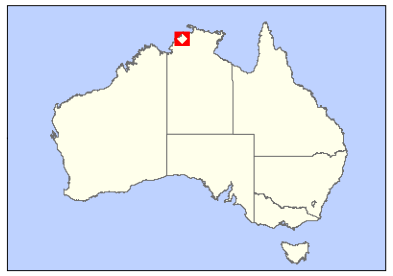
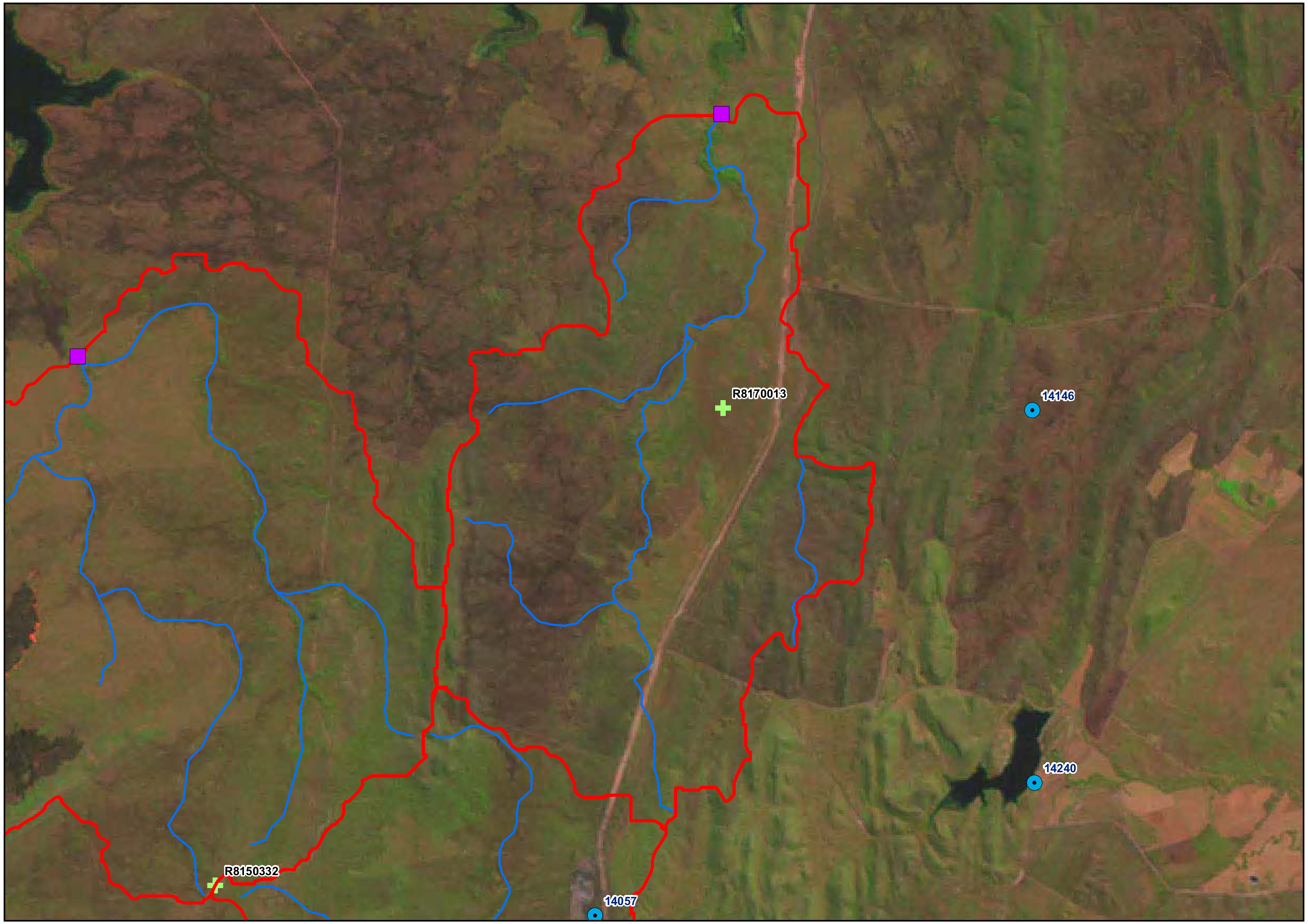
[GDA94 | MGA55]

0 1,800
Meters



G8170066; Coomalie Creek @ Stuart Highway

SKM



Legend

Gauge Location
Catchment Boundary
Rainfall Gauge

Pluviograph Stations

Bureau of Meteorology
Other Sources
Watercourse
Waterbody
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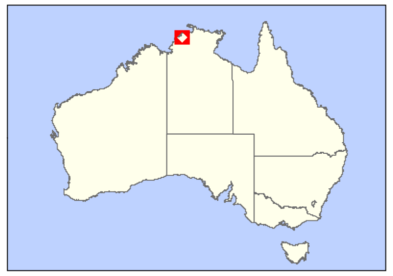
[GDA94 | MGA55]

0 1,040
Meters



G8170075; Manton River u/s Manton Dam

Appendix C   Pre-burst distribution for each duration

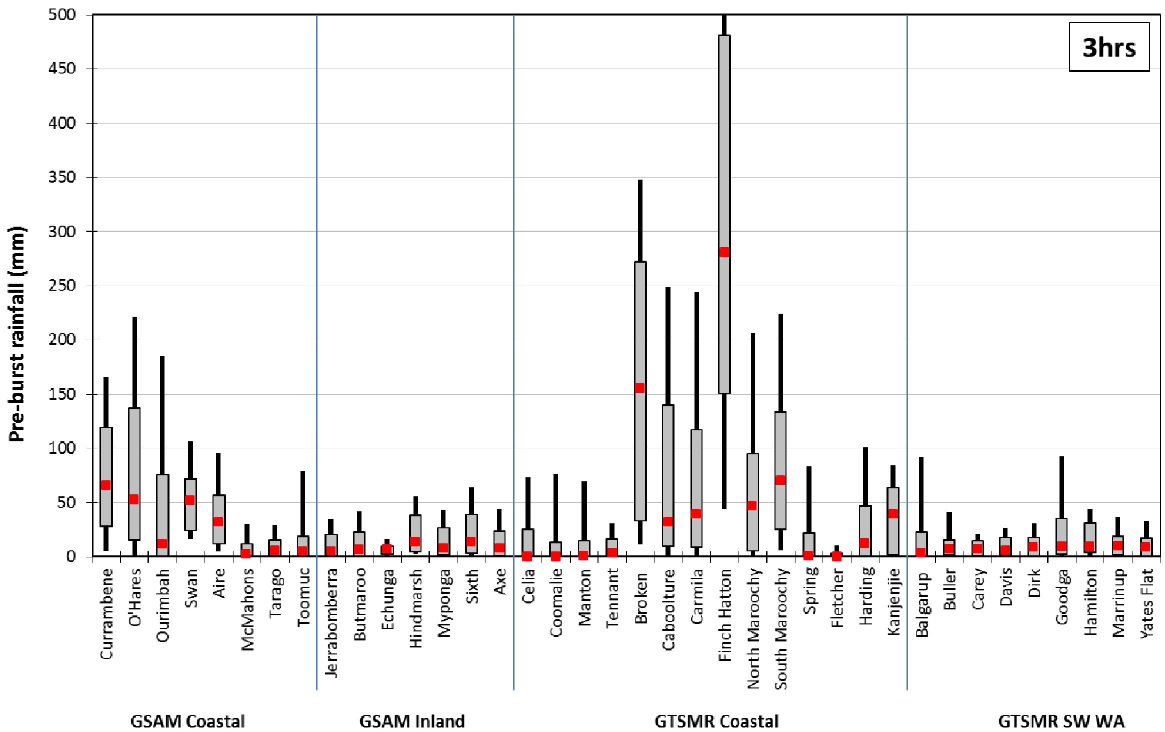


Figure C-1 Range of pre-burst rainfall for 3-hour bursts (box indicates quartiles and line shows 10th and 90th percentile values)

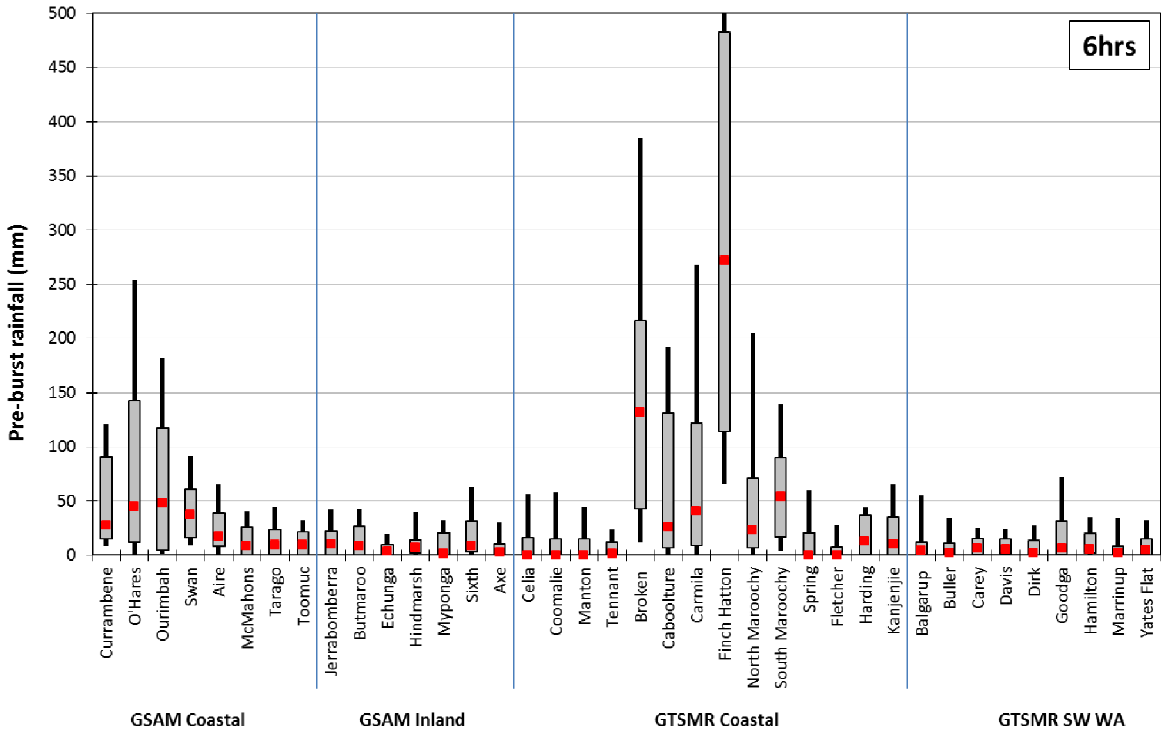


Figure C-2 Range of pre-burst rainfall for 6-hour bursts (box indicates quartiles and line shows 10th and 90th percentile values)

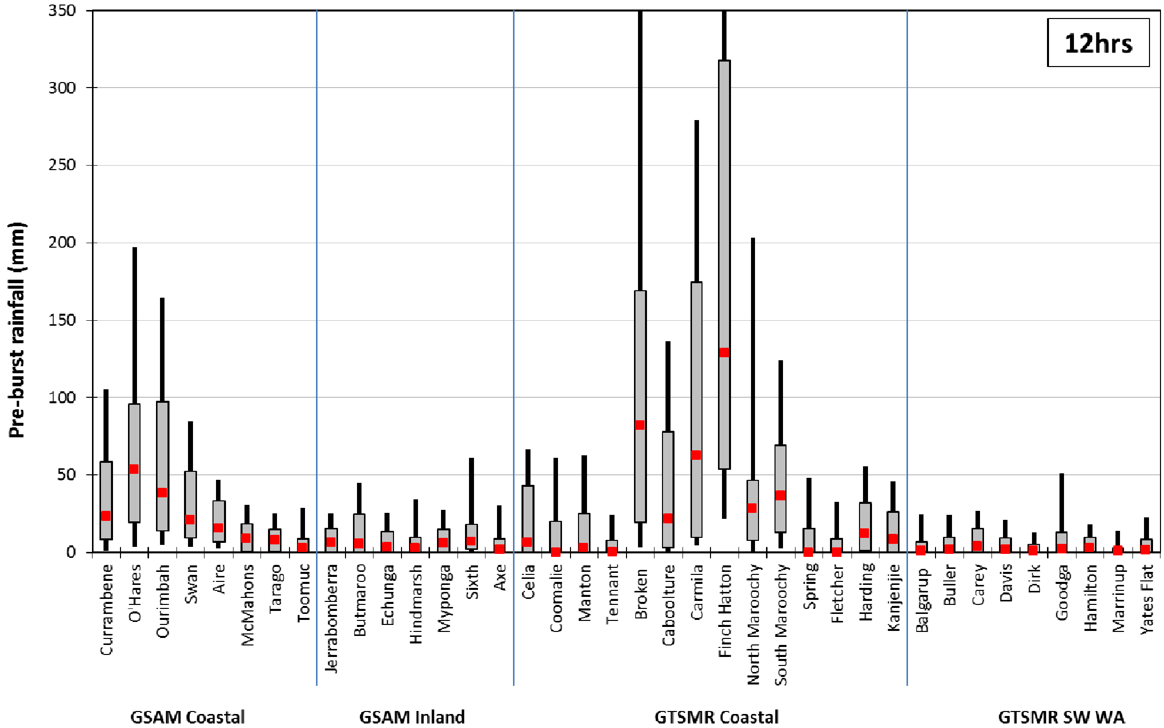


Figure C-3 Range of pre-burst rainfall for 12-hour bursts (box indicates quartiles and line shows 10th and 90th percentile values)

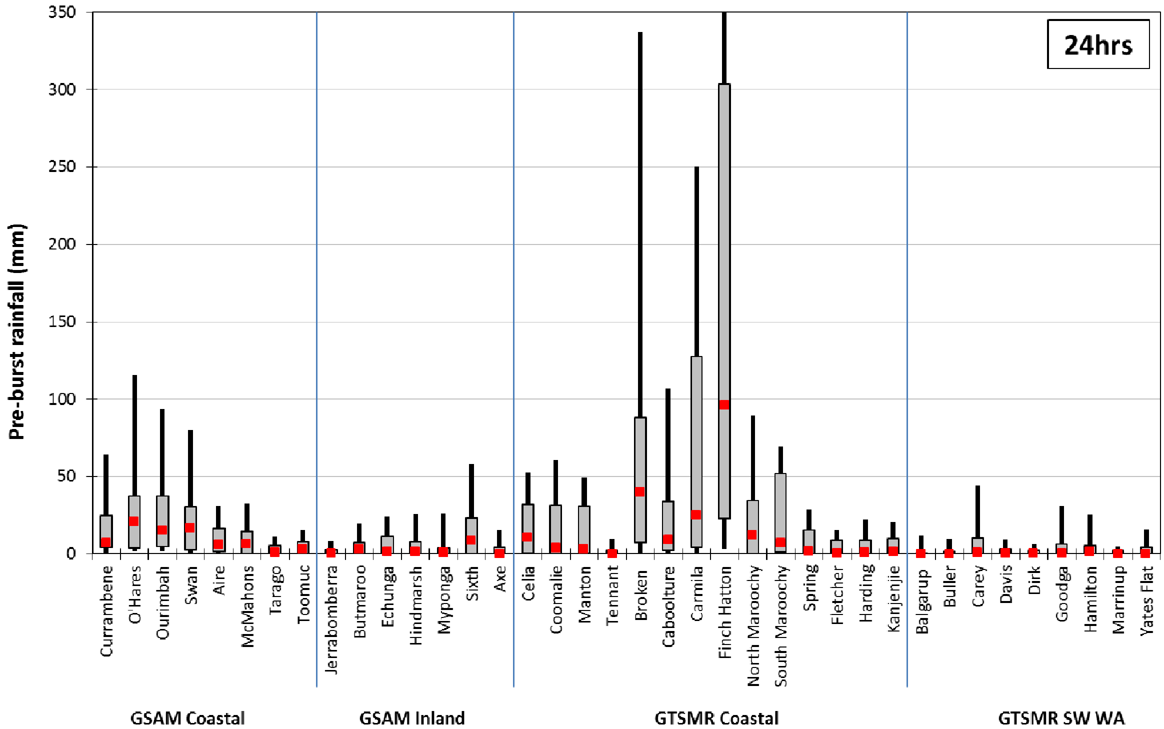


Figure C-4 Range of pre-burst rainfall for 24-hour bursts (box indicates quartiles and line shows 10th and 90th percentile values)

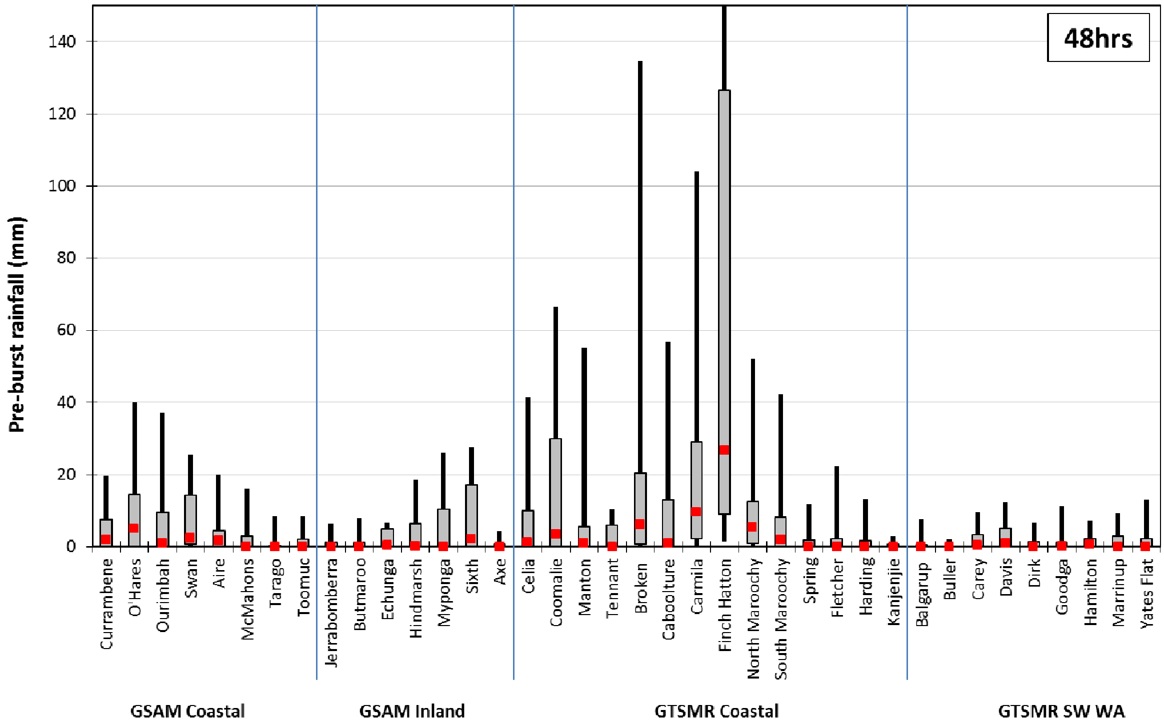


Figure C-5 Range of pre-burst rainfall for 48-hour bursts (box indicates quartiles and line shows 10th and 90th percentile values)

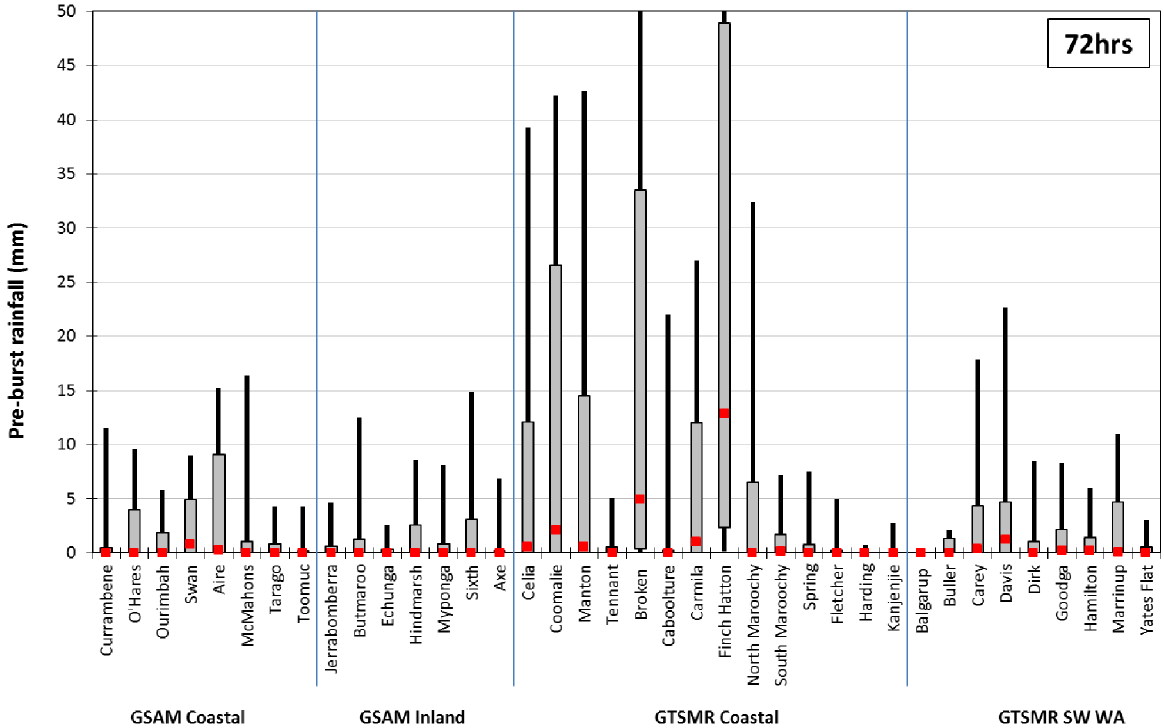
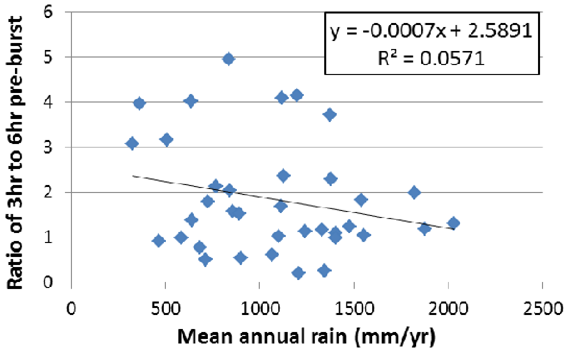
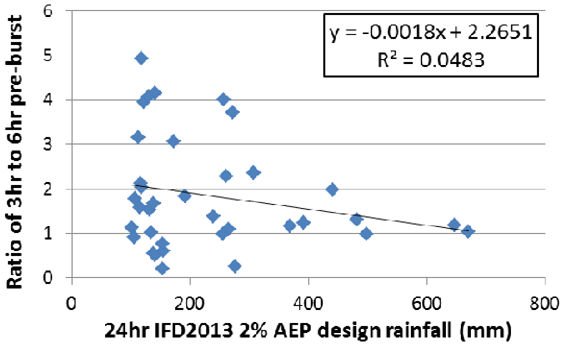
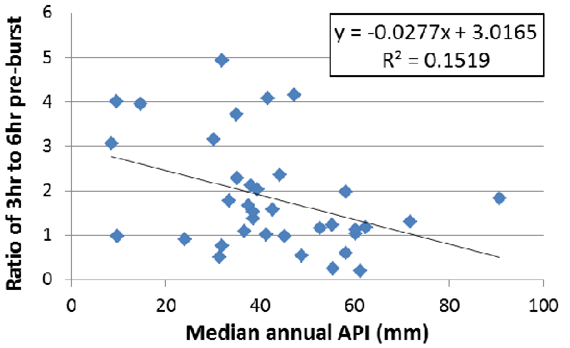


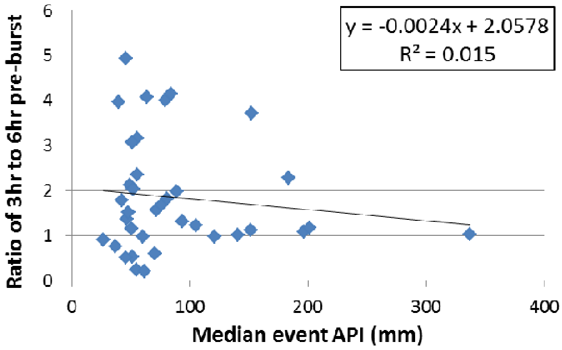
Figure C-6 Range of pre-burst rainfall for 72-hour bursts (box indicates quartiles and line shows 10th and 90th percentile values)

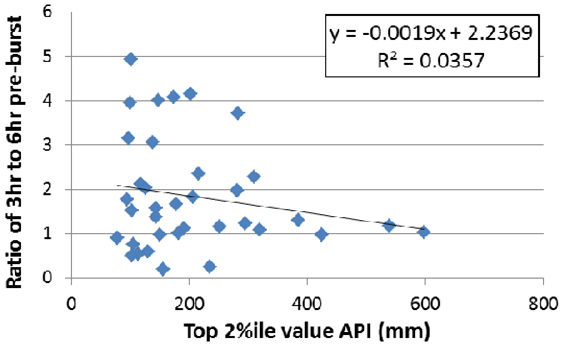
Appendix D Ratio of 3 hour to 6 hour pre-burst relationships

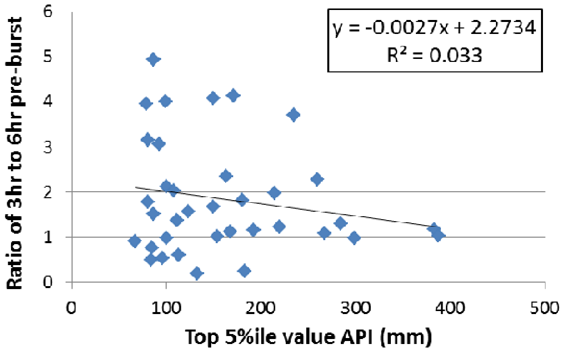


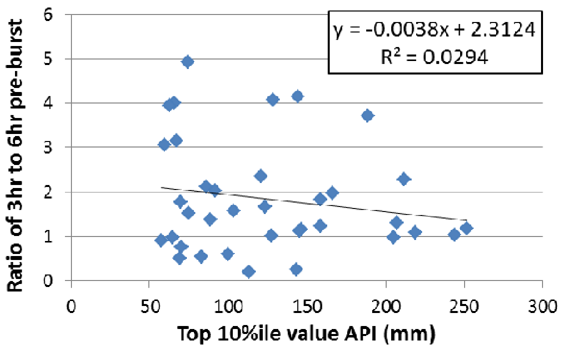


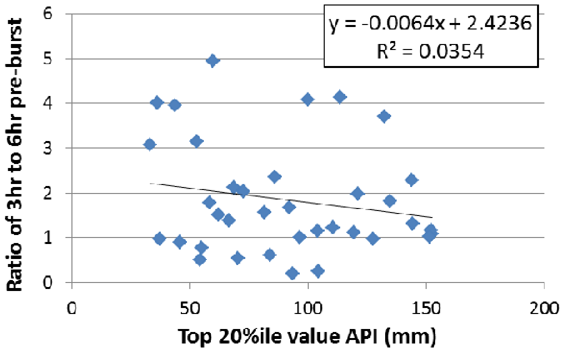






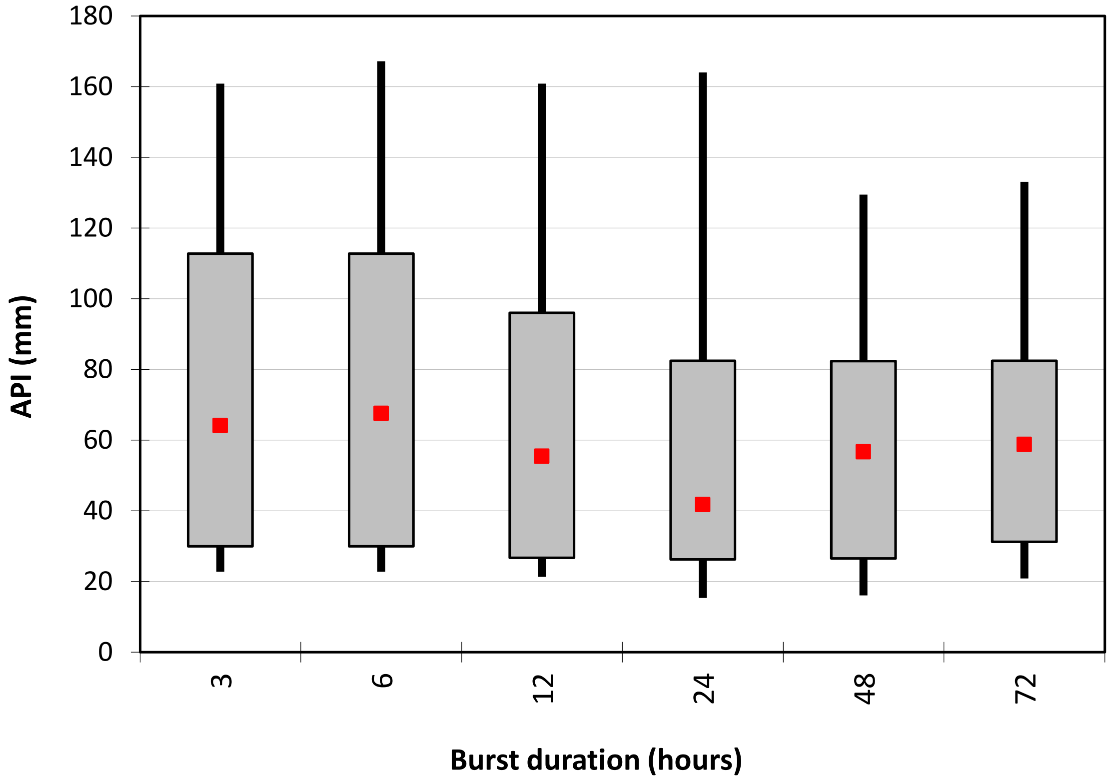


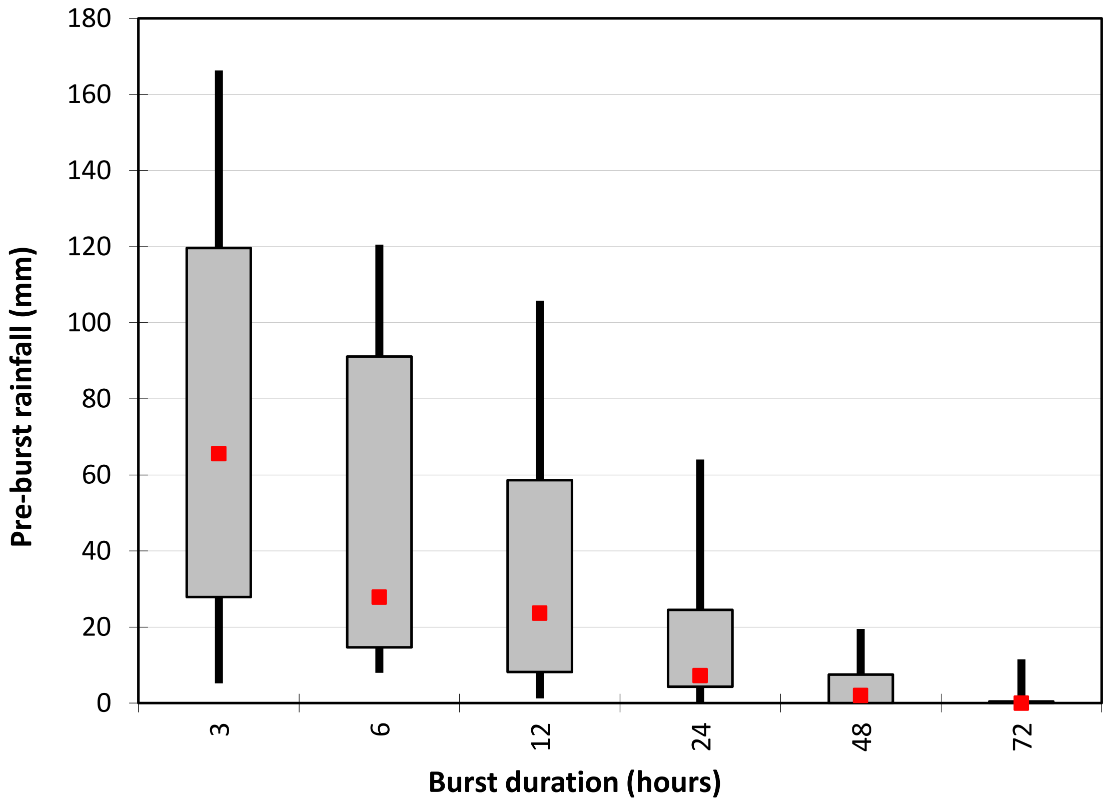




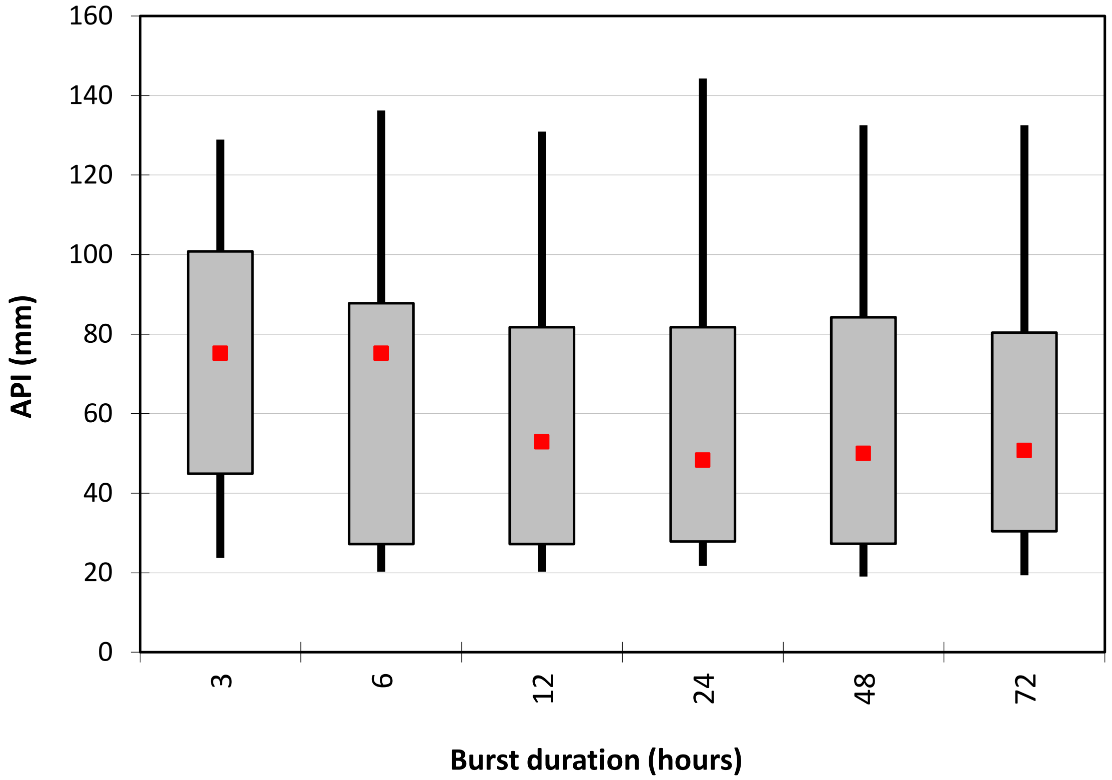
Appendix E Pre-burst distributions and API for each site and duration

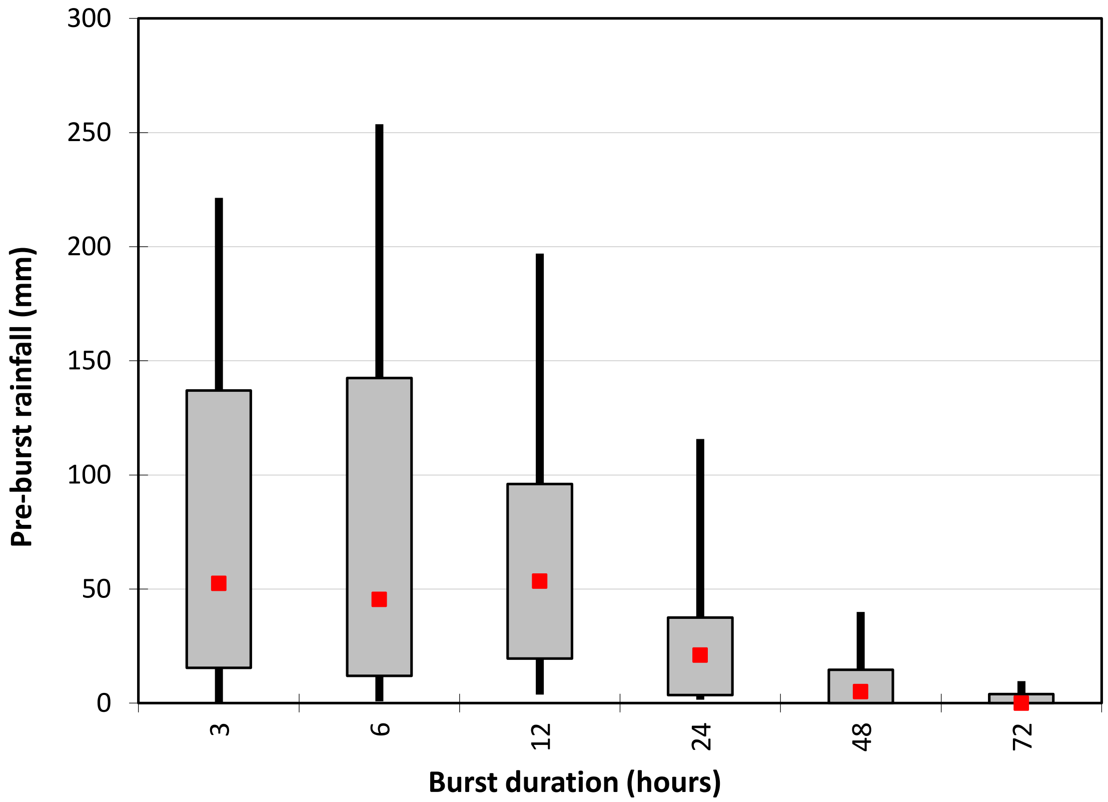
Currambene Creek @ Falls Ck (NSW)



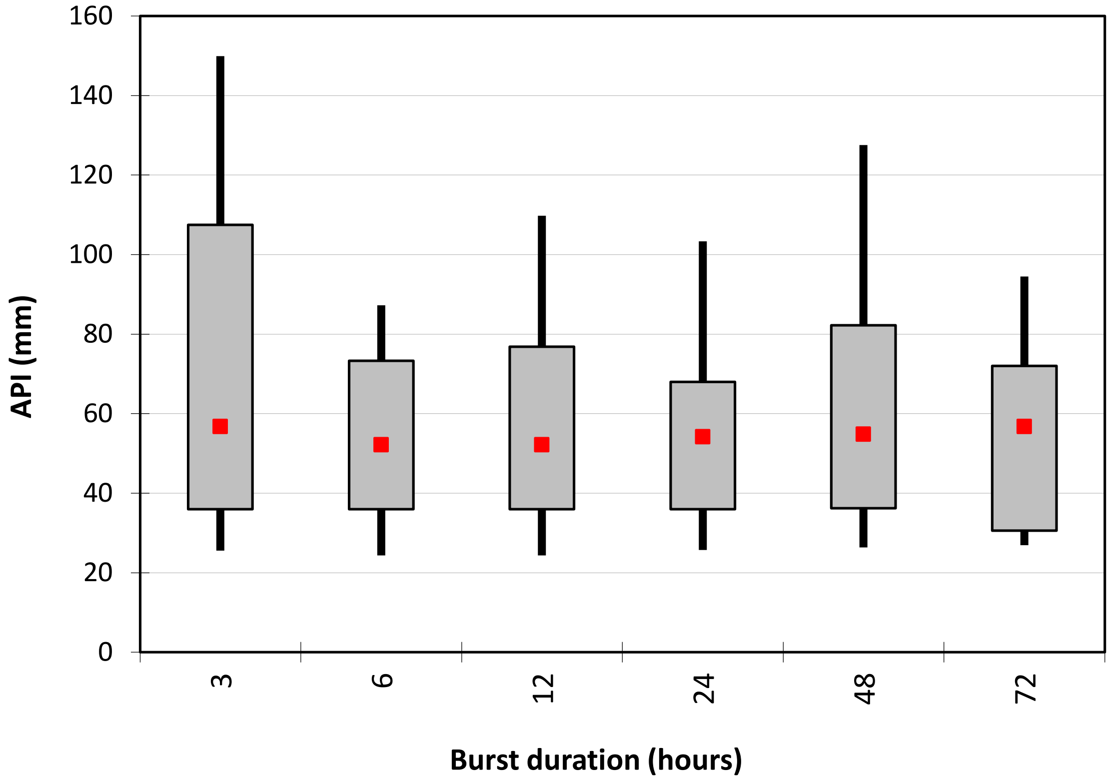


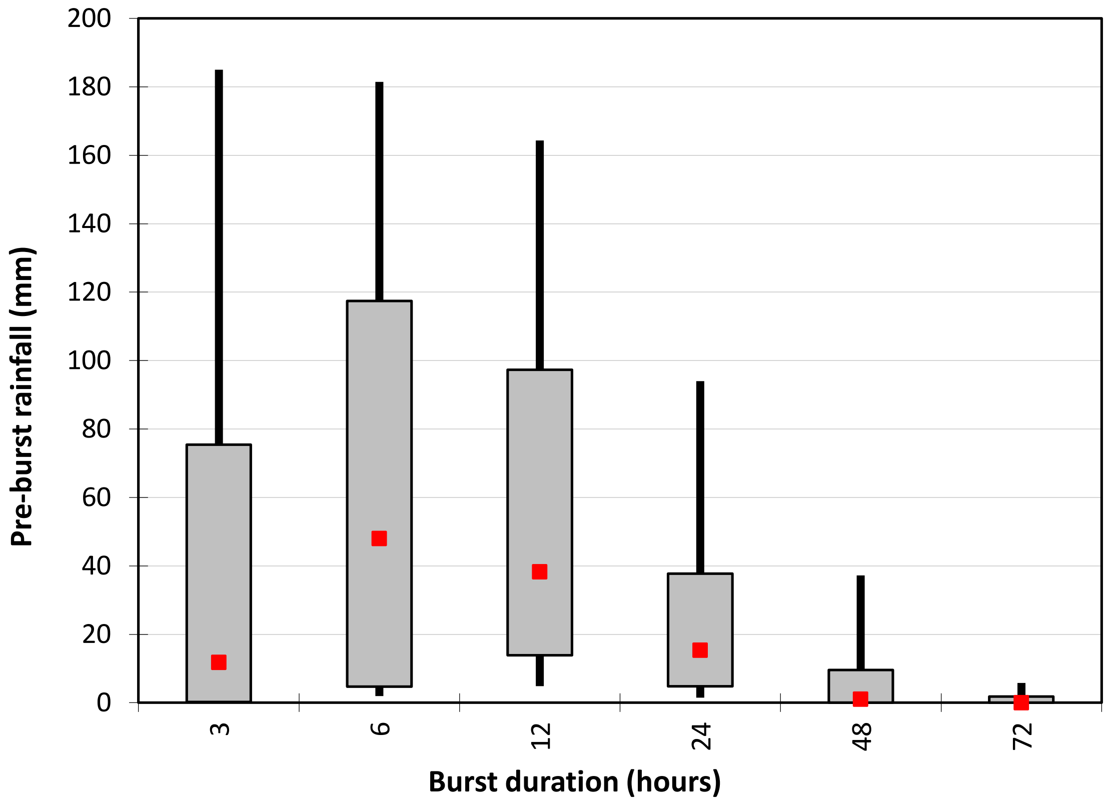
O'Hares Creek @ Wedderburn (NSW)



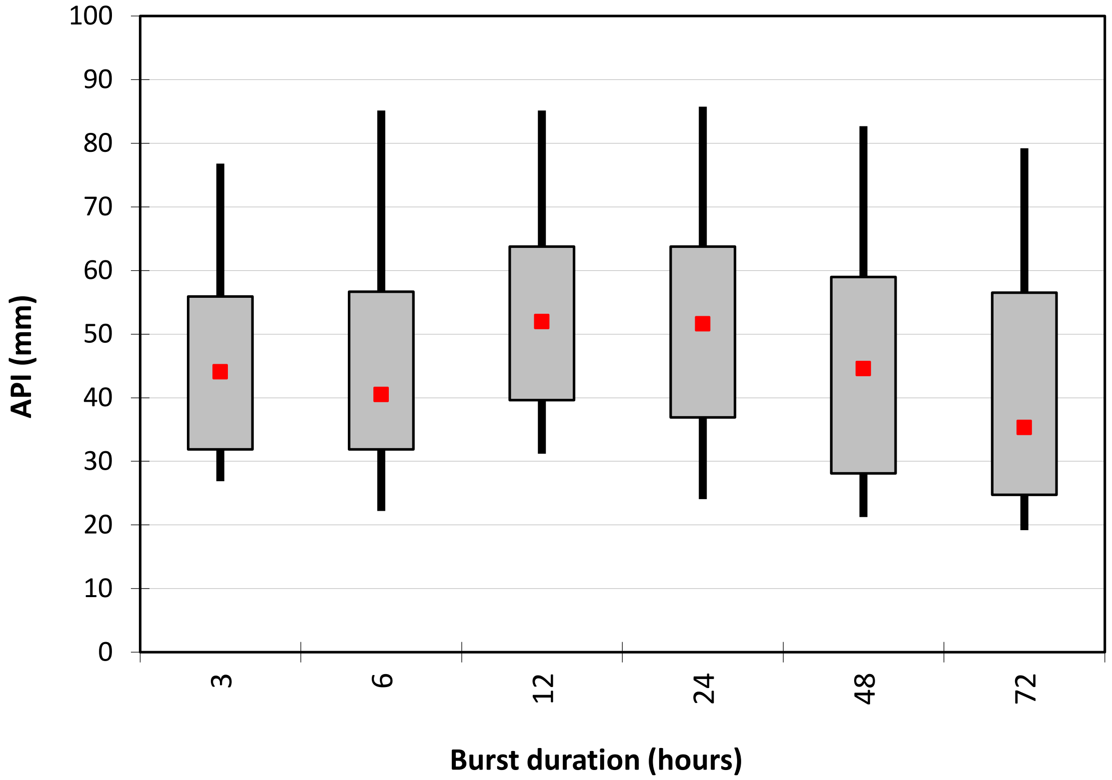


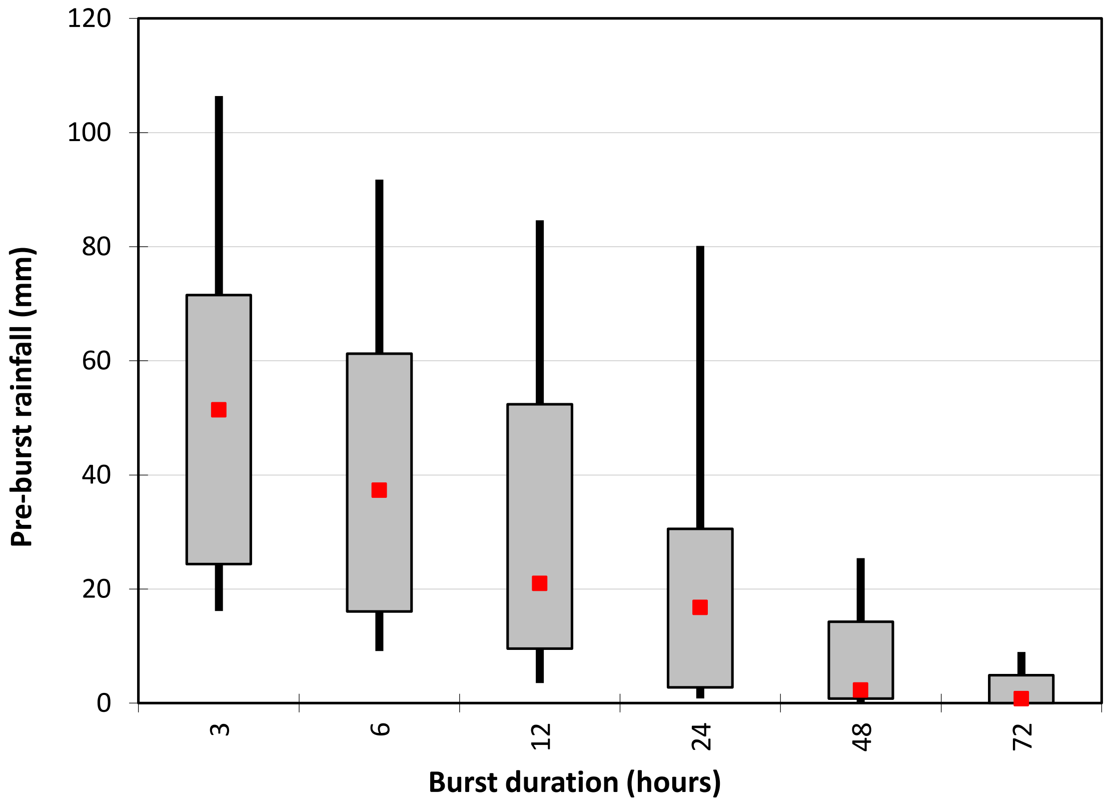
Ourimbah Creek @ U/S Weir (NSW)



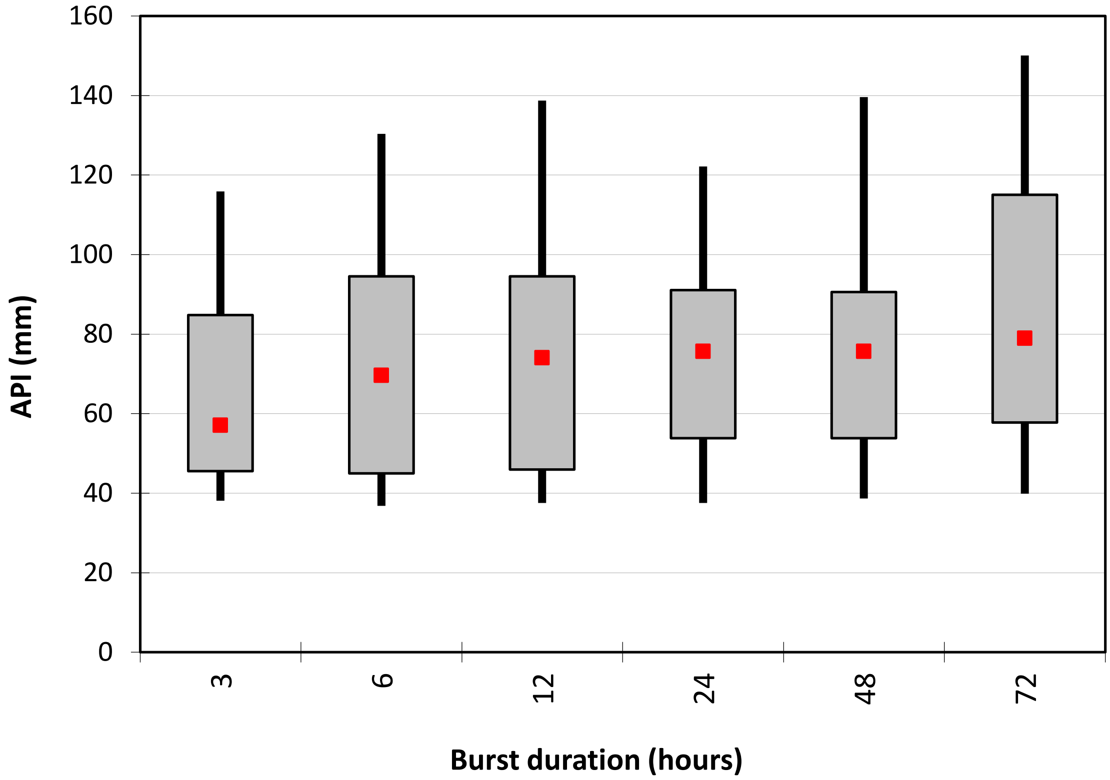


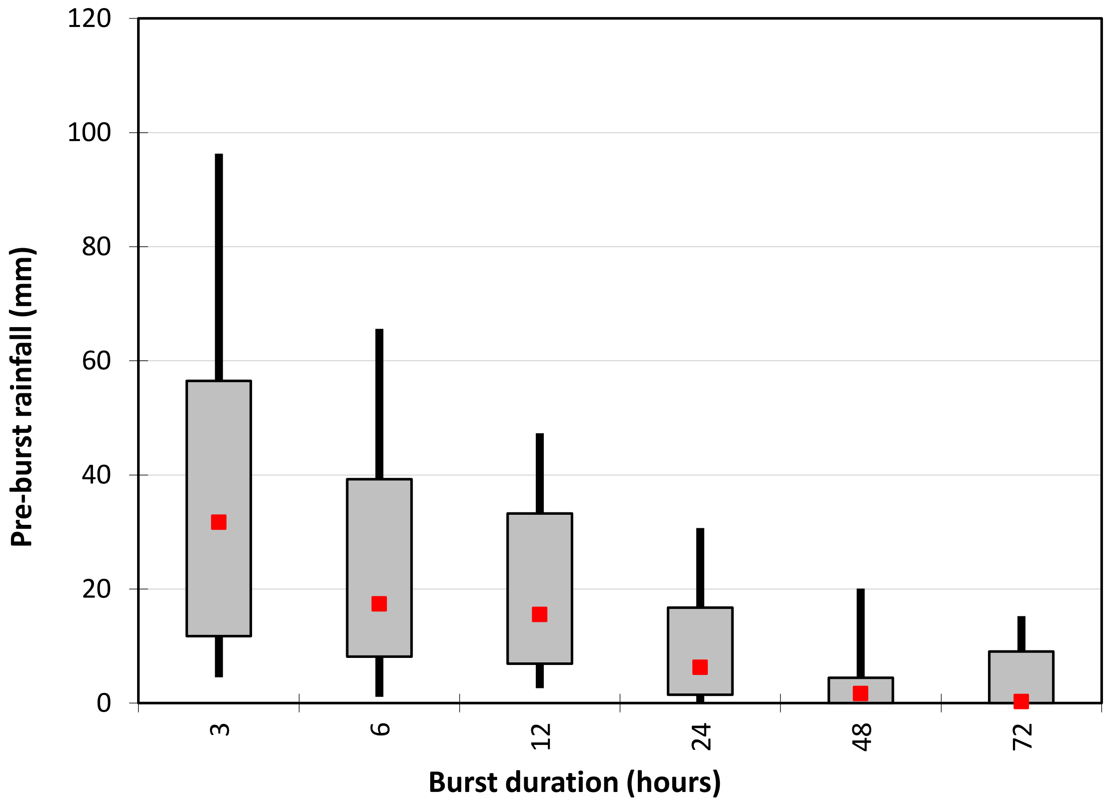
Swan River @ U/S Hardings Falls (TAS)



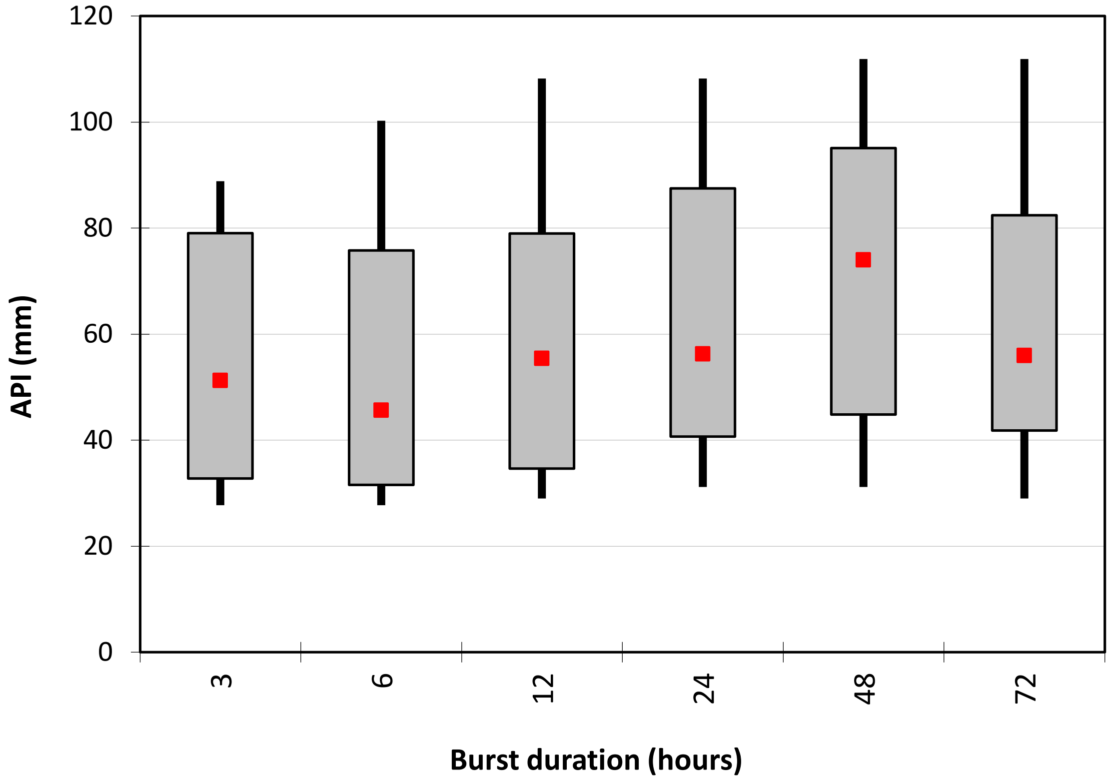


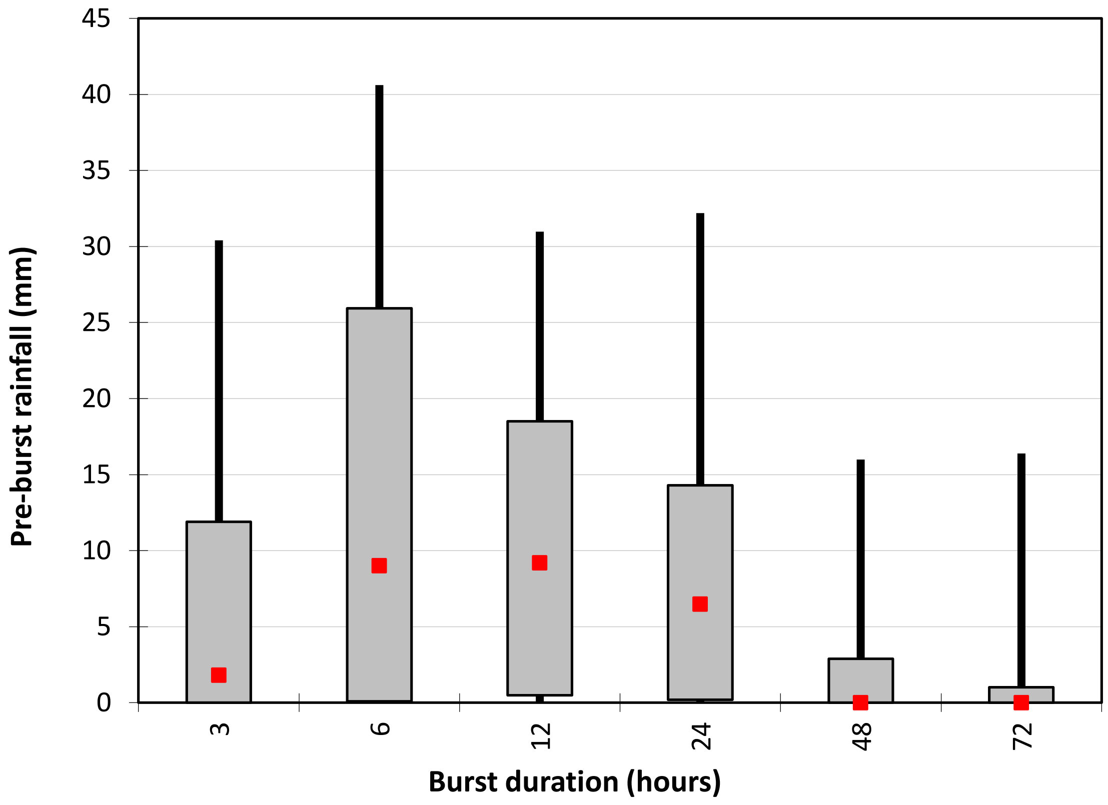
Aire River @ Wyelangata (VIC)



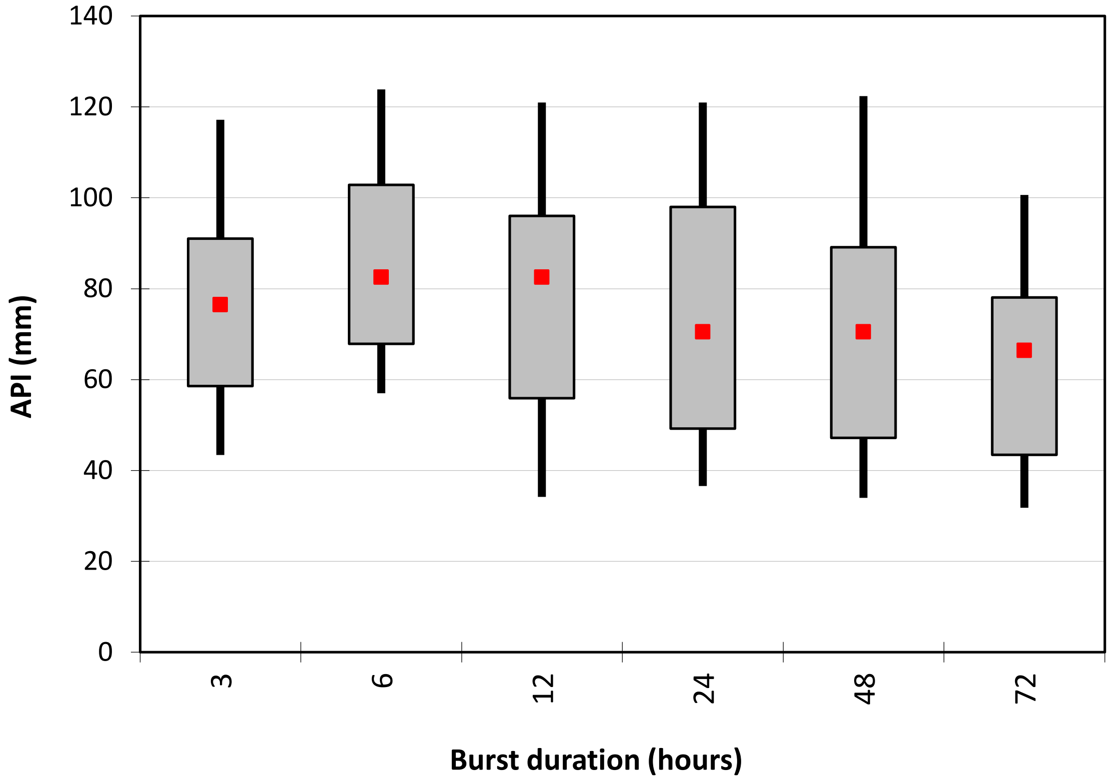


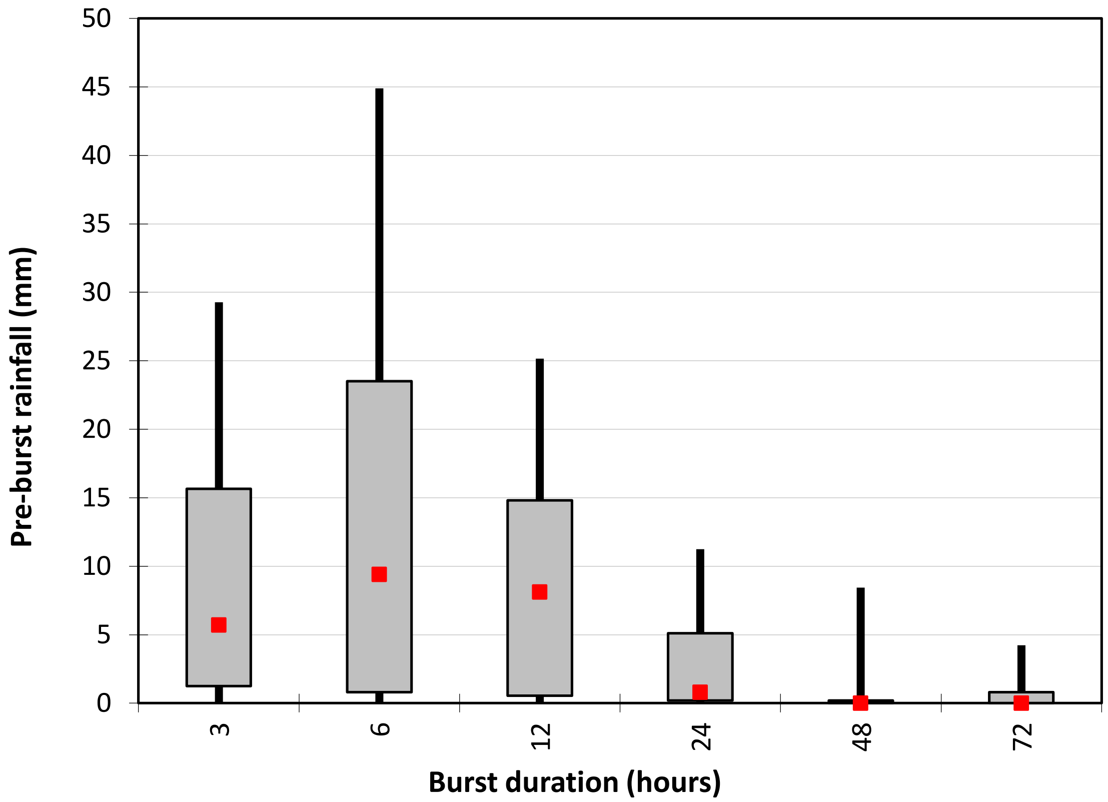
McMahons Creek @ U/S Weir (VIC)



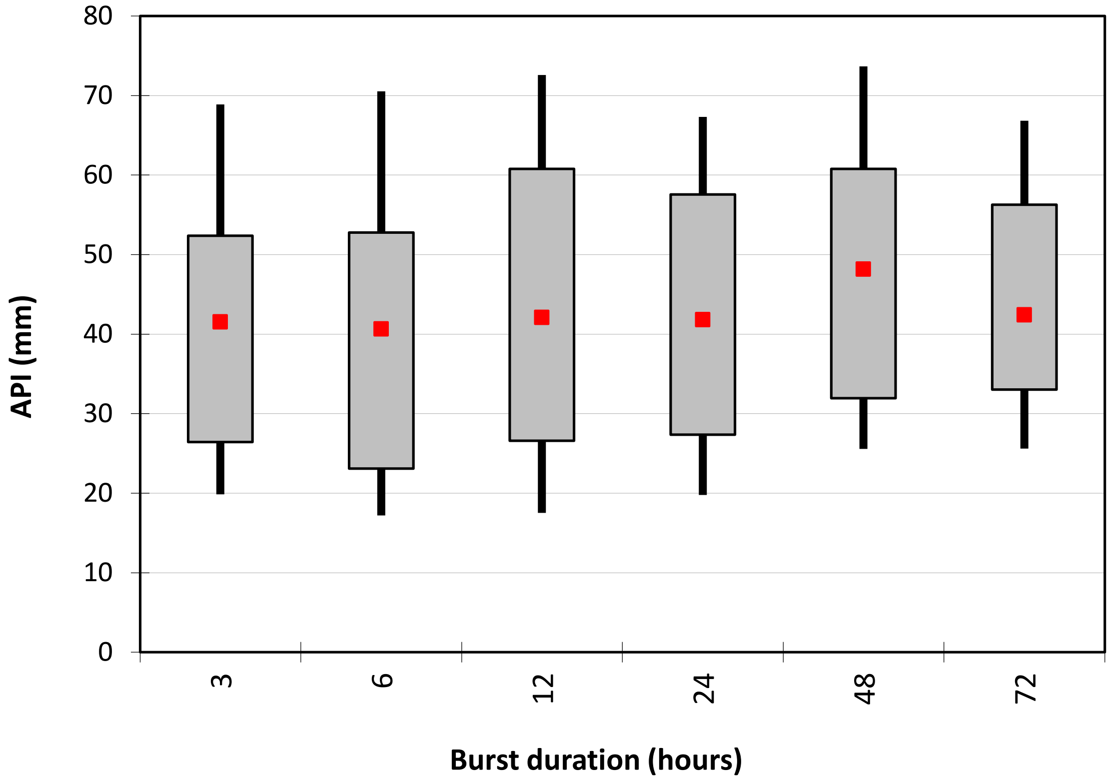


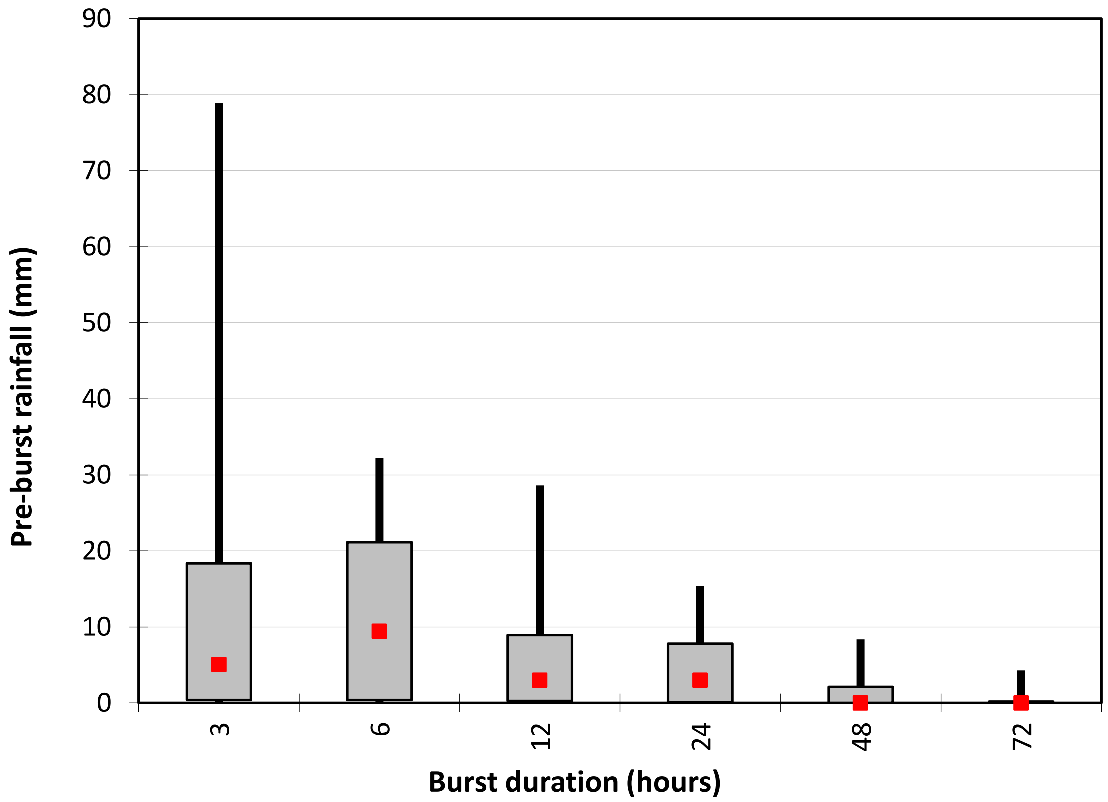
Tarago @ Neerim (VIC)



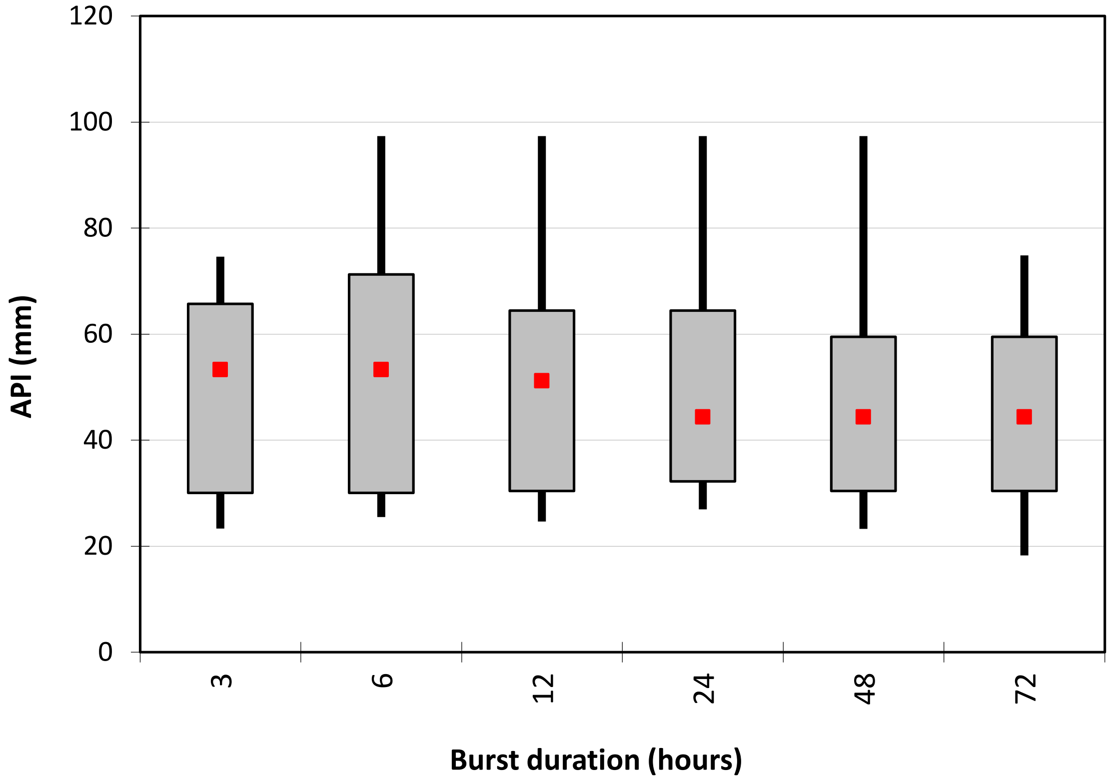


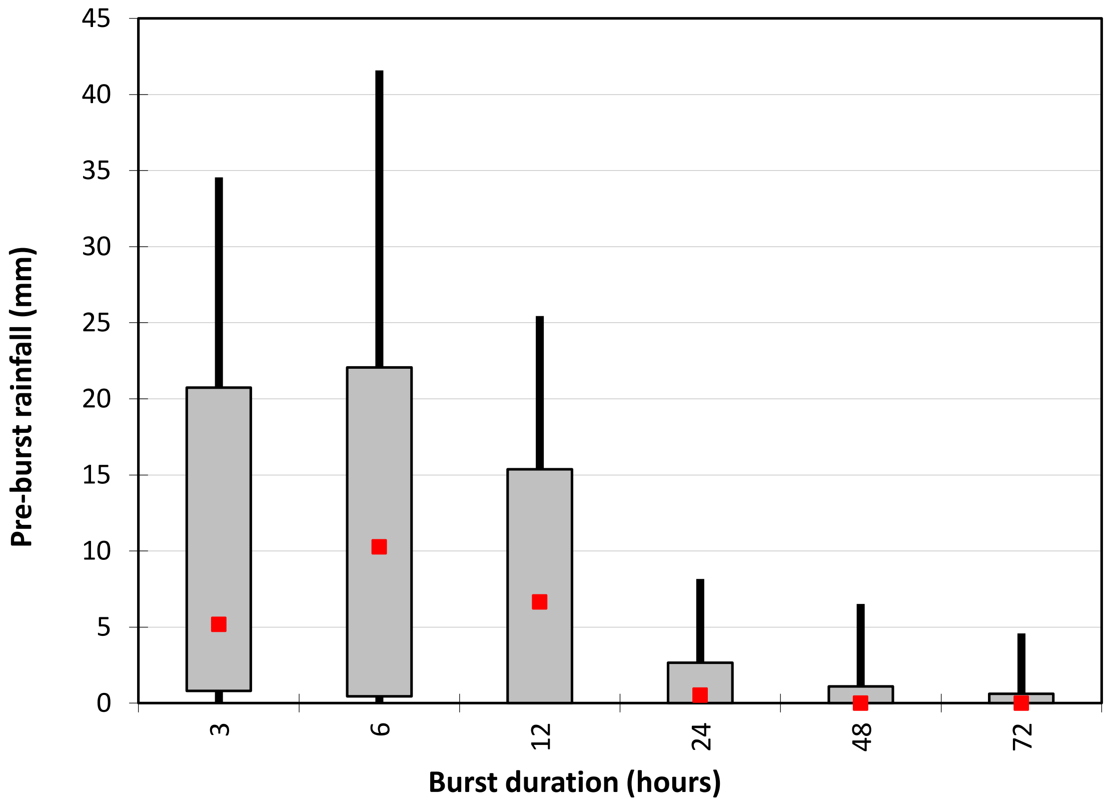
Toomuc Creek @ Pakenham (VIC)



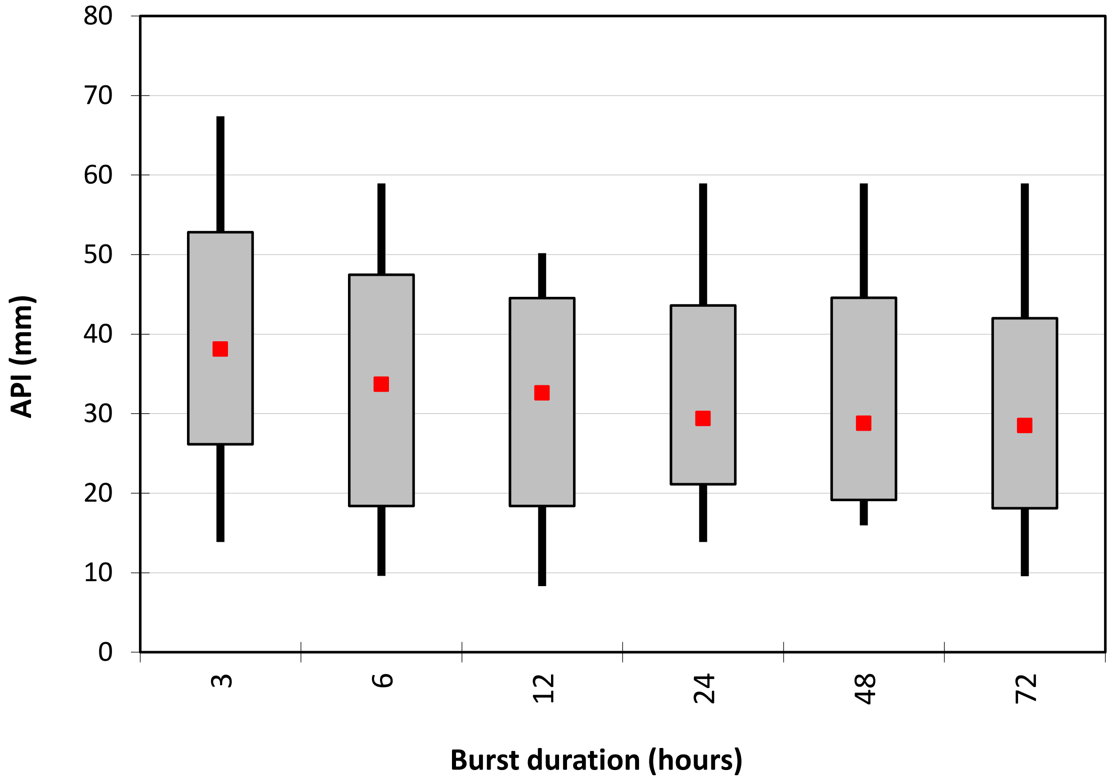


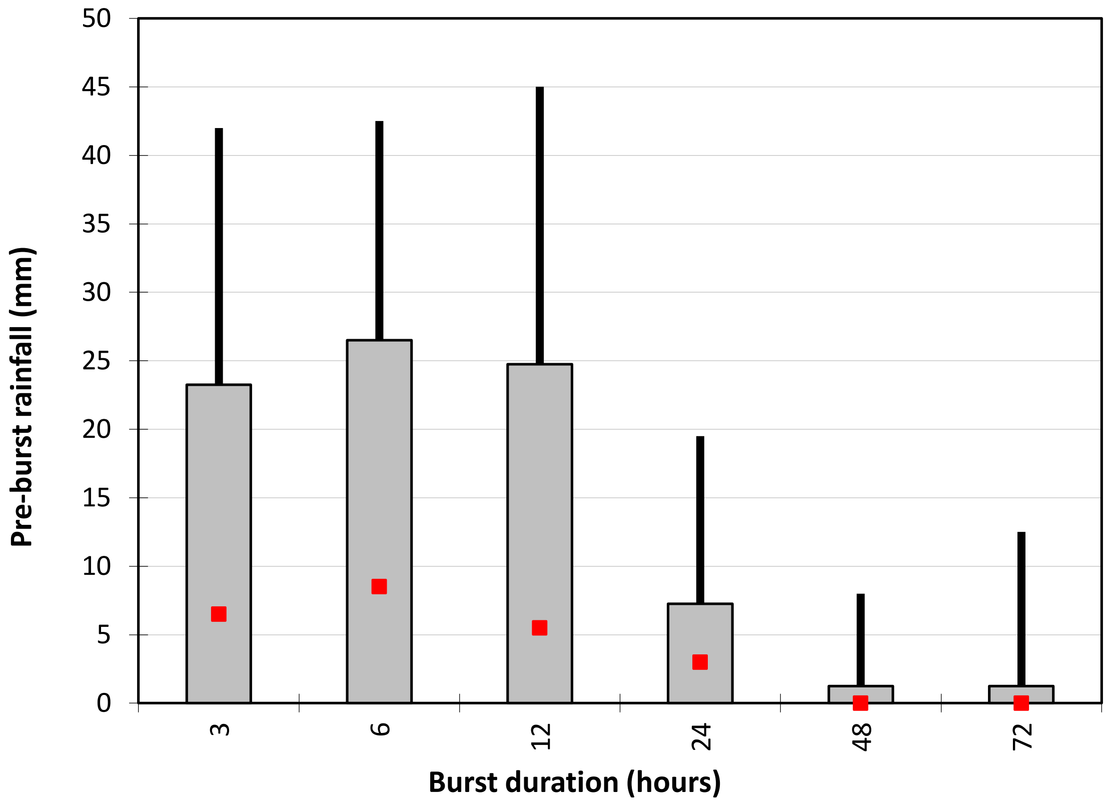
Jerrabomberra Creek @ Four Mile Creek (ACT)



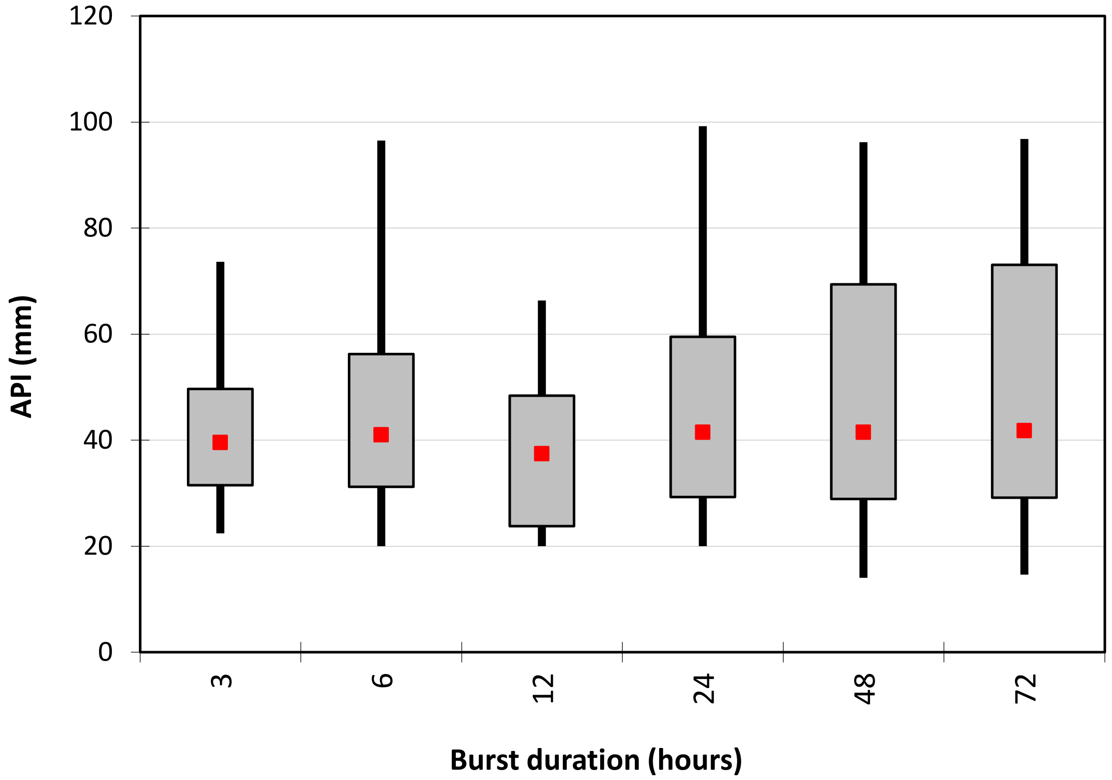


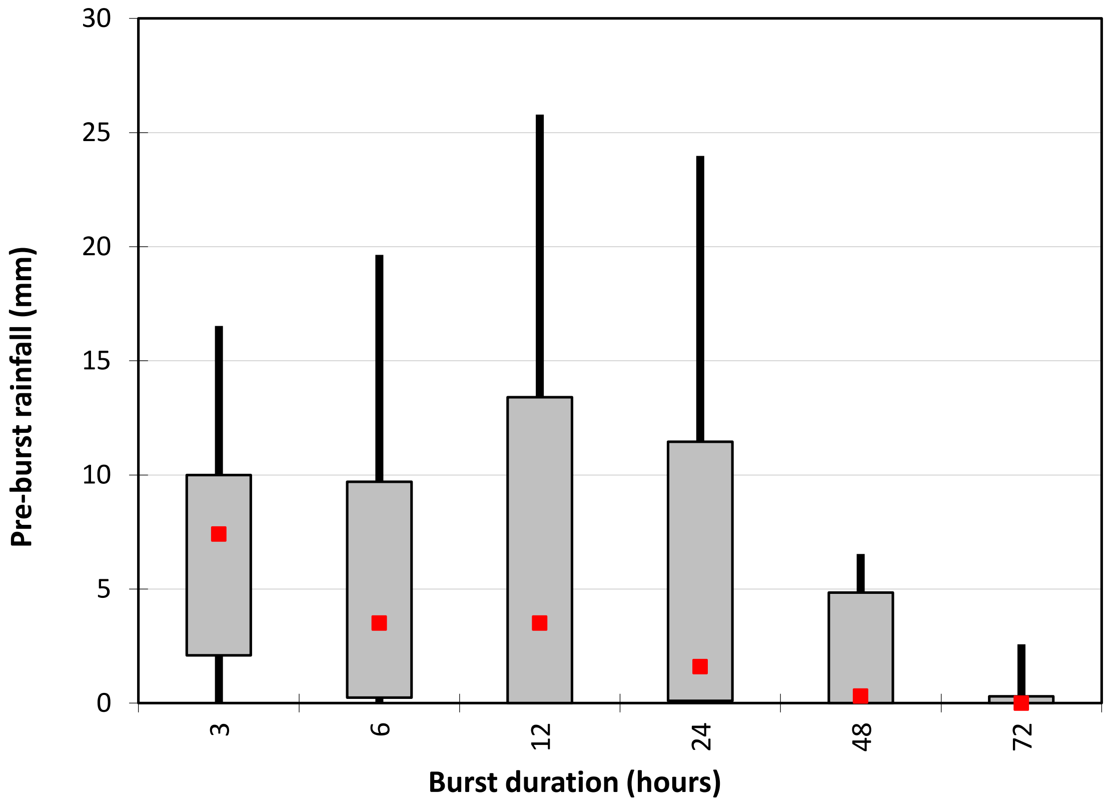
Butmaroo Ck @ Butmaroo (NSW)



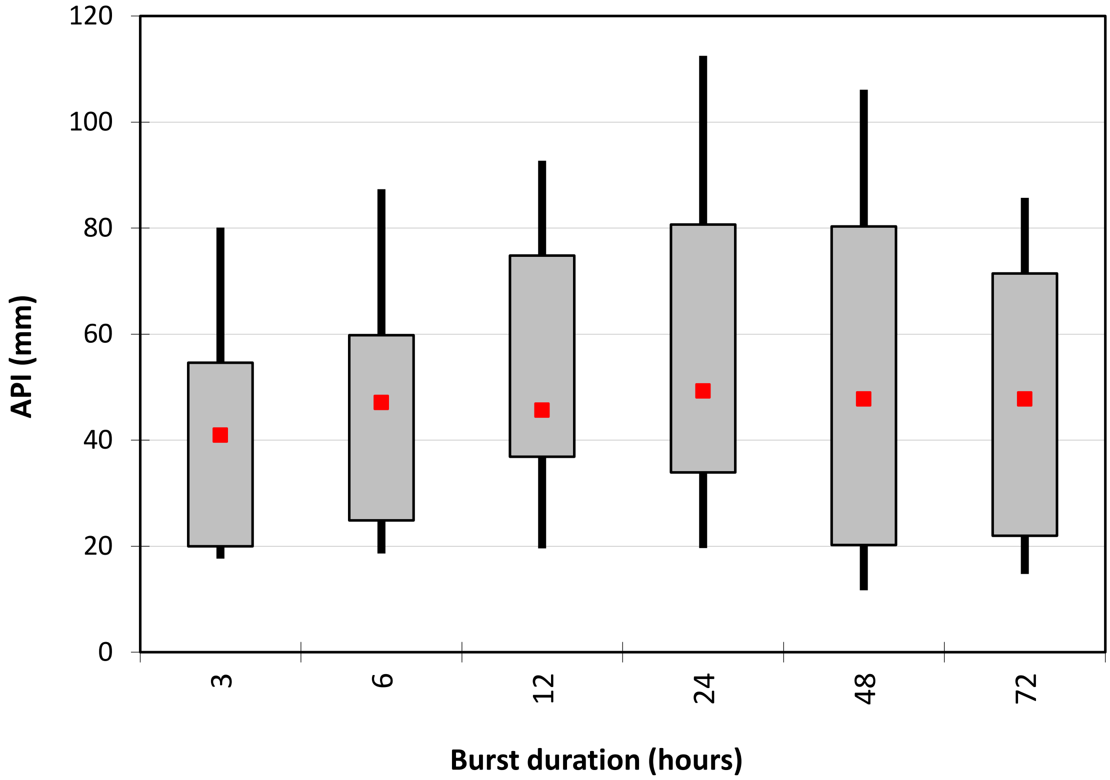


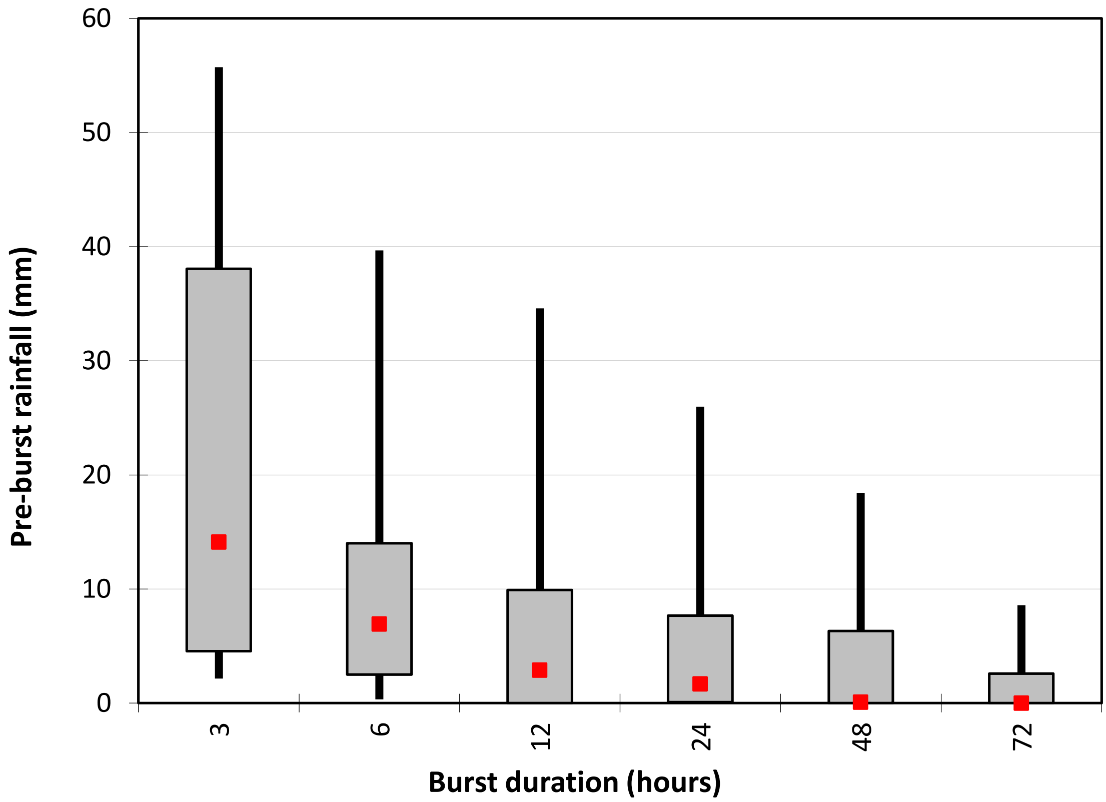
Echunga Creek @ U/S Mt Bold Res. (SA)



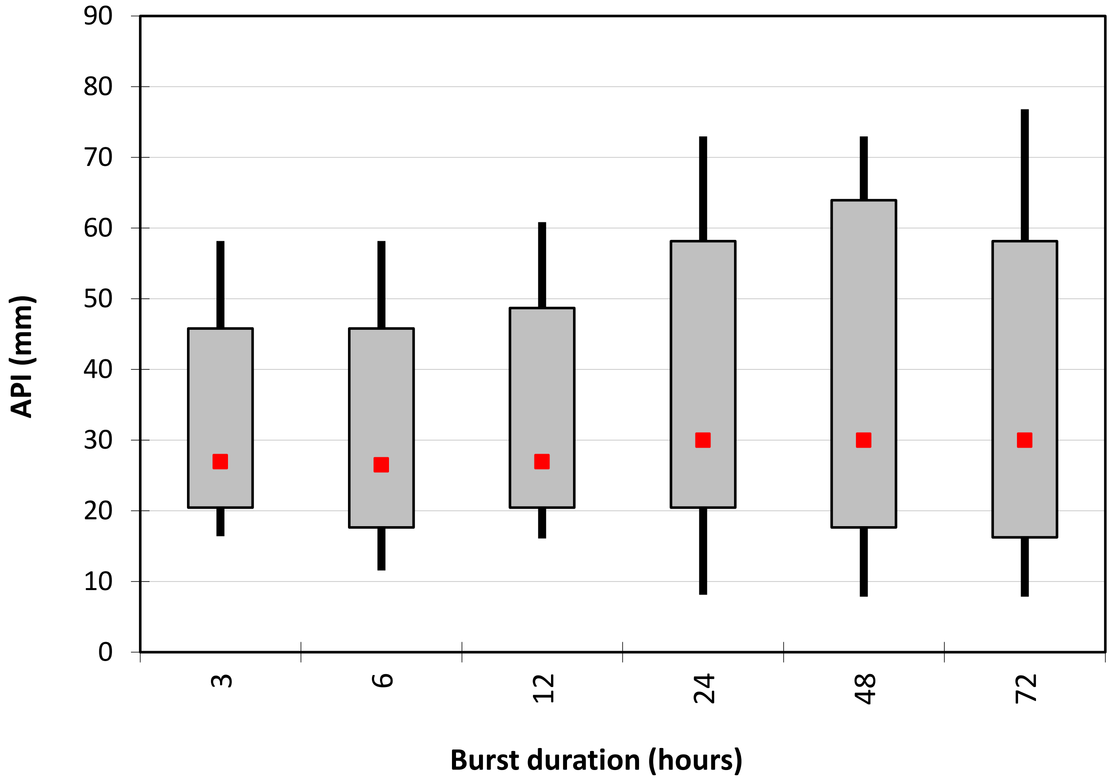


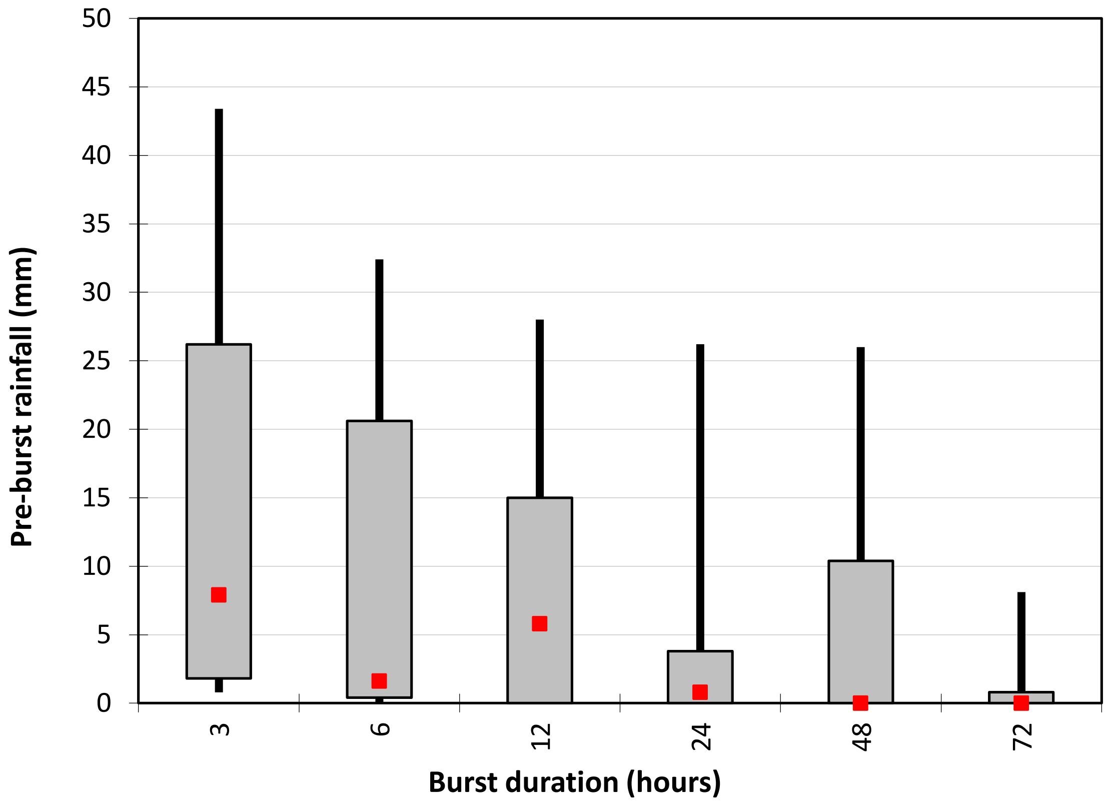
Hindmarsh River @ Hindmarsh Vy Res Offtake (SA)



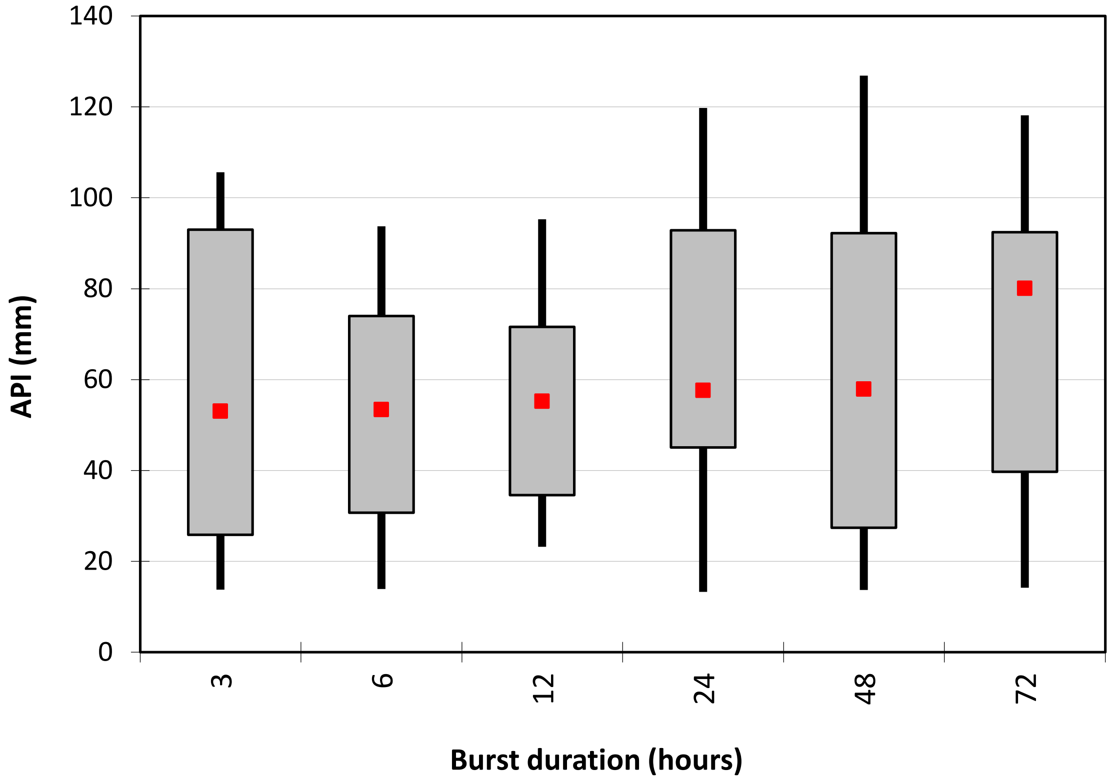


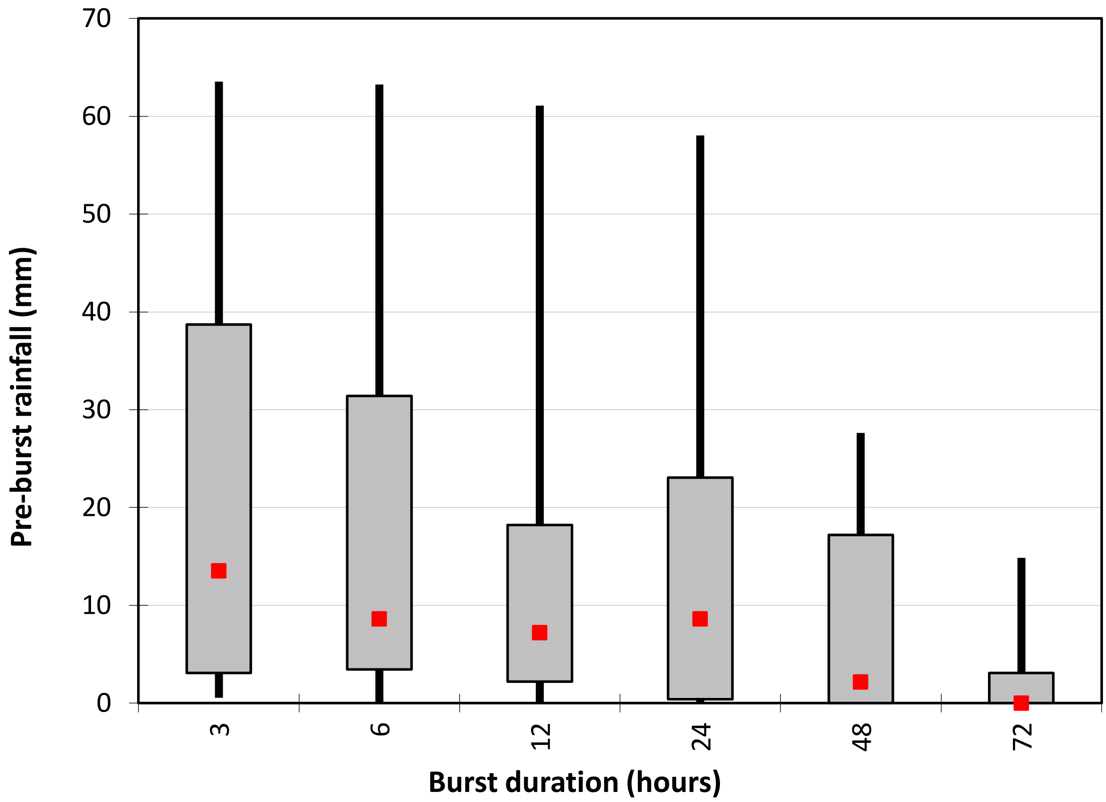
Myponga River @ U/S Dam and Rd Br (SA)



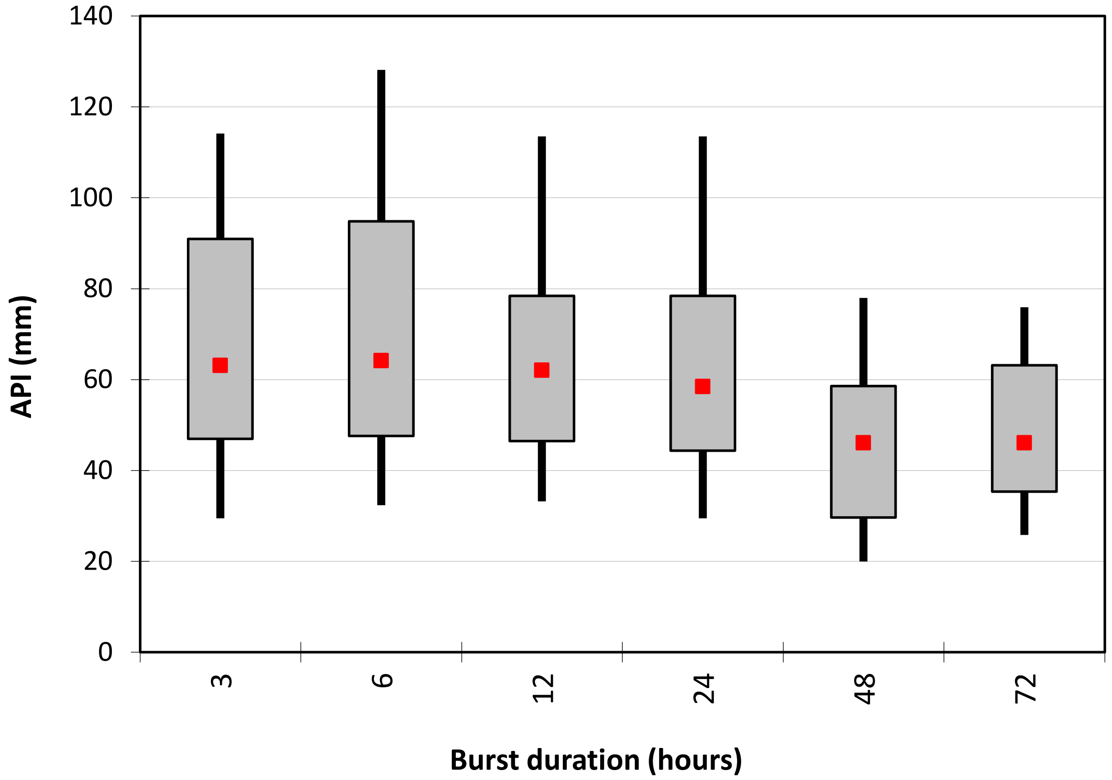


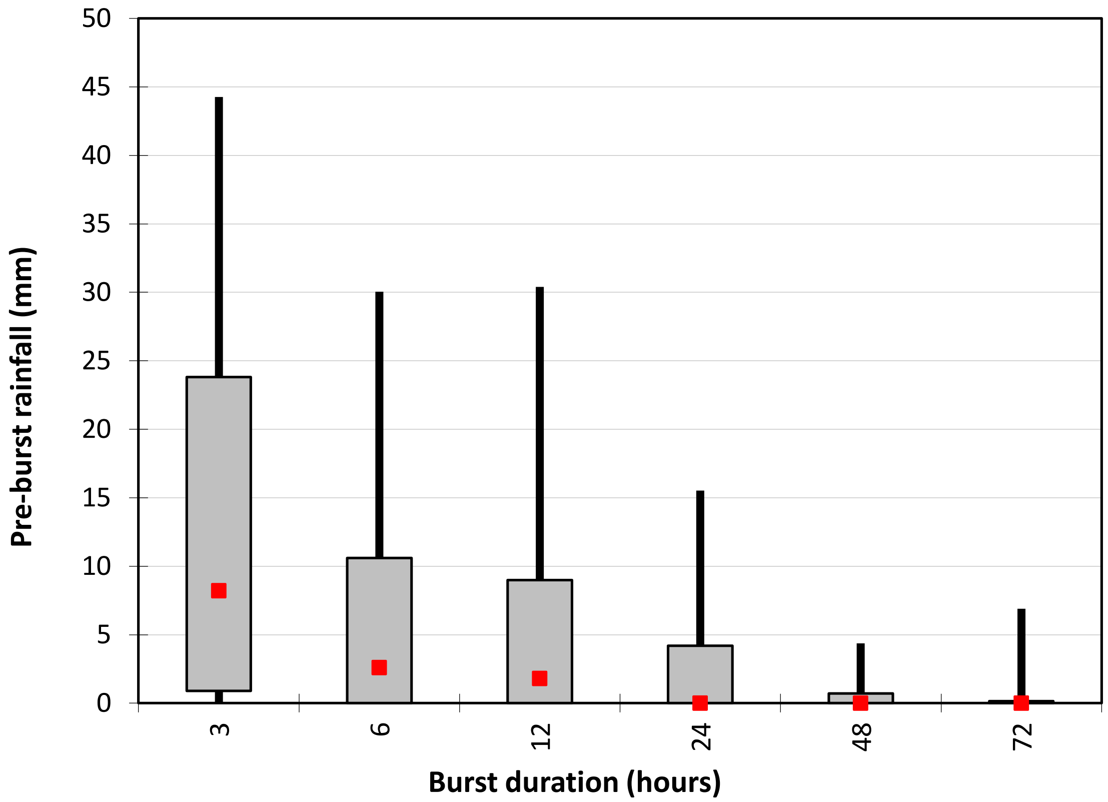
Sixth Creek @ Castambul (SA)



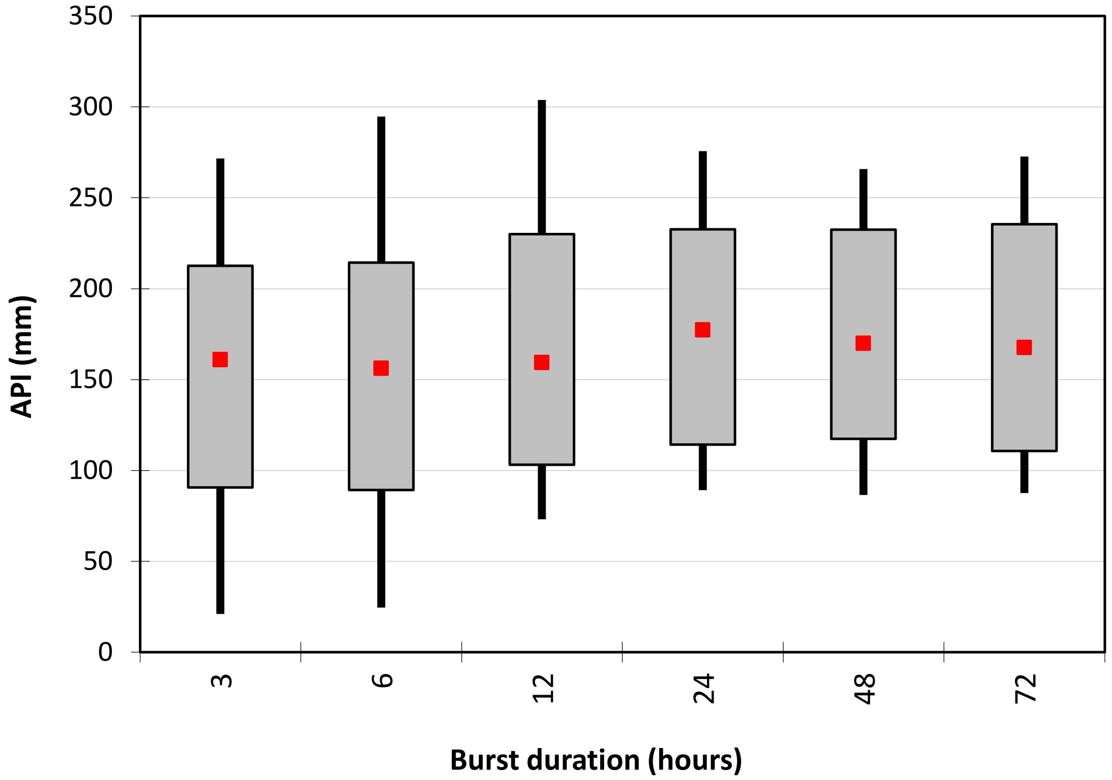


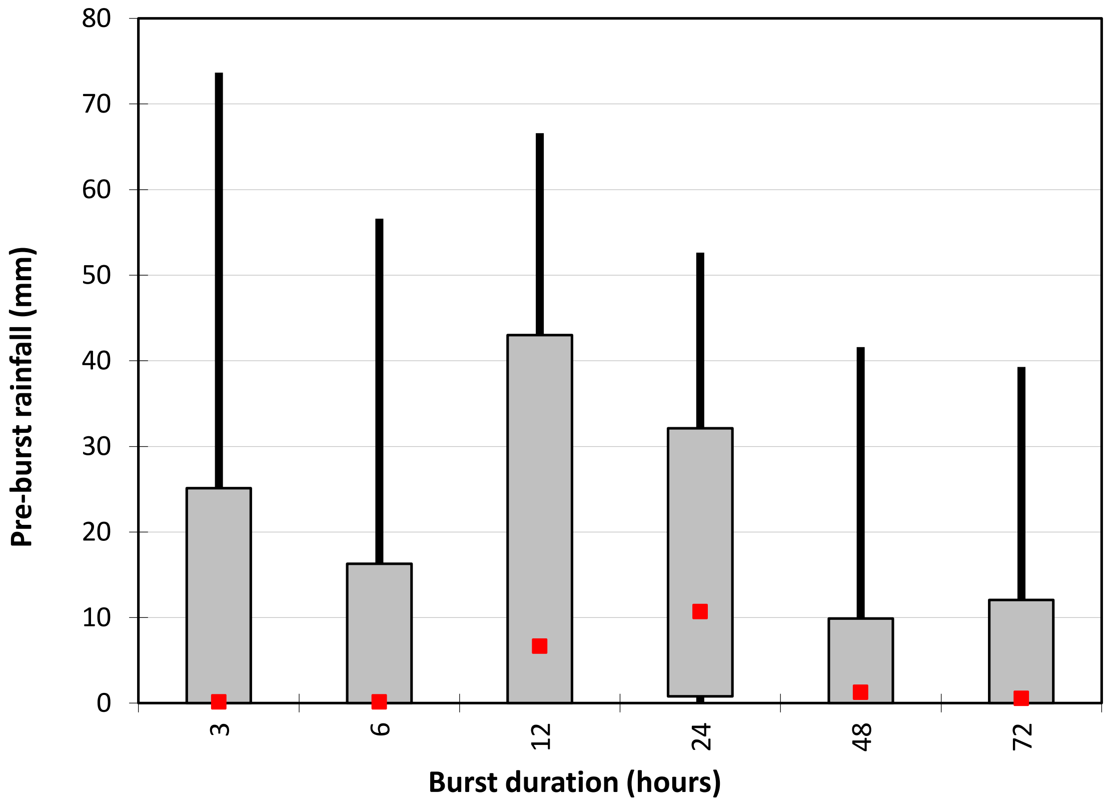
Axe Creek @ Sedgewick (VIC)



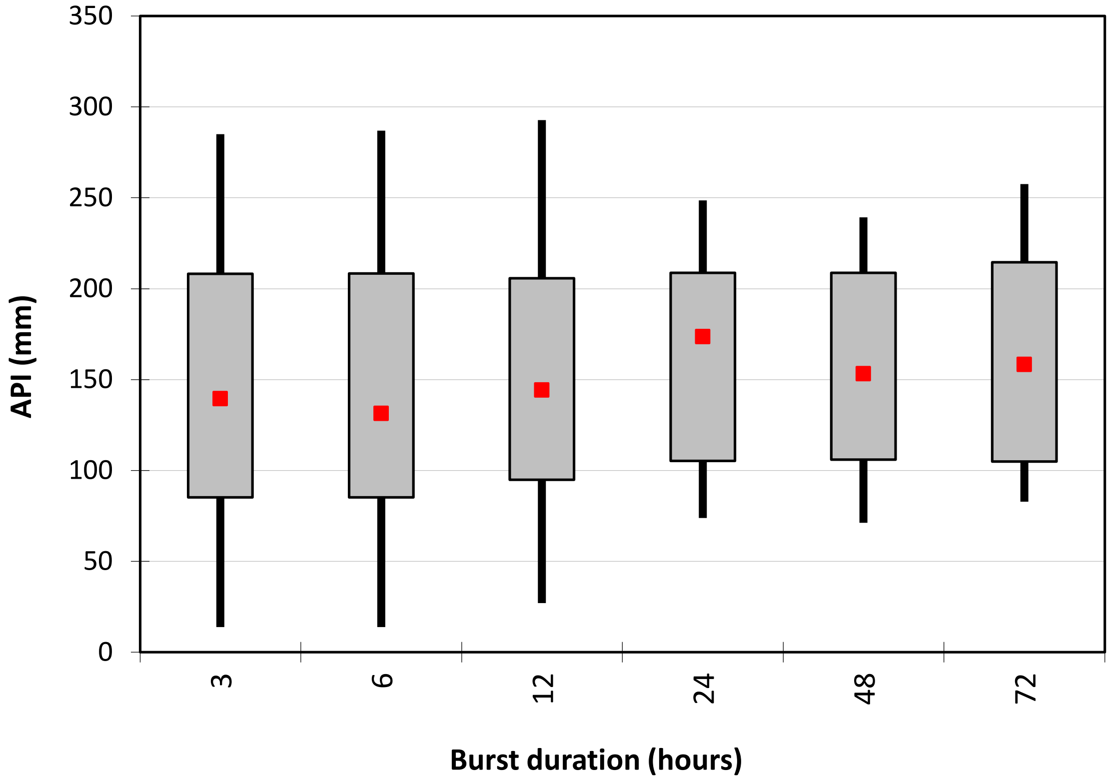


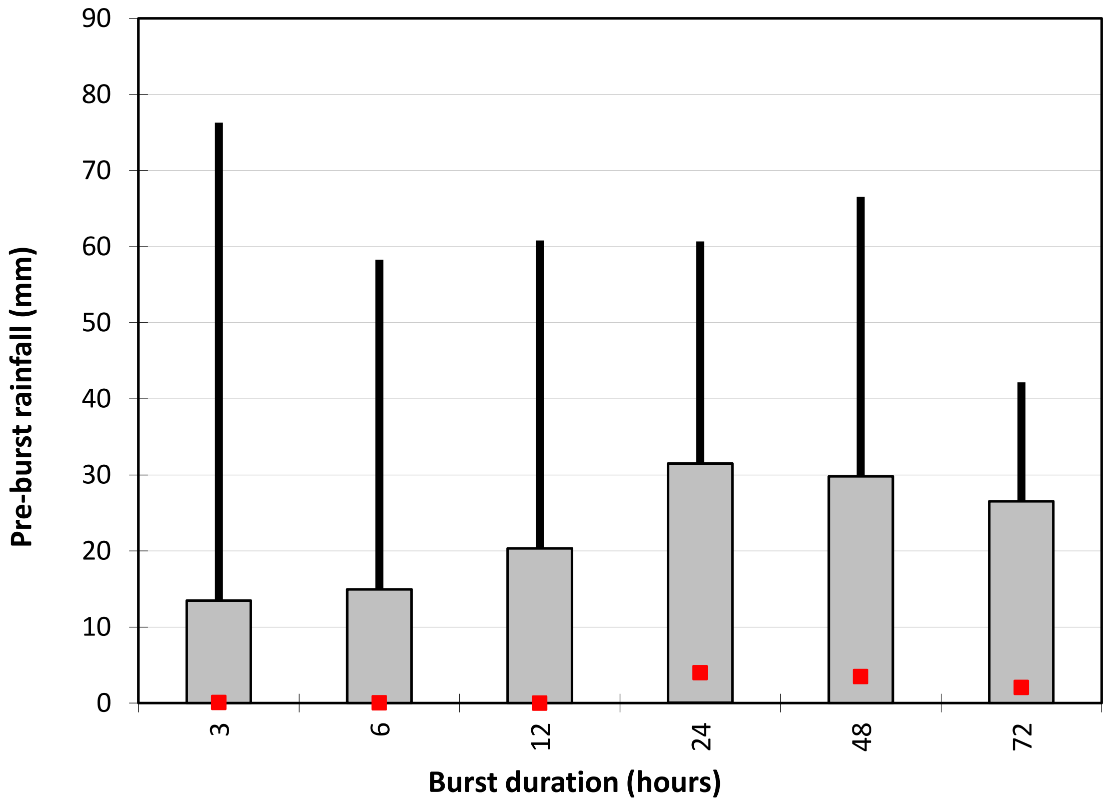
Celia Ck @ U/S Darwin R Dam (NT)



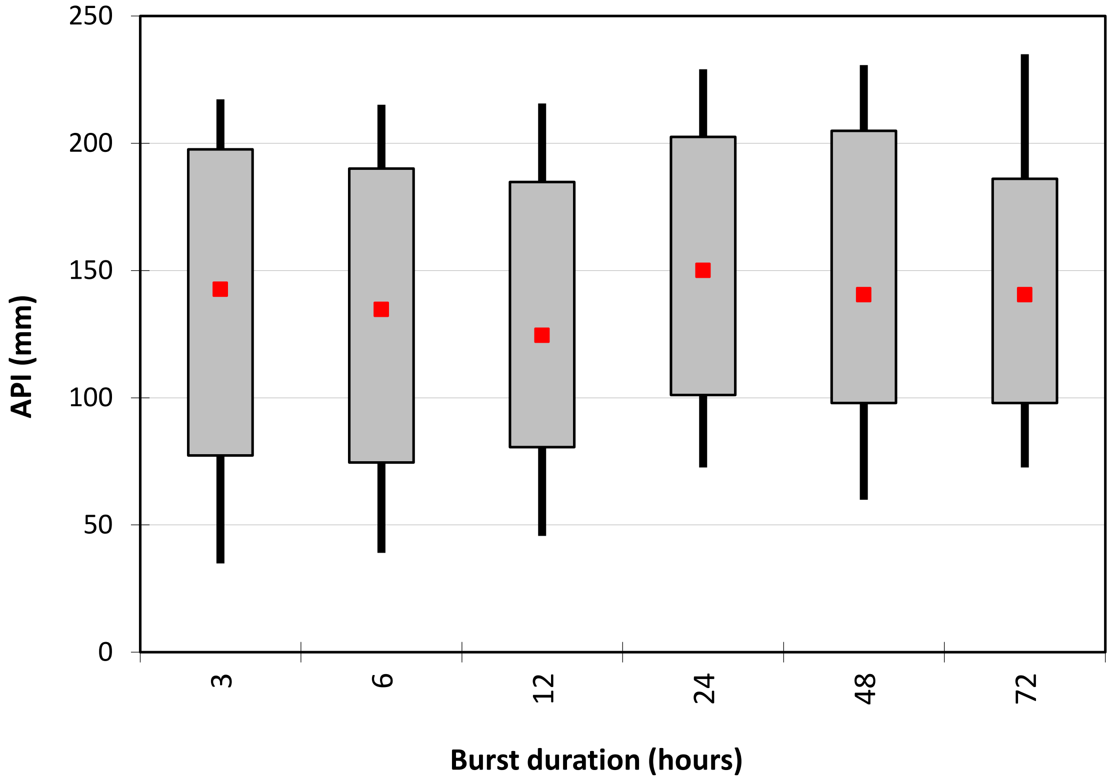


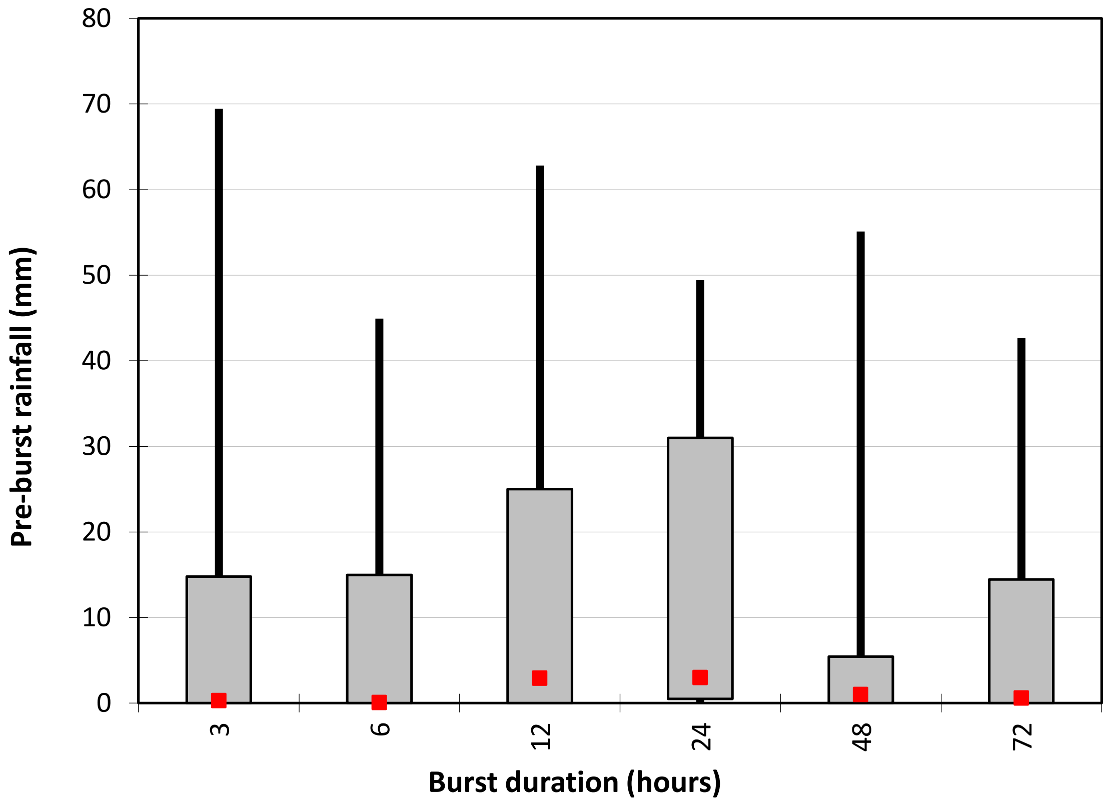
Coomalie @ Stuart Highway (NT)



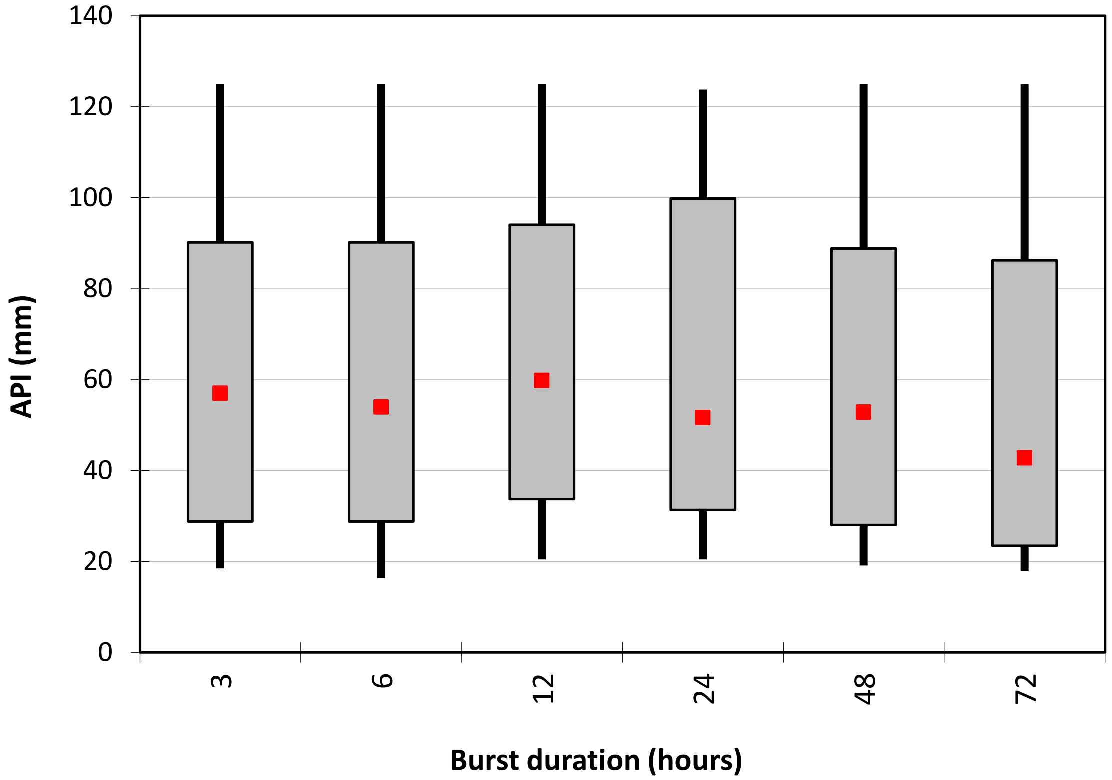


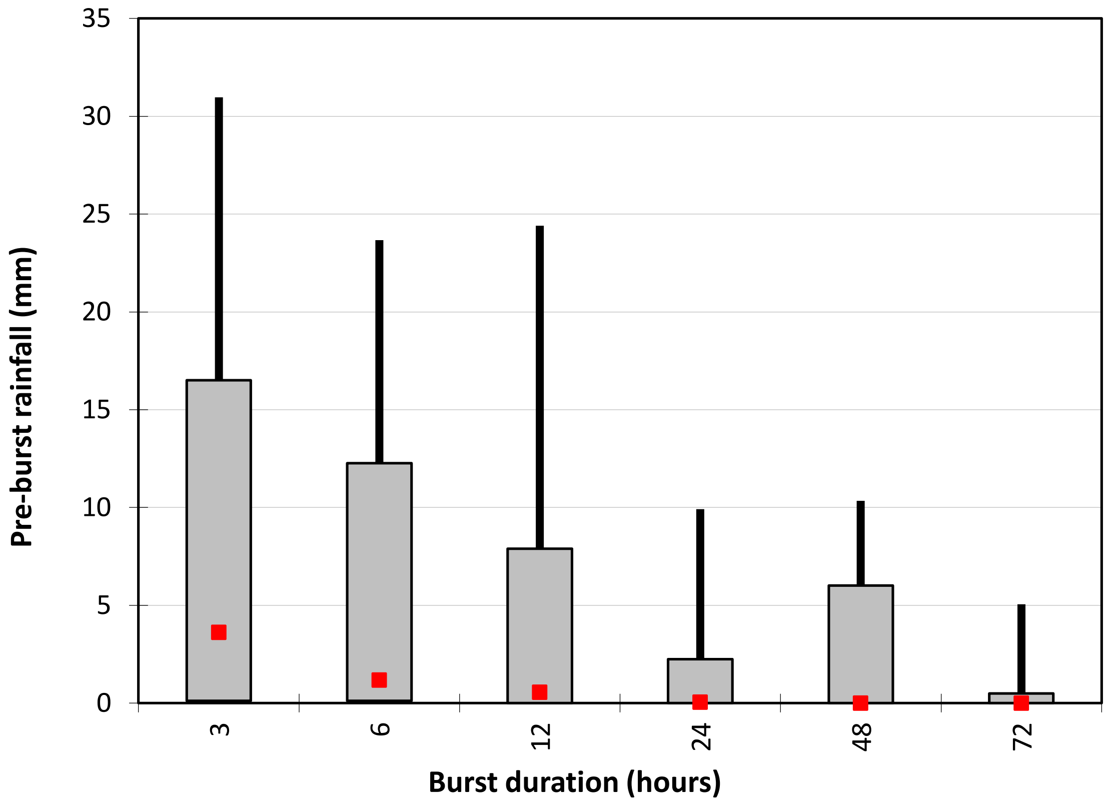
Manton River @ U/S Manton Dam (NT)



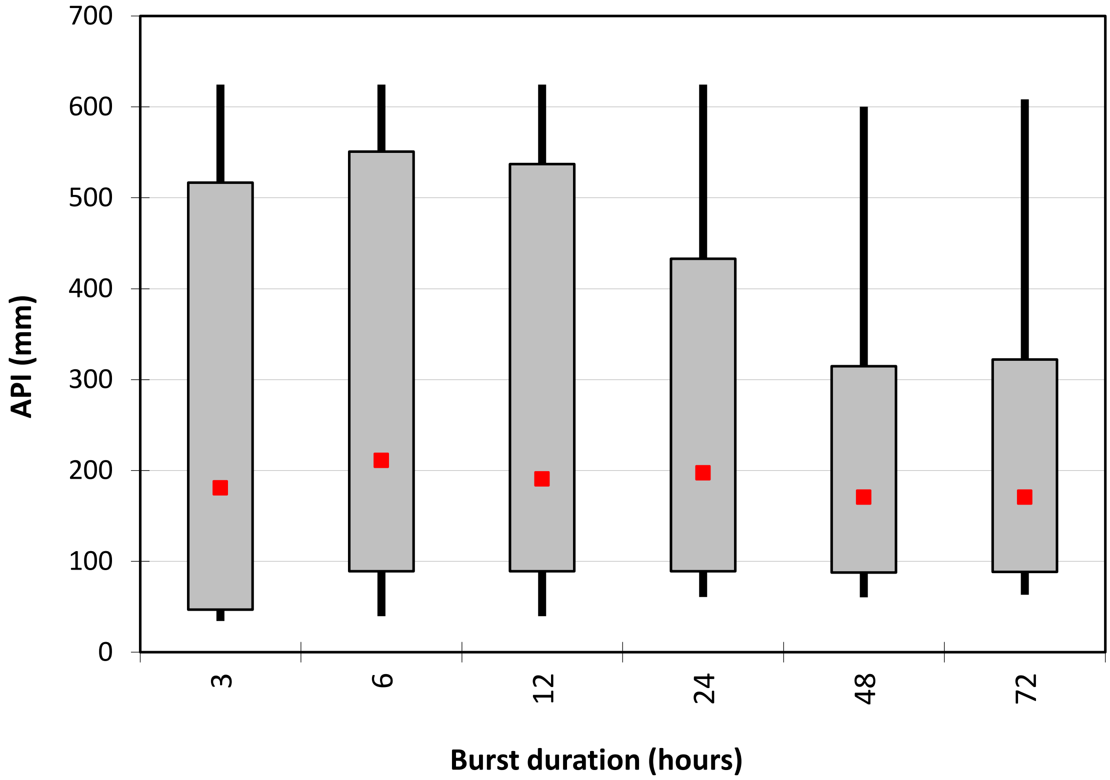


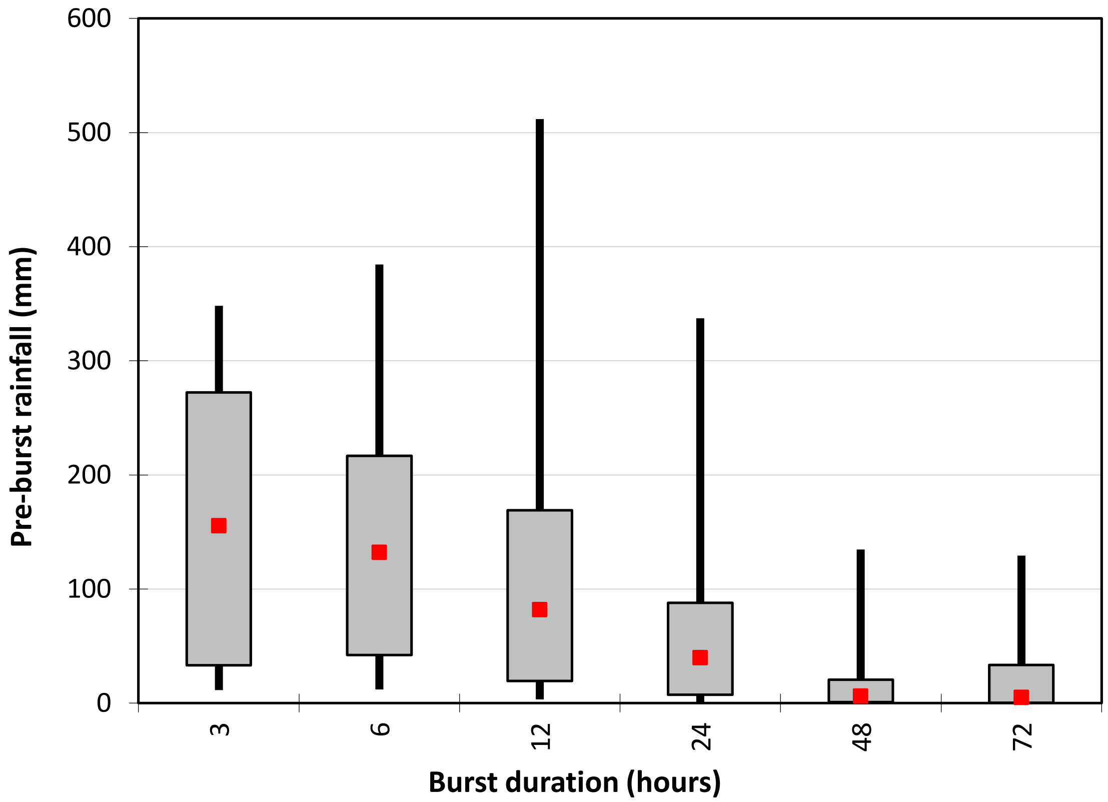
Tennant Ck @ Old Telegraph Station (NT)



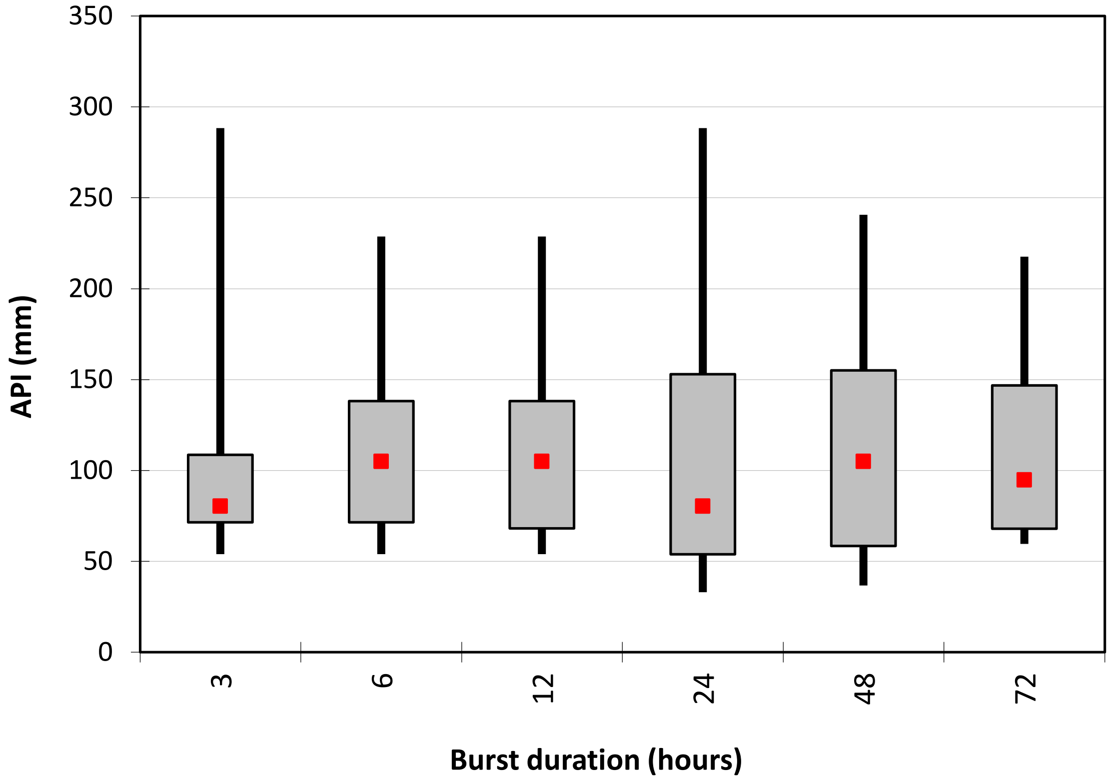


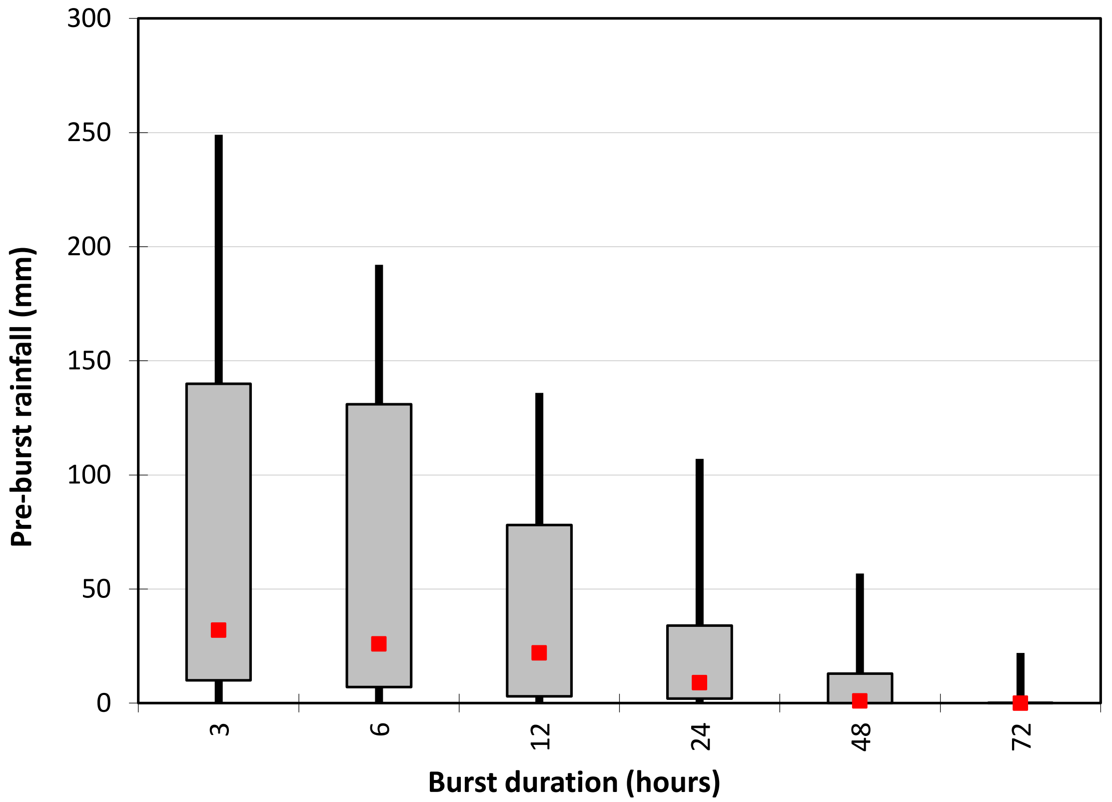
Broken River @ Old Racecourse (QLD)



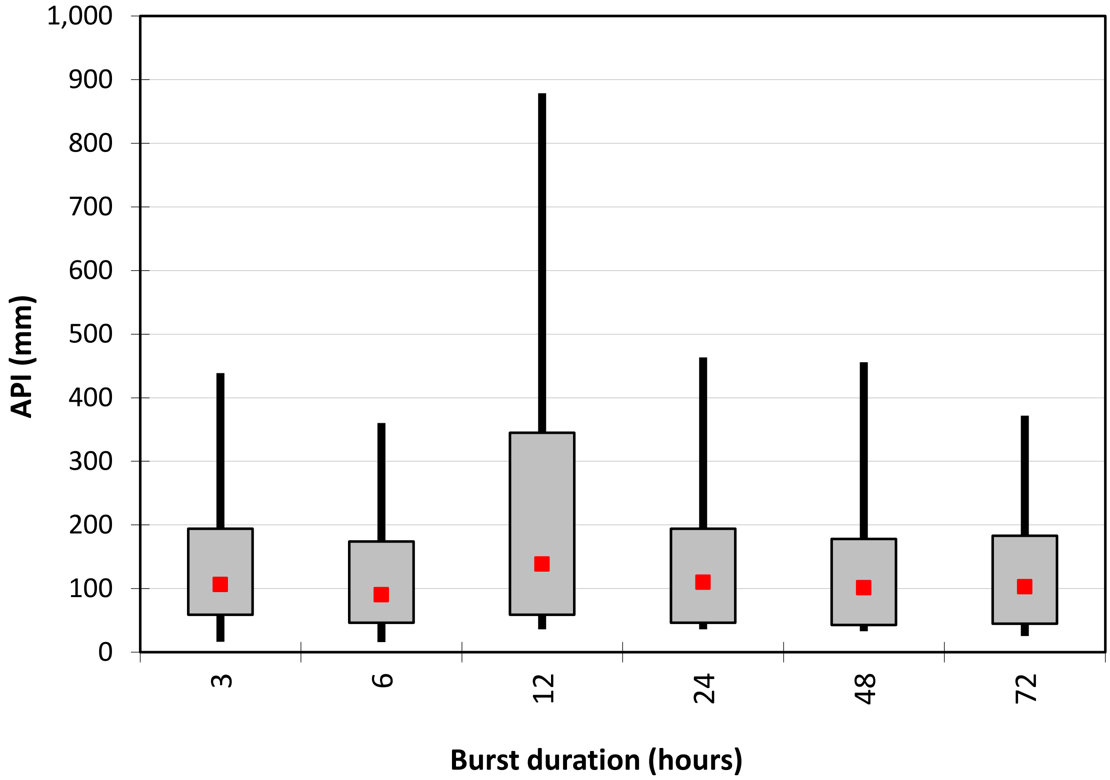


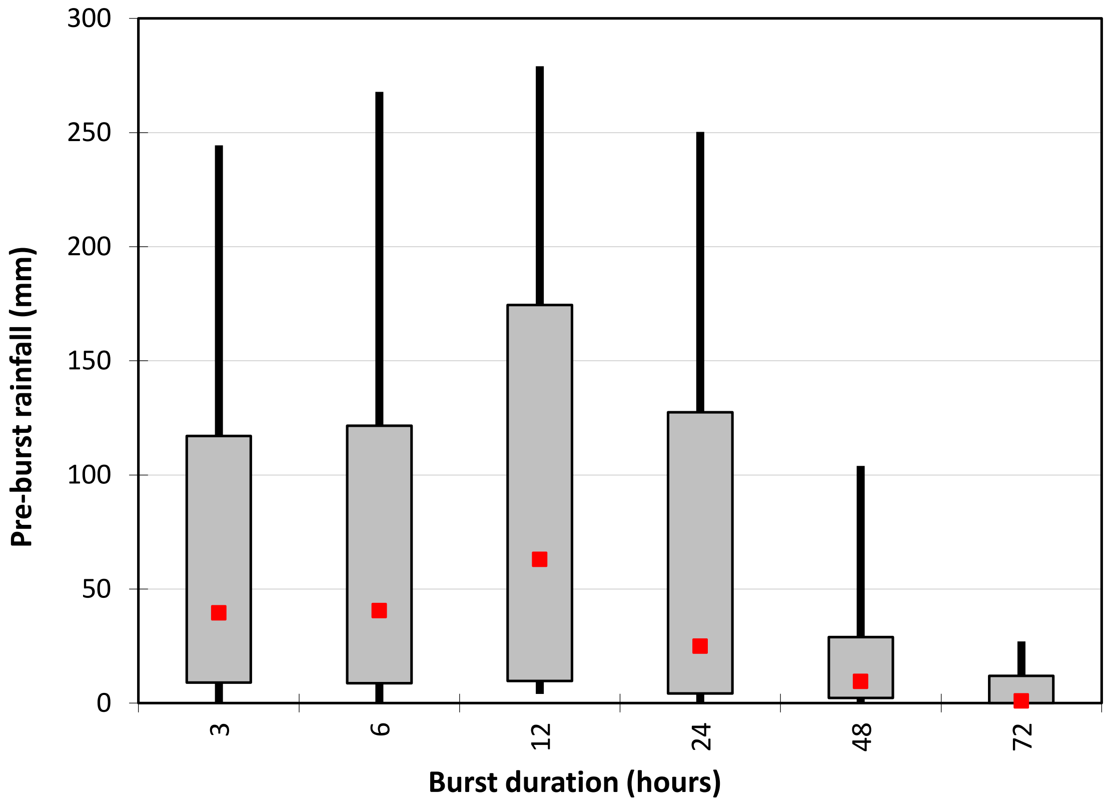
Caboolture River @ Upper Caboolture (QLD)



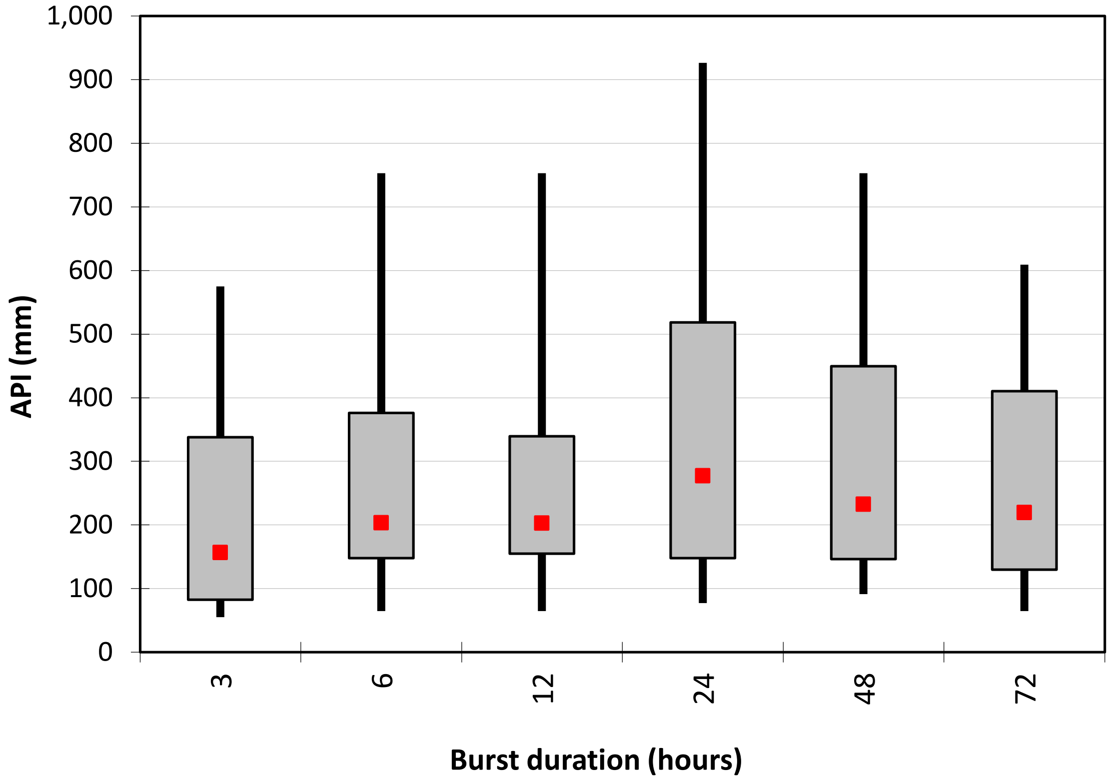


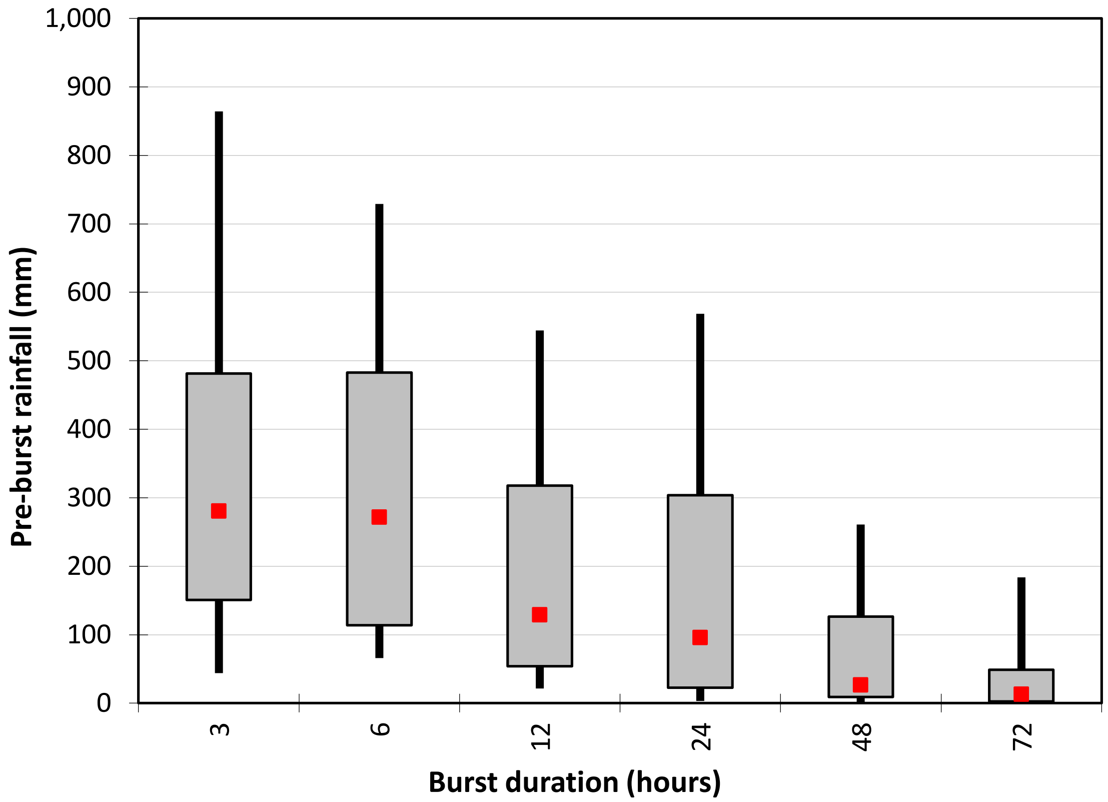
Carmila Creek @ Carmila (QLD)



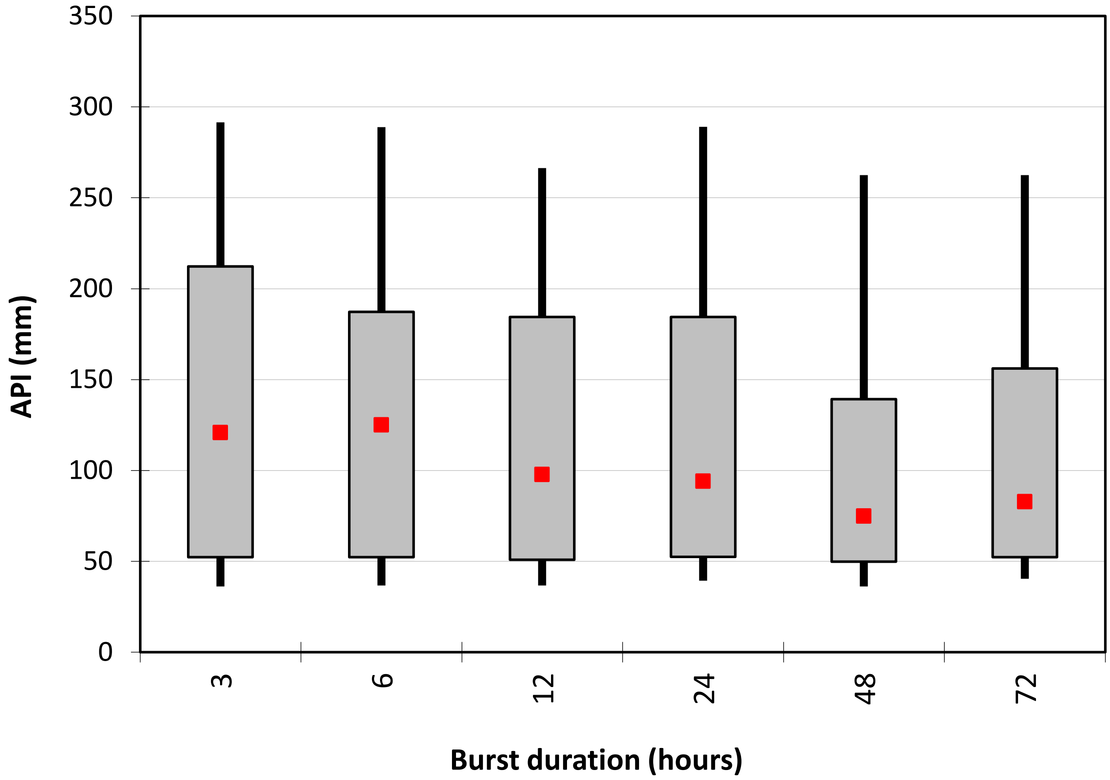


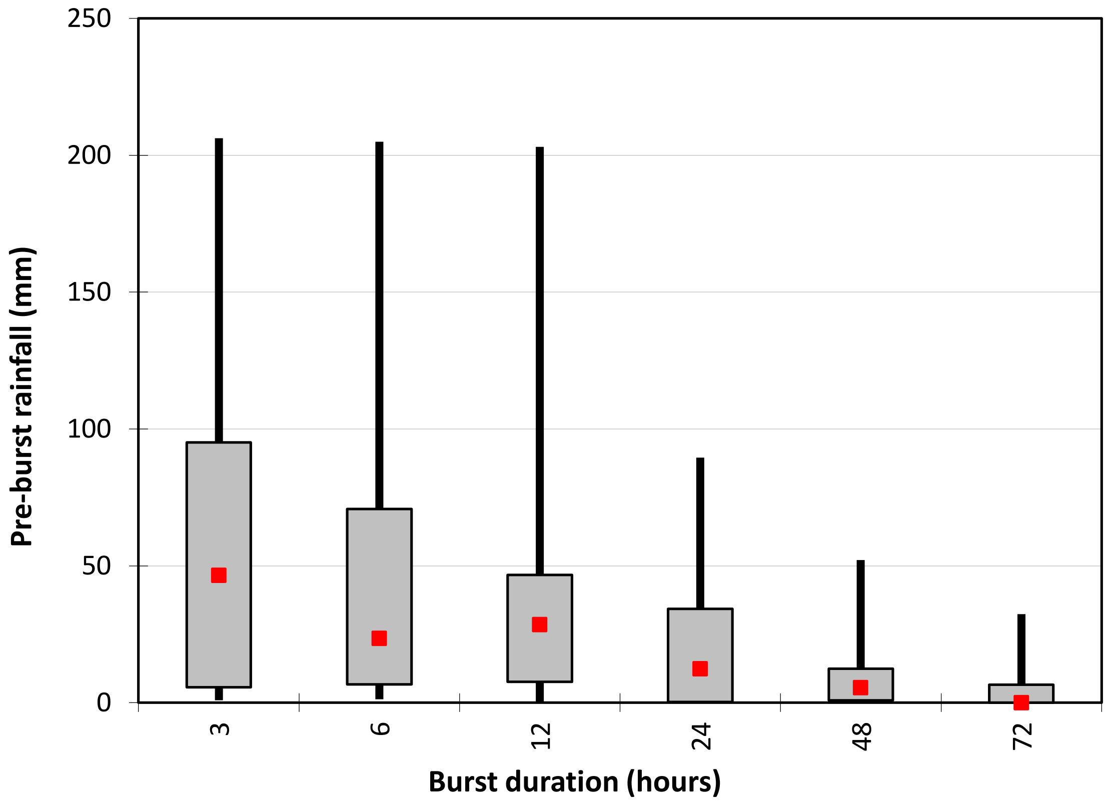
Finch Hatton Ck @ Dam Site (QLD)



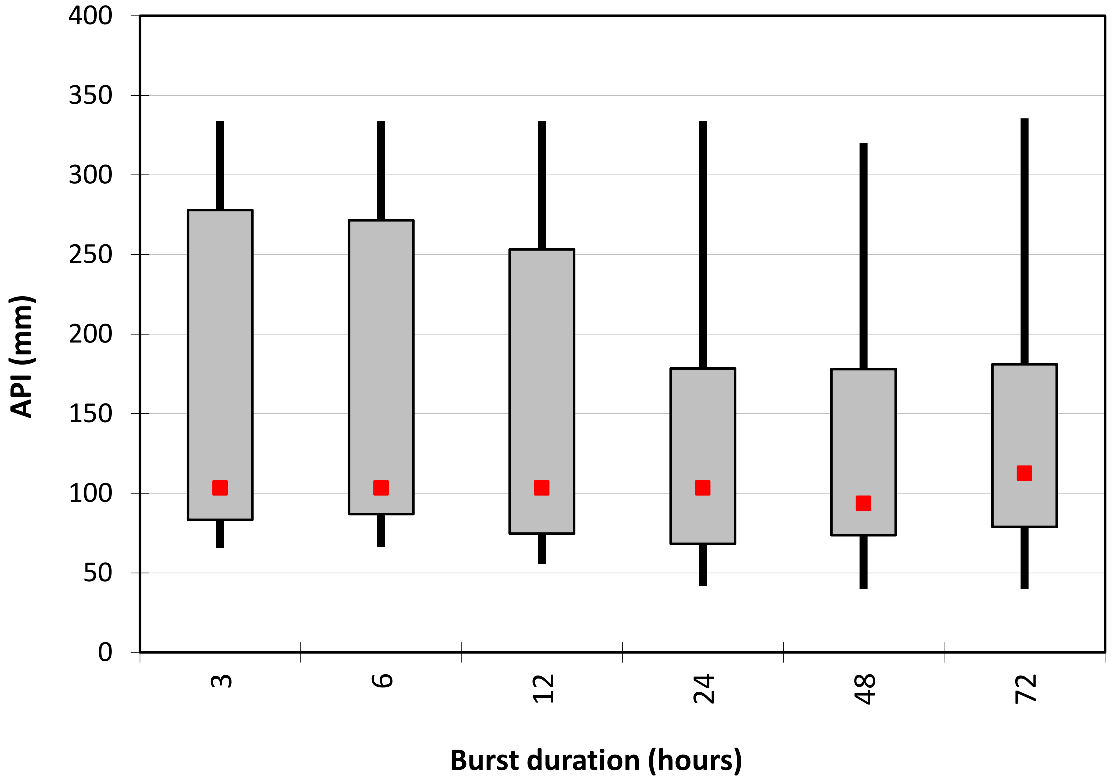


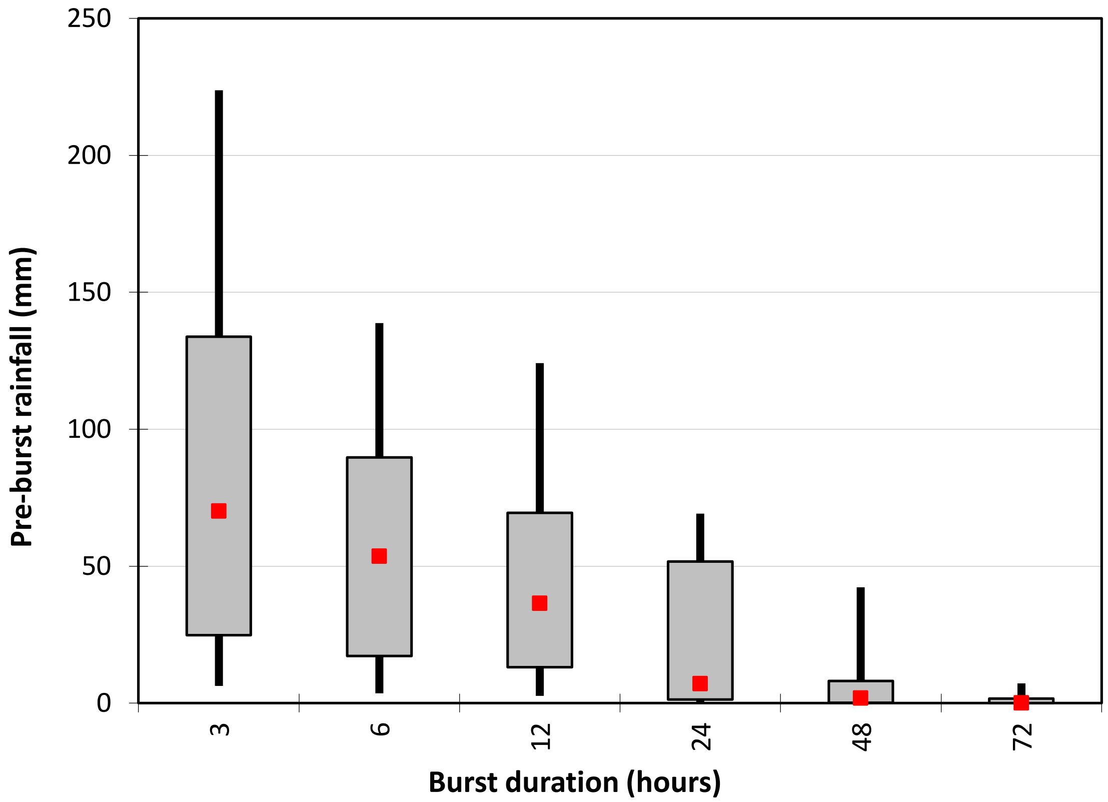
North Maroochy River @ Eumundi (QLD)



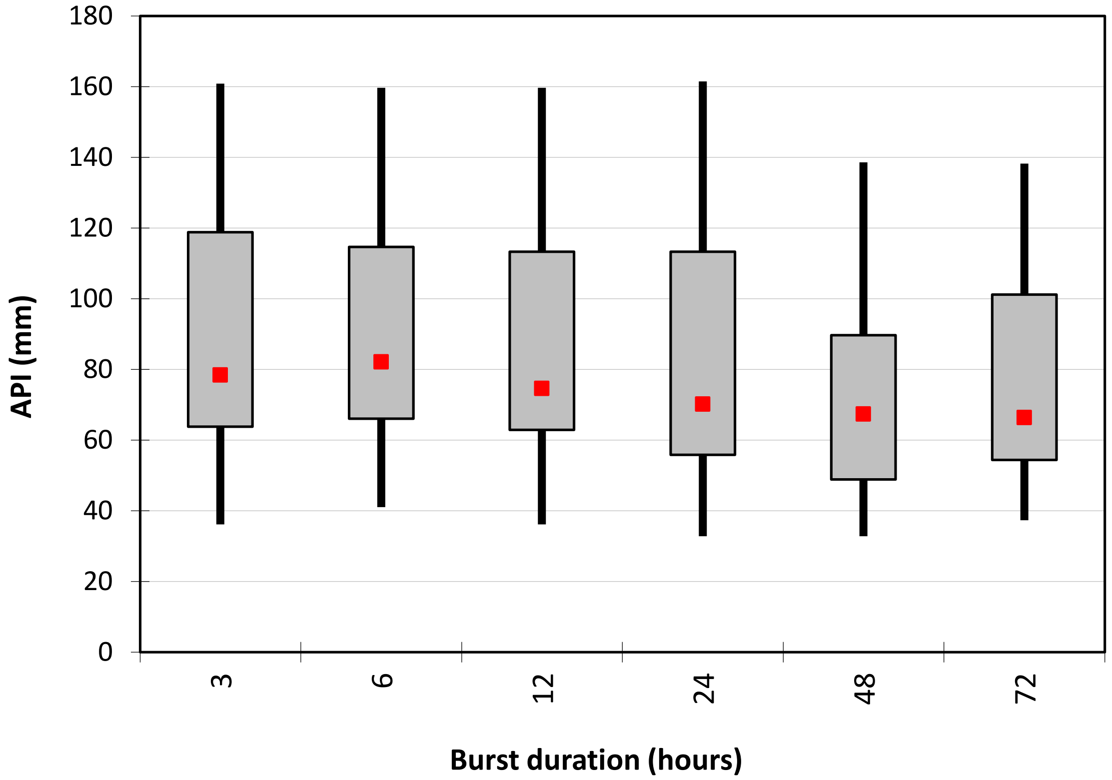


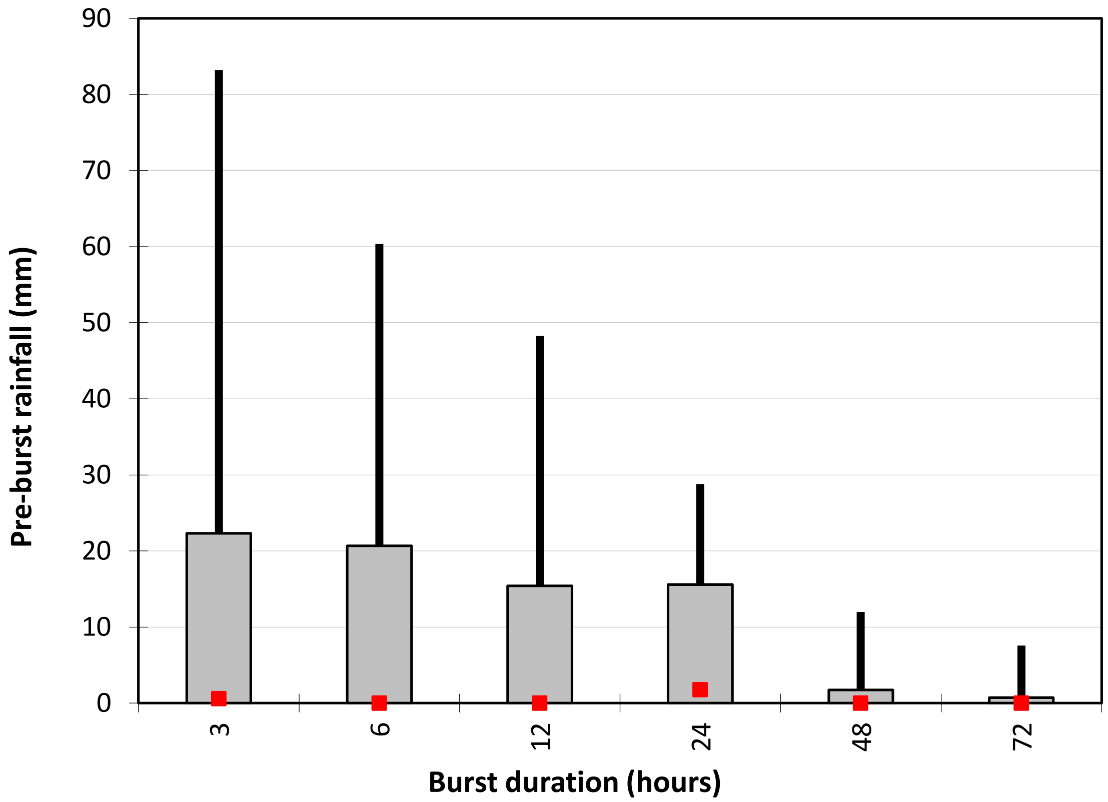
South Maroochy @ Kiamba (QLD)



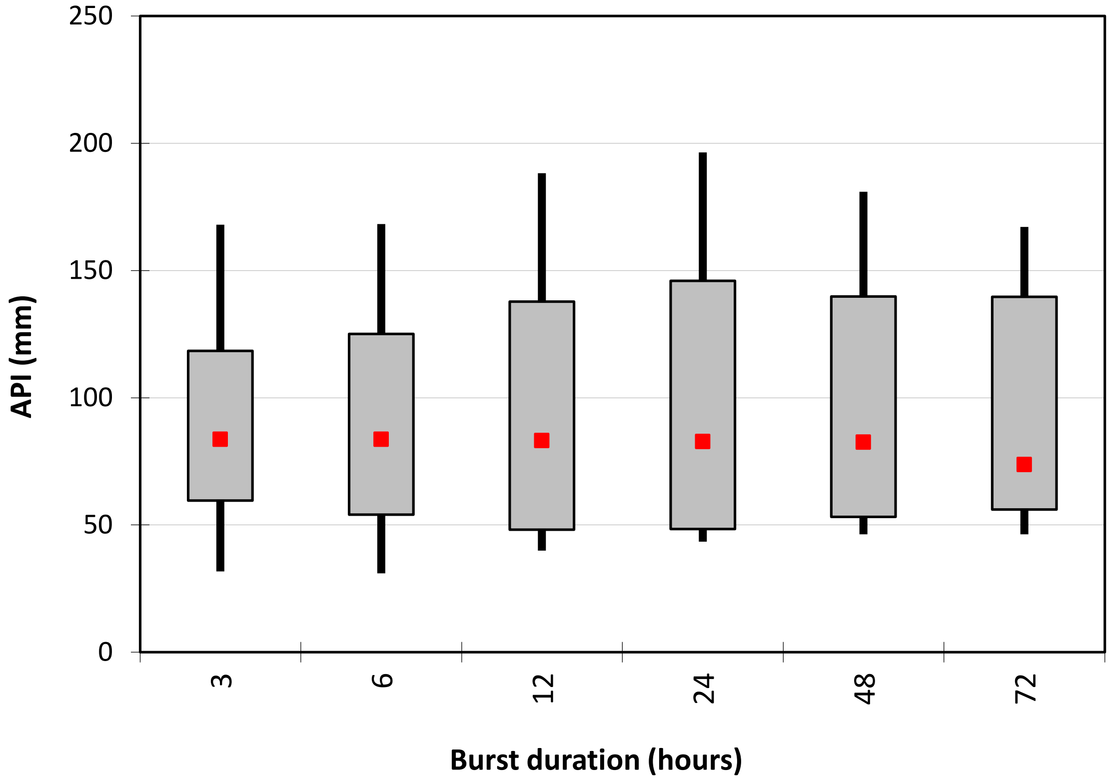


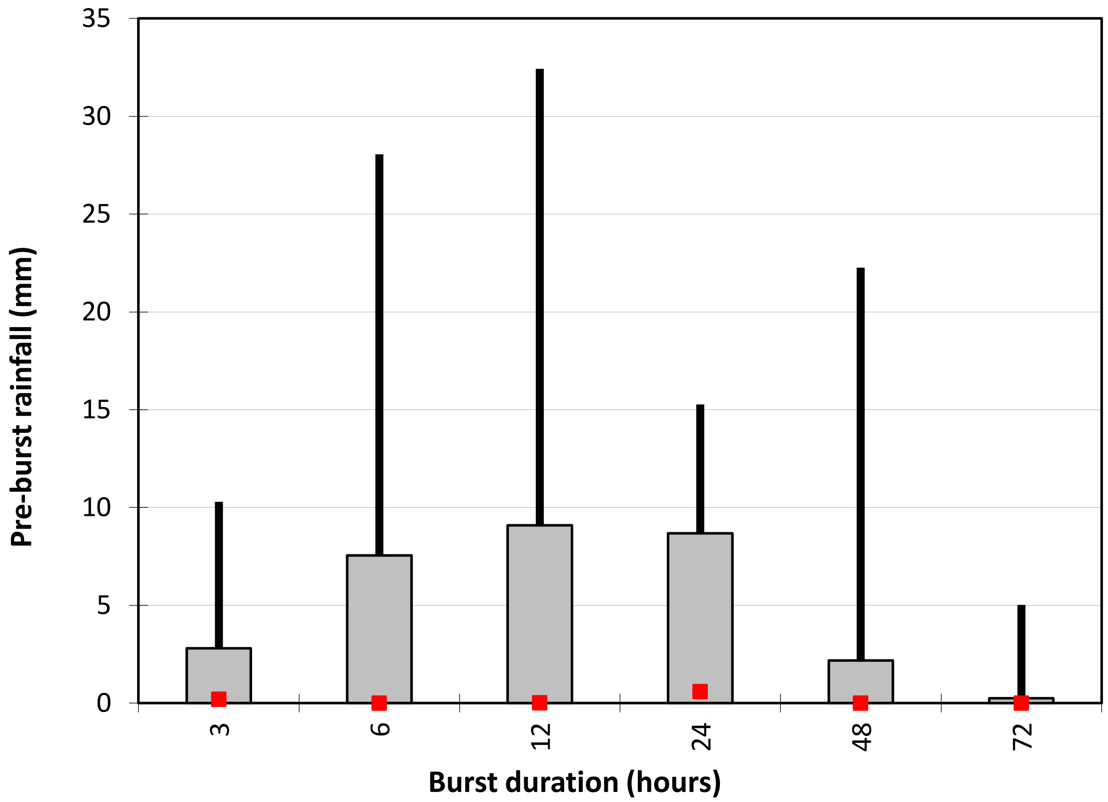
Spring Creek @ Killarney (QLD)



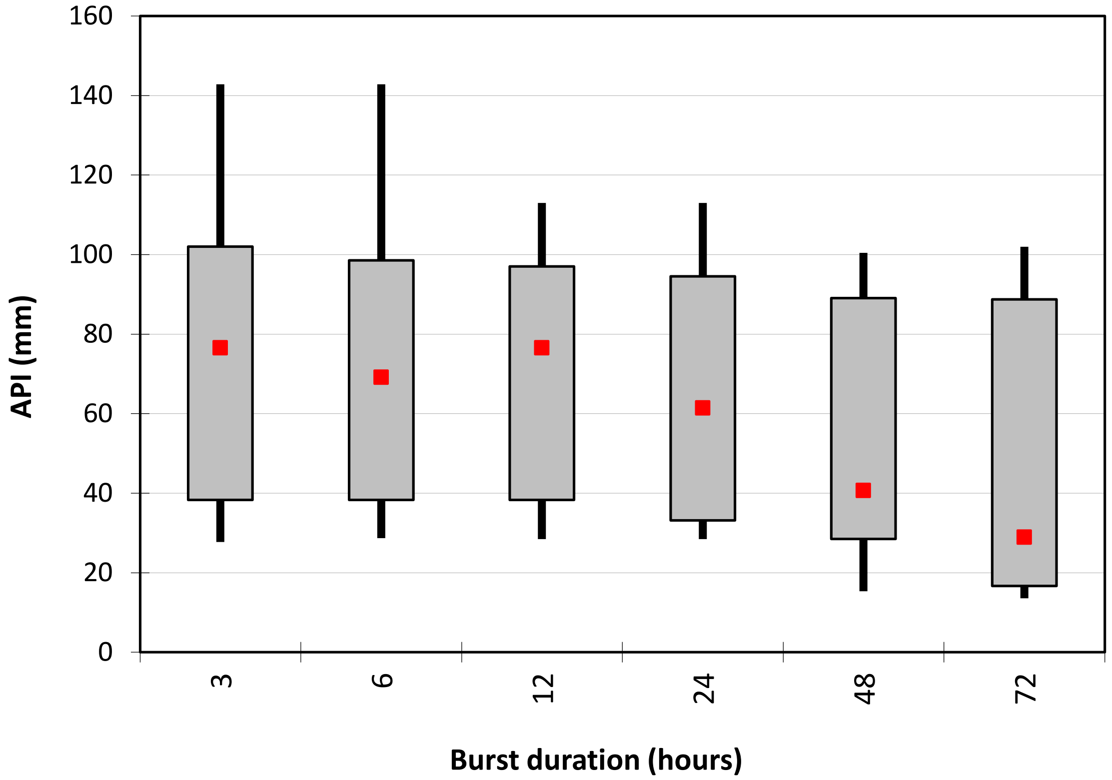


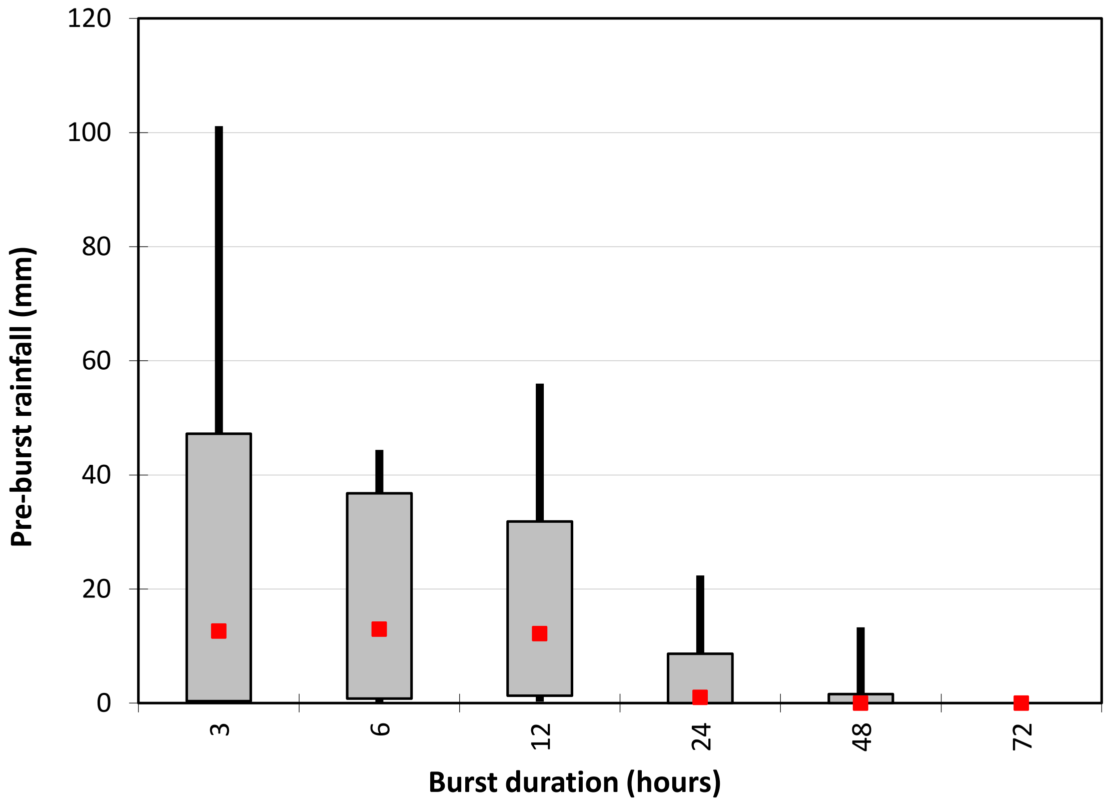
Fletcher Creek Trib. @ Frog Hollow (WA)



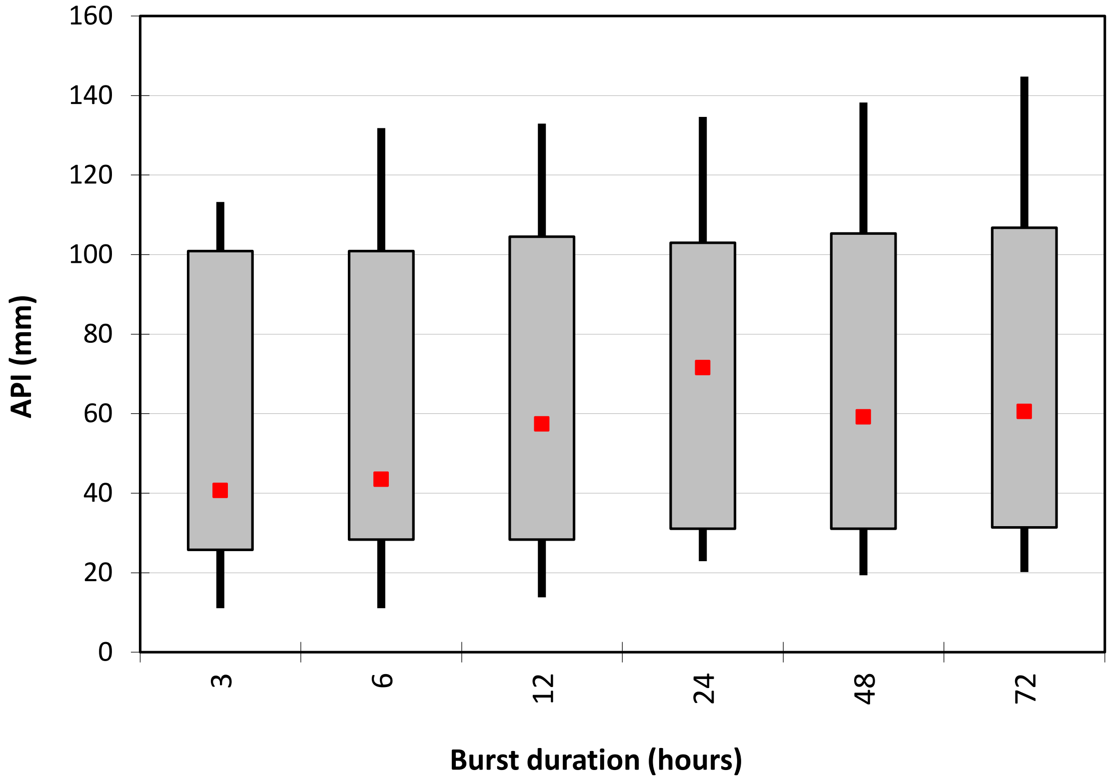


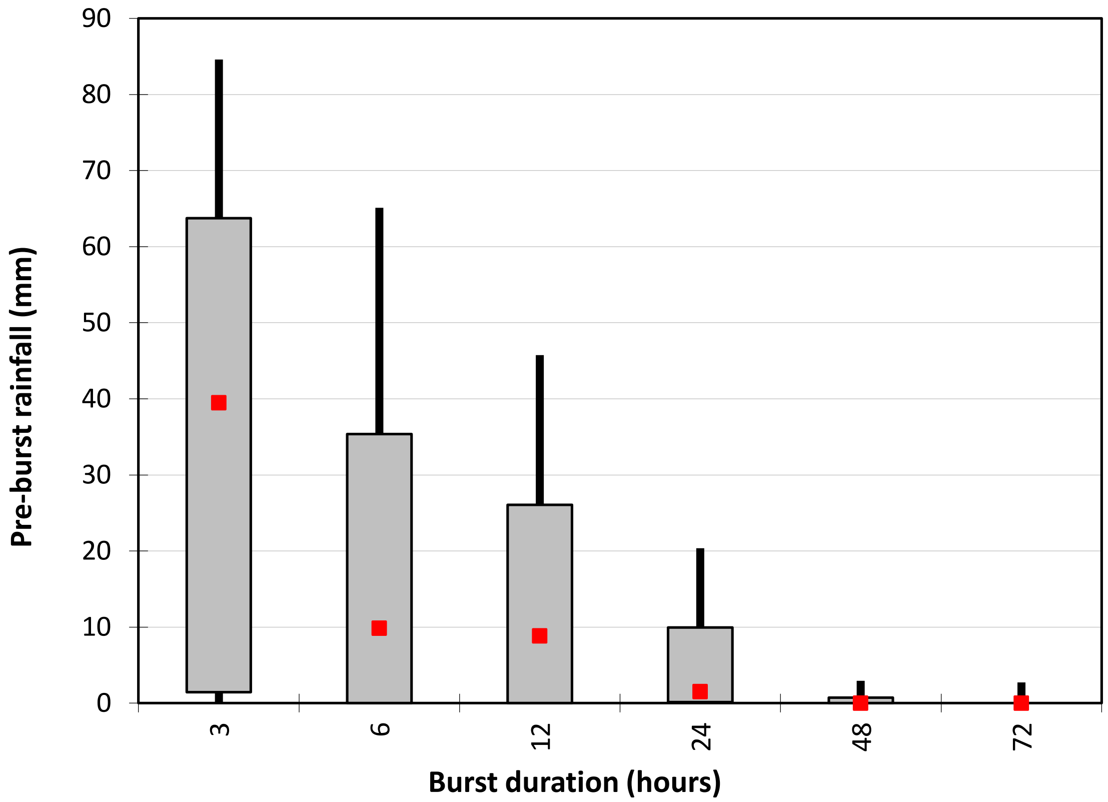
Harding River @ Marmurrina Pool U-South (WA)



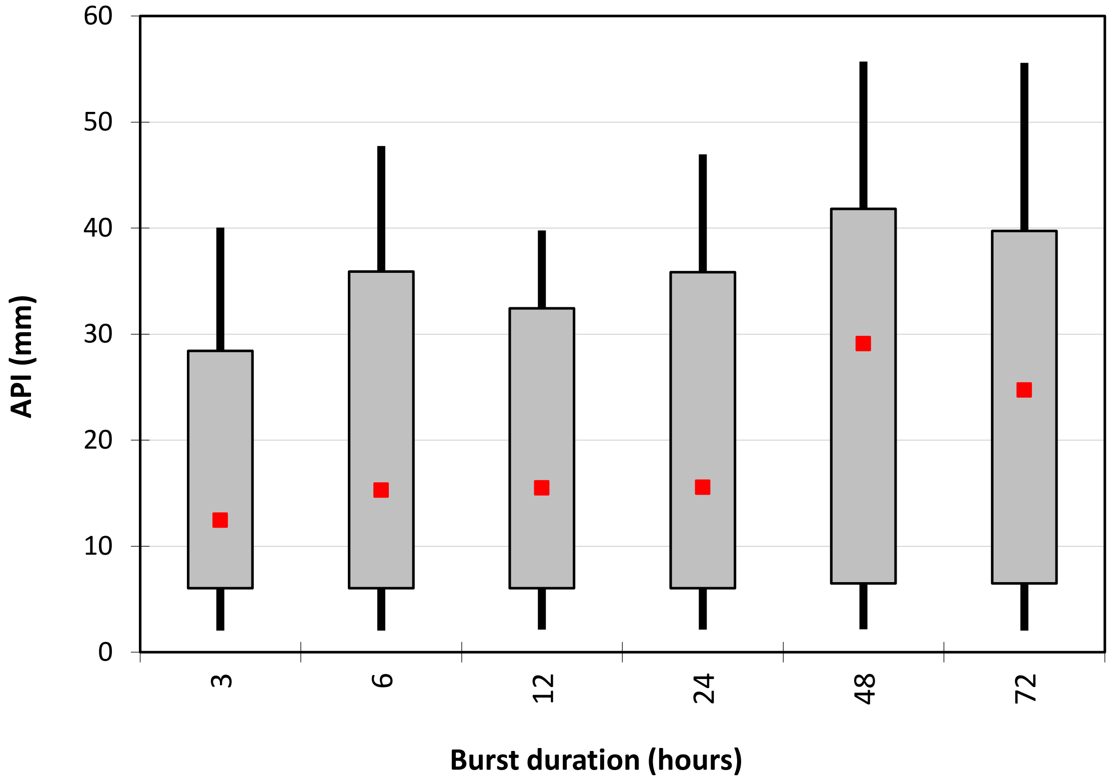


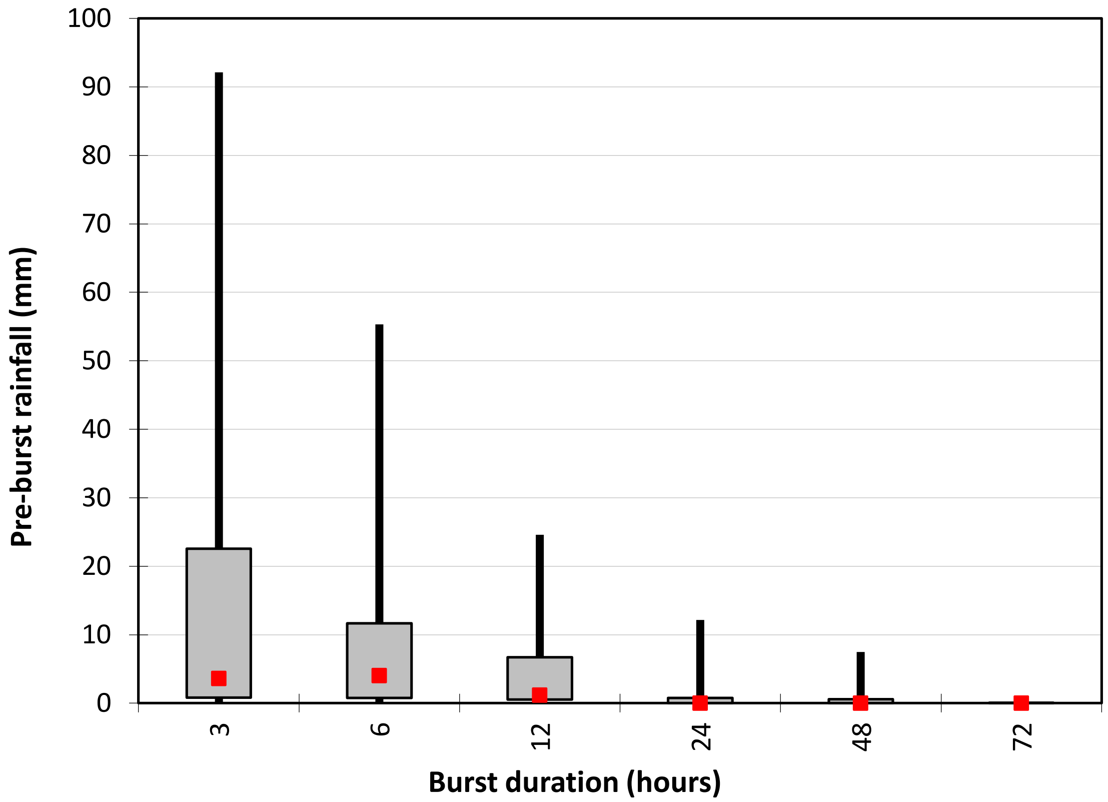
Kanjenjie Creek Trib. @ Fish Pool (WA)



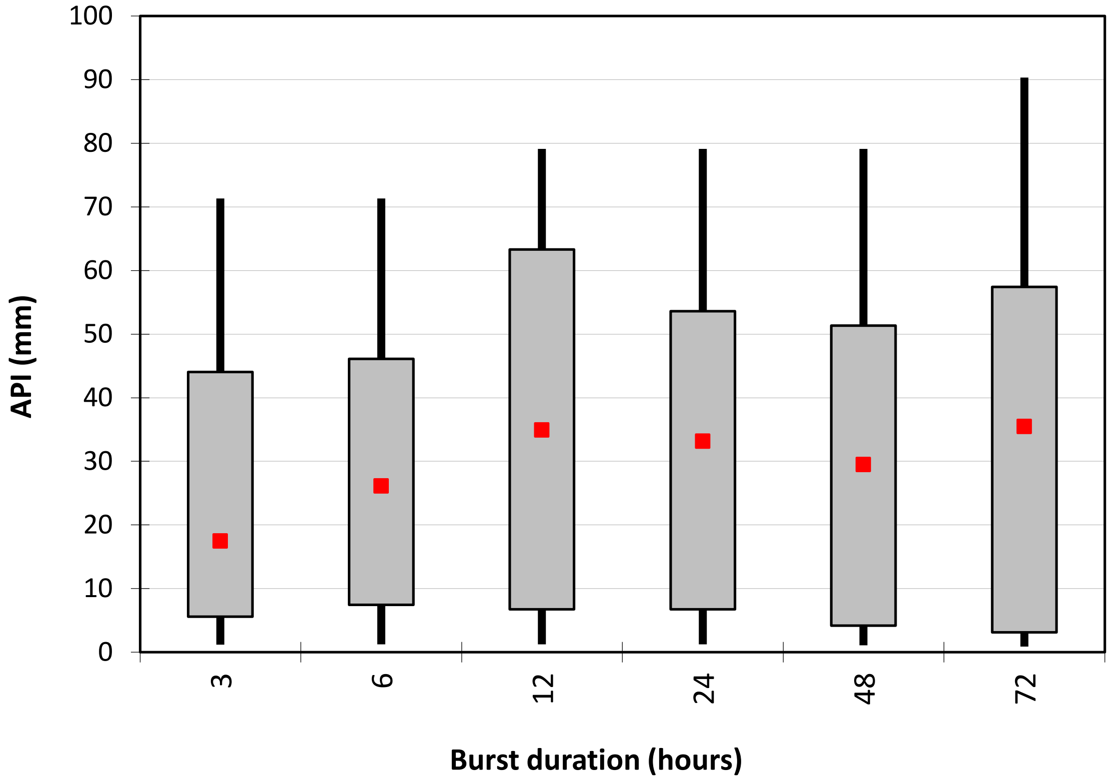


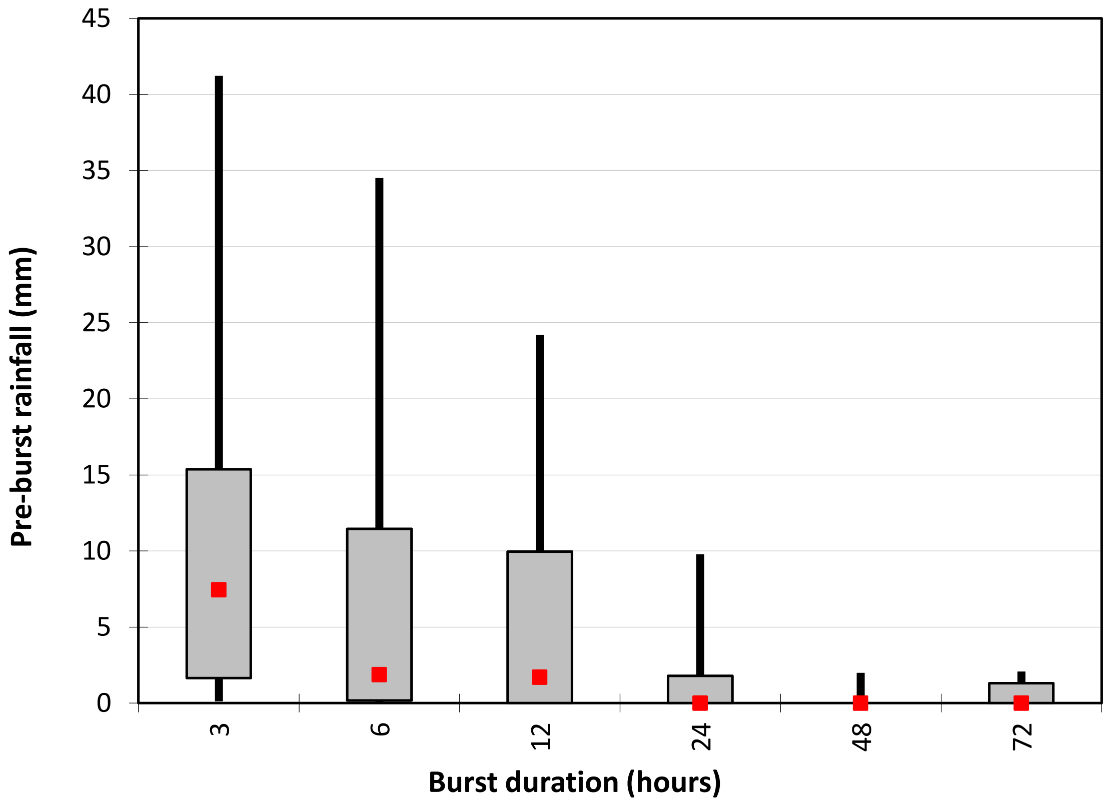
Balgarup River @ Mandelup Pool (WA)



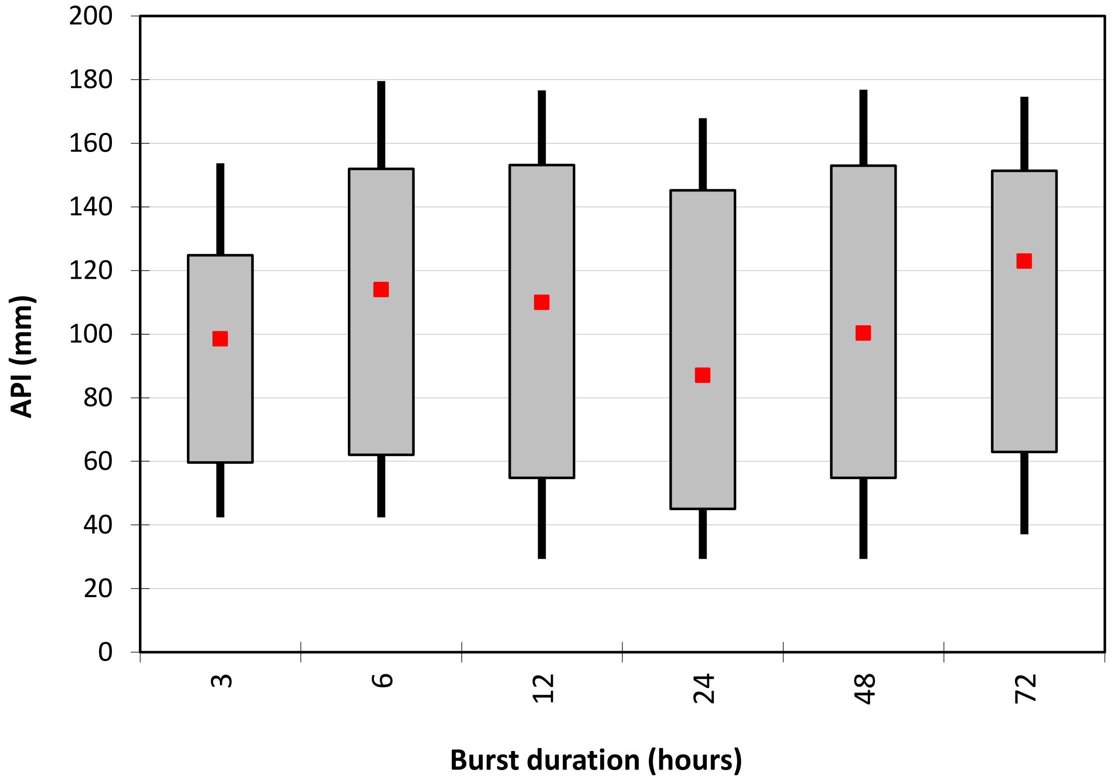


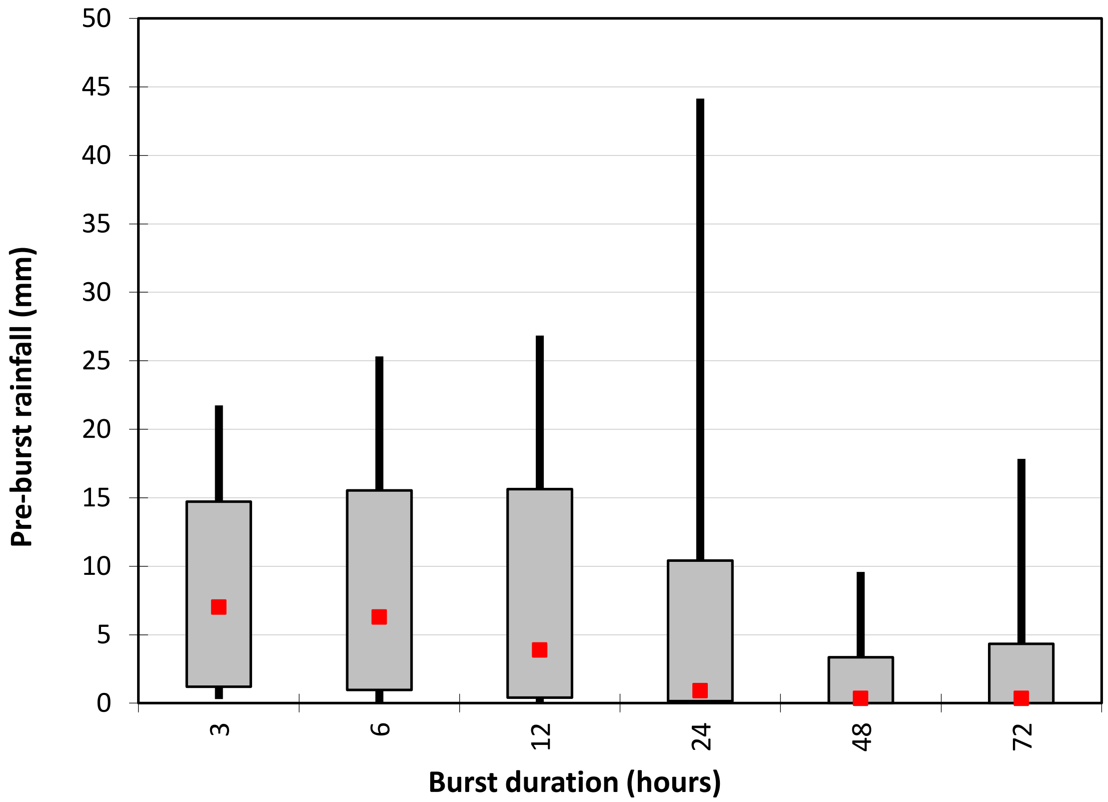
Buller River @ Buller (WA)



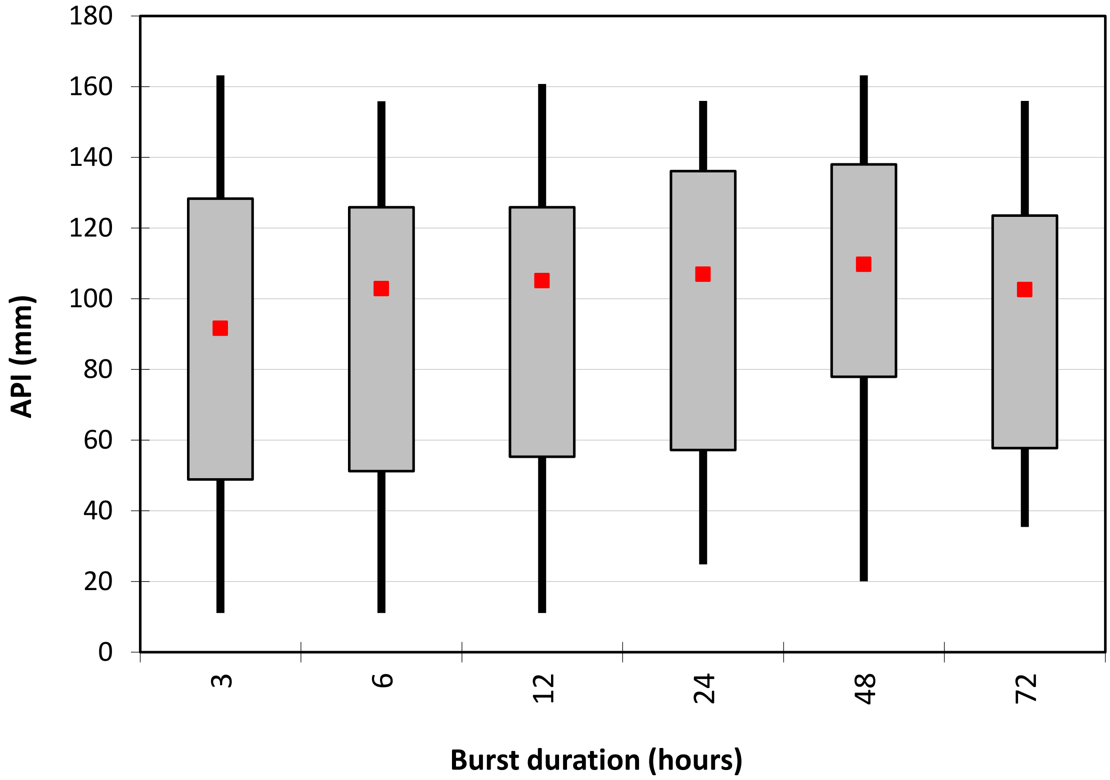


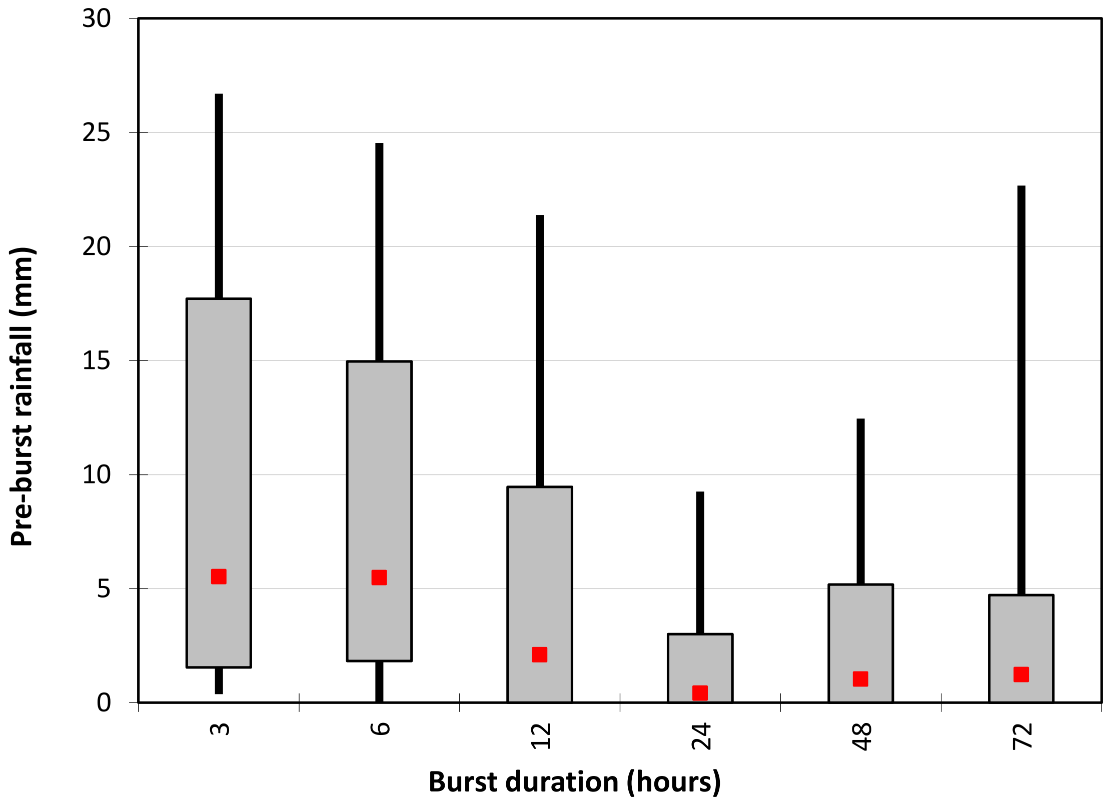
Carey Brook @ Staircase Rd (WA)



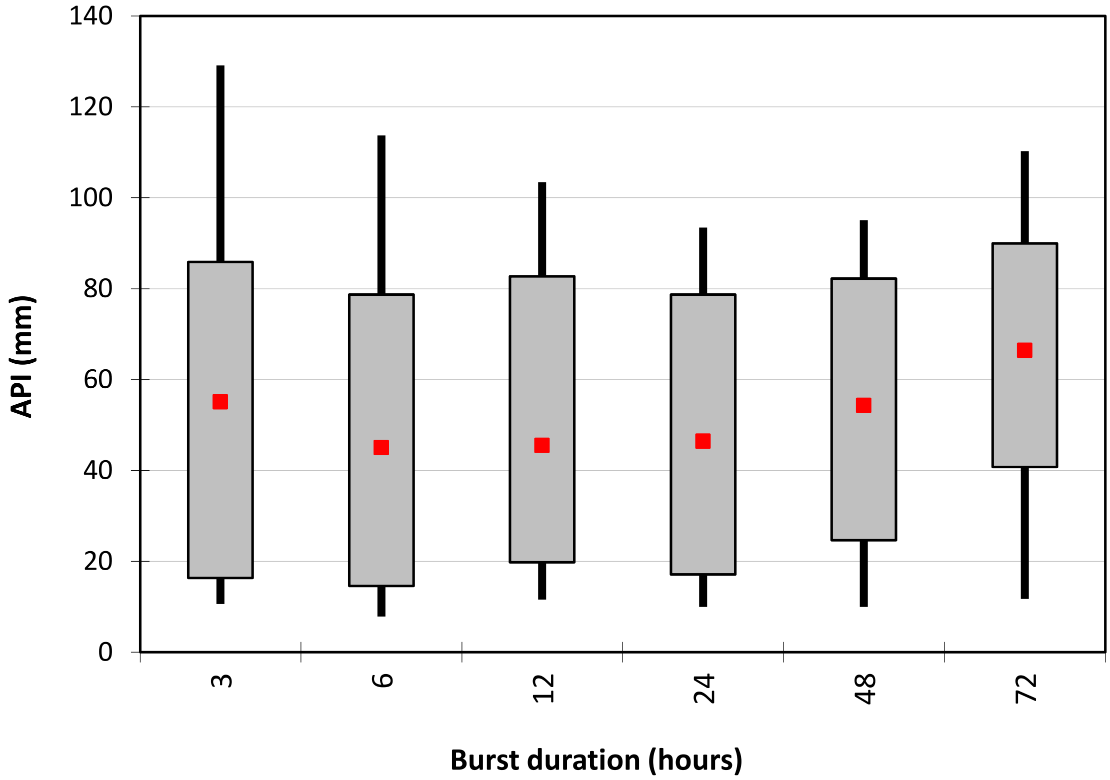


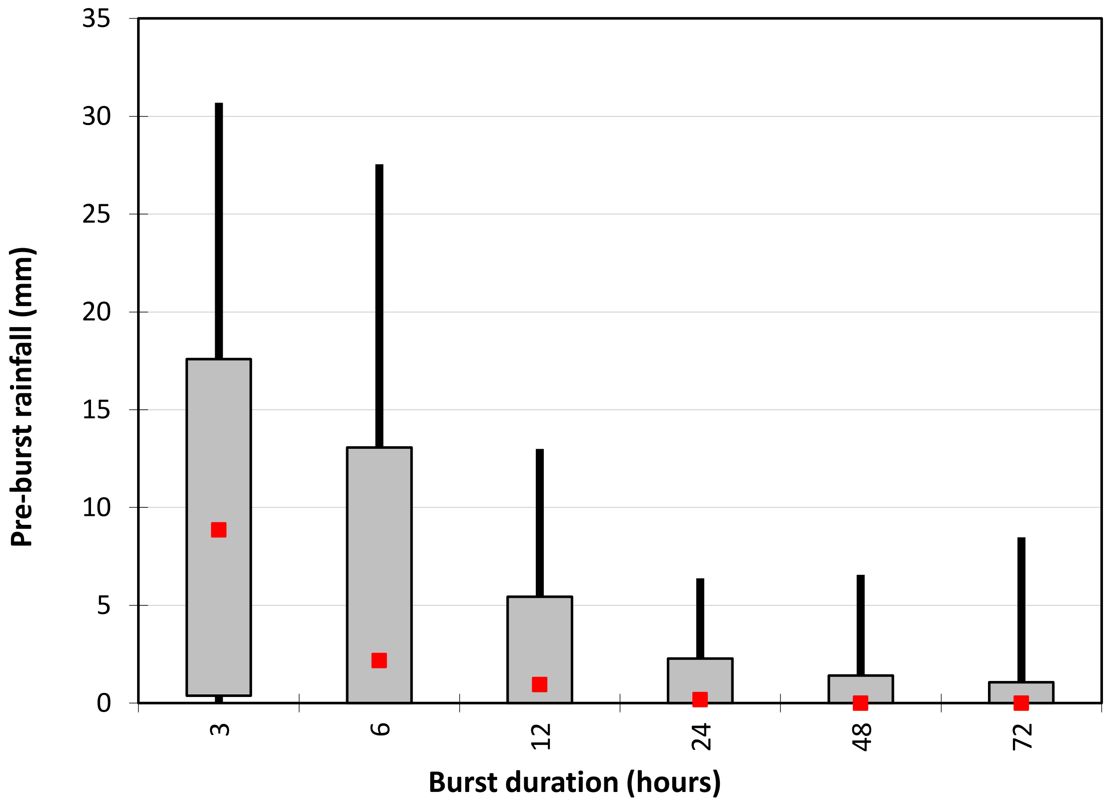
Davis Brook @ Murray Valley Plntn (WA)



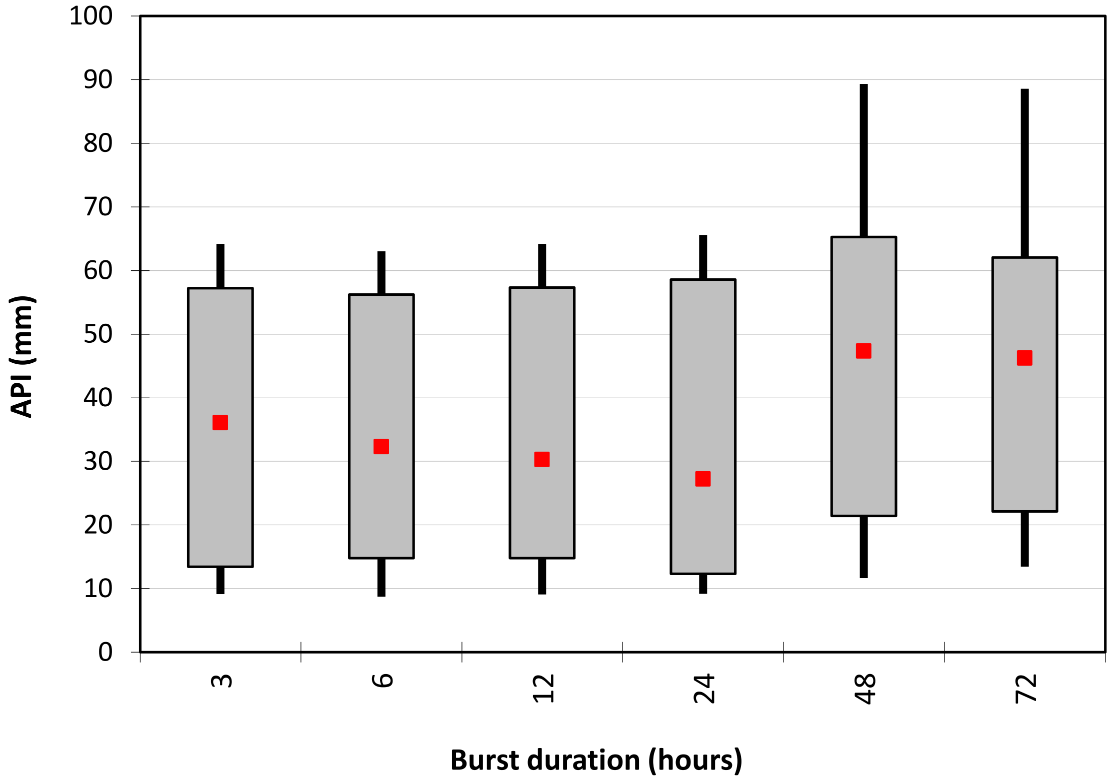


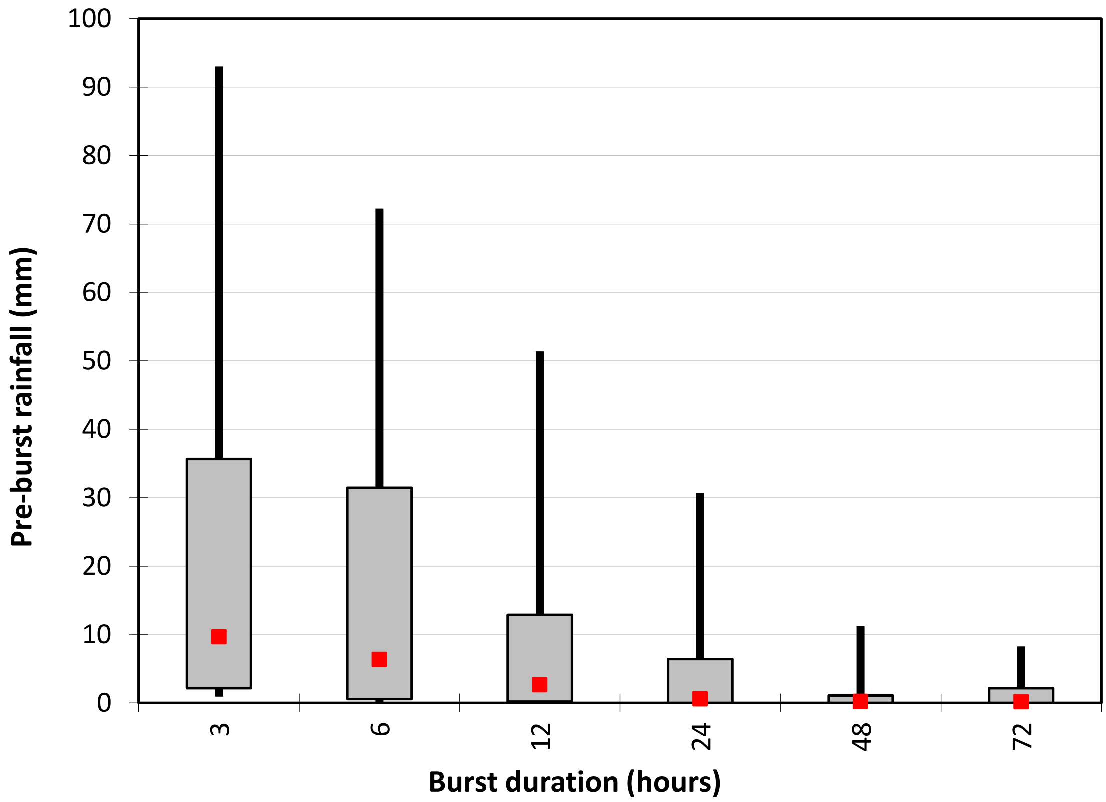
Dirk Brook @ Kentish Farm (WA)



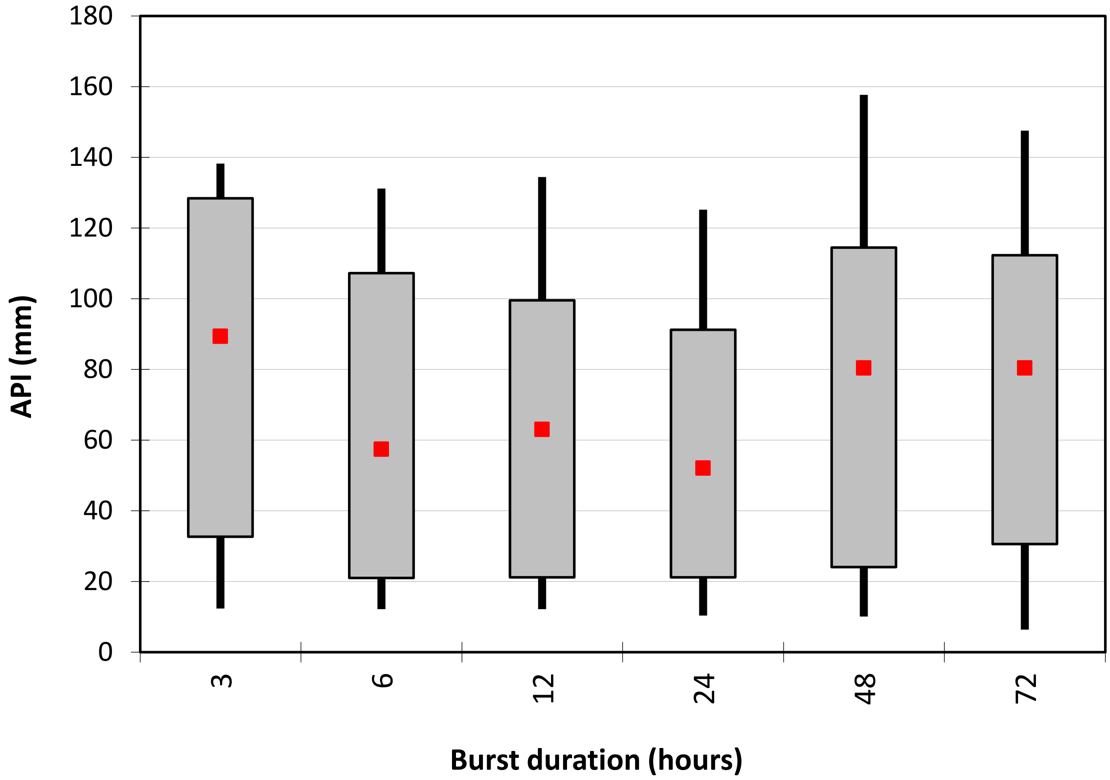


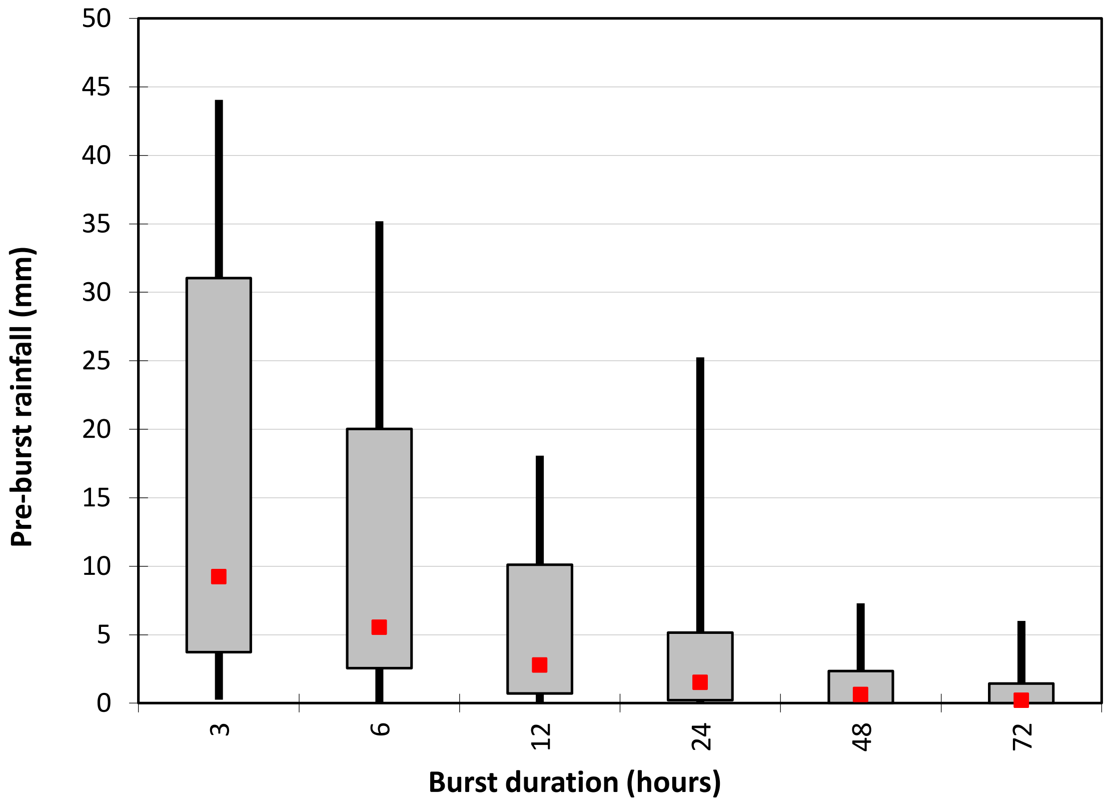
Goodga River @ Black Cat (WA)



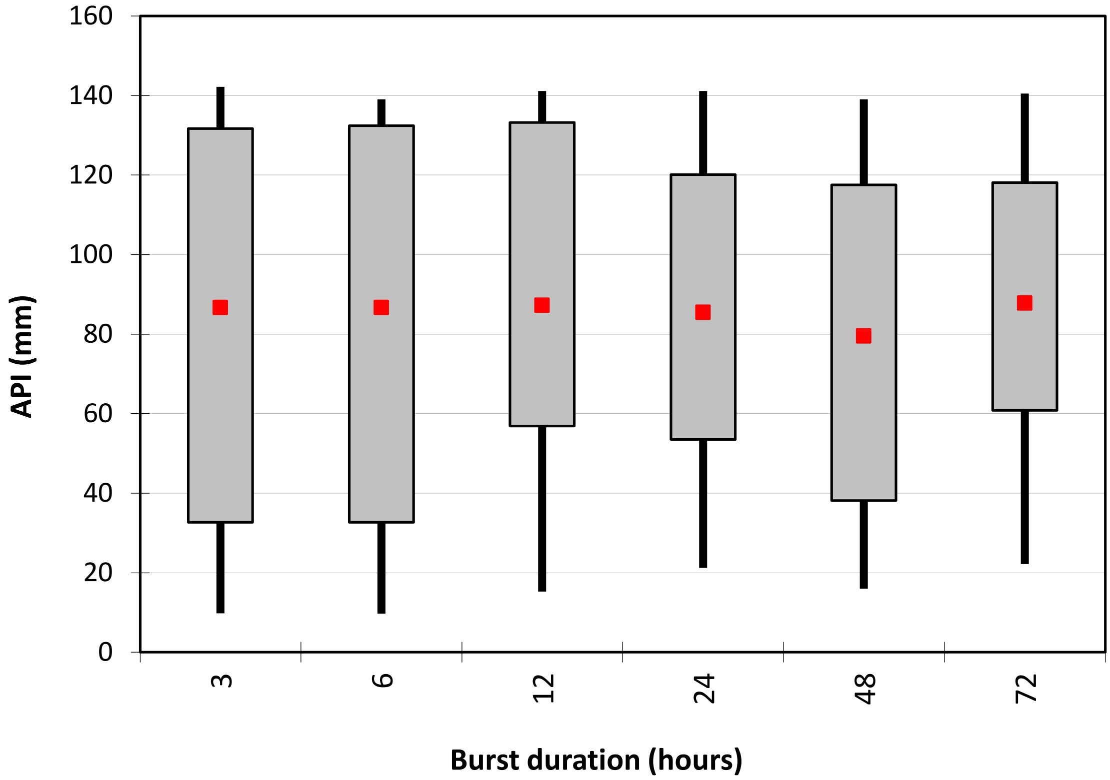


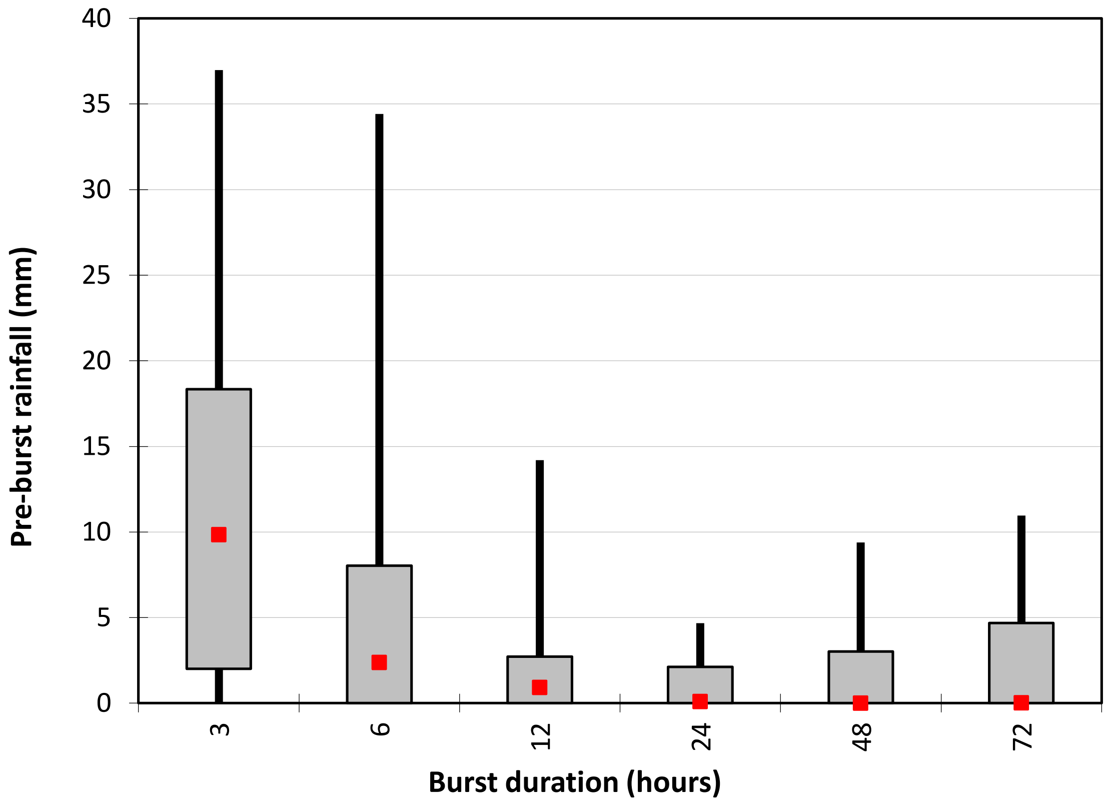
Hamilton River @ Worsley (WA)



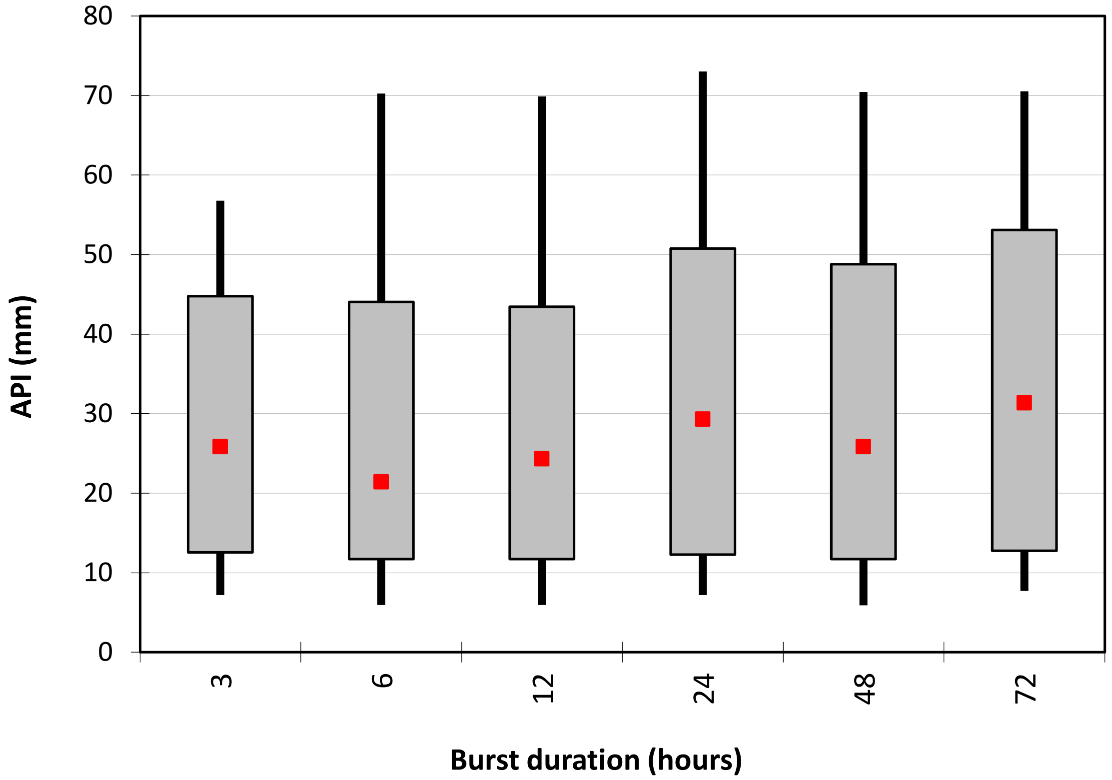


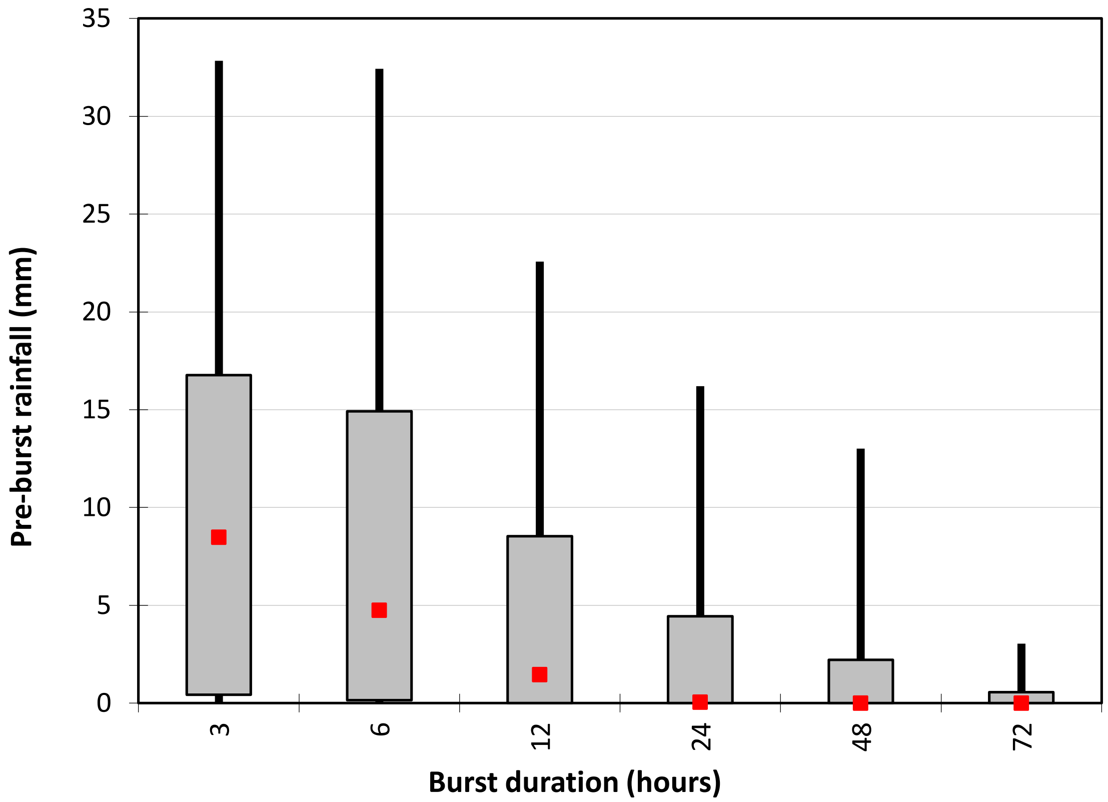
Marrinup Brook @ Brookdale Siding (WA)





Yates Flat @ Woonanup (WA)





Appendix F Distribution of pre-burst rainfall for each region

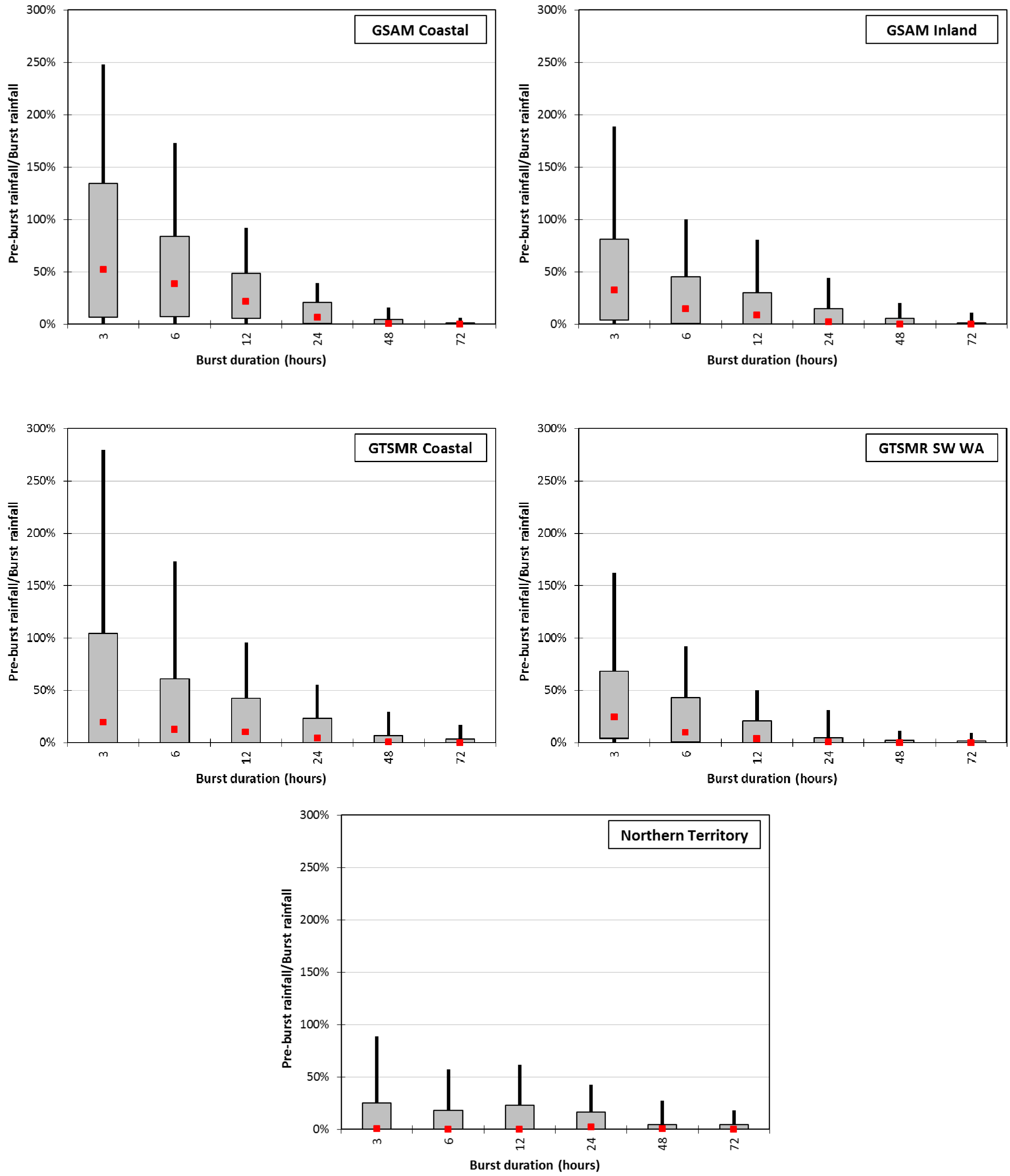


Figure F-1 Distribution of pre-burst rainfall normalized by burst rainfall for each PMP method region. Northern Territory catchments and Fletcher Creek are shown in a separate plot.

Appendix G Sensitivity of loss values to approach

G.1 Introduction

Prior to commencing to Phase 4 the ARR Technical Committee endorsed some additional investigations to explore different approaches to estimate loss values. The variability between users is considered in terms of both losses and modelled flow volume error. The sensitivity of the model to the routing characteristics is tested by repeating the calibrations using three methods of selecting RORB routing parameter k_c. Finally, the influence of the runoff routing model structure is assessed by calibrating losses using the URBS runoff routing model and comparing these values to those achieved using RORB.

This appendix documents the sensitivity of the Initial Loss – Continuing Loss (IL/CL) conceptual loss model to the subjective nature of user calibration, the selection of routing parameter and the flood model utilized. The work concentrated on the Initial Loss – Continuing Loss (IL/CL) model but the broad conclusions are expected to also be applicable to the application of SWMOD.

Phase 1 also noted that the application of SWMOD was constrained by the lack of information on the hydraulic properties of soils. Some further analysis was undertaken to explore the sensitivity of the SWMOD parameters to assumptions regarding the soil hydraulic properties.

G.2 IL/CL - Sensitivity to modeller

Introduction

In estimating the loss values for the pilot catchments, the modelled hydrograph is fitted to the surface runoff (derived from recorded streamflow with the baseflow removed). The goodness of fit is assessed subjectively using the following criteria:

- Volume
- Overall shape
- Peak
- Timing

This subjective procedure leads to changes in loss estimates based on the user calibrating the model. To assess the sensitivity of the calibration to this subjectivity, calibrations performed as part of the Phase 1 pilot study are revisited using different modellers in a blind test.

Table G-1 Summary of catchments examined

Gauge	Catchment	Area (km^2)	State	Mean Annual Rainfall (mm)	No. events
614005	Dirk Brook @ Kentish Farm	36	WA	1150	20
125006	Finch Hatton Creek @ Dam Site	36	QLD	1800	27
410743	Jerrabomberra Creek @ Four Mile Creek	52	ACT	820	20
G8170075	Manton River u/s Manton Dam	29	NT	1430	28
141009	North Maroochy River @ Eumundi	41	QLD	1650	27
A5040523	Sixth Creek @ Castambul	44	SA	1000	15
422321	Spring Creek @ Killarney	32	QLD	1210	29
2219	Swan River u/s Hardings Falls	38	TAS	920	20
228217	Toomuc Creek @ Pakenham	42	VIC	1060	10
603190	Yates Flat Creek @ Woonanup	53	WA	800	7

Variation in Initial Loss values

The resulting estimates of loss are summarised in the following figures and tables. Although there are significant differences for some individual events (Figure G-1), there is no bias; both the pilot and revisited calibrations have a similar distribution of Initial Loss values across the events (this is seen by the low changes in median losses for each catchment seen in Table G-2).

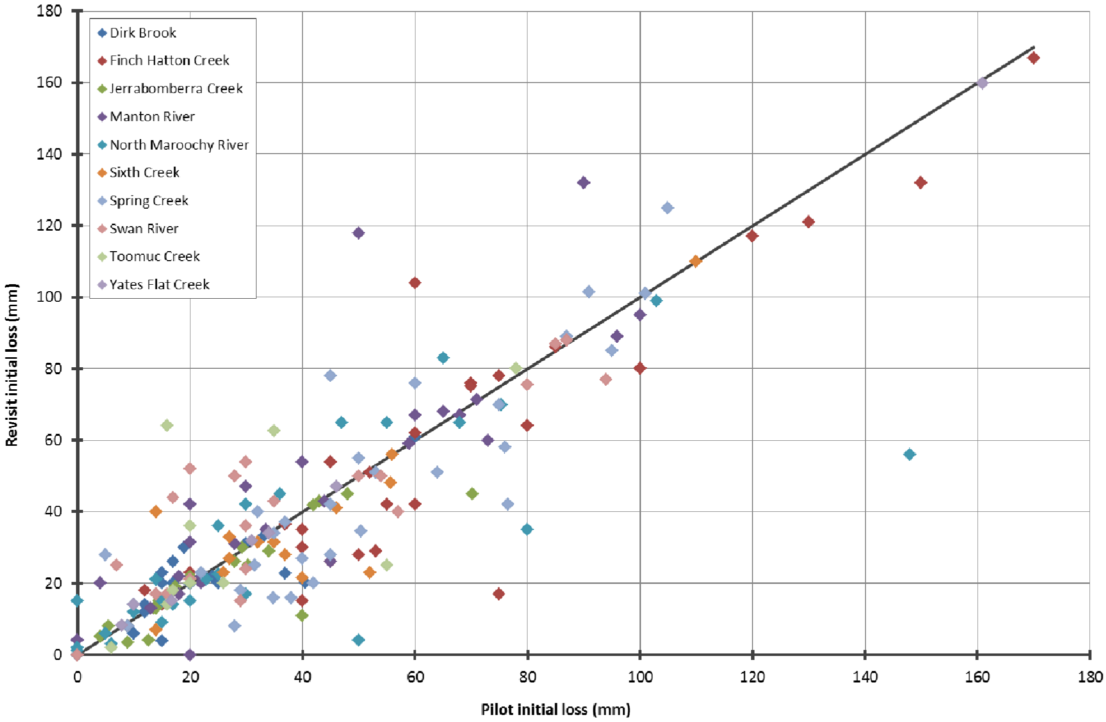


Figure G-1 Initial Loss values for the original pilot calibration and the revisited calibration

Table G-2 Median Initial Loss values for pilot and revisited calibrations

Gauge	Catchment	Initial Loss (mm)	
		Pilot calibration	Revisited calibration
614005	Dirk Brook @ Kentish Farm	17	20
125006	Finch Hatton Creek @ Dam Site	60	51
410743	Jerrabomberra Creek @ Four Mile Creek	19	17
G8170075	Manton River u/s Manton Dam	32	39
141009	North Maroochy River @ Eumundi	25	21
A5040523	Sixth Creek @ Castambul	36	32
422321	Spring Creek @ Killarney	45	40
2219	Swan River u/s Hardings Falls	30	44
228217	Toomuc Creek @ Pakenham	20	23
603190	Yates Flat Creek @ Woonanup	31	32

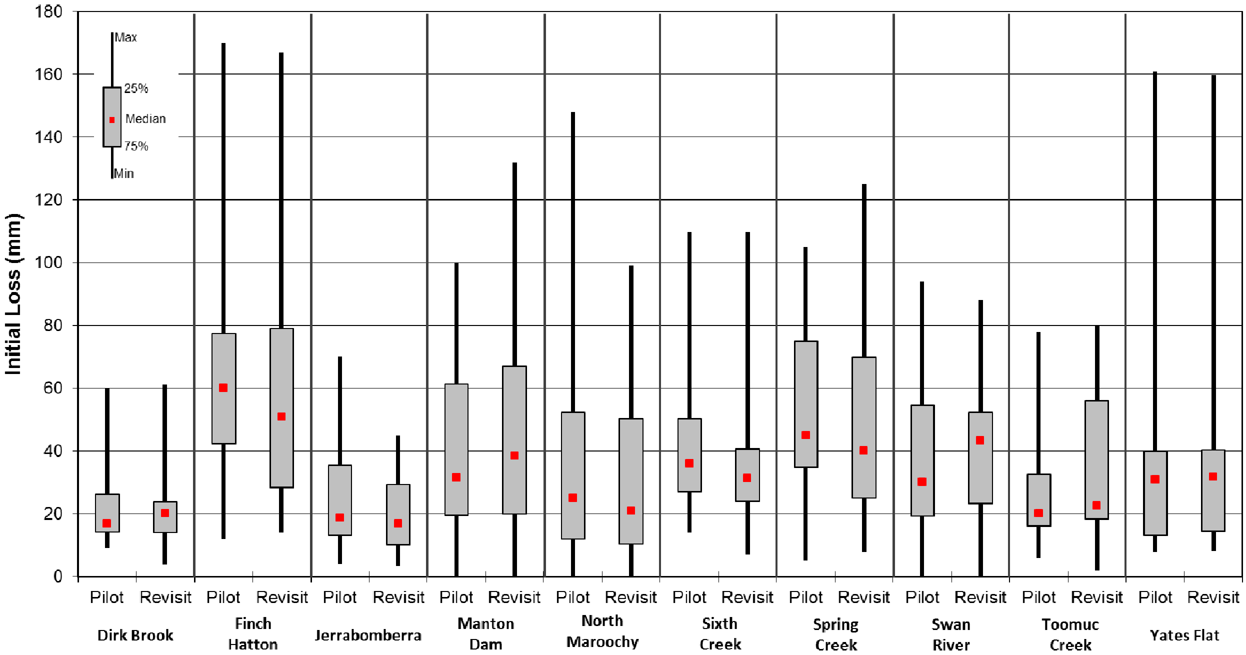


Figure G-2 Comparison of Initial Loss boxplots for pilot and revisited calibrations

Variation in Continuing Loss values

The results for Continuing Loss are presented in the following figures and table. Similar to Initial Loss, estimates of Continuing Loss are sensitive to the user. Additionally, there is a small bias present; the revisited calibration has slightly higher Continuing Loss than the original pilot study. Furthermore, the median Continuing Loss for the revisit is slightly higher than the pilot study value for seven of the ten catchments (Table G-3).

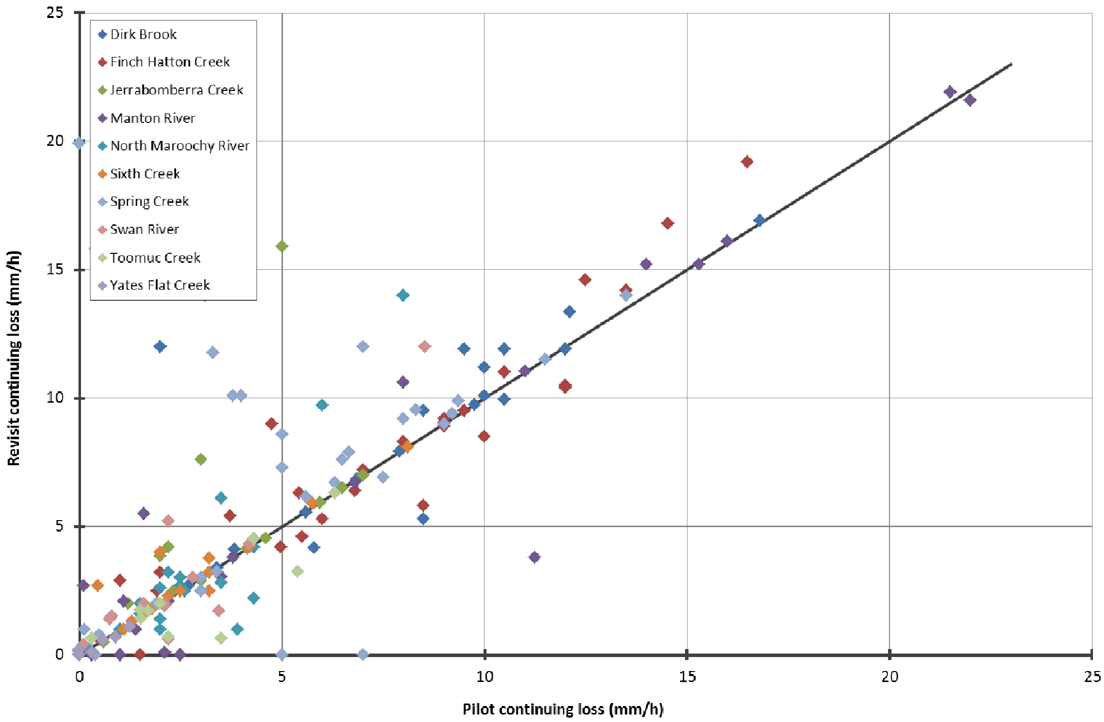


Figure G-3 Continuing Loss values for the original pilot calibration and the revisited calibration

Table G-3 Median Continuing Loss values for pilot and revisited calibrations

Gauge	Catchment	Continuing Loss (mm/h)	
		Pilot calibration	Revisited calibration
614005	Dirk Brook @ Kentish Farm	8.8	9.6
125006	Finch Hatton Creek @ Dam Site	7.0	7.2
410743	Jerrabomberra Creek @ Four Mile Creek	2.3	3.4
G8170075	Manton River u/s Manton Dam	2.4	2.4
141009	North Maroochy River @ Eumundi	2.0	1.7
A5040523	Sixth Creek @ Castambul	2.4	2.6
422321	Spring Creek @ Killarney	5.0	7.9
2219	Swan River u/s Hardings Falls	1.2	1.5
228217	Toomuc Creek @ Pakenham	2.1	1.7
603190	Yates Flat Creek @ Woonanup	0.3	0.2

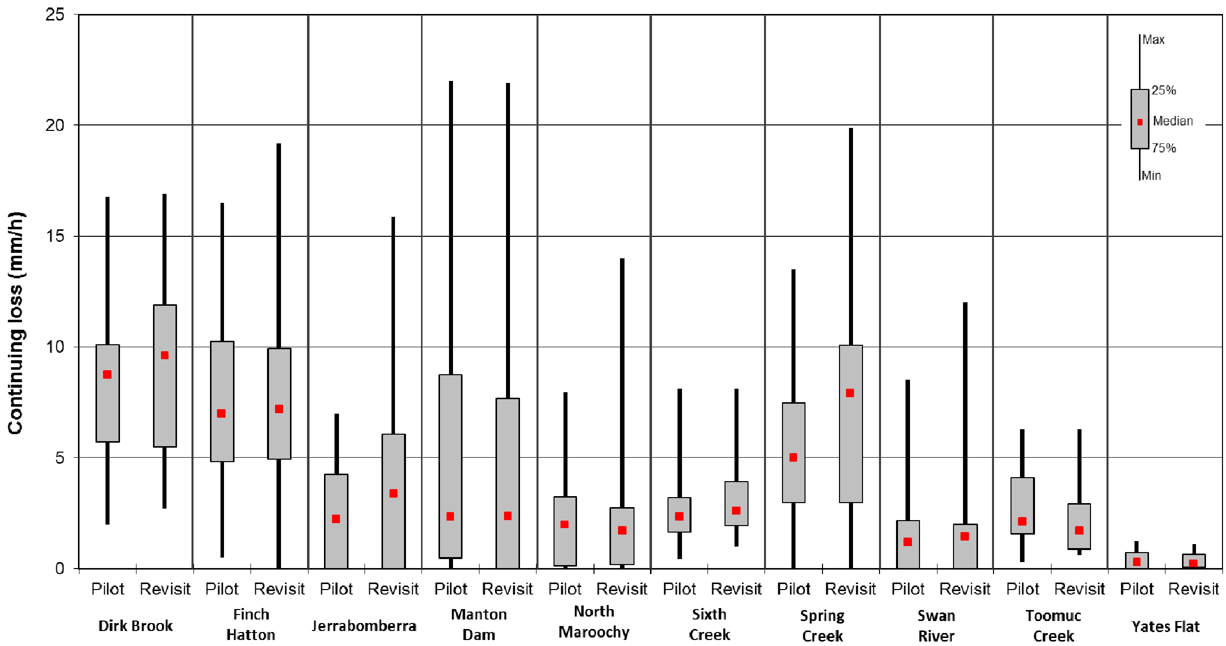


Figure G-4 Comparison of Continuing Loss boxplots for pilot and revisited calibrations

Variation in volume error

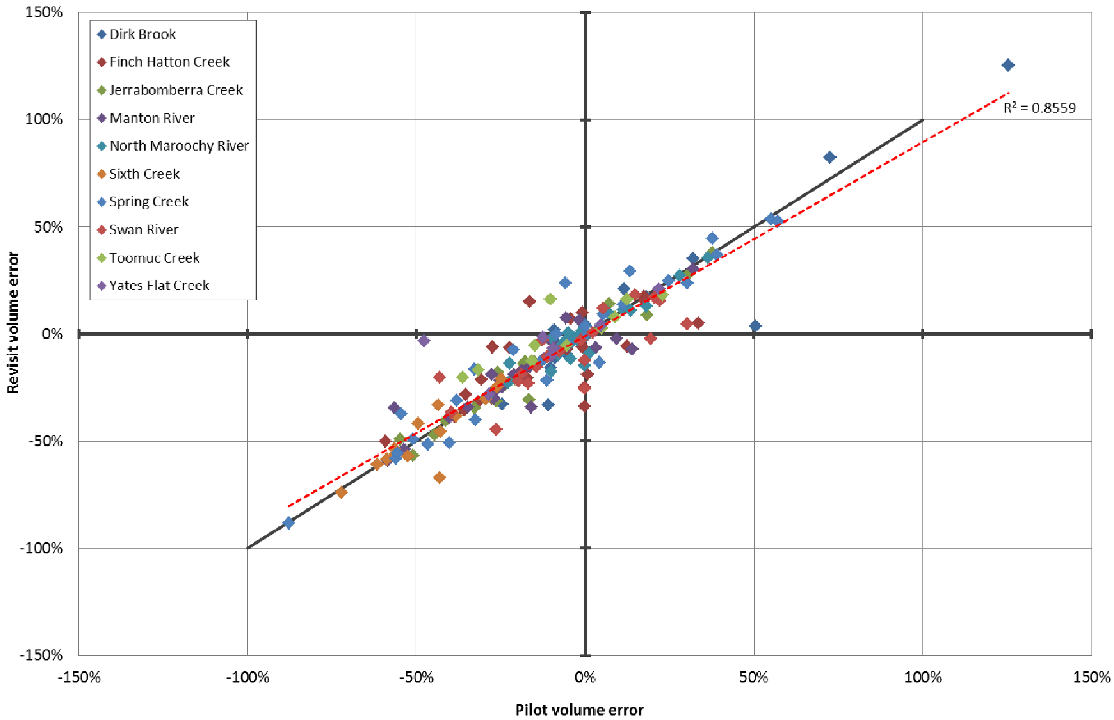


Figure G-5 Volume error for the original pilot calibration and the revisited calibration

In the revisited calibrations matching flow volume was prioritised over matching peaks. Resultantly, the volume error tends to be closer to zero in the revisited calibrations (Figure G-5). This is particularly apparent in the Yates Flat, Toomuc Creek and Dirk Brook catchments (as seen in Figure G-6). For Sixth Creek there is a consistent underestimation of the volume which indicates an error in the separation of baseflow, or else possibly in the adopted routing parameters or in the representativeness of the input rainfalls.

Table G-4 Median volume error for pilot and revisited calibrations

Gauge	Catchment	Volume Error (%)	
		Pilot calibration	Revisited calibration
614005	Dirk Brook @ Kentish Farm	-4.4%	-0.8%
125006	Finch Hatton Creek @ Dam Site	-6.8%	-7.0%
410743	Jerrabomberra Creek @ Four Mile Creek	-17.9%	-16.0%
G8170075	Manton River u/s Manton Dam	-17.5%	-17.9%
141009	North Maroochy River @ Eumundi	-4.3%	-2.8%
A5040523	Sixth Creek @ Castambul	-49.4%	-49.7%
422321	Spring Creek @ Killarney	-8.5%	-7.3%
2219	Swan River u/s Hardings Falls	-4.4%	-9.4%
228217	Toomuc Creek @ Pakenham	-7.9%	-1.4%
603190	Yates Flat Creek @ Woonanup	-10.1%	-3.3%

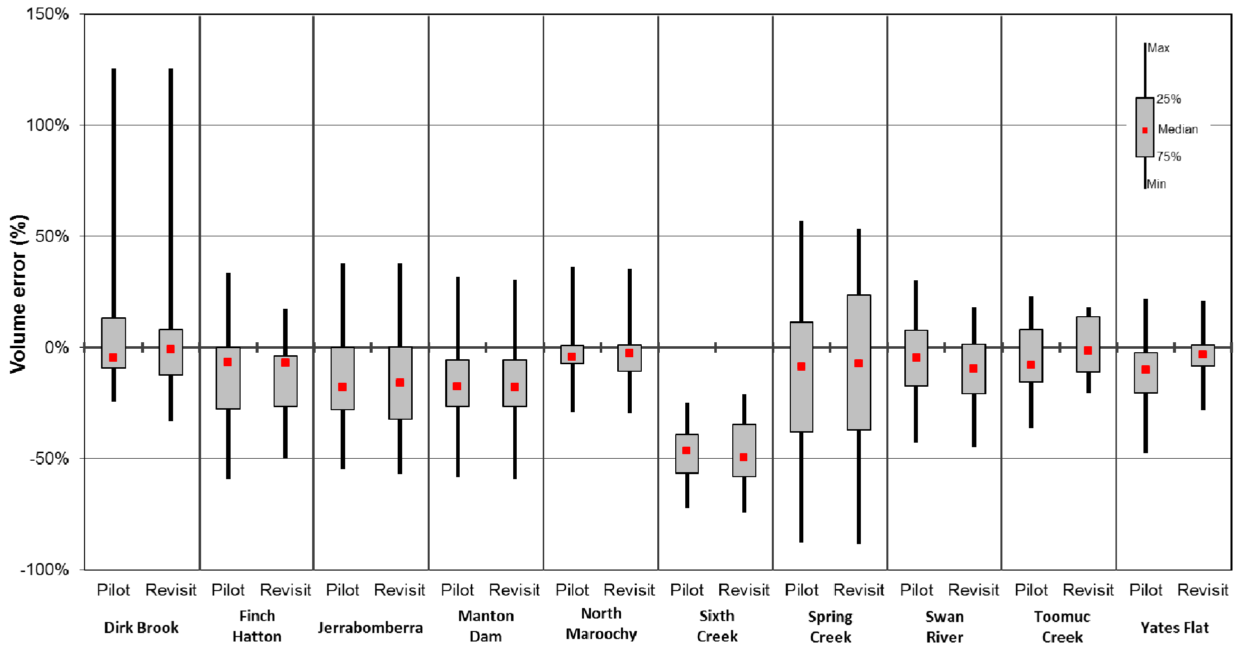


Figure G-6 Comparison of volume error between the pilot and revisited calibrations

G.3 IL/CL - Sensitivity to routing parameter

Introduction

The results from stage 1 of this investigation (SKM, 2012) made it clear that to reduce errors in the identification of the loss parameters some account needs to be given to the time-lags involved in the travel of rainfall-excess through the catchment. While it was apparent that simple empirical equations are not adequate to represent the lag, it is worth exploring the improvements that can be gained by adopting routing approaches based on different levels of accuracy. To this end, the sensitivity of loss values was evaluated for 3 different approaches to specifying the routing parameter, k_c, namely:

- Variable k_c – The routing parameter was adjusted for each event to ensure the best fit to the surface runoff hydrograph. Due to the freedom of not having a fixed k_c this method is time intensive for a large number of events but resulted in the best match to the recorded hydrographs
- Adopted k_c – As part of Phase 1, k_c values were derived for each catchment from calibration to the largest events on record. Using this fixed k_c value for all events in a catchment is less demanding than having a variable value; however, the procedure of calibrating k_c for each catchment takes time.
- Regional k_c – The routing parameter was based upon the regional prediction procedure described in Pearse et al. (2002) where the k_c is a simply a product of the average flow distance in the catchment. A value of 1.14 was adopted as this was the median of the CRCCH data set compiled by Dyer (1994). The simplicity of this method makes it considerably more time effective than either the variable or adopted k_c procedures.

Range of routing parameter values examined

The range of k_c values to estimate the loss values is shown in Table G-5 and Figure G-7.

Table G-5 Adopted and regional routing parameter values

Gauge	Catchment	Adopted k_c	Regional k_c
614005	Dirk Brook @ Kentish Farm	14	6.9
125006	Finch Hatton Creek @ Dam Site	4	6.4
410743	Jerrabomberra Creek @ Four Mile Creek	4	9.4
G8170075	Manton River u/s Manton Dam	8	8.4
141009	North Maroochy River @ Eumundi	20	9.1
A5040523	Sixth Creek @ Castambul	6	9.8
422321	Spring Creek @ Killarney	6	6.6
2219	Swan River u/s Hardings Falls	10	8.1
228217	Toomuc Creek @ Pakenham	12	10.2
603190	Yates Flat Creek @ Woonanup	10	7.0

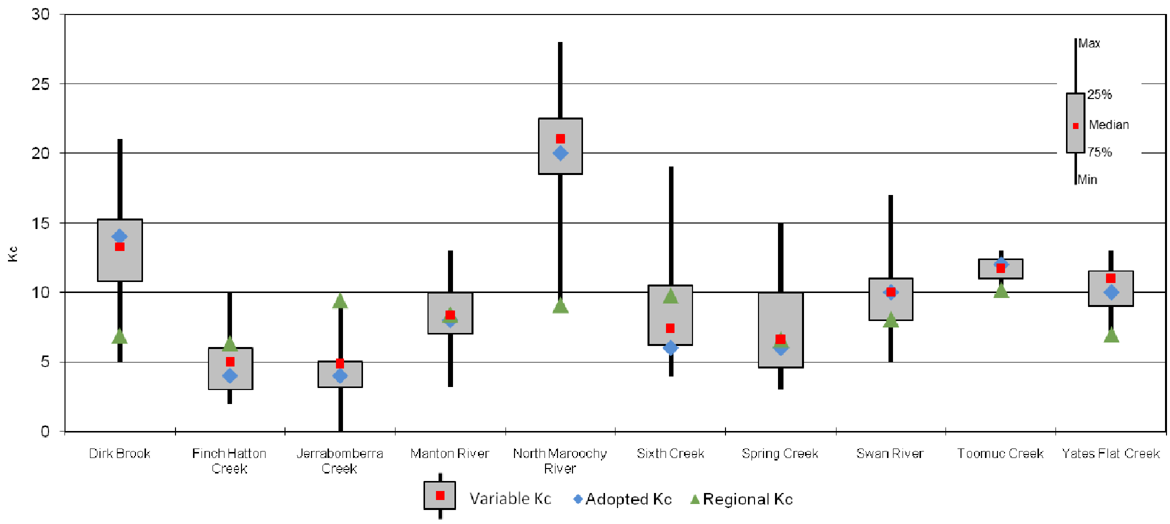


Figure G-7 Range of routing parameter values used

It can be seen that for all 10 catchments the adopted k_c values are similar to the median value from the variable k_c calibrations. This confirms that the routing characteristics of a catchment can be effectively estimated from a "handful" of events.

The effectiveness of the regional k_c approach varies between catchments. For Finch Hatton, Manton River and Toomuc Creek the regional k_c is close to the adopted and median values, however, for Jerrabomberra, North Maroochy and Yates Flat the regional approach resulted in values that were towards the end of the observed range.

Variation of Initial Loss values

The Initial Loss values resulting from the application of the different routing parameters are shown in Figure G-8 and the median values are summarised in Table G-6.

Table G-6 Median Initial Loss values for different k_c values

Gauge	Catchment	IL (mm)		
		Variable k_c	Adopted k_c	Regional k_c
614005	Dirk Brook @ Kentish Farm	20	20	24
125006	Finch Hatton Creek @ Dam Site	54	51	30
410743	Jerrabomberra Creek @ Four Mile Creek	15	17	17
G8170075	Manton River u/s Manton Dam	32	39	31
141009	North Maroochy River @ Eumundi	24	21	45
A5040523	Sixth Creek @ Castambul	25	32	33
422321	Spring Creek @ Killarney	35	40	37
2219	Swan River u/s Hardings Falls	40	44	41
228217	Toomuc Creek @ Pakenham	22	23	23
603190	Yates Flat Creek @ Woonanup	28	32	18

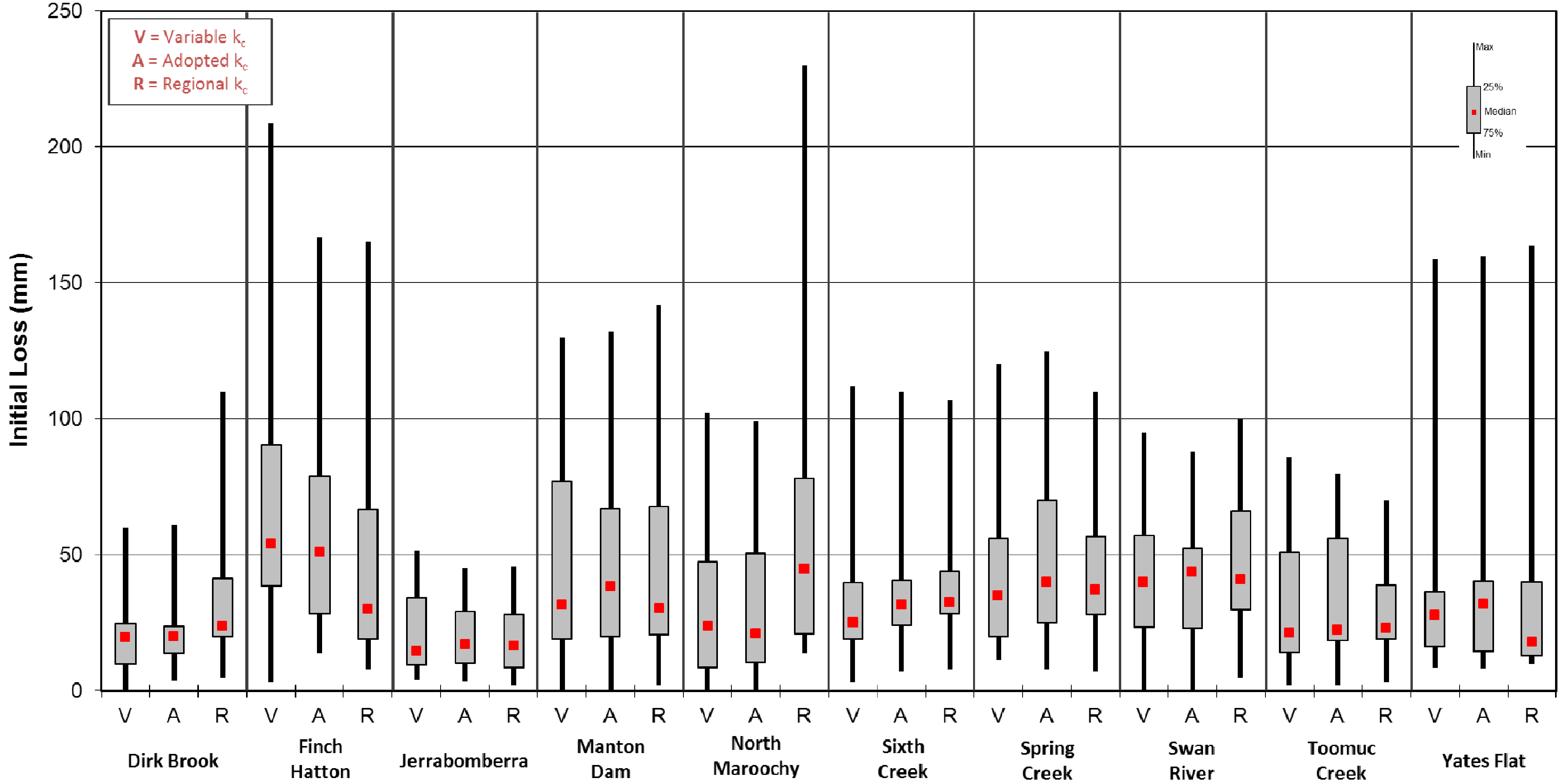


Figure G-8 Comparison of Initial Loss for different routing parameter values

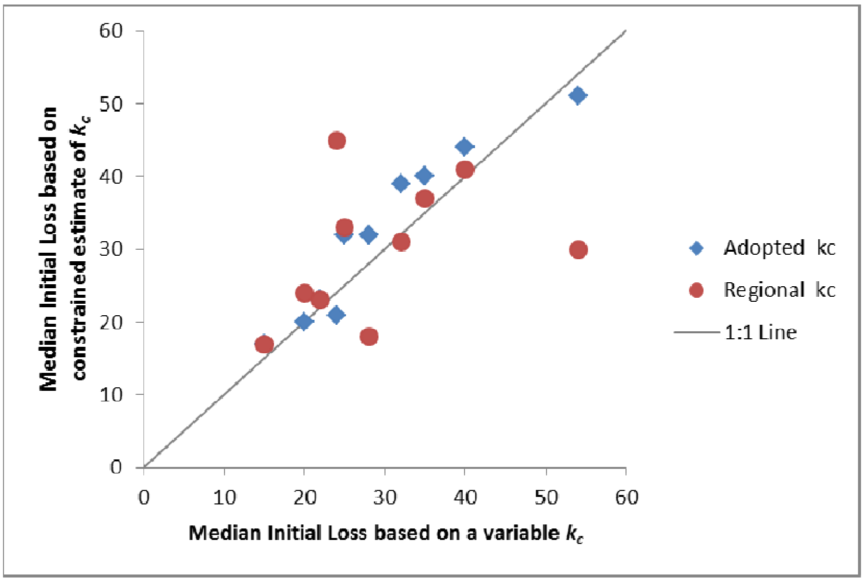


Figure G-9 Comparison of median Initial Loss obtained from using different routing approaches

The increase in scatter in Initial Loss associated with adoption of the simpler (more constrained) approach to specification of the routing parameter is evident in Figure G-10.

Variation in Continuing Loss values

The Continuing Loss values resulting from the application of the different routing parameters are shown in Figure G-10 and the median values are summarised in Table G-7.

Table G-7 Median Continuing Loss values for different k_c values

Gauge	Catchment	CL (mm/h)		
		Variable k_c	Adopted k_c	Regional k_c
614005	Dirk Brook @ Kentish Farm	9.5	9.6	8.5
125006	Finch Hatton Creek @ Dam Site	6.0	7.2	6.3
410743	Jerrabomberra Creek @ Four Mile Creek	2.5	3.4	0.7
G8170075	Manton River u/s Manton Dam	2.2	2.4	1.9
141009	North Maroochy River @ Eumundi	1.7	1.7	3.4
A5040523	Sixth Creek @ Castambul	2.7	2.6	1.9
422321	Spring Creek @ Killarney	8.2	7.9	5.0
2219	Swan River u/s Hardings Falls	1.2	1.5	7.2
228217	Toomuc Creek @ Pakenham	1.8	1.7	2.3
603190	Yates Flat Creek @ Woonanup	0.2	0.2	0.3

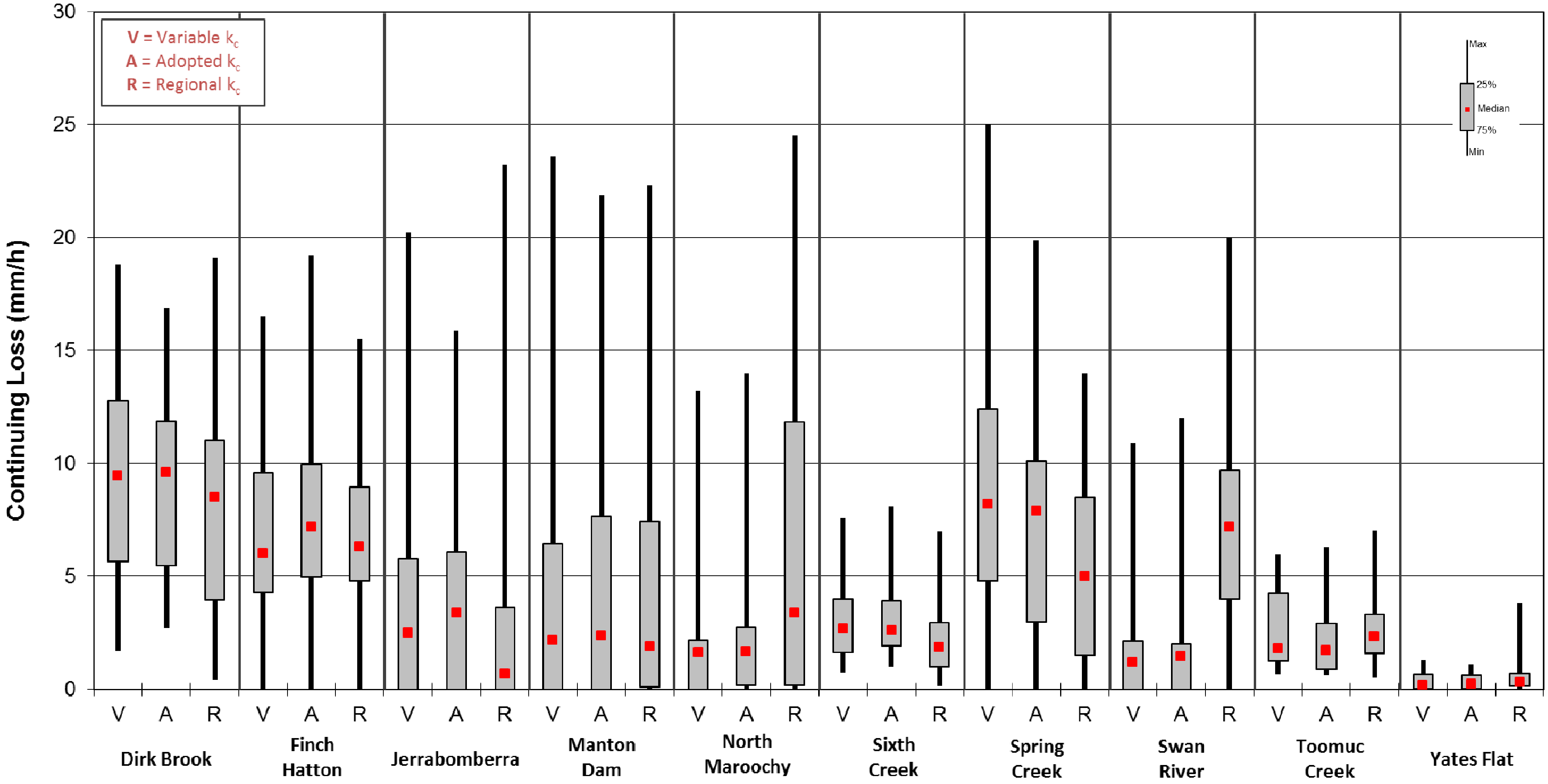


Figure G-10 Comparison of Continuing Loss for different routing parameter values

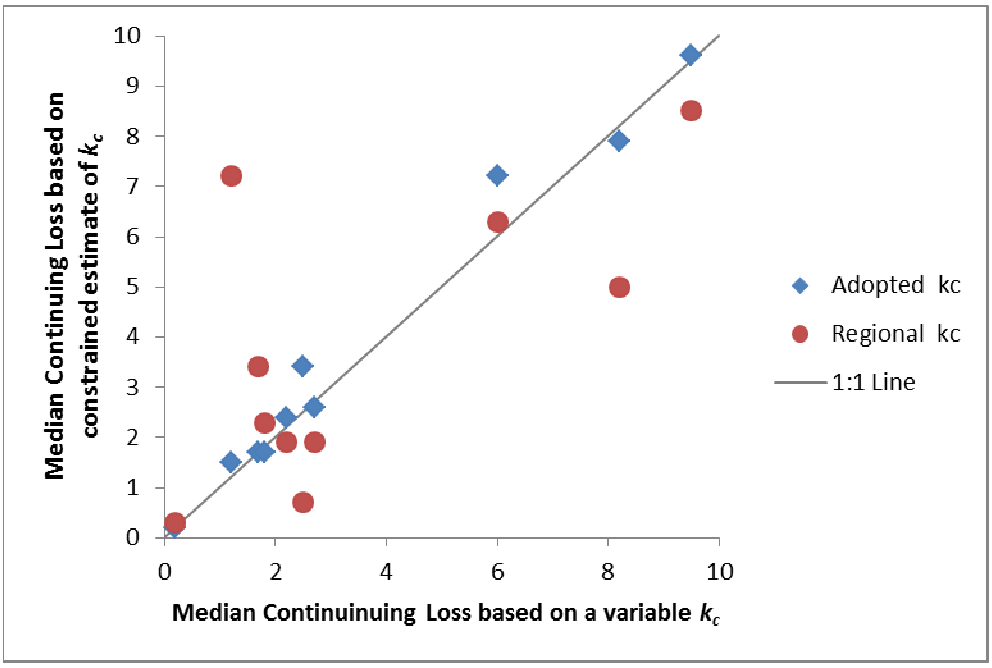


Figure G-11 Comparison of median Continuing Loss obtained from using different routing approaches

The increase in scatter in Continuing Loss associated with adoption of the simpler (more constrained) approach to specification of the routing parameter is evident in Figure G-11.

Variation of volume error

The volume errors resulting from the application of the different routing parameters are shown in Figure G-12 and the median values are summarised in Table G-8.

Table G-8 Median continuing volume error for different k_c values

Gauge	Catchment	Volume Error (%)		
		Variable k_c	Adopted k_c	Regional k_c
614005	Dirk Brook @ Kentish Farm	-7.2%	-0.8%	-44.1%
125006	Finch Hatton Creek @ Dam Site	-8.4%	-7.0%	-2.7%
410743	Jerrabomberra Creek @ Four Mile Creek	-1.9%	-16.0%	31.4%
G8170075	Manton River u/s Manton Dam	-4.4%	-17.9%	-16.9%
141009	North Maroochy River @ Eumundi	-0.4%	-2.8%	-42.6%
A5040523	Sixth Creek @ Castambul	-36.3%	-49.7%	-17.9%
422321	Spring Creek @ Killarney	-8.3%	-7.3%	-9.9%
2219	Swan River u/s Hardings Falls	-5.1%	-9.4%	0.0%
228217	Toomuc Creek @ Pakenham	0.3%	-1.4%	-14.3%
603190	Yates Flat Creek @ Woonanup	-2.5%	-3.3%	-22.2%

It is shown in Figure G-12 that the variable k_c approach represents the best hydrograph fitting in terms of volume (in terms of both the median and spread of error for all catchments). This is an expected result – the freedom afforded by a variable k_c allows more events to be fitted suitably.

The adopted k_c calibrations perform largely better than the regional k_c approach. The poorest performing catchments using the regional method are the same catchments with large differences between the regional and adopted k_c (Dirk Brook, Jerrabomberra and North Maroochy). A notable exception is Sixth Creek, which performed better under the regional method. It can be seen that regardless of the chosen method the volume is consistently under predicted for Sixth Creek events. As investigated in the Phase 1 pilot study, this underestimation is also present when using the IL/PL and SWMOD models. This implies that the baseflow separation for this catchment needs to be revisited.

An increase in k_c generally corresponded to an increase in the absolute value of the median volume error for most catchments. For given losses an increase in the routing parameter leads to a smoother hydrograph and lower peak flows that occur over a longer time, whereas a smaller k_c leads to shorter, more intense peak flows. Once the losses are estimated and the peaks fitted a lower k_c typically results in a lower flow volume. This translates into a correlation between correlation between k_c and volume error.

The increase in scatter in volume error associated with adoption of the simpler (more constrained) approach to specification of the routing parameter is evident in Figure G-13.

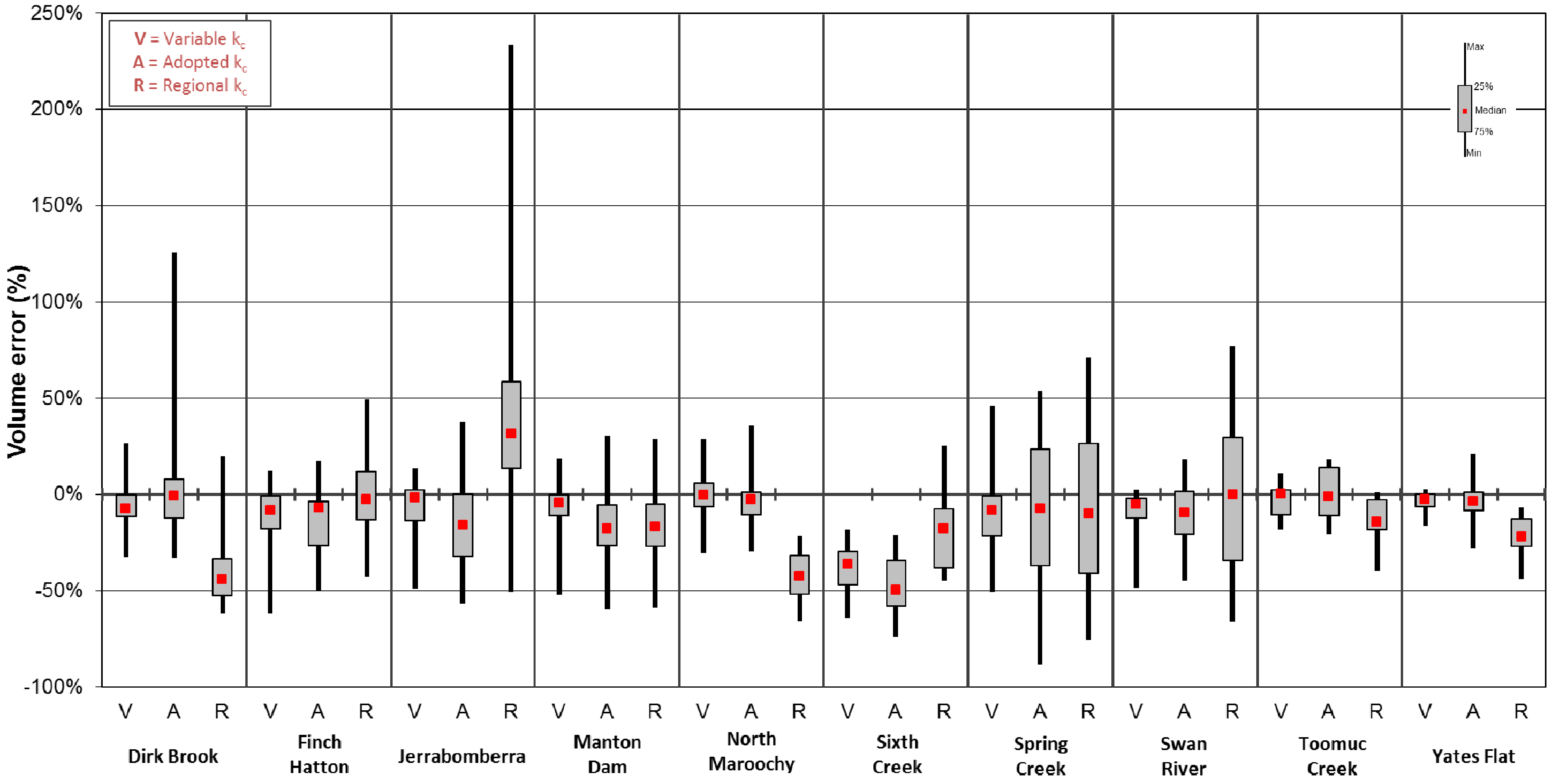


Figure G-12 Comparison of volume error for different routing parameter values

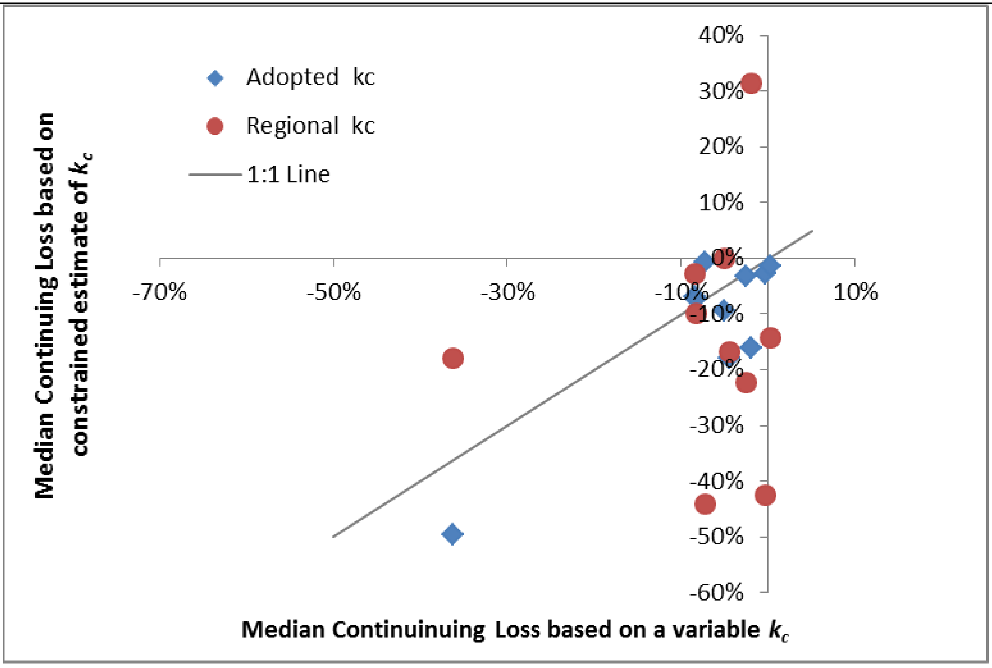


Figure G-13 Comparison of median volume error obtained from using different routing approaches

G.4 IL/CL - Sensitivity to model selection

Introduction

To test whether the estimation of losses is sensitive to the runoff routing model selected, loss values were also estimated using an URBS model with separate routing parameter defined for channel and overland routing (α and β). Given that regional predictions are not available for URBS, these parameters were varied for each event. The estimated loss values were then compared to those estimated using RORB where the k_c parameter was varied with each event.

Variation in Initial Loss values

The comparison of the Initial Loss values estimated from the 2 models is shown in Figure G-14. Although there are a small number of events which have large differences, the majority of loss values derived from the two models are similar and there is no obvious bias in the values.

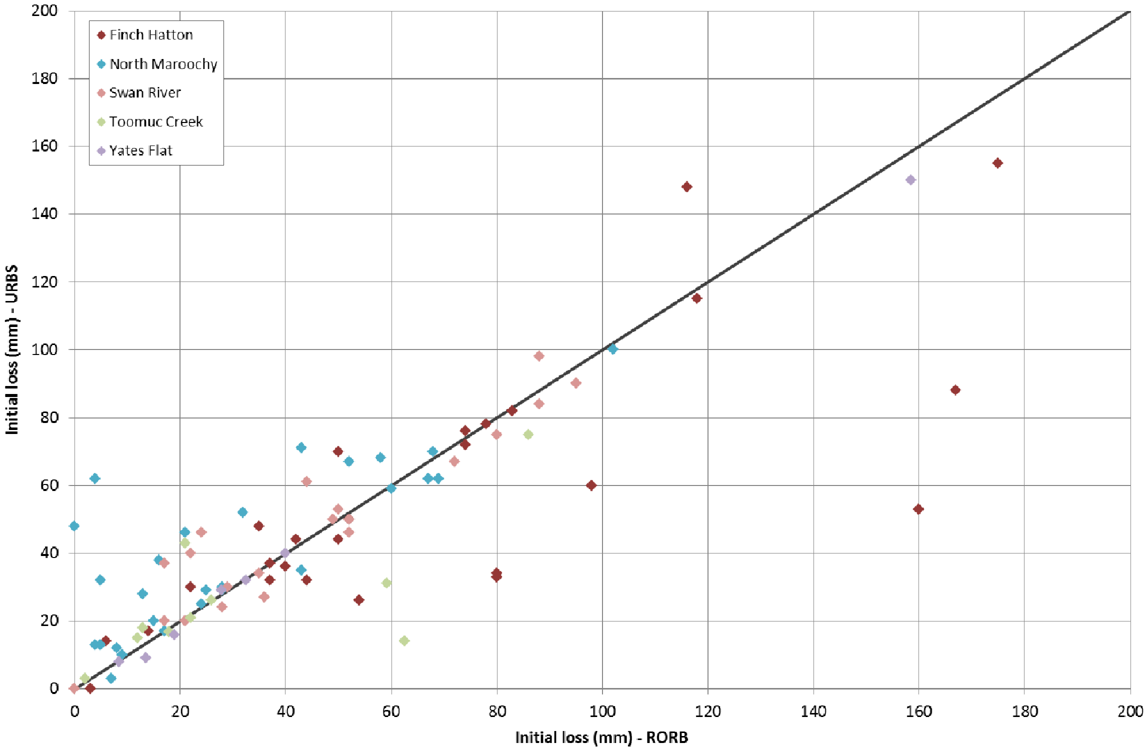


Figure G-14 Initial Loss values for the RORB and URBS calibrations

This is reinforced by the similarity of the two boxplots for each catchment, seen in Figure G-15. It should be noted that Toomuc Creek had few storm events suited to calibration and consequently the shape of the boxplot is more sensitive to changes in the losses of individual events than the other catchments.

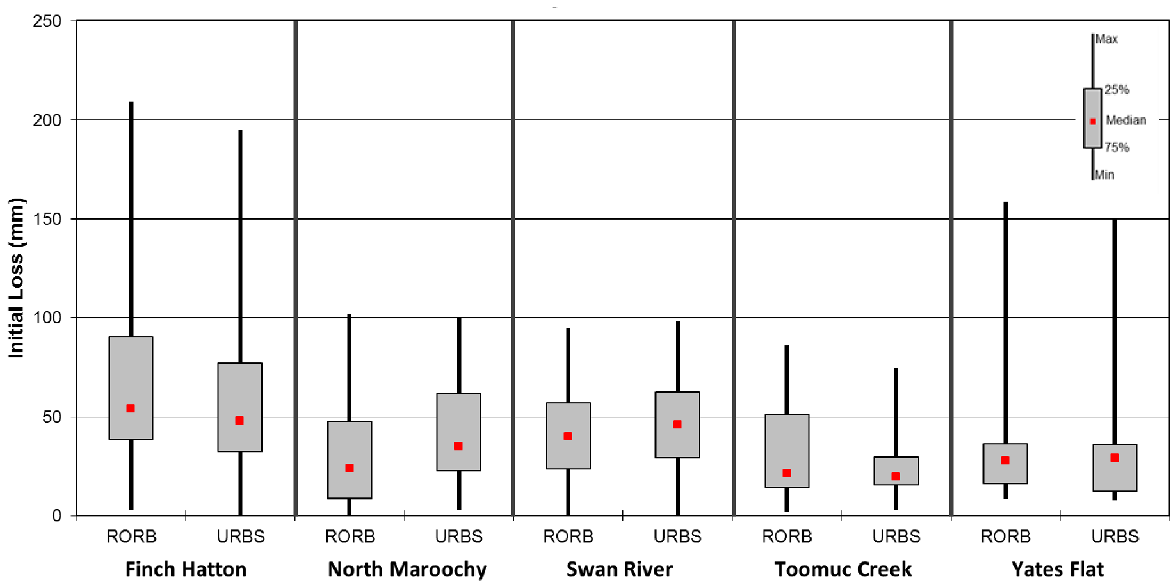


Figure G-15 Comparison of Initial Loss boxplots for RORB and URBS calibrations

Variation in Continuing Loss values

Figure G-16 shows the Continuing Loss values from the two different models. Once again although there are some events with quite different values of loss, there is no obvious bias in the results and the median values from the two models are quite similar (Figure).

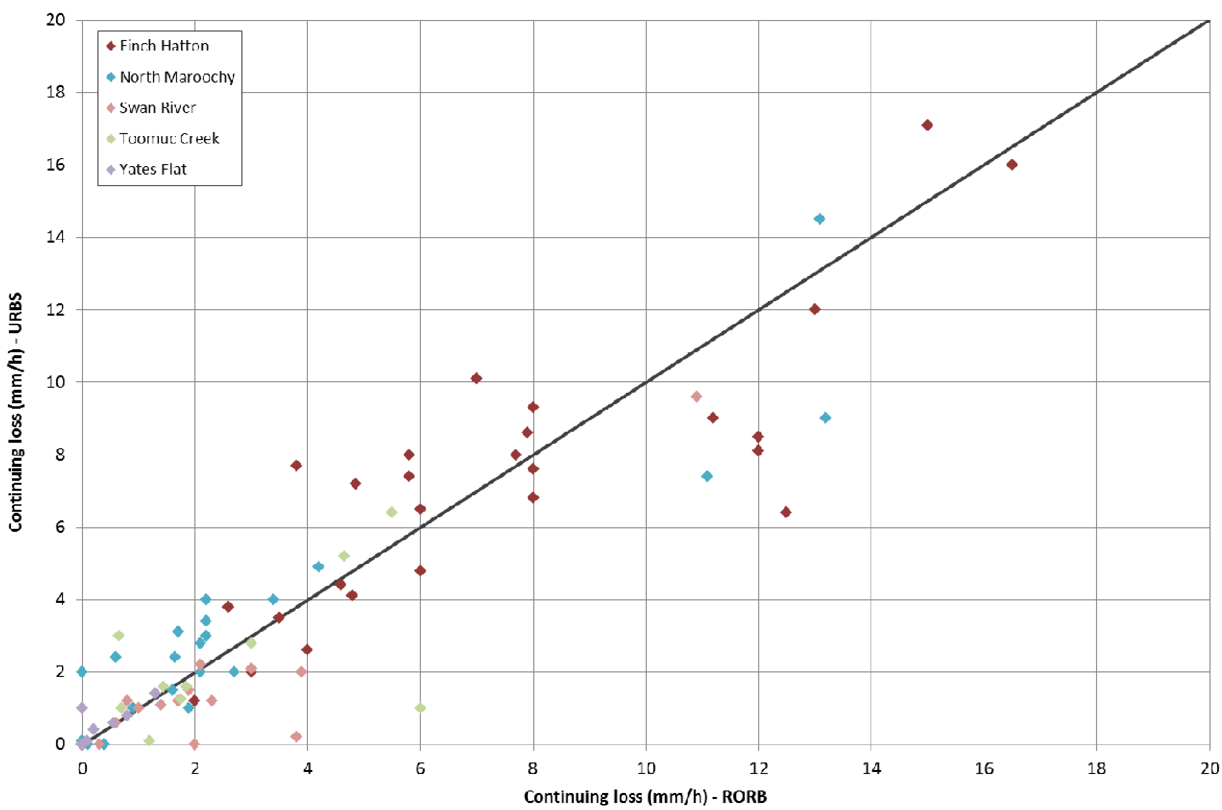


Figure G-16 Initial Loss values for the RORB and URBS calibrations

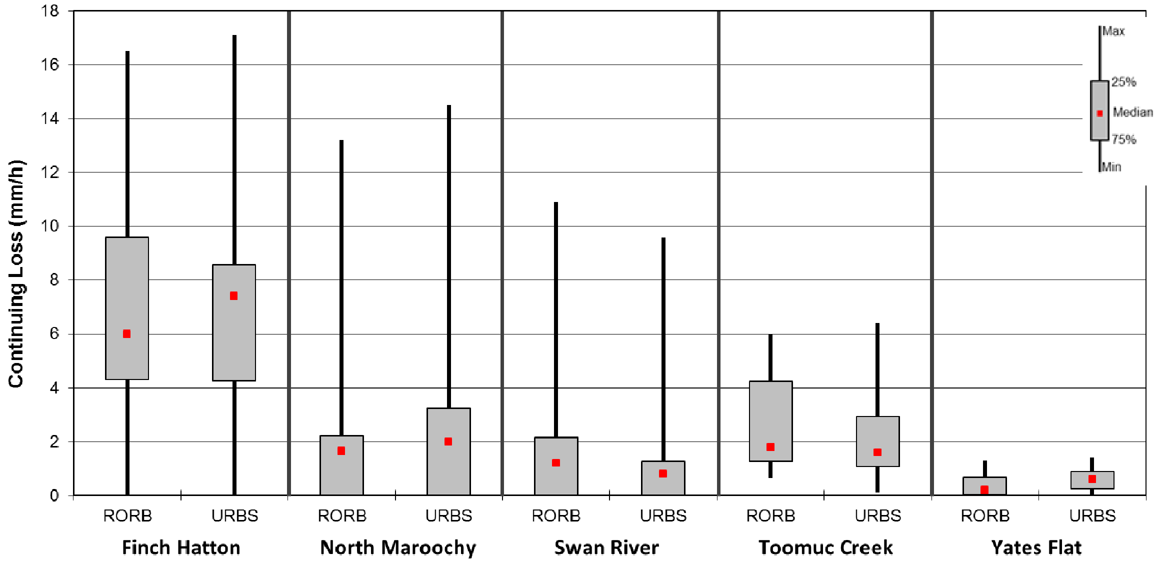


Figure G-17 Comparison of Continuing Loss boxplots for RORB and URBS calibrations

Variation in volume error

The volume error from the each of the models is compared in Figure G-18. It can be seen in that in terms of volume error the URBS model performed marginally better than the RORB model. Of the performed calibrations, URBS described flow volume better for 55% of the events. This result can be attributed to the greater freedom afforded in URBS by the separation of routing into overland and in-channel routing (which provides additional fitting flexibility).

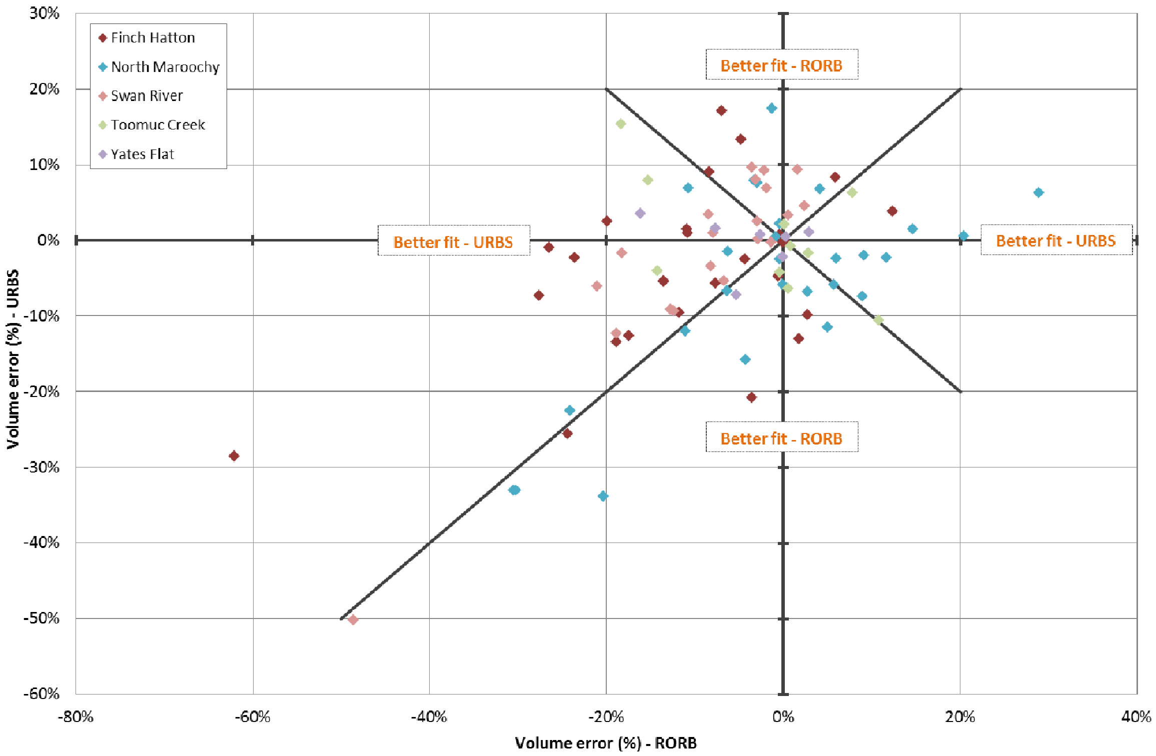


Figure G-18 Volume error for the RORB and URBS calibrations

G.5 SWMOD - Sensitivity to soil water storage curve shape

Introduction

As a variable infiltration capacity model, the SWMOD model utilizes a relationship between infiltration capacity and the saturated fraction of the catchment. This relationship is governed by:

$$C_f = C_{\max} - (C_{\max} - C_{\min}) \times \left(\frac{1}{F}\right)^{\frac{1}{\beta}}$$

Where

C_f is the infiltration capacity at fraction F of the sub-catchment;
F is the saturation fraction of the sub-catchment;
β is the shape parameter;
$C_{\max}$ is the maximum infiltration capacity; and
$C_{\min}$ is the minimum infiltration capacity

In this study, the soil water retention curve was constructed using properties provided by McKenzie et al (2000). 5th percentile and 95th percentile estimates of the soil water holding capacity were used as estimates for minimum and maximum infiltration capacity respectively, and were used in conjunction with the median estimate to fit shape parameter β.

This analysis is concerned with testing if there is any appreciable increase in model performance when using a fitted β over assuming a linear relationship (that is, $\beta = 1$). Calibrations using both fitted β values and linear relationships were performed for four of the pilot catchments.

Table G-9 Fitted β values for each soil type

Catchment	Soil id	β	Proportion of catchment area
Dirk Brook	19482	1.7	90.8%
	19505	1.26	9.2%
Spring Creek	15532	5.2	61.7%
	16358	1.6	38.1%
	16530	1.05	0.1%
	16585	1.05	0.1%
Finch Hatton Creek	7364	1.39	100%
Toomuc Creek	21769	1.33	74.5%
	21885	1.24	21.1%
	21990	1.0	4.4%

Initial Moisture Content

Figure G-19 shows the different Initial Moisture contents estimated for the linear and Beta infiltration capacity relationships. The Initial Moisture content was not sensitive to the shape of the infiltration capacity relationship. This is an expected result; altering β does not change the minimum infiltration capacity – resultantly, the Initial Moisture deficit for a given Initial Moisture content should not be affected.

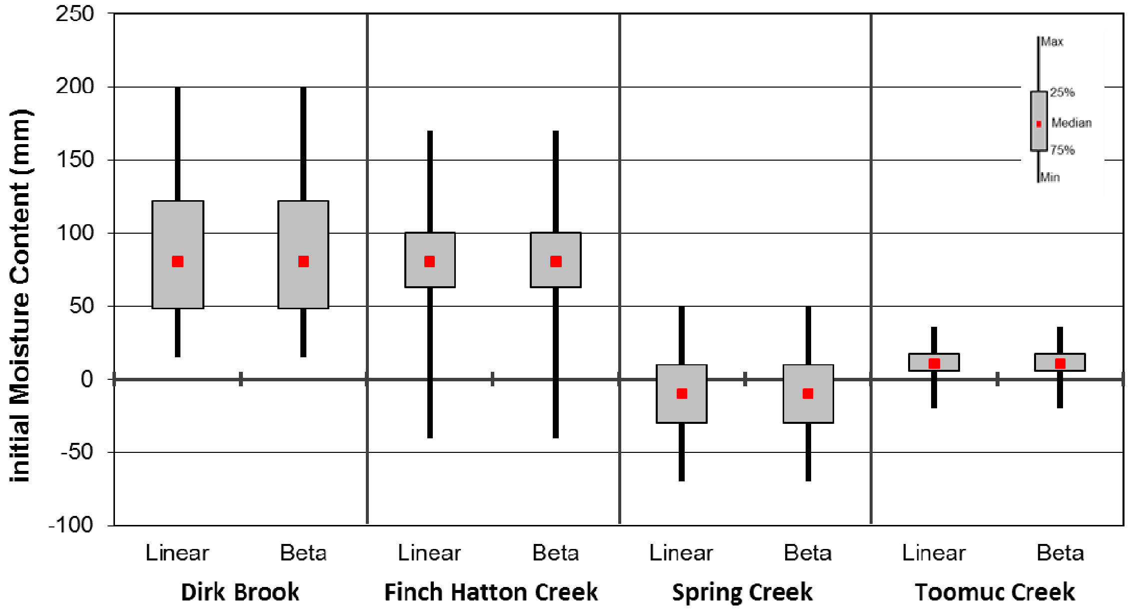


Figure G-19 Comparison of Initial Moisture content boxplots for both the linear and fitted beta infiltration capacity relationships

Capacity Factor

In initial conceptualization SWMOD only used one parameter – Initial Moisture content. After it was shown that this parameter did not allow the model to match observations effectively the Capacity Factor was introduced to increase flexibility.

Figure G-20 shows the resulting Capacity Factors for the 2 infiltration capacity relationships. For all catchments the Capacity Factor is no closer to one for the β calibrations than the linear calibrations. In fact, for Spring Creek both the median Capacity Factor and the range of values are larger for the β calibrations. This implies that there is no advantage to using the fitted infiltration capacity relationship in terms of Capacity Factor.

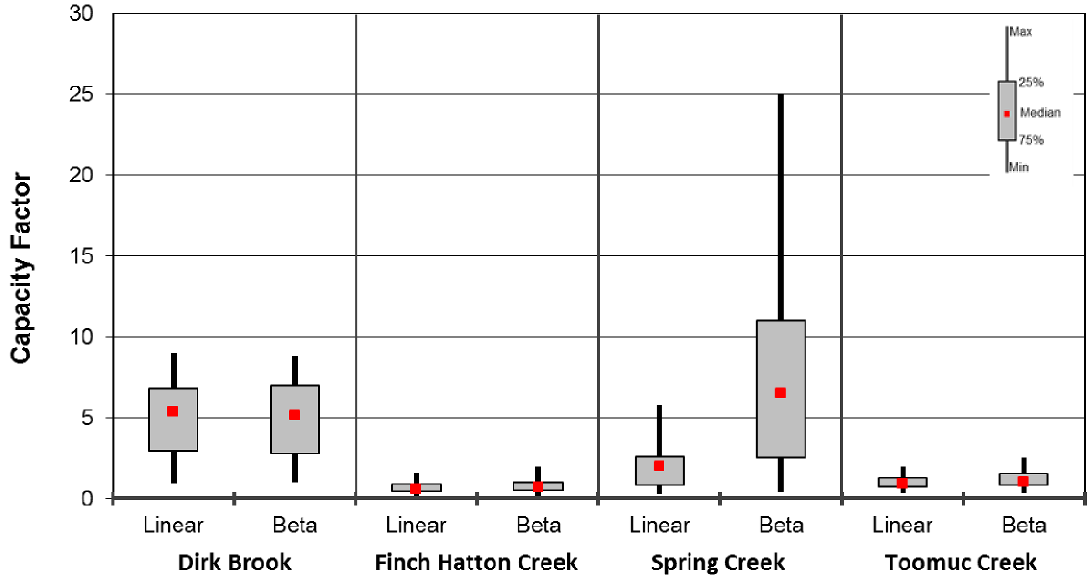


Figure G-20 Comparison of Capacity Factor boxplots for both the linear and fitted beta infiltration capacity relationships

Volume Error

Figure G-21 shows the volume errors for the 2 infiltration capacity relationships. It can be seen that volume error is consistent between calibrations for all but the Dirk Brook catchment, where model performance has improved significantly. It is therefore highlighted that the potential benefits of using fitted β values are catchment specific. All of the catchments use relationships with β significantly larger than one; however, the change in performance does not correspond with how non-linear the infiltration capacity relationship is.

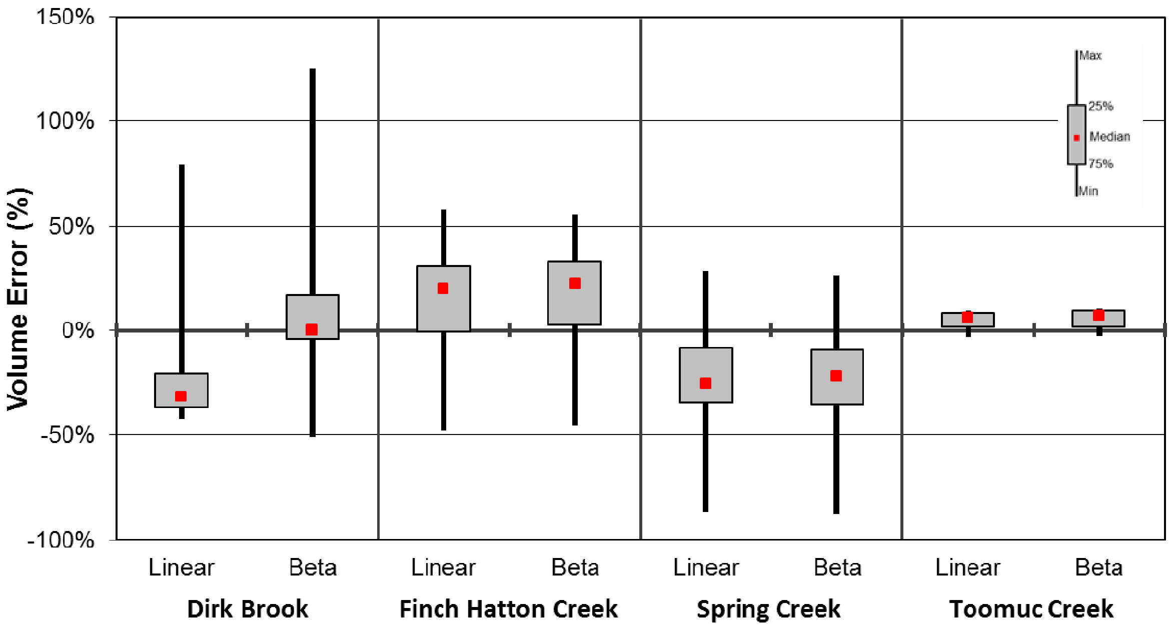


Figure G-21 Comparison of volume error content boxplots for both the linear and fitted beta infiltration capacity relationships

G.6 SWMOD - Sensitivity to scaling of soil water holding capacity

Introduction

As detailed in the pilot study, estimates of water holding capacity compiled by the Water Corporation in Western Australia and the findings of Ladson et al. (2006) have highlighted the possibility that water holding capacity values estimated using the values presented by McKenzie et al. (2000) may lead to an under-prediction of water holding capacity. Indeed, in a comparison of four Western Australian catchments, estimates calculated McKenzie et al. (2000) were over three times smaller than those compiled with the Department of Water data.

Table G-10 Comparison of water holding capacity calculated using McKenzie et al. (2000) values and calculated using soil water storage relationships in SWMOD by DoW, WA (Leanne Pearce, Water Corporation., pers. Comm.)

Catchment	Calculated using McKenzie et al. (2000) (mm)	Department of Water (mm)	Ratio of difference
Serpentine Creek	132	447	0.29
Samson Brook Dam	141	525	0.26
South Dandalup Dam	127	467	0.27
Wellington Dam	285	521	0.54

To explore potential improvements to model performance gained by addressing this discrepancy, the linear relationship ($\beta = 1$) calibrations are compared to a revisited set of calibrations where all soil water holding capacity values have been multiplied by three (denoted "linear x3 calibrations"). This analysis is performed for six of the pilot catchments.

Initial Moisture Content

As expected, the Initial Moisture content is higher in the "linear x3 calibration". Figure G-22 shows that when the infiltration capacity values are scaled there are fewer negative values used (particularly in Spring Creek). This is a desirable result; negative Initial Moisture content represents where $C_{\min}$ is not high enough for an Initial Moisture content of zero to give a high enough Initial Moisture deficit (which somewhat corresponds with Initial Loss). The reduction in negative values for the "linear x3 calibrations" suggests that the scaled infiltration capacity values may be closer to the actual capacity for some catchments.

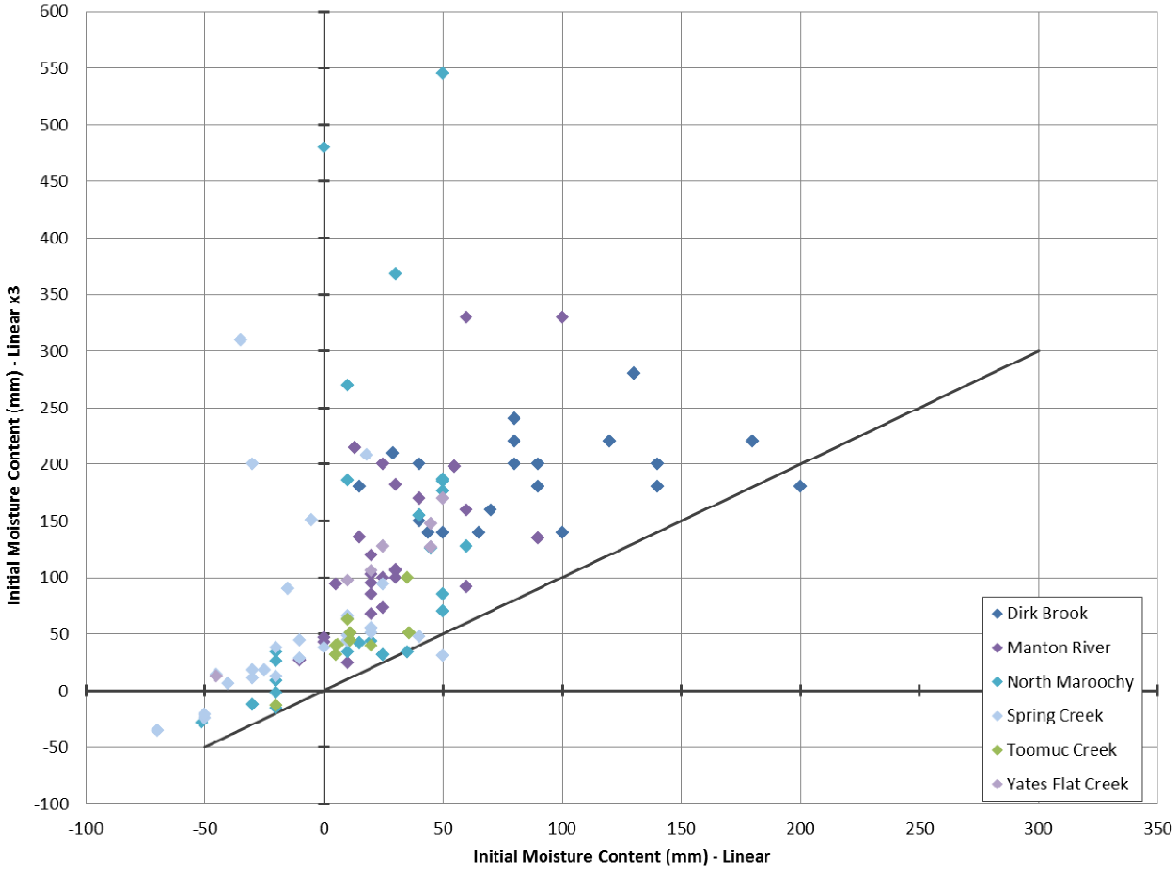


Figure G-22 Initial Moisture Content values for the 3x multiplier both not applied and applied to the linear infiltration capacity relationship

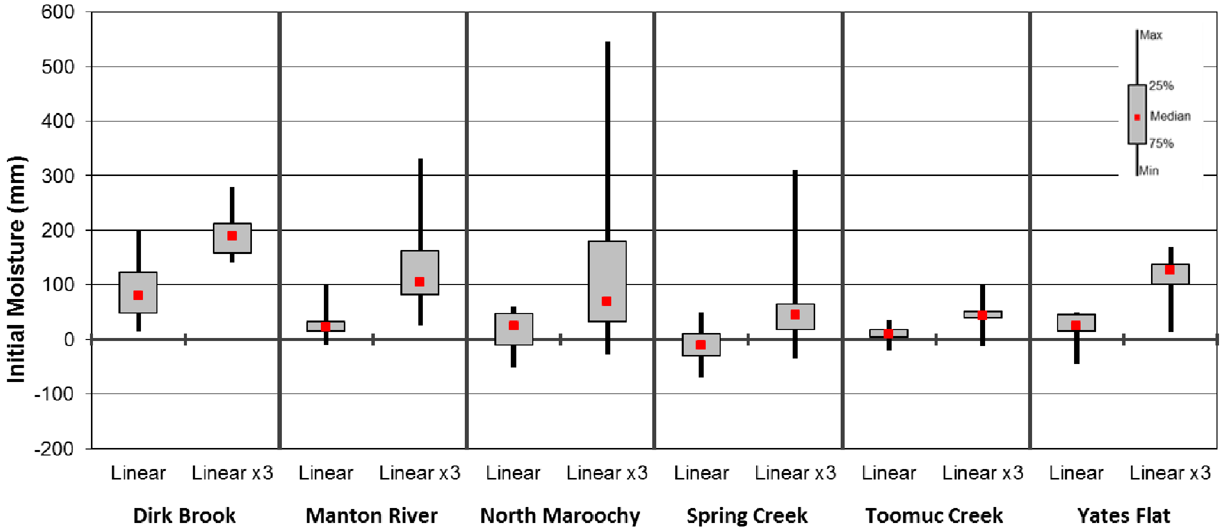


Figure G-23 Comparison of Initial Moisture content boxplots for the 3x multiplier both not applied and applied to the linear infiltration capacity relationship

Capacity Factor

Figure G-24 shows the impact of increasing the capacities on the Capacity Factor. The Capacity Factor is systematically higher without the application of the multiplier than it is with it. This reduction is particularly apparent in the Dirk Brook and Spring Creek catchments (which have high median Capacity Factor values without the multiplier).

It should be noted that the Capacity Factor reduction also occurs in catchments where the value is acceptable before applying the multiplier. This can be seen in Toomuc Creek, Yates Flat and North Maroochy, where the Capacity Factor values are further from one after applying the multiplier.

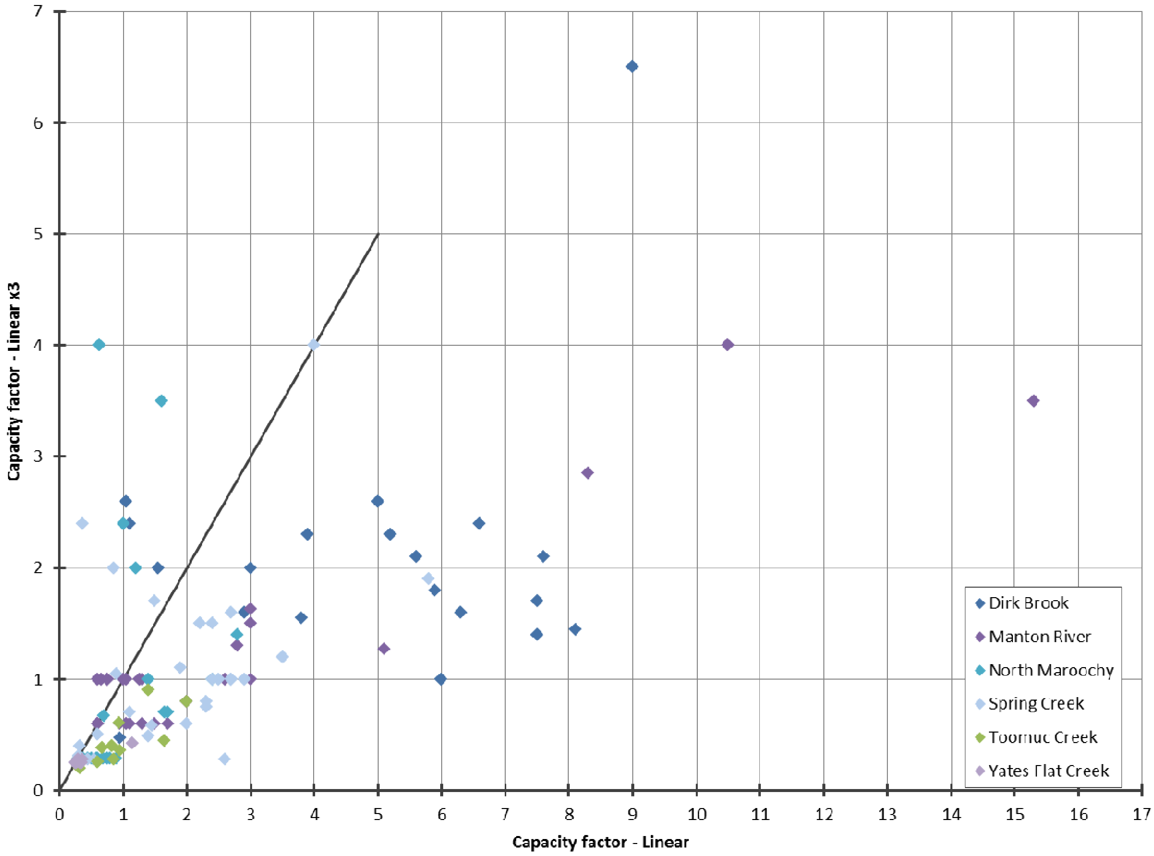


Figure G-24 Capacity Factor values for the 3x multiplier applied to the linear infiltration capacity relationship

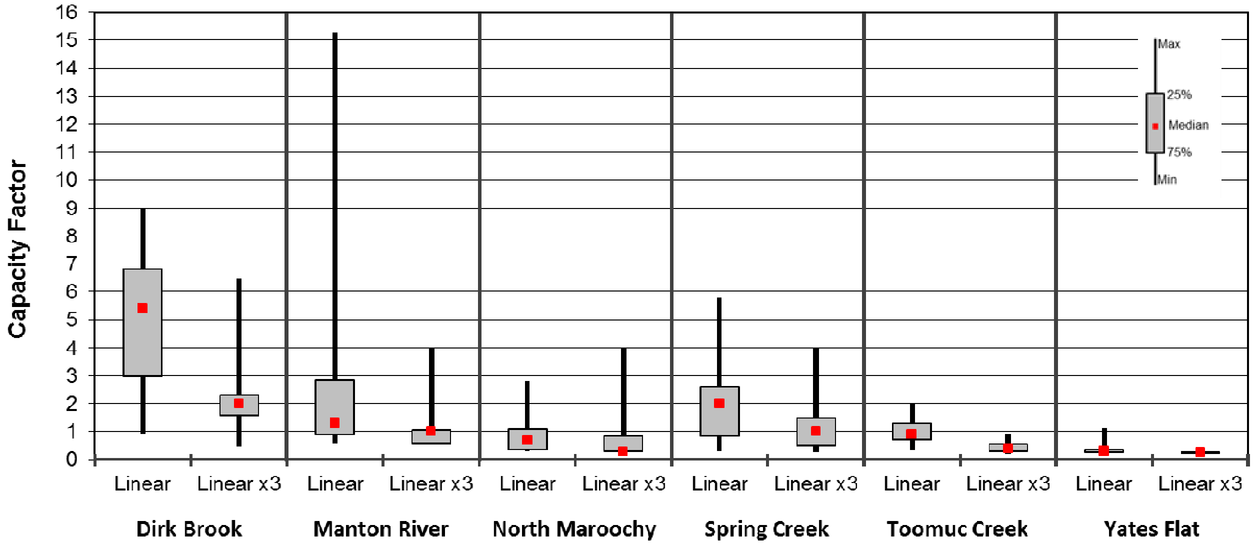


Figure G-25 Comparison of Capacity Factor boxplots for the 3x multiplier both not applied and applied to the linear infiltration capacity relationship

Volume error

It is seen in Figure G-27 that the volume error is largely consistent between the linear and "linear x3 calibrations" except for Spring Creek (where there is moderate improvement when the multiplier is used).

Though similar volume errors between calibrations may suggest that model performance has not changed significantly, the resulting value of the Capacity Factor must be considered. The Capacity Factor was originally introduced to the model when the Initial Moisture content alone did not allow the model to adequately fit observations and therefore a better fit can also be attributed to a Capacity Factor closer to unity.

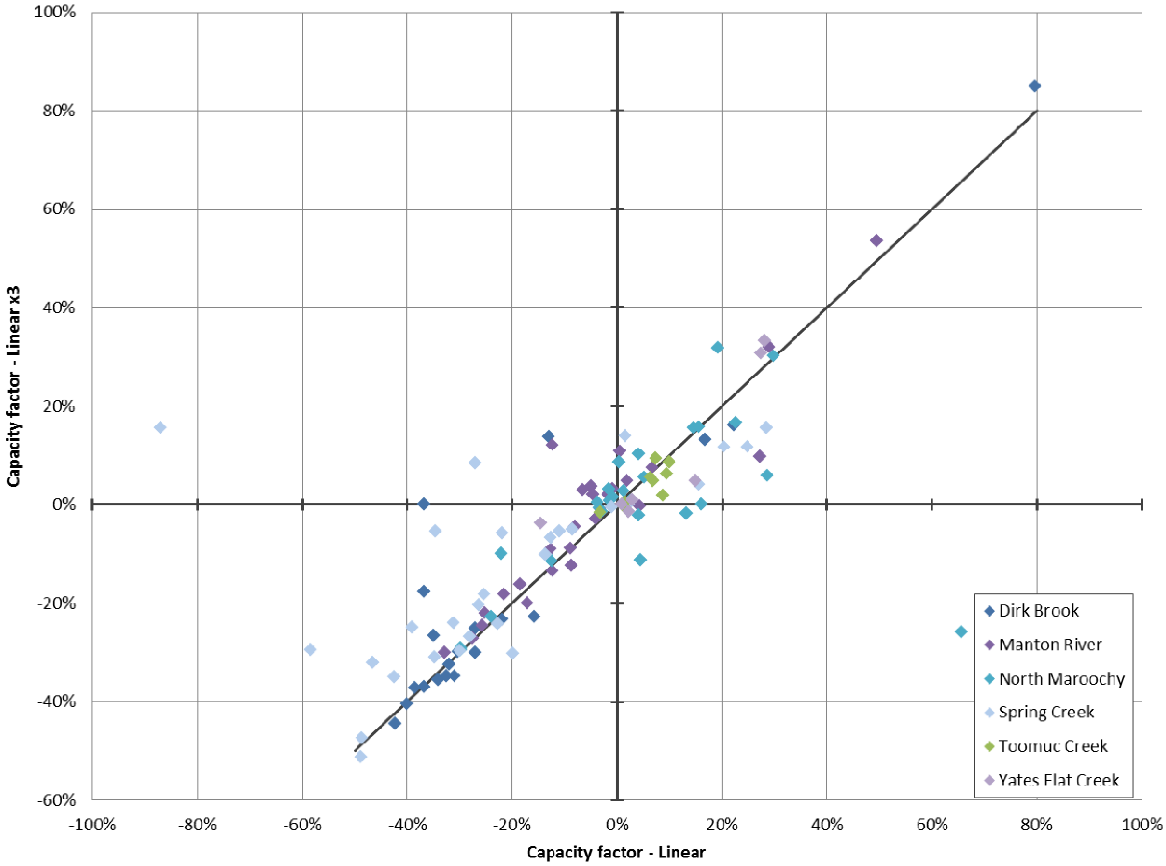


Figure G-26 Volume error for the 3x multiplier both not applied and applied to the linear infiltration capacity relationship

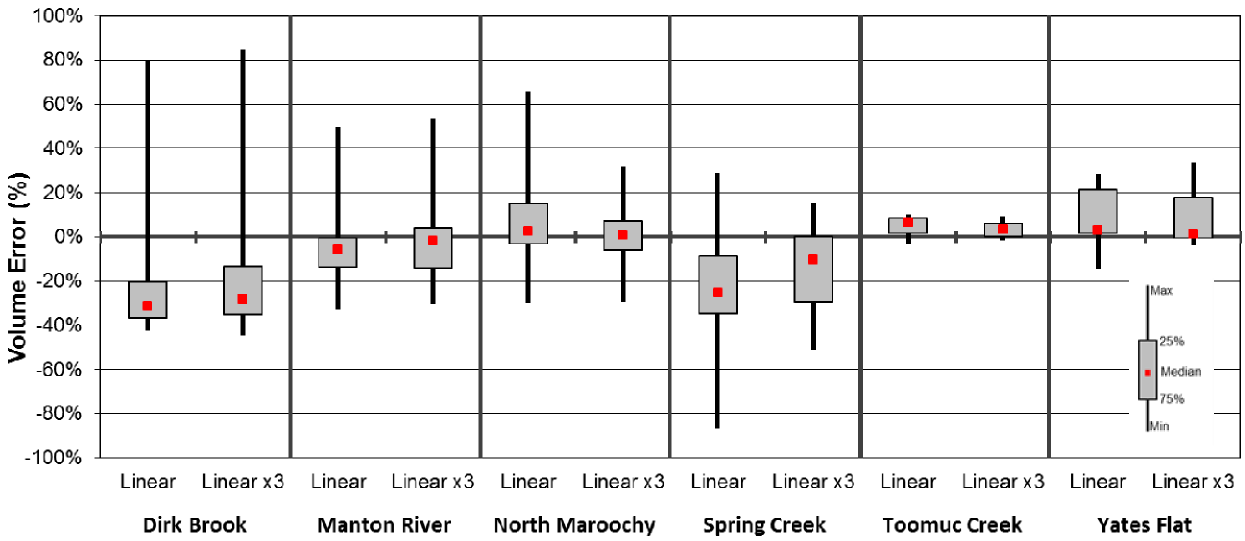


Figure G-27 Comparison of volume error boxplots for the 3x multiplier both not applied and applied to the linear infiltration capacity relationship

G.7 Correlation between Initial Loss and SWMOD Initial Moisture deficit

Introduction

Initial Moisture deficit is defined as $C_{\min}$ minus the Initial Moisture content. This represents the amount of moisture that initially must enter the soil before runoff can commence – in this regard it is conceptually similar to Initial Loss in the IL/CL loss model.

This analysis is concerned with examining the correlation between Initial Loss and Initial Moisture deficit. A representative $C_{\min}$ for each catchment is defined by weighted average where each soil's associated $C_{\min}$ is scaled by catchment area that soil type covers. The Initial Moisture deficit for each event in all ten catchments is compared to the Initial Loss value derived in the adopted k_c IL/CL RORB calibrations.

Results

It can be seen in Figure G-28 that some moderate correlation exists between IL and Initial Moisture deficit in some catchments (in particular North Maroochy and Spring Creek). It is clear that this relationship is catchment-specific – for instance, there is no correlation seen in Finch Hatton or Toomuc Creek.

The use of a weighted average $C_{\min}$ could be re-evaluated in further analysis – a weighted average was chosen to ensure that the infiltration properties of each soil in a catchment are adequately represented, however runoff will begin in soils with the lowest $C_{\min}$ value first (hence minimum $C_{\min}$ may be a useful alternate representative value).

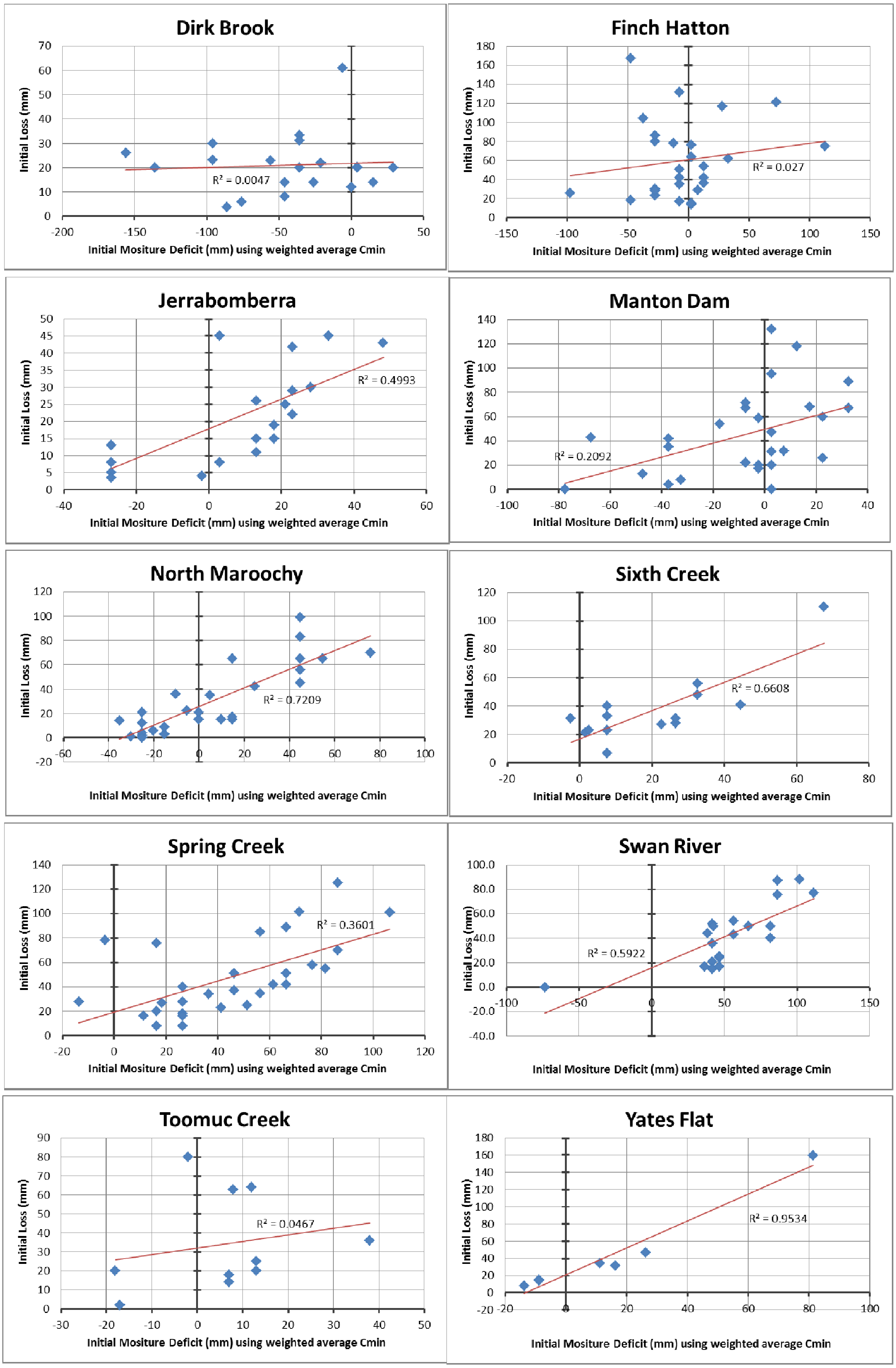


Figure G-28 Initial Moisture deficit vs. Initial Loss for each catchment

G.8 Conclusions

The investigation described in this report is based on limited scope of work, however on the basis of the results presented it can be concluded that:

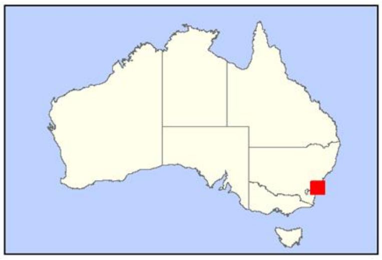
- Differences in results arising from subjective judgements by different practitioners has a negligible to small influence on estimates of initial and Continuing Loss rates;
- Calibration performance improves when site- and event-specific characteristics are considered, and any increase in the uncertainty in the timing of simulated hydrographs propagates through to additional uncertainty in estimates of loss parameters;
- The selection of an alternative routing model structure has little influence on the derived estimates of the loss parameters;
- Loss parameters are not sensitive to the shape of the soil water storage curve adopted for the variable infiltration capacity (SWMOD) model;
- While it is necessary to scale regional estimates of soil water holding capacity to yield values that are consistent with site-specific analyses, the impact on calibration performance is low; and,
- There is moderate correlation between Initial Loss characteristics obtained from fixed- and variable- infiltration models, though further investigation would be required to understand whether it would be possible to use this for predictive purposes.

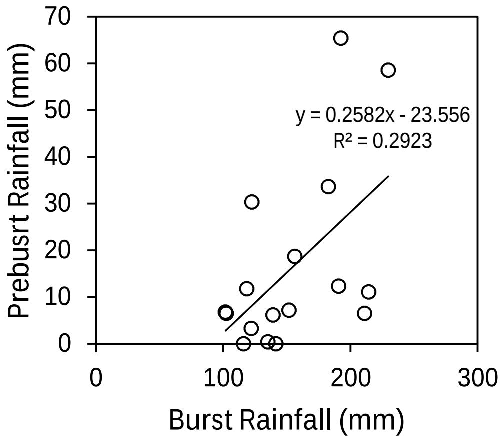
Appendix H Adopted routing and baseflow parameters

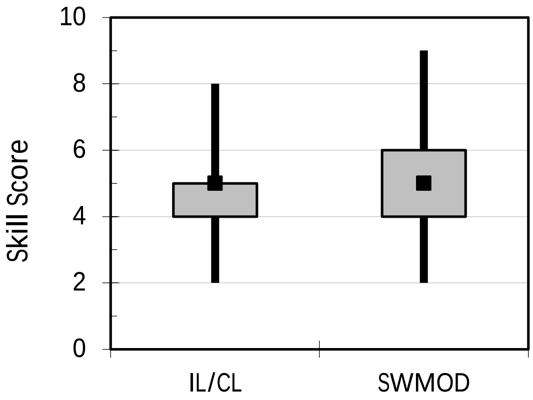
	Name		Location	$c_{0.8}$		d_{av}		Baseflow separation	
	Gauge No.	Stream	State	IL/CL	SWMOD	IL/CL	SWMOD	Factor	No. Passes
GSAM - Coastal	216004	Currambene	NSW	1.07	0.97	11	10	0.925	7
	213200	O'Hares	NSW	0.87	0.72	9	7.5	0.925	7
	211013	Ourimbah	NSW	2.05	1.86	22	20	0.925	9
	2219	Swan	Tas	1.41	1.41	10	10	0.925	7
	235219	Aire	VIC	1.58	1.21	17	13	0.925	7
	229106	McMahons	VIC	3.30	1.82	20	11	0.925	7
	228206B	Tarago	VIC	2.06	1.61	16	12.5	0.925	7
	228217	Toomuc	VIC	1.62	1.12	14.5	10	0.925	7
GSAM - Inland	410743	Jerrabomberra	NSW	0.85	0.57	7	4.75	0.925	7
	411003	Butmaroo	NSW	0.61	0.44	7	5	0.925	7
	AW503506	Echunga	SA	1.14	0.82	6.92	5	0.925	7
	AW501500	Hindmarsh	SA	1.40	1.14	11	8.94	0.925	9
	AW502502	Myponga	SA	2.04	1.73	16.5	14	0.925	7
	A5040523	Sixth	SA	1.16	0.64	10	5.5	0.925	7
	406216	Axe	VIC	1.21	1.00	8.5	7	0.925	7
GTSMR - Coastal	G8150151	Celia	NT	2.35	2.01	14	12	0.925	7
	G8170066	Coomalie	NT	2.26	1.76	18	14	0.925	9
	G8170075	Manton	NT	1.62	1.22	12	9	0.925	7
	G0290240	Tennant	NT	1.17	0.52	8.9	4	0.925	9
	120216A	Broken	Qld	0.78	0.57	11	8	0.925	9
	142001A	Caboolture	Qld	0.89	0.77	11	9.5	0.925	7
	126003A	Carmila	Qld	1.03	0.87	9.5	8	0.925	9
	125006	Finch Hatton	Qld	1.14	0.72	6.38	4	0.925	7
	141009	North Maroochy	Qld	2.25	2.25	18	18	0.925	9
	141001	South Maroochy	Qld	1.54	1.23	10	8	0.925	7
	422123	Spring	Qld	1.29	1.55	7.5	9	0.925	7
	809312	Fletcher	WA	0.47	0.37	2.5	2	0.925	7
	709007	Harding	WA	0.68	0.41	5	3	0.925	7
	708009	Kanjenjie	WA	1.50	1.34	9.5	8.5	0.925	7
GTSMR – SW WA	609005	Balgarup	WA	1.14	0.95	9.56	8	0.925	7
	701006	Buller	WA	0.60	0.38	3.2	2	0.925	7
	608002	Carey	WA	3.40	2.45	25	18	0.925	7
	614047	Davis	WA	2.98	2.10	18.5	13	0.925	7
	614005	Dirk	WA	2.88	1.81	17.5	11	0.925	9
	602199	Goodga	WA	2.63	2.14	16	13	0.925	9
	612004	Hamilton	WA	4.44	3.74	19	16	0.925	7
	614003	Marrinup	WA	3.33	1.90	17.5	10	0.925	7
	603190	Yates Flat	WA	2.04	1.63	12.5	10	0.925	7

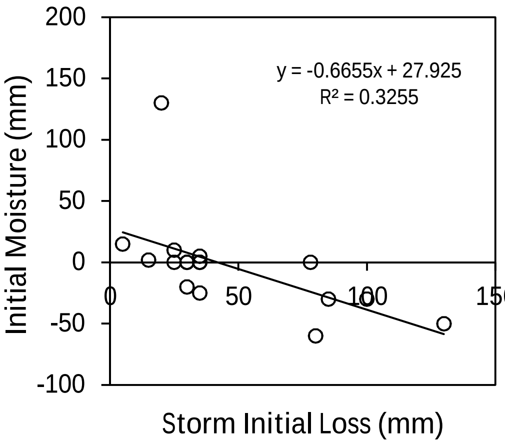
Appendix I Loss summaries for 24h bursts

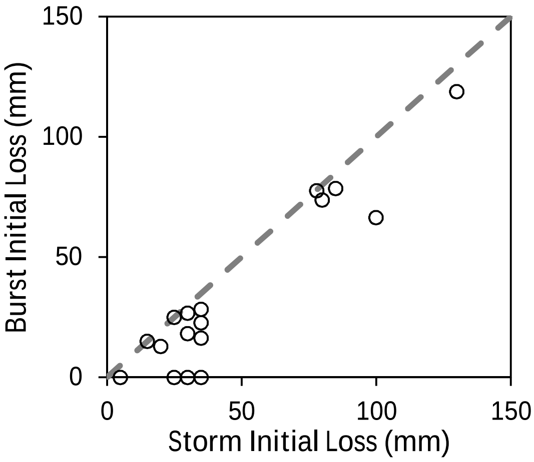
Currambene Ck @ Falls Ck (NSW) - 24 hour bursts

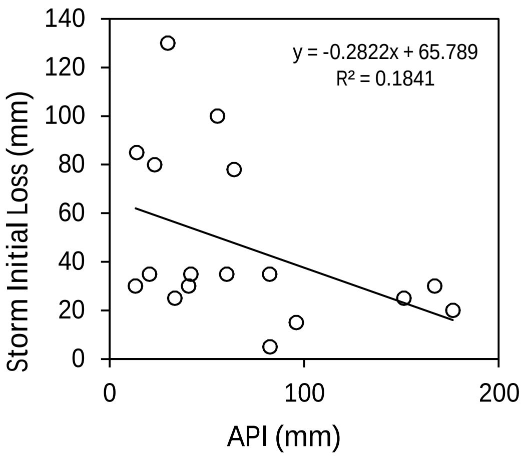


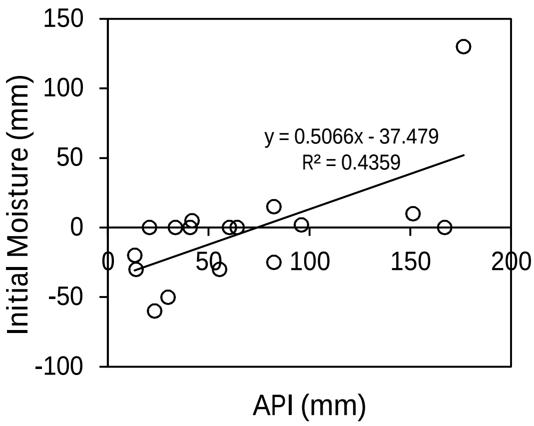




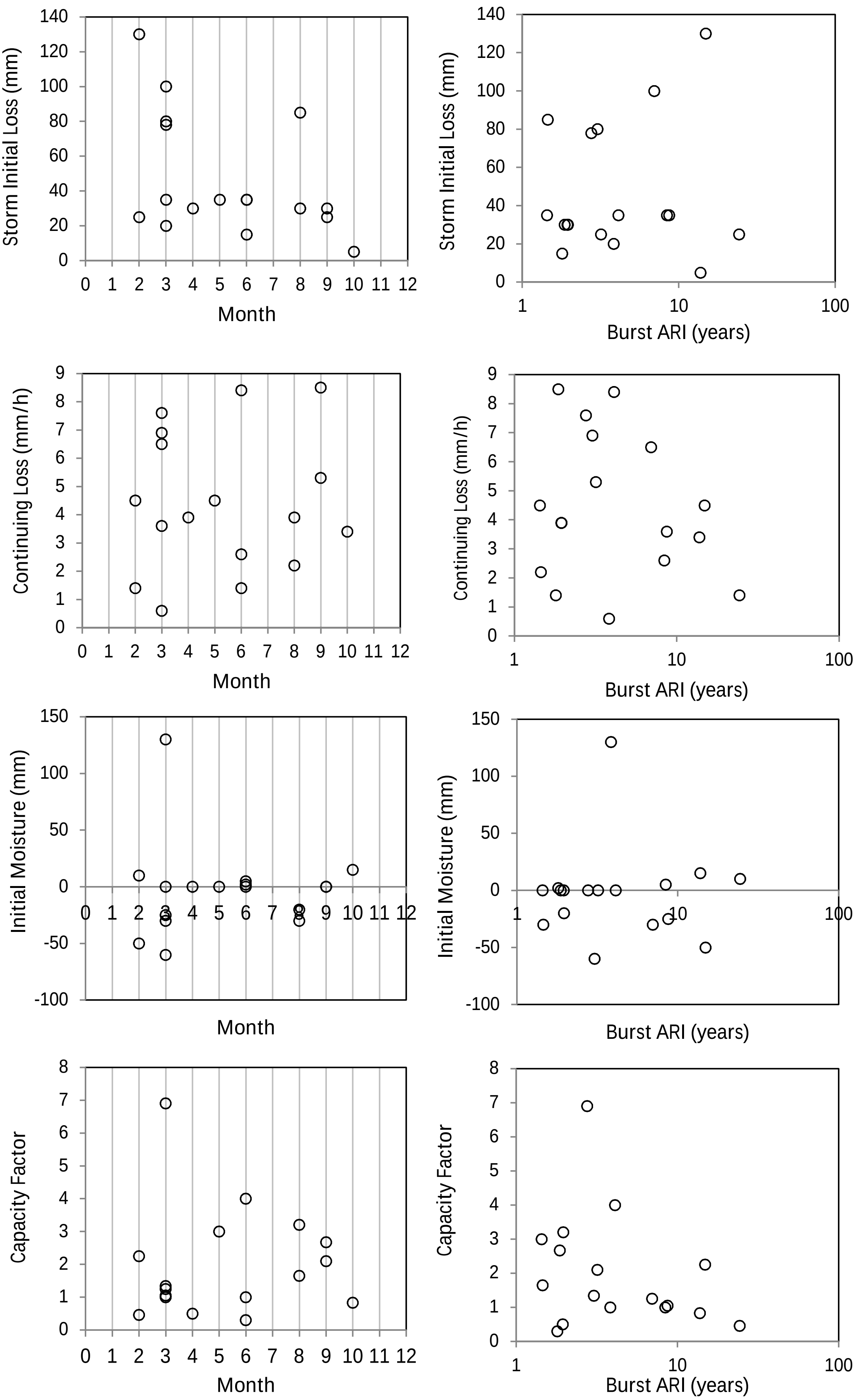




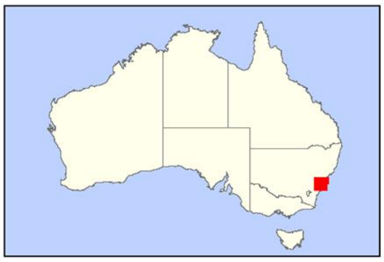


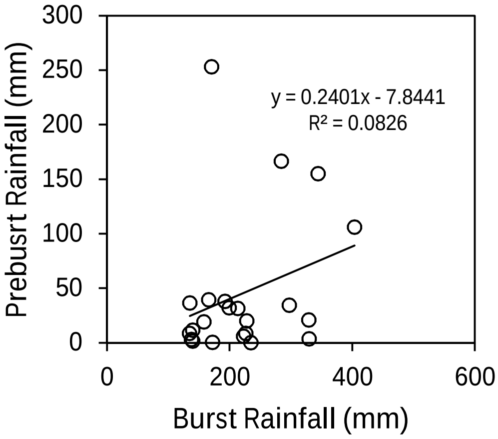


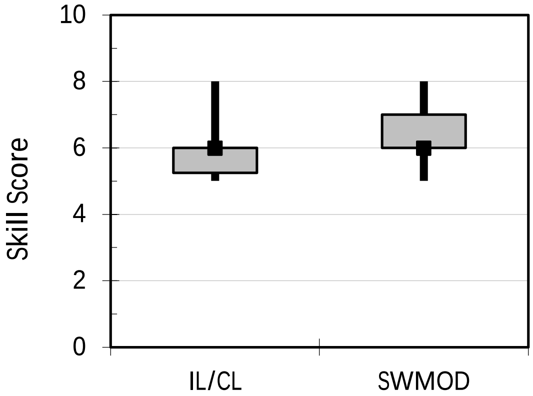
Currambene Ck @ Falls Ck (NSW) - 24 hour bursts

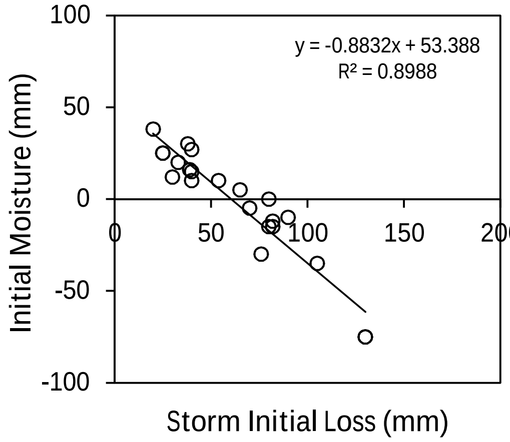


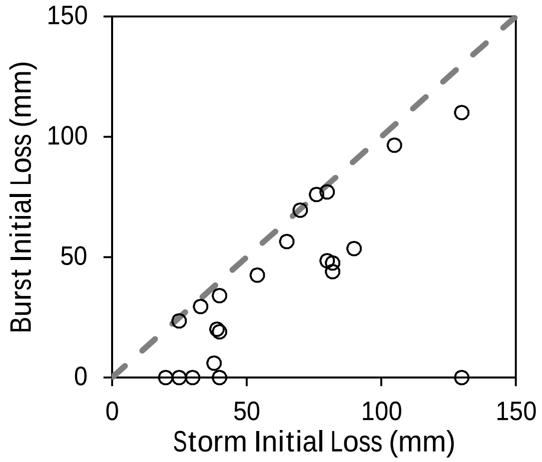
O'Hares Ck @ Wedderburn (NSW) - 24 hour bursts

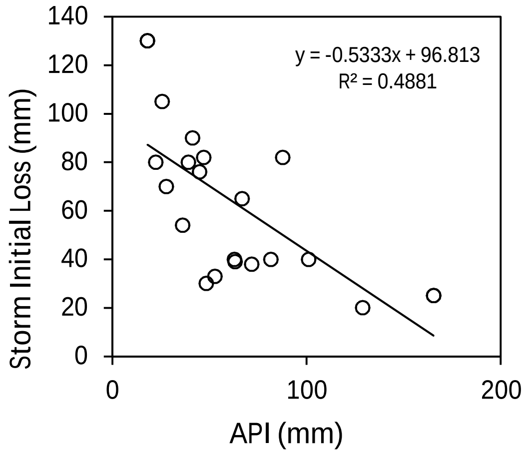


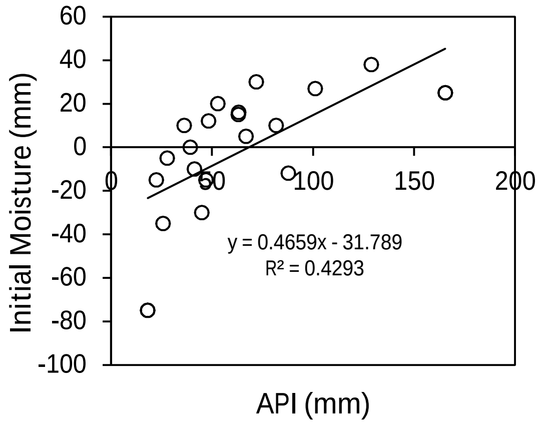




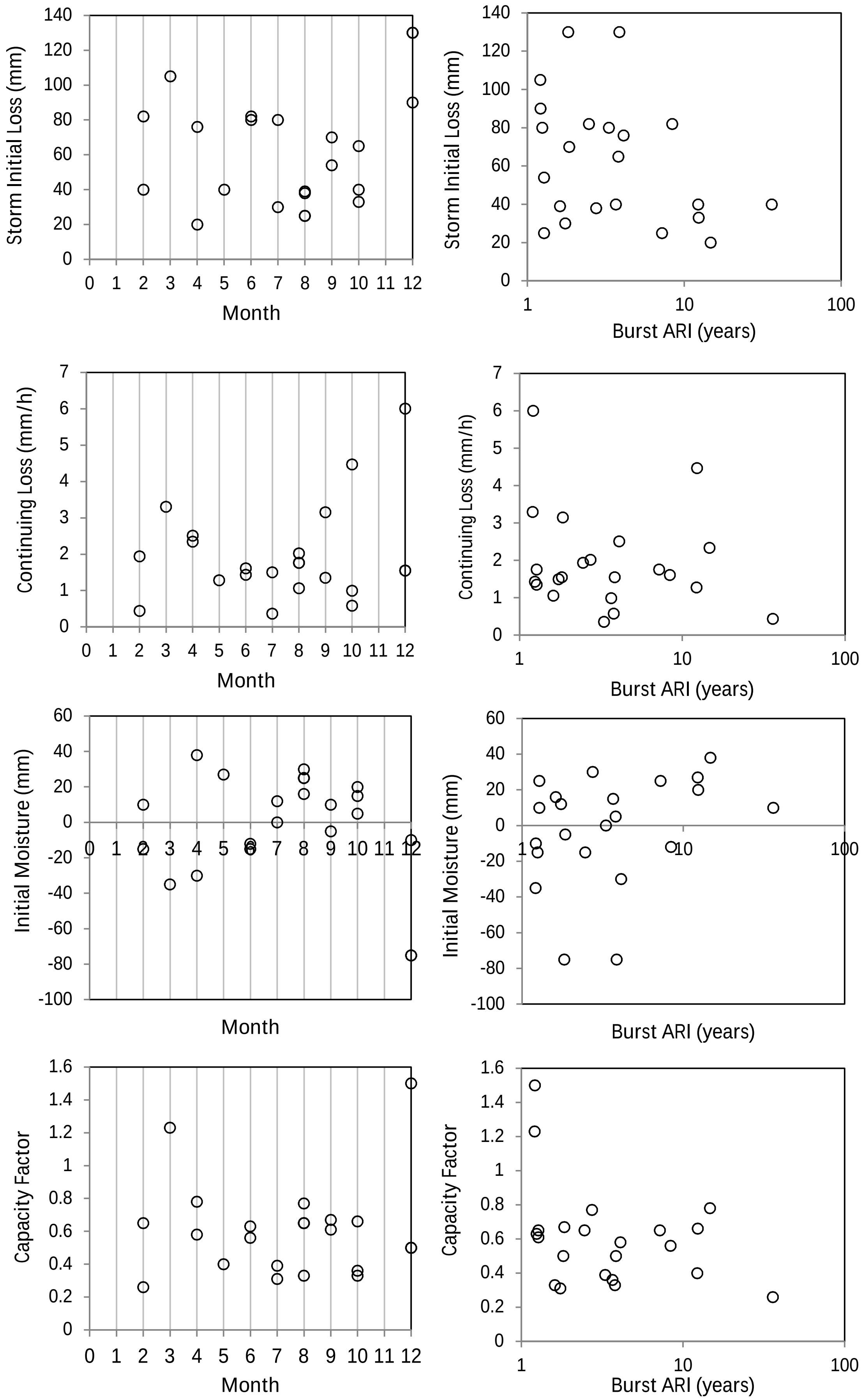




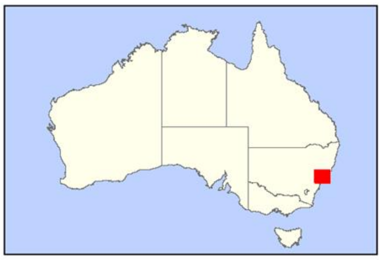


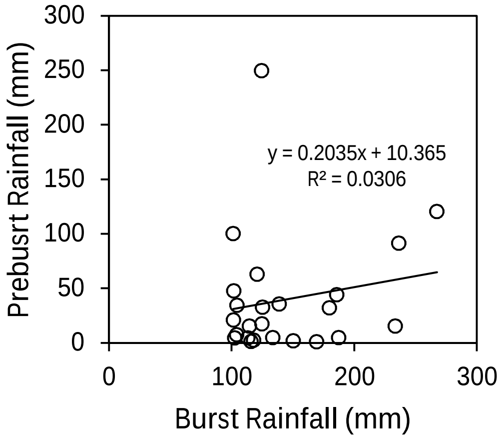


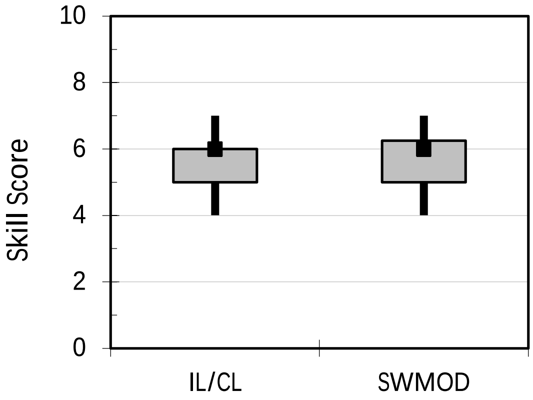
O'Hares Ck @ Wedderburn (NSW) - 24 hour bursts

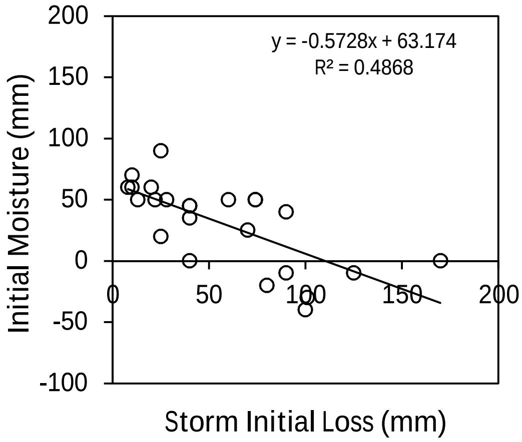


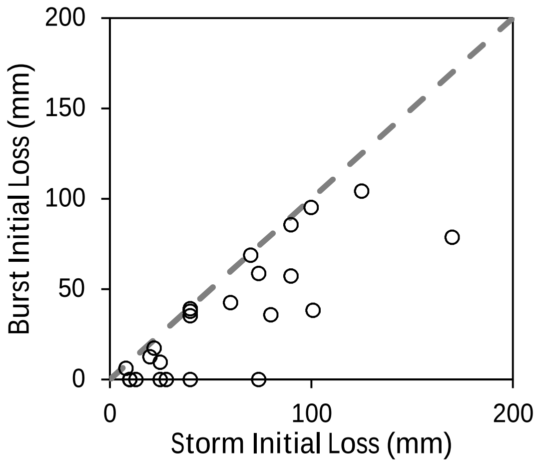
Ourimbah Ck @ U/S Weir (NSW) - 24 hour bursts

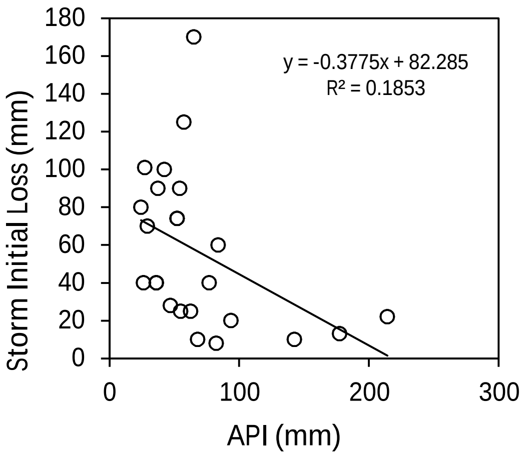


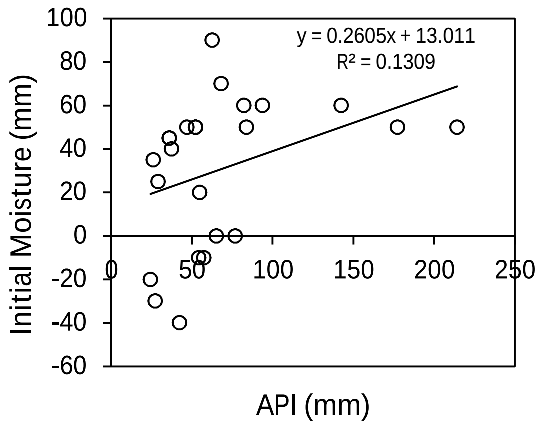




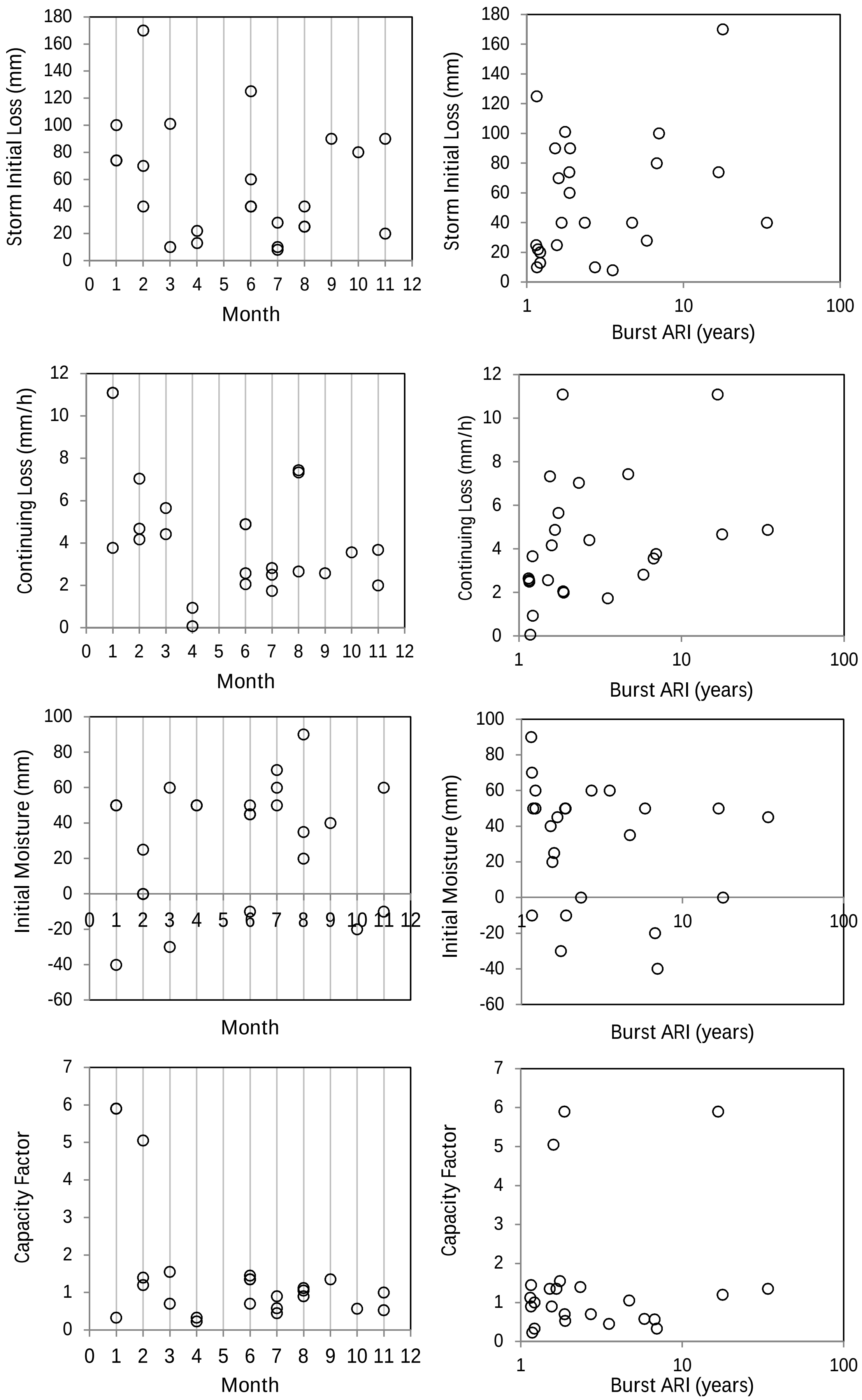




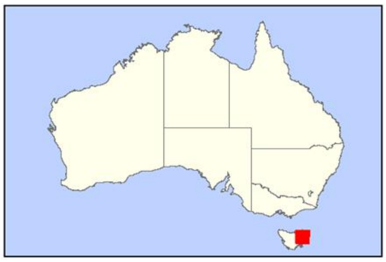


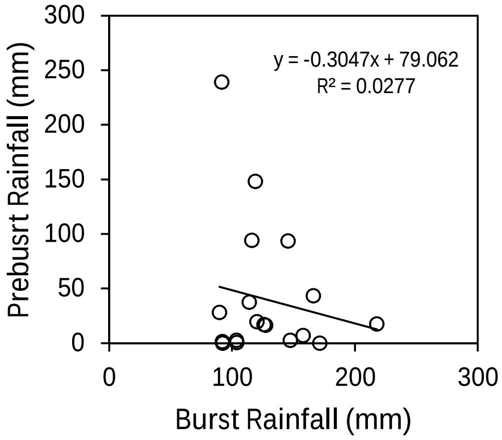


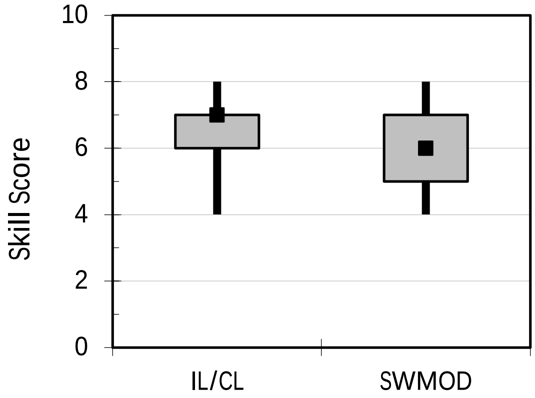
Ourimbah Ck @ U/S Weir (NSW) - 24 hour bursts

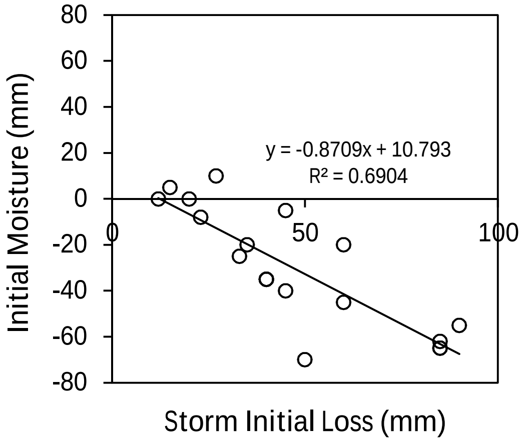


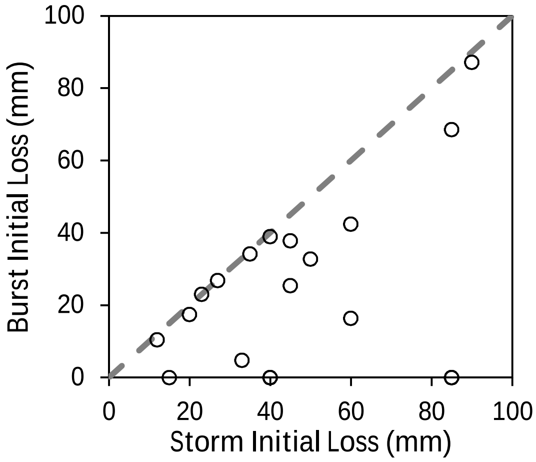
Swan River @ Harding Falls (Tas) - 24 hour bursts

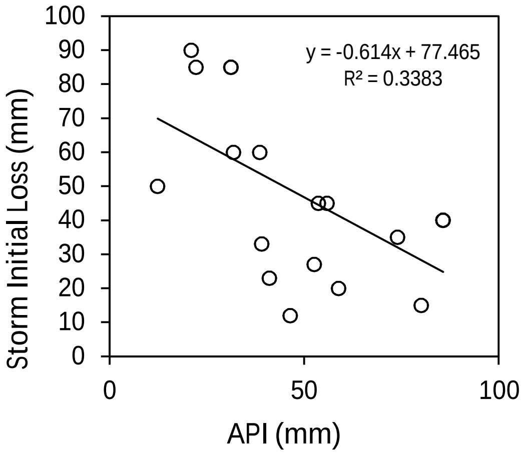


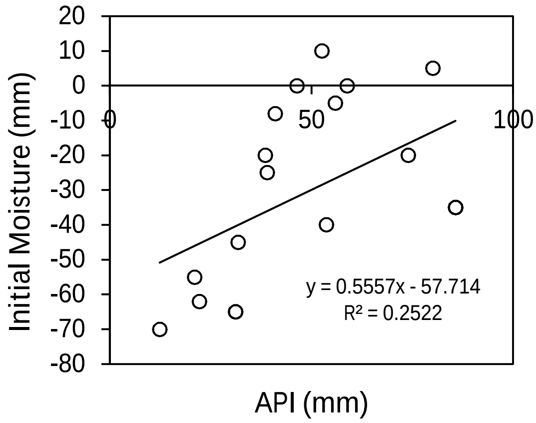




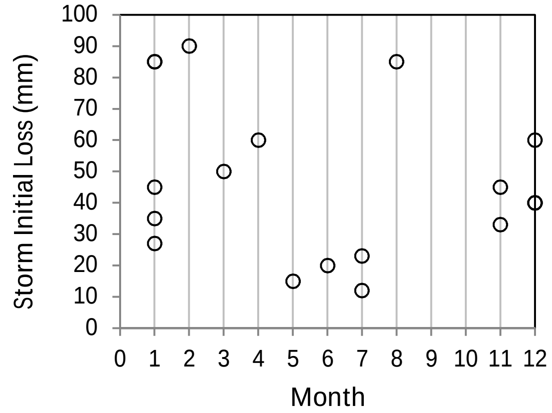


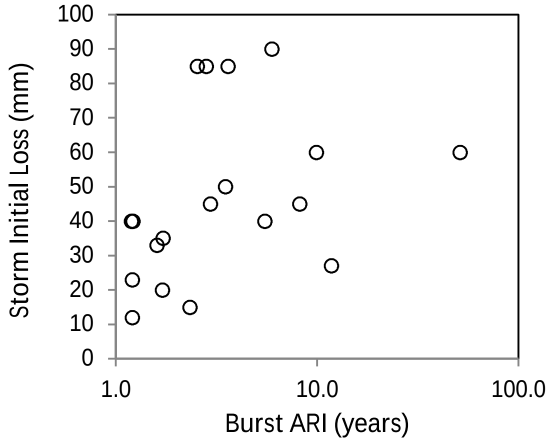


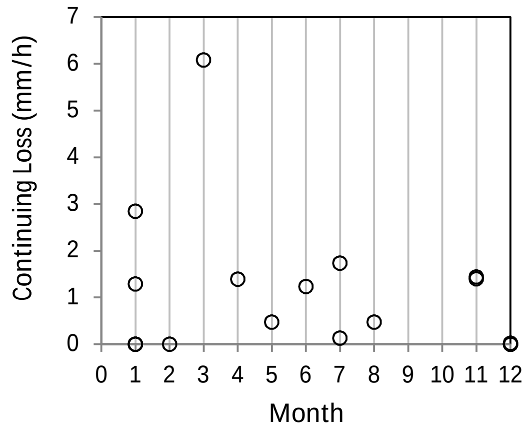


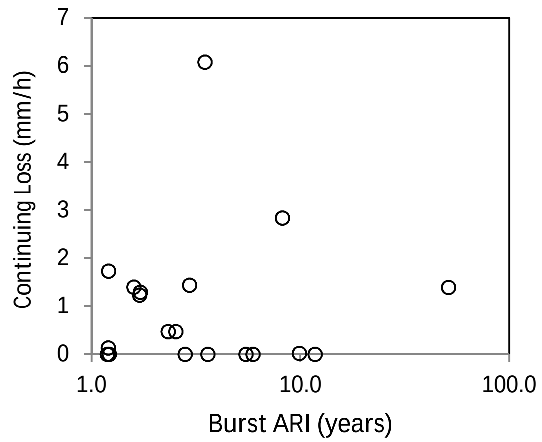


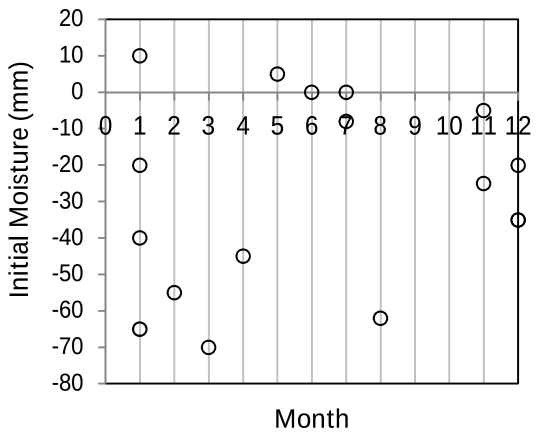
Swan River @ Harding Falls (Tas) - 24 hour bursts

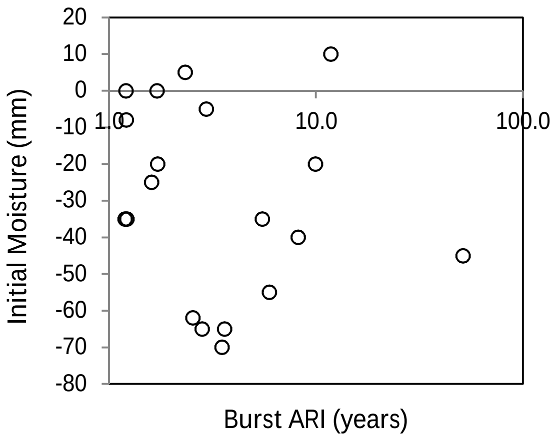


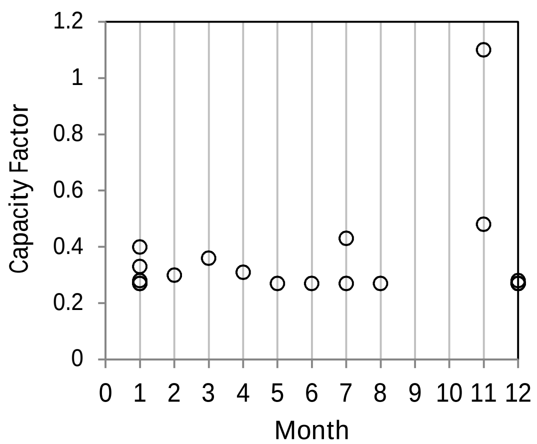


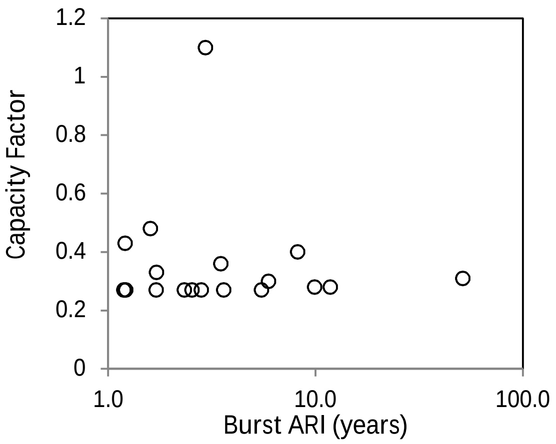




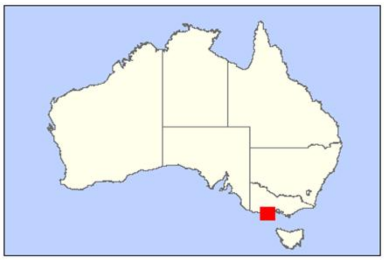


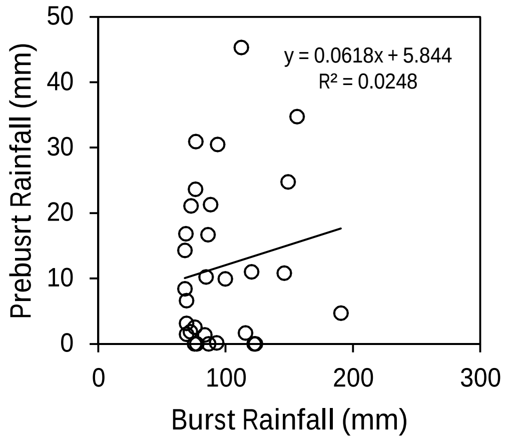


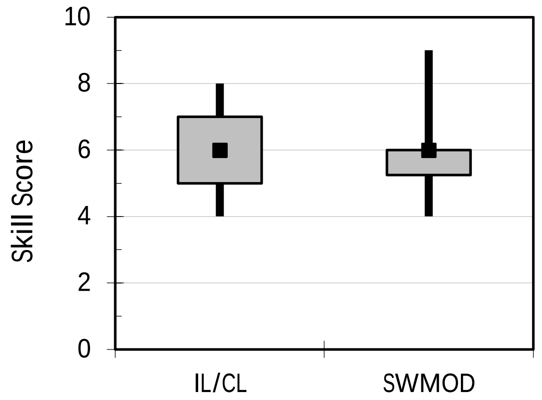


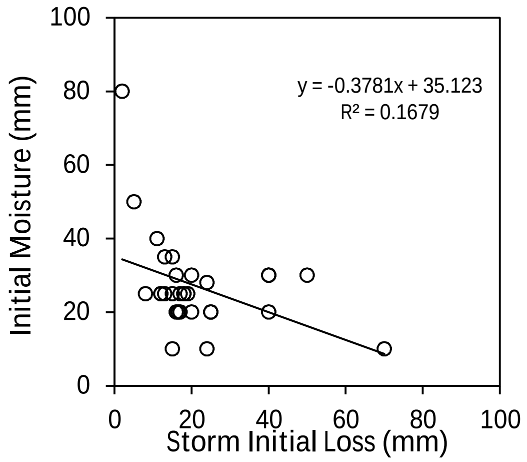


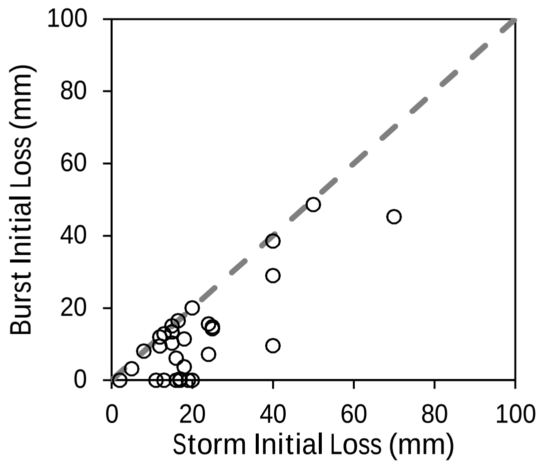
Aire @ Wyelangta (VIC) - 24 hour bursts

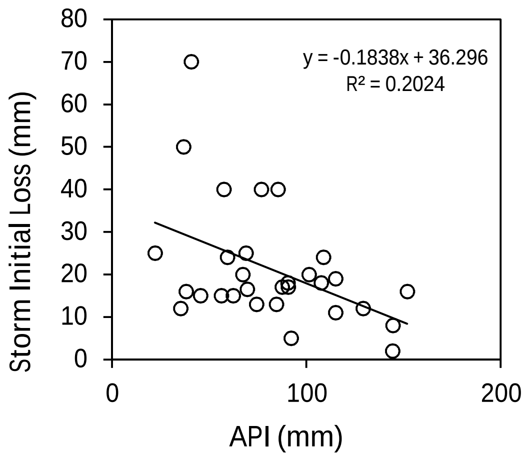


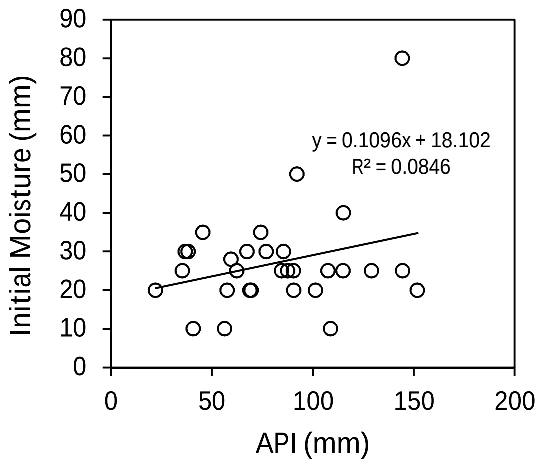




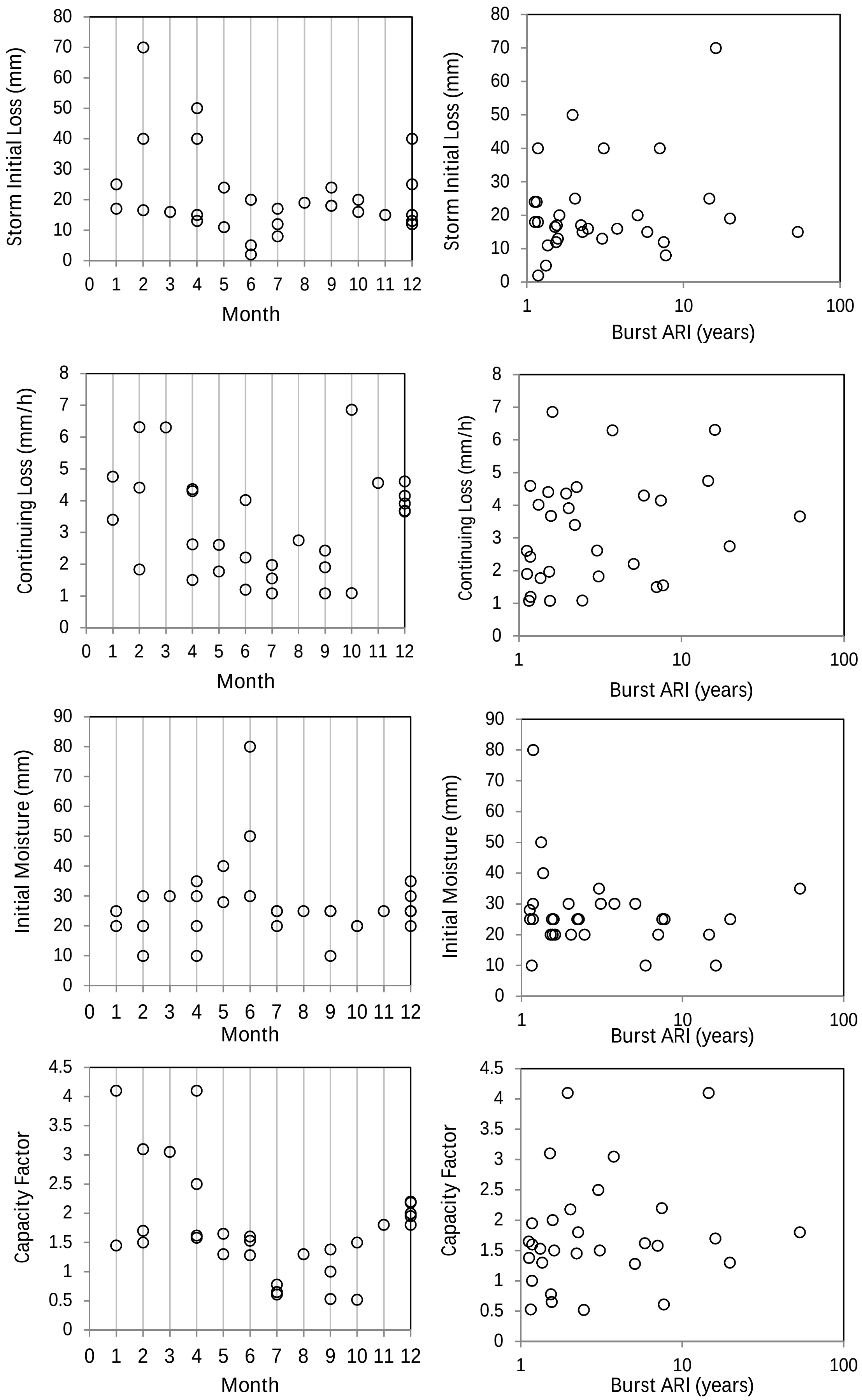




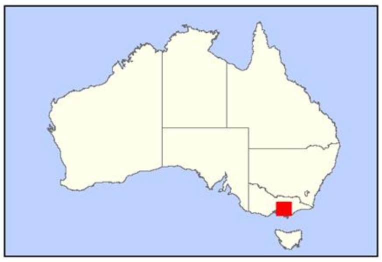


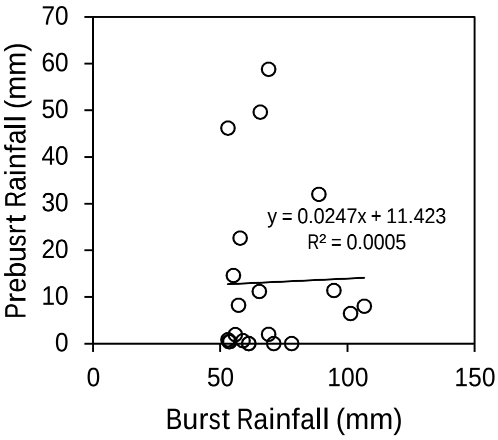


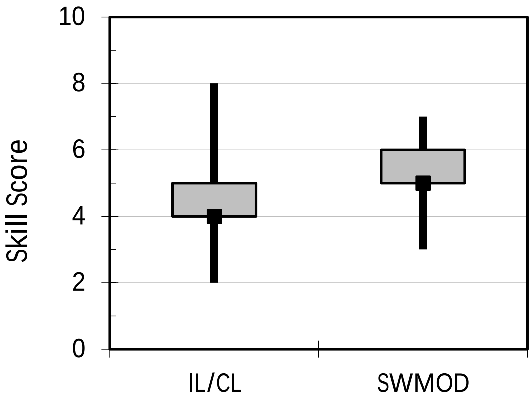
Aire @ Wyelangta (VIC) - 24 hour bursts

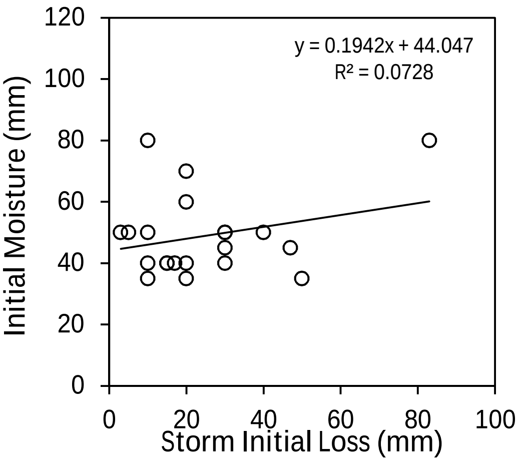


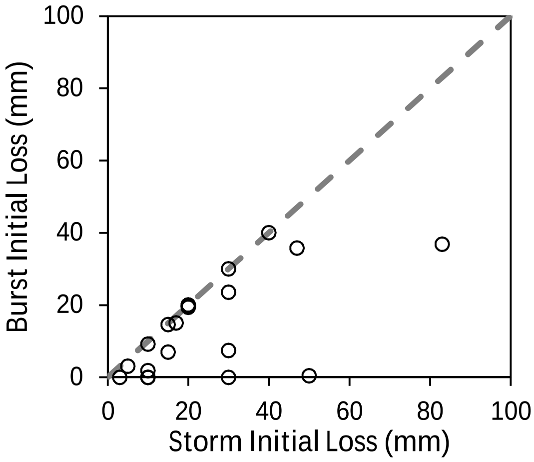
McMahons Ck @ Upstreams Weir (VIC) - 24 hour bursts

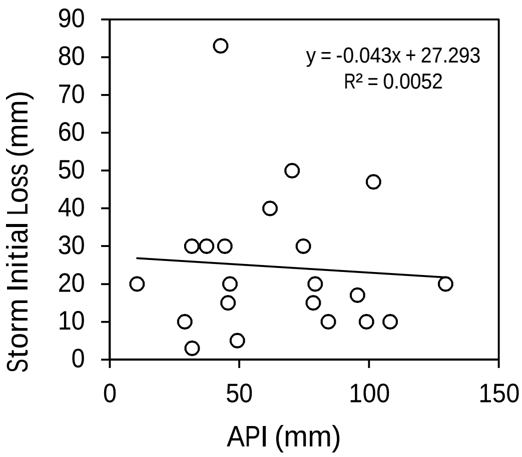


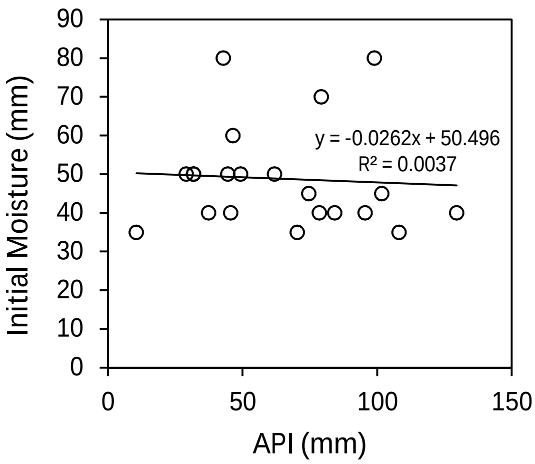




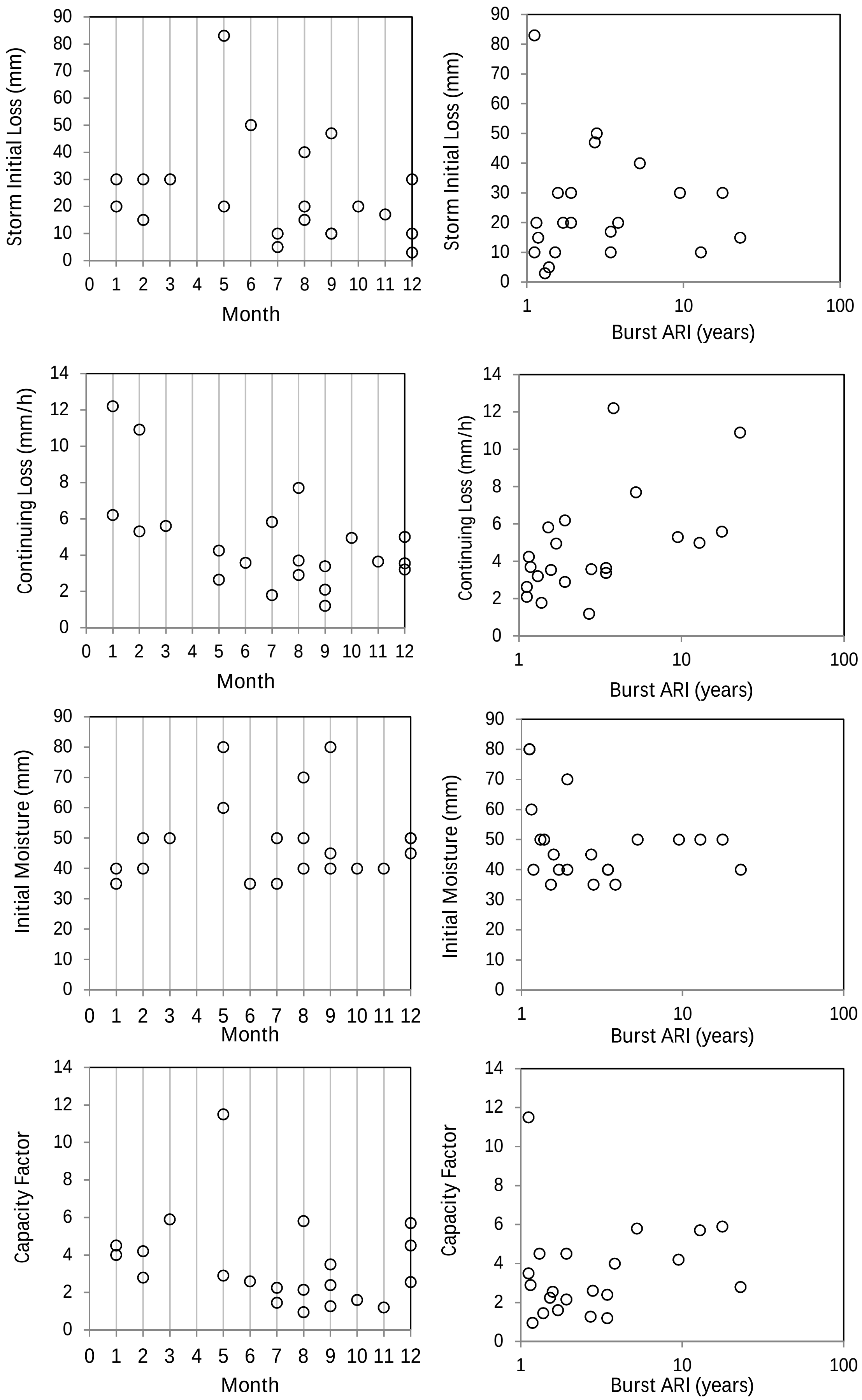




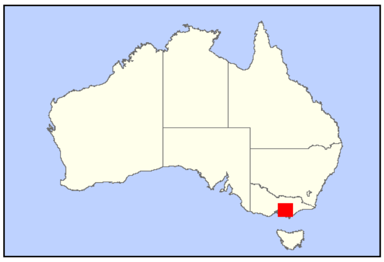


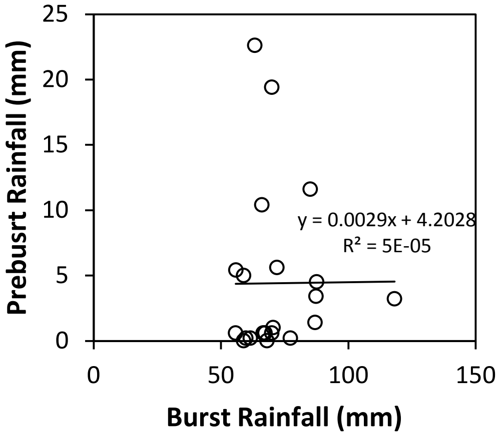


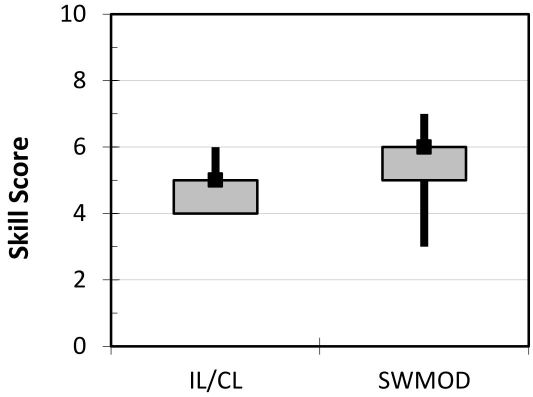
McMahons Ck @ Upstreams Weir (VIC) - 24 hour bursts

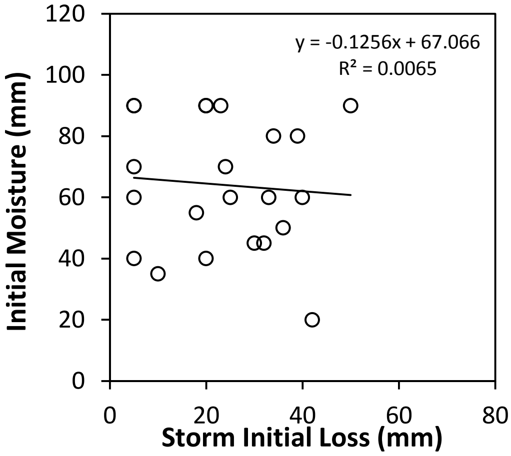


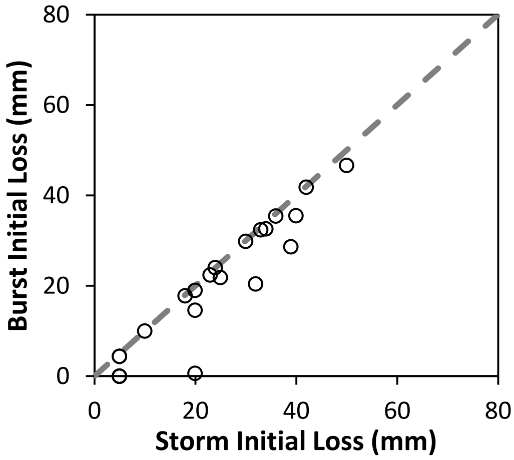
Tarago @ Neerim (VIC) - 24 hour bursts

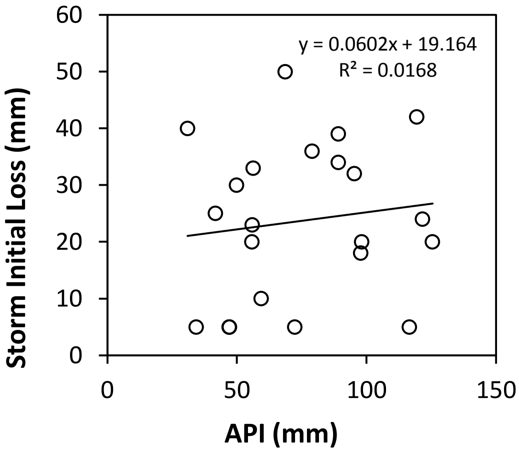


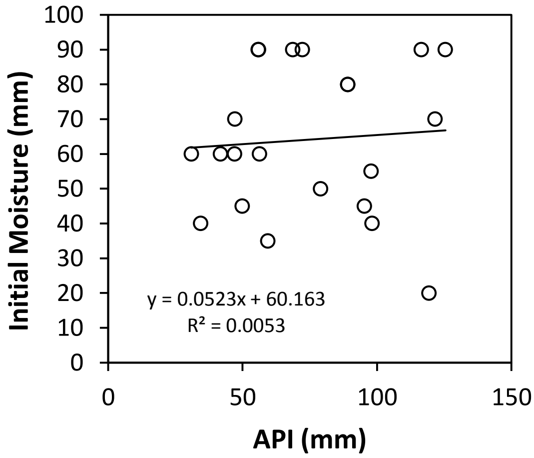




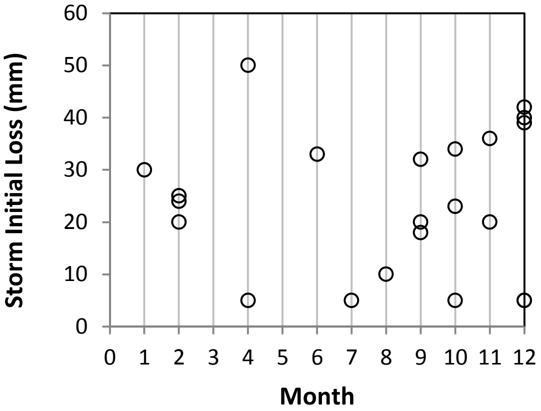


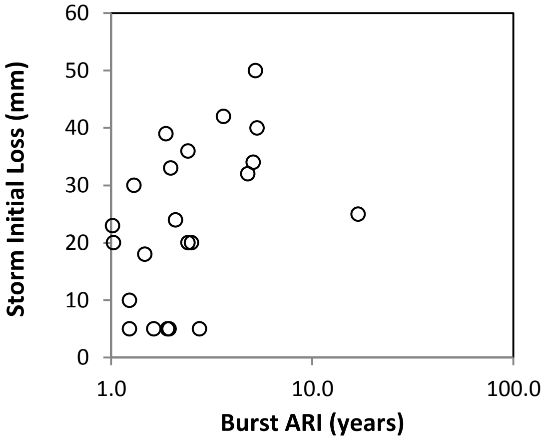


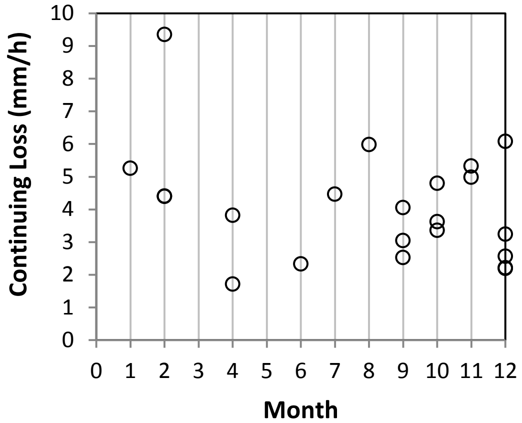


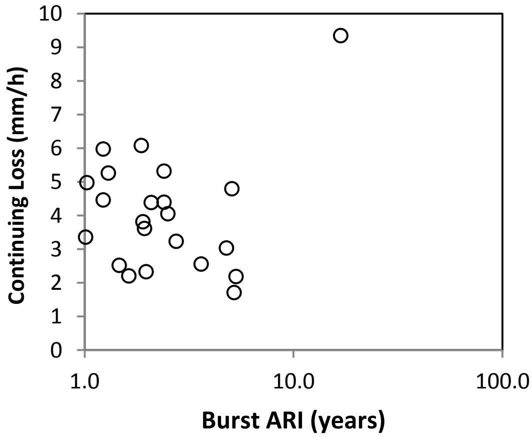


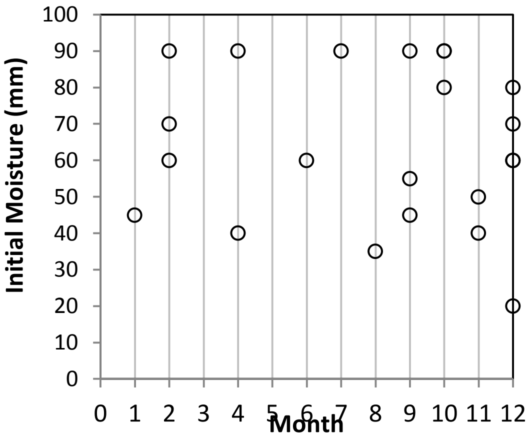
Tarago @ Neerim (VIC) - 24 hour bursts

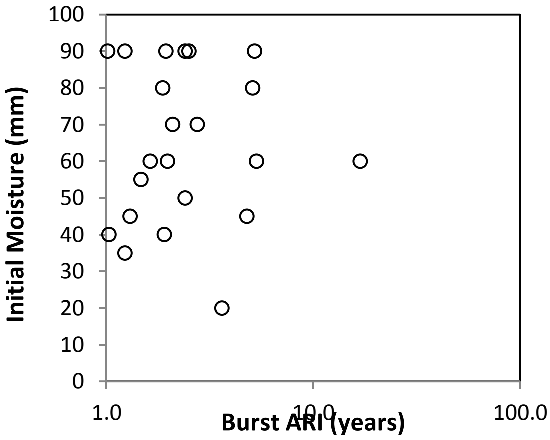


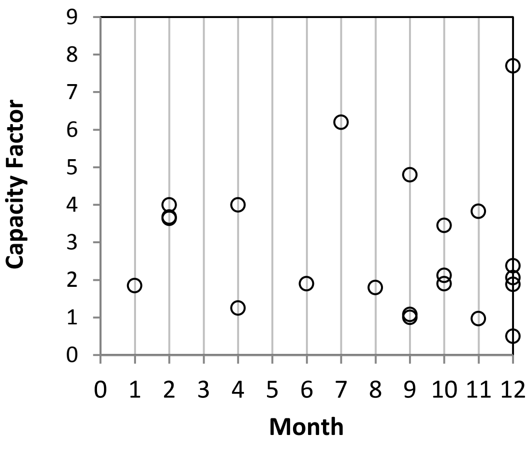


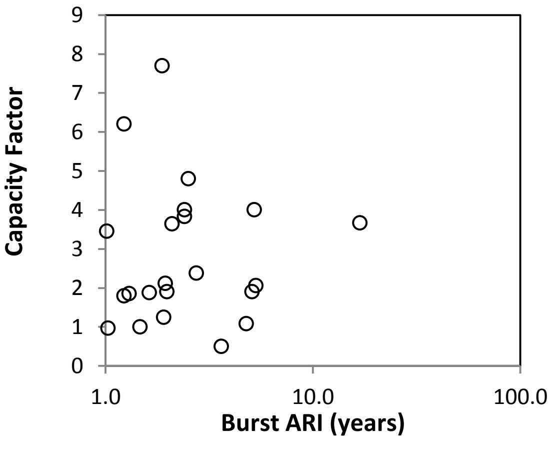




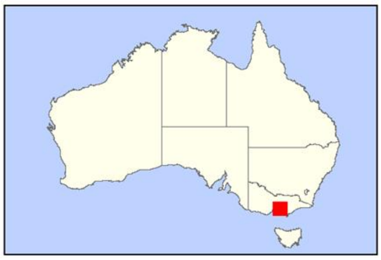


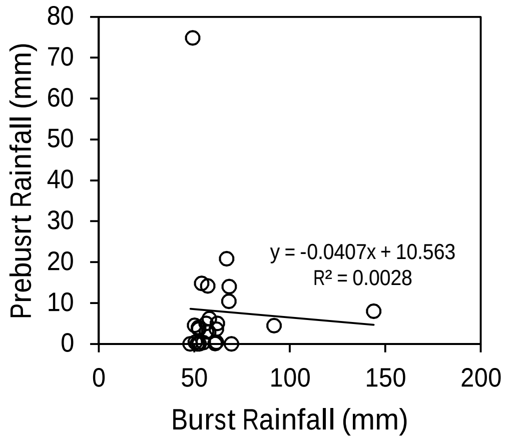


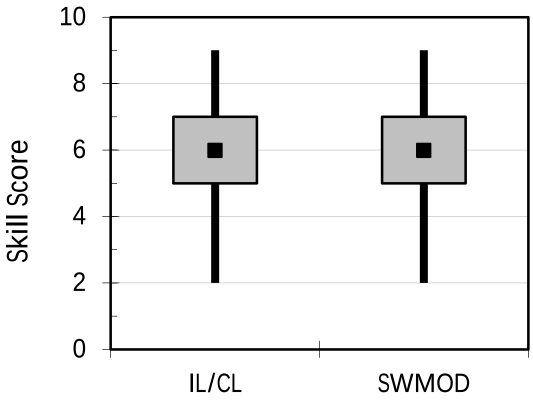


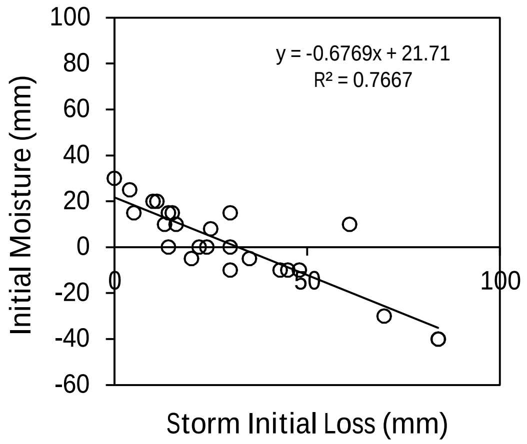


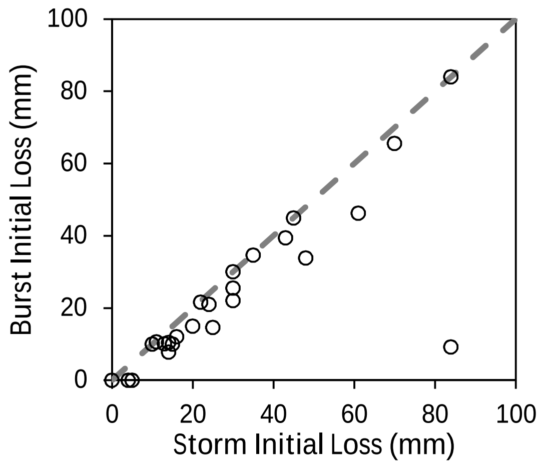
Toomuc Ck @ Pakenham (VIC) - 24 hour bursts

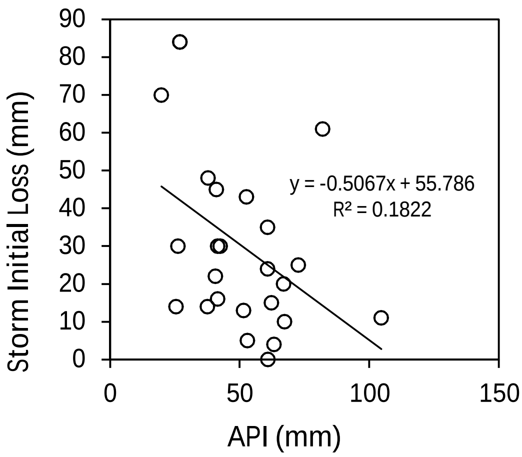


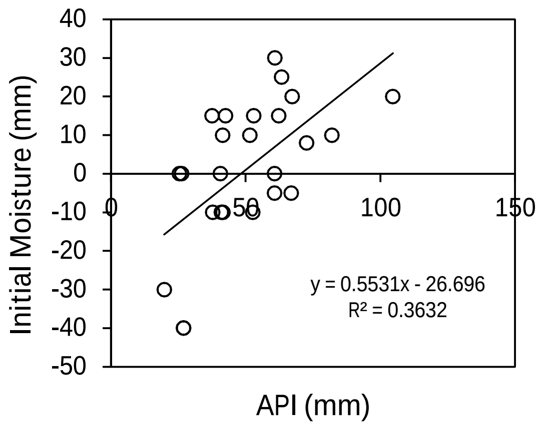




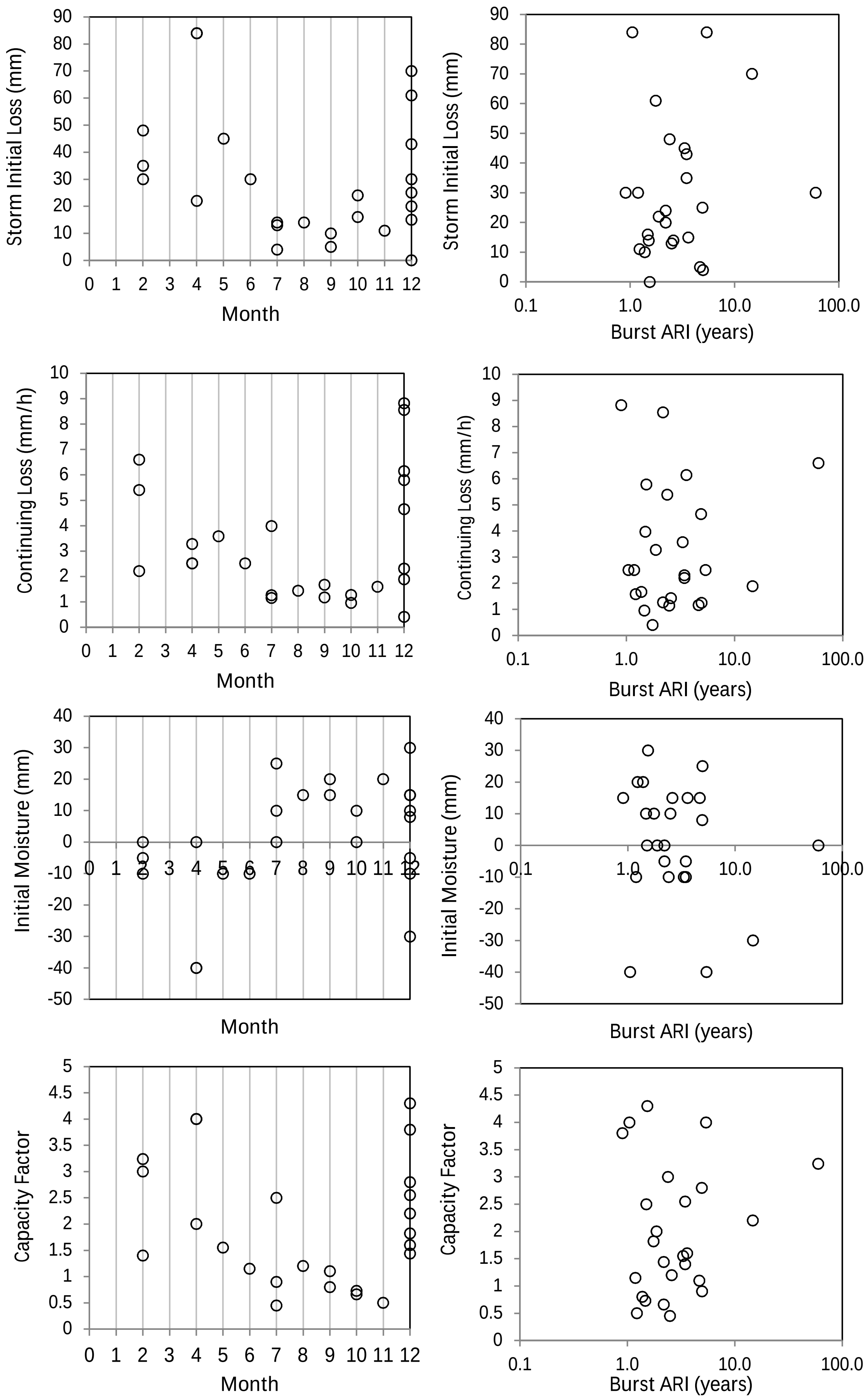




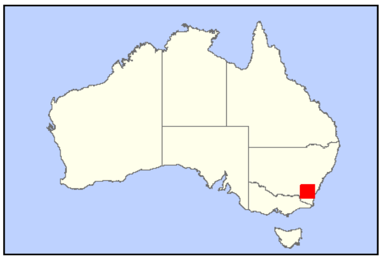


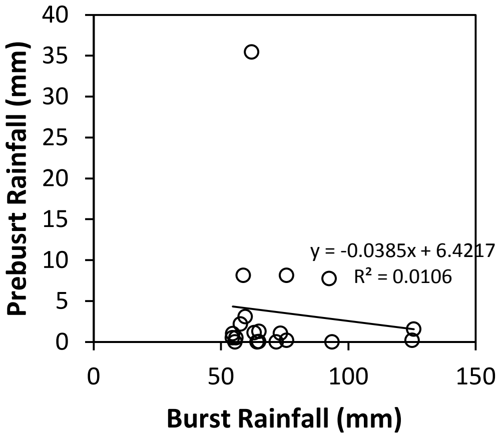


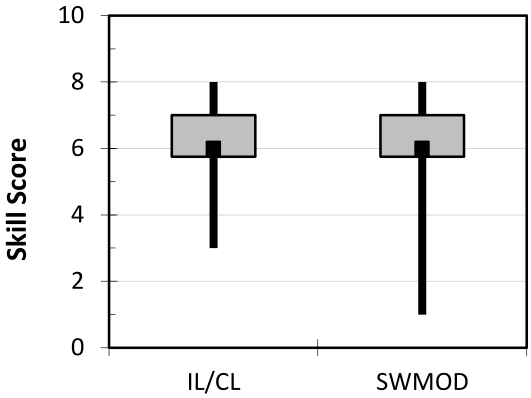
Toomuc Ck @ Pakenham (VIC) - 24 hour bursts

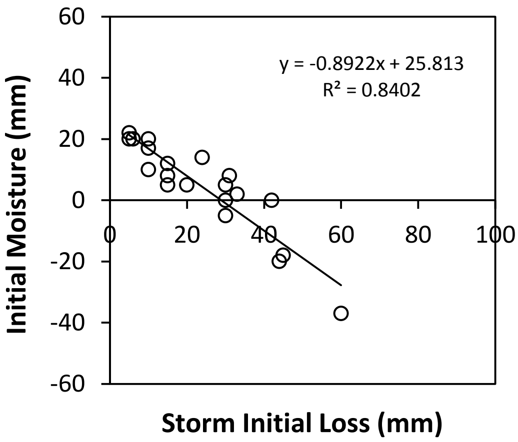


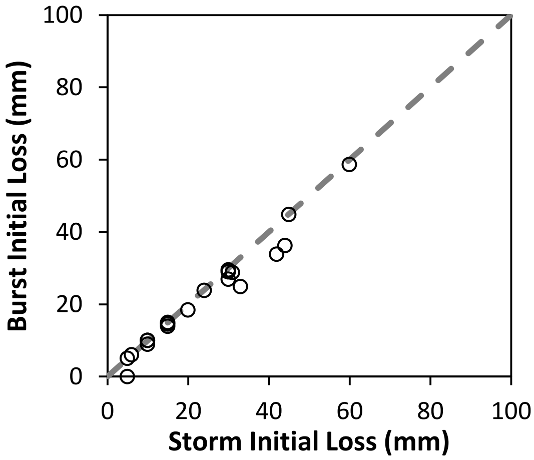
Jerrabomberra Ck @ Four Mile Creek (ACT) - 24 hour bursts

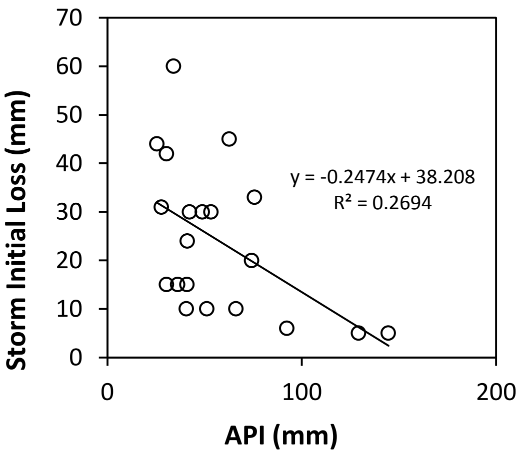


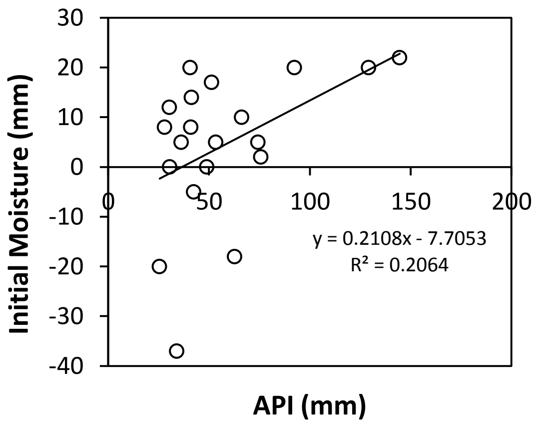




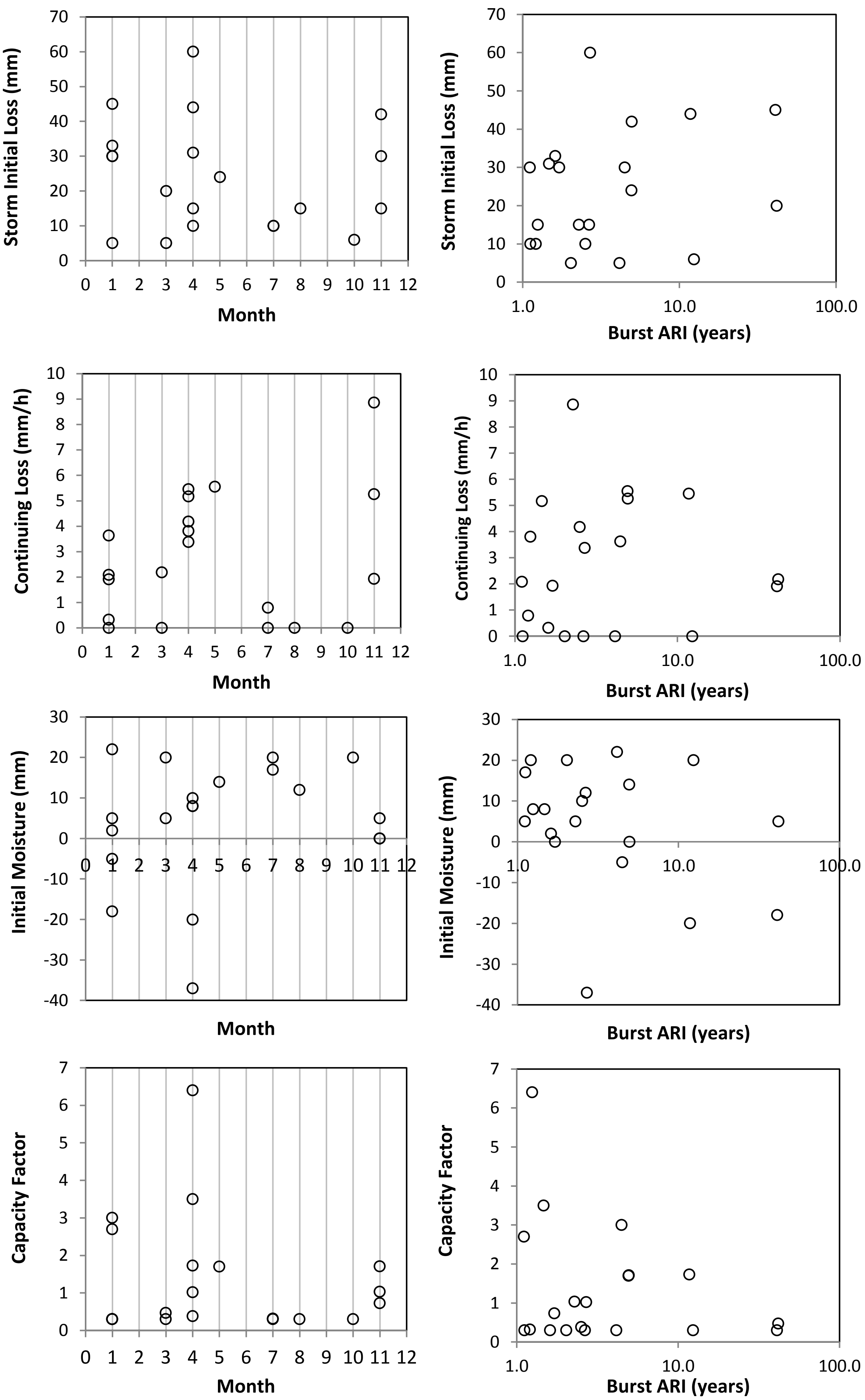




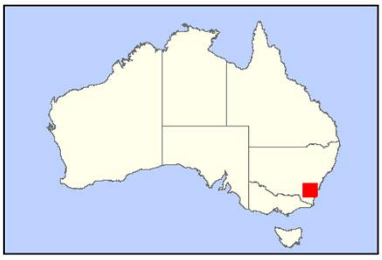


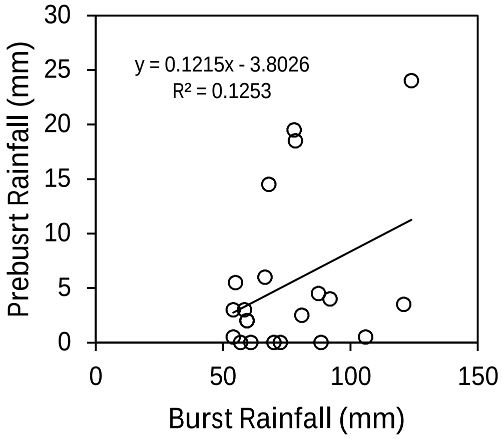


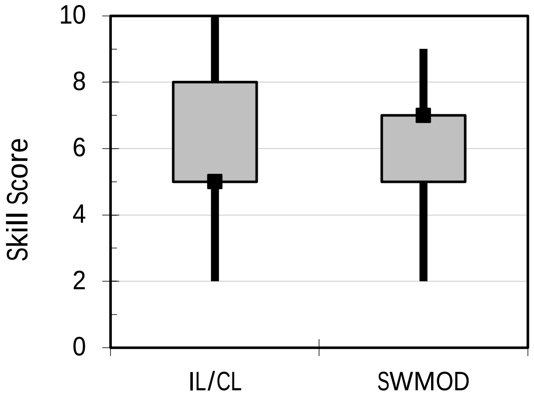
Jerrabomberra Ck @ Four Mile Creek (ACT) - 24 hour bursts

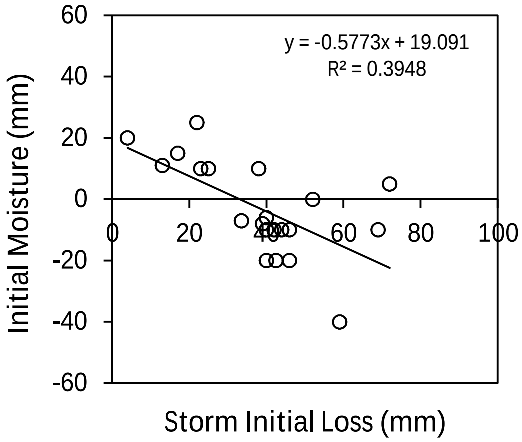


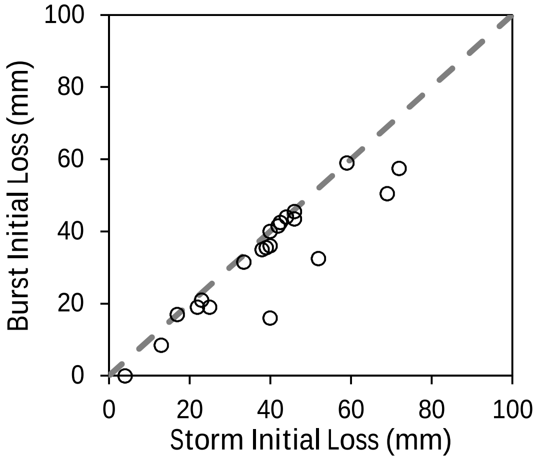
Butmaroo Ck @ Butmaroo (NSW) - 24 hour bursts

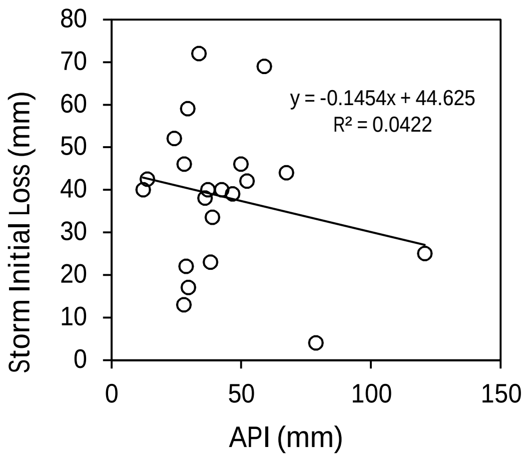


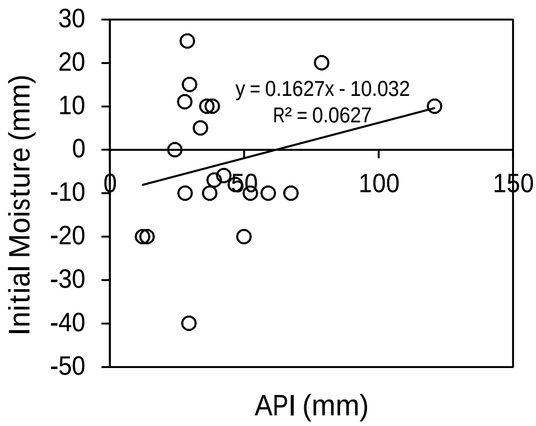




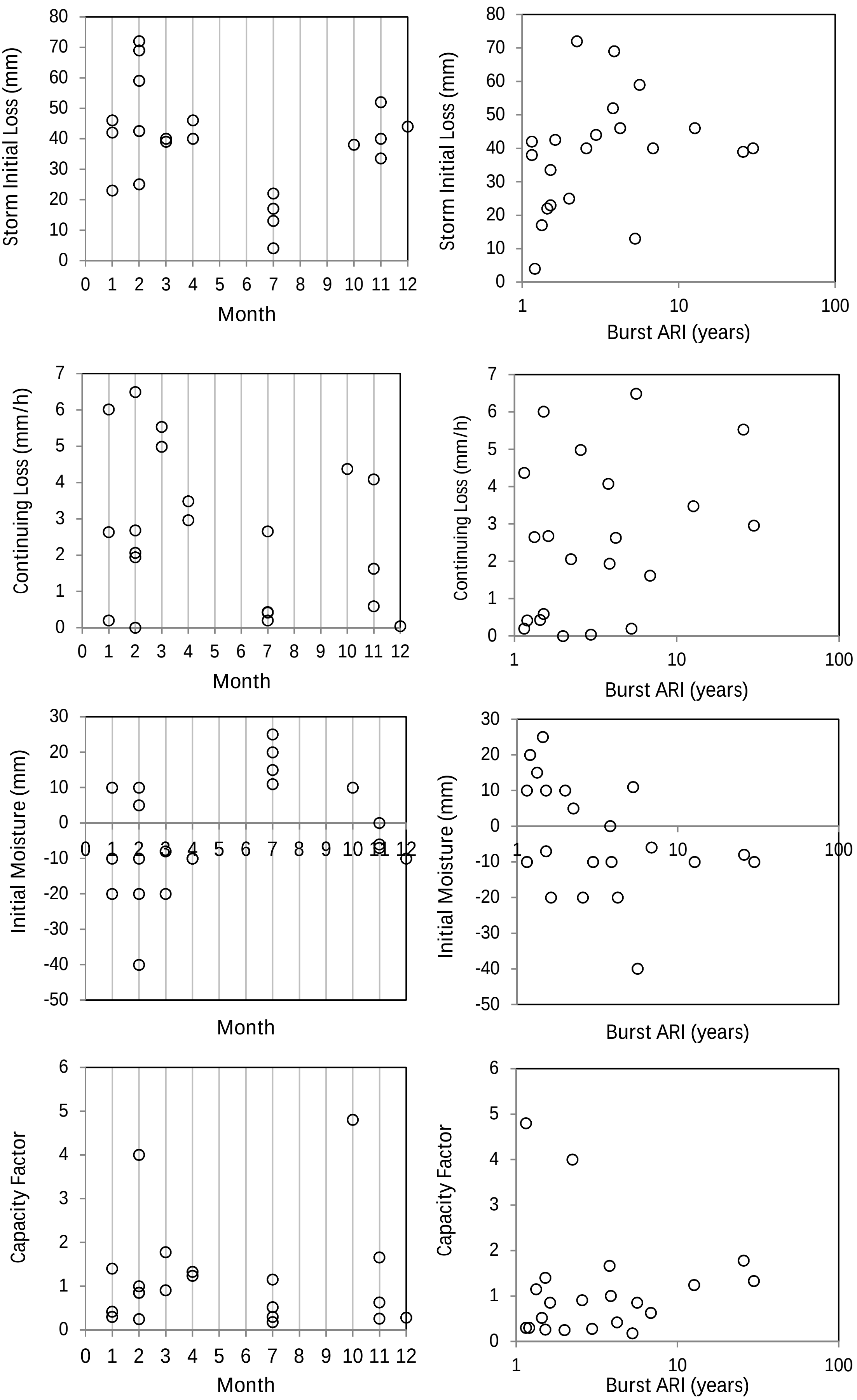




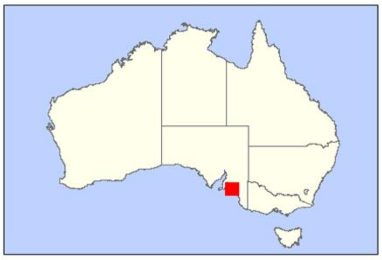


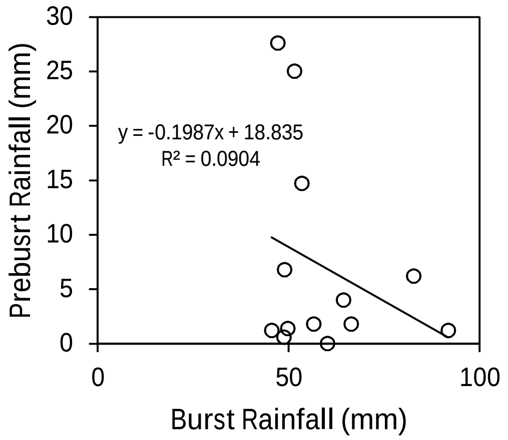


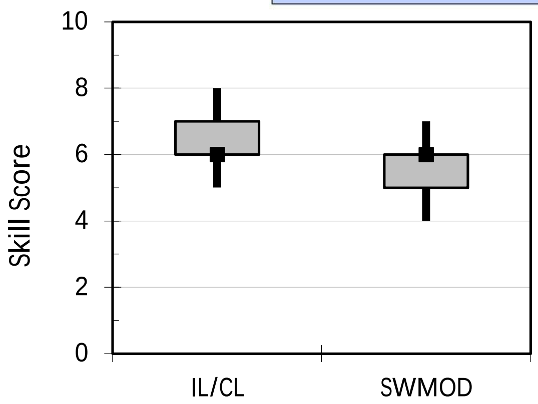
Butmaroo Ck @ Butmaroo (NSW) - 24 hour bursts

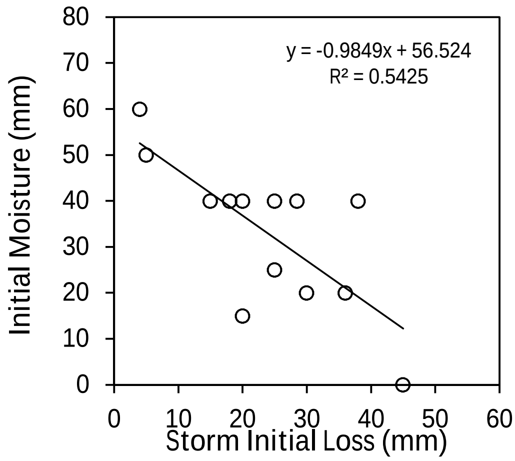


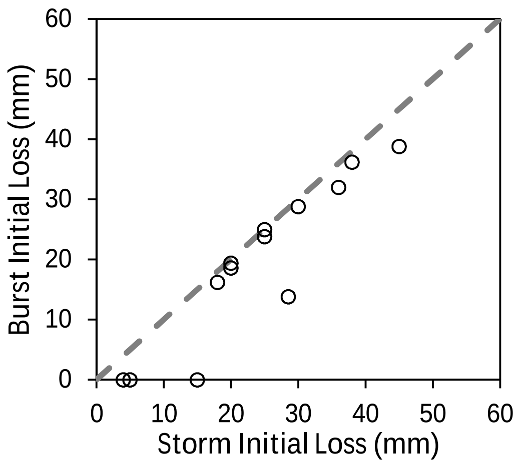
Echunga Ck @ U/S Mt Bold Res. (SA) - 24 hour bursts

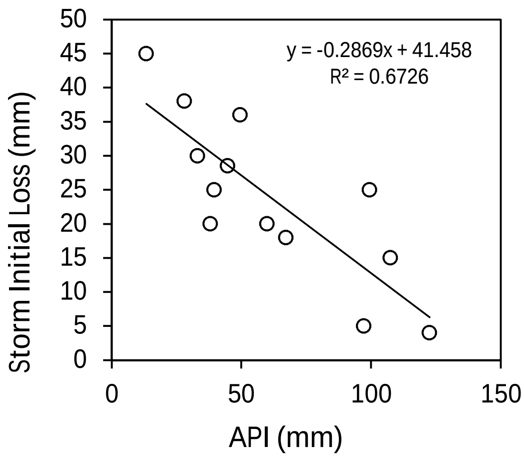


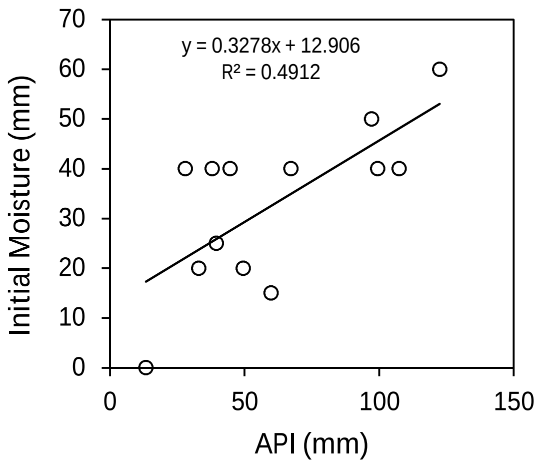




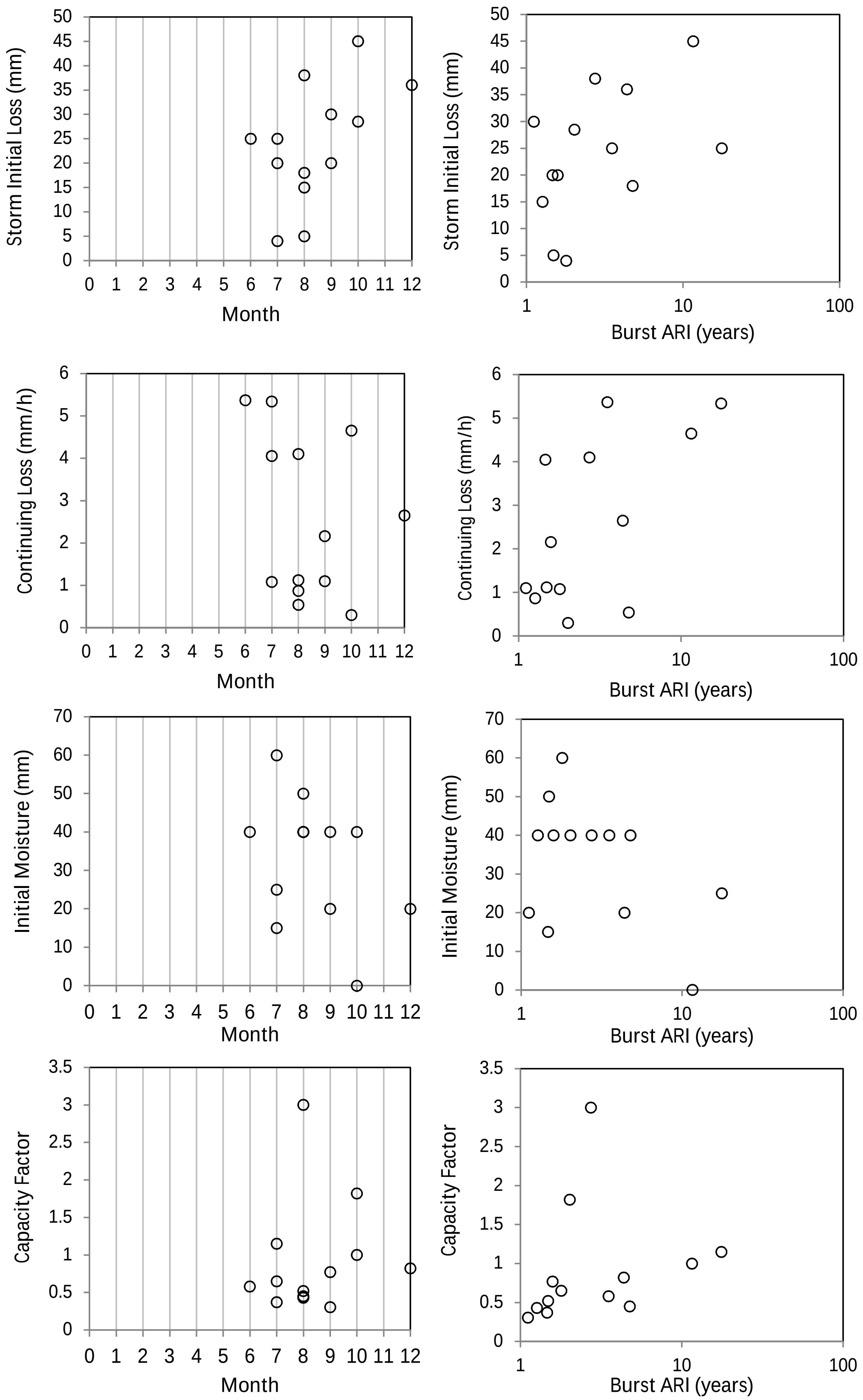




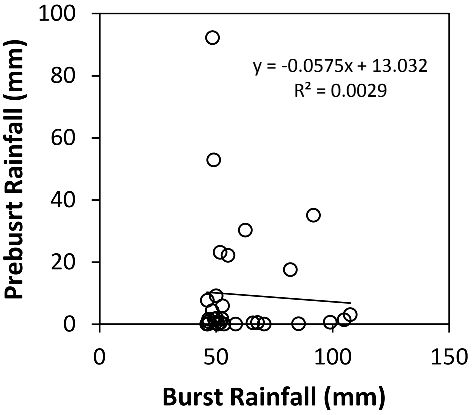


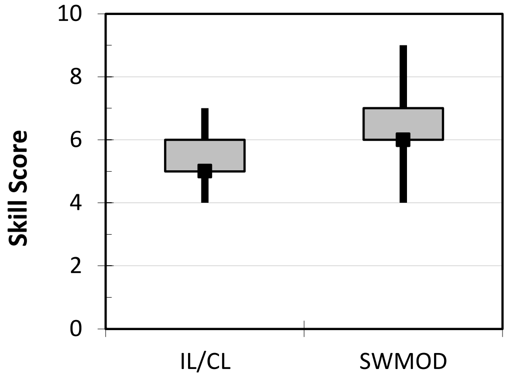


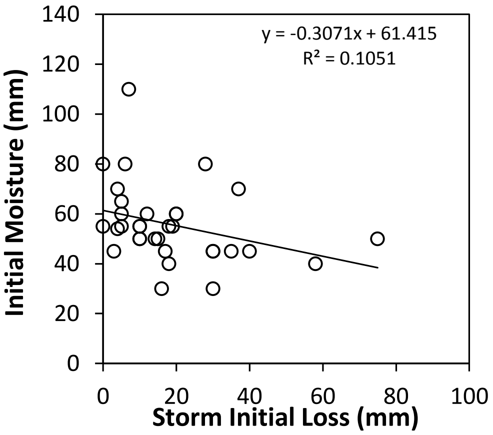
Echunga Ck @ U/S Mt Bold Res. (SA) - 24 hour bursts

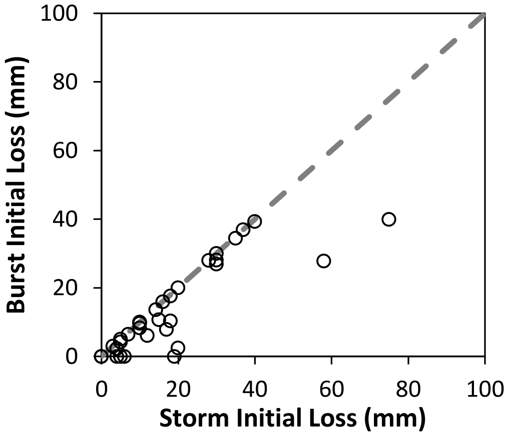


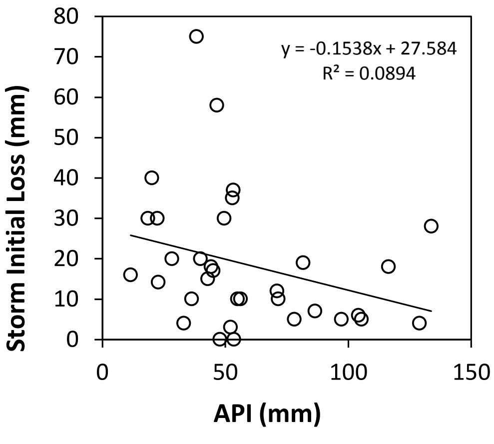
Hindmarsh @ Hindmarsh Vy Res Offtake W (SA) - 24 hour bursts

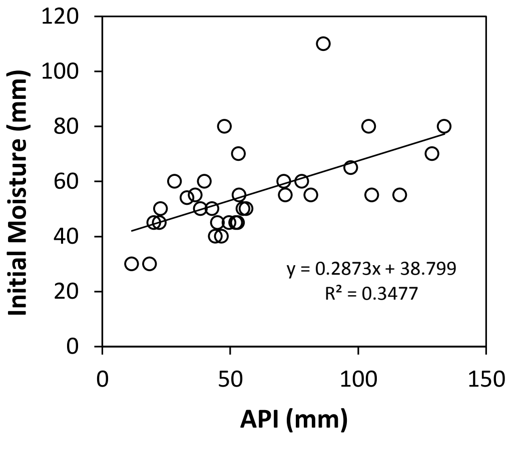




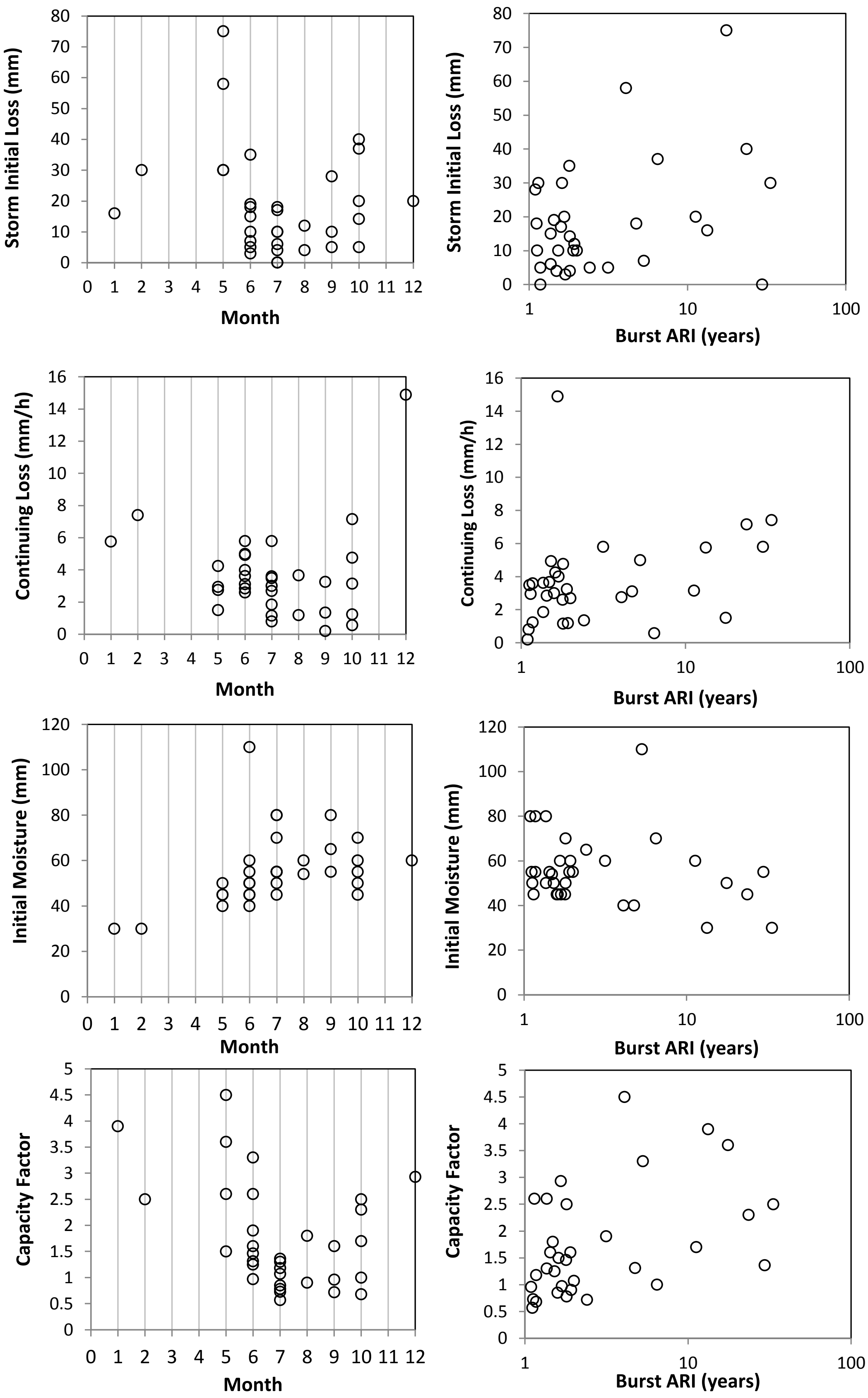




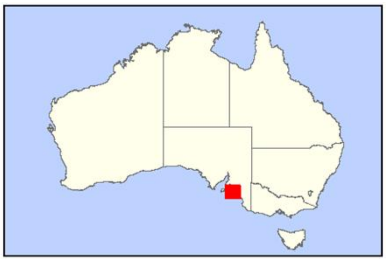


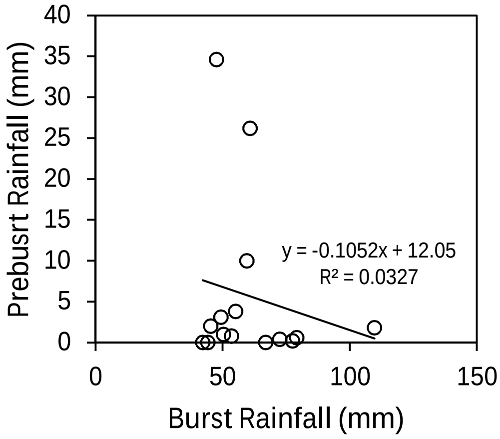


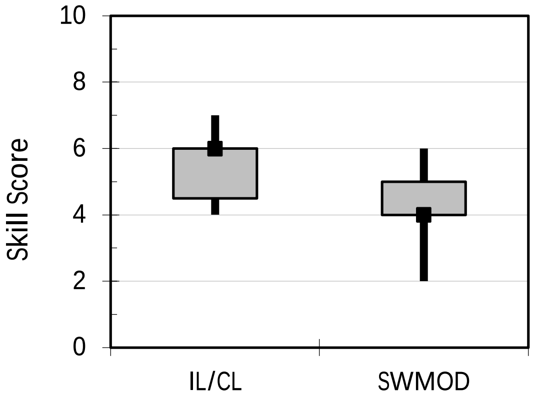
Hindmarsh @ Hindmarsh Vy Res Offtake W (SA) - 24 hour bursts

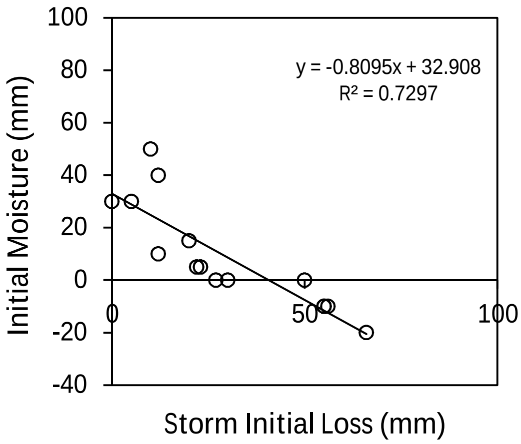


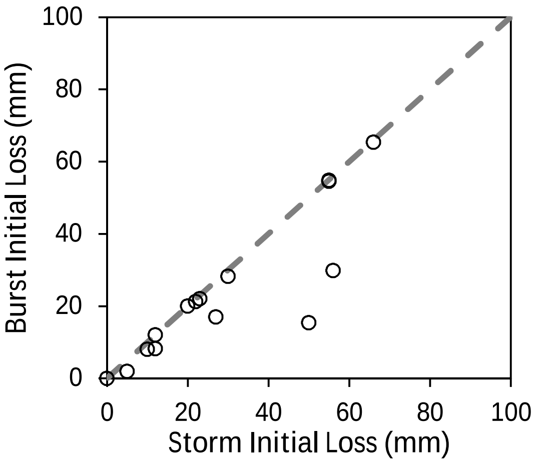
Myponga @ U/S Dam and Rd Br (SA) - 24 hour bursts

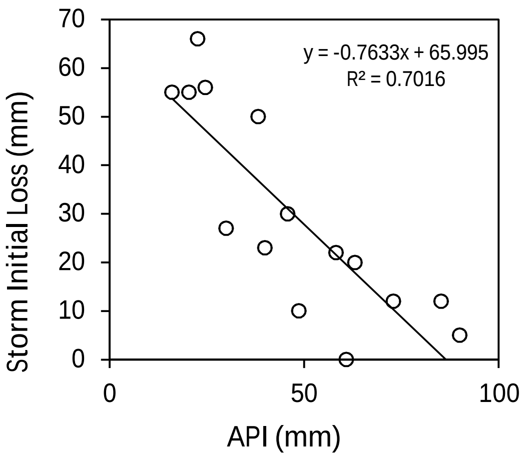


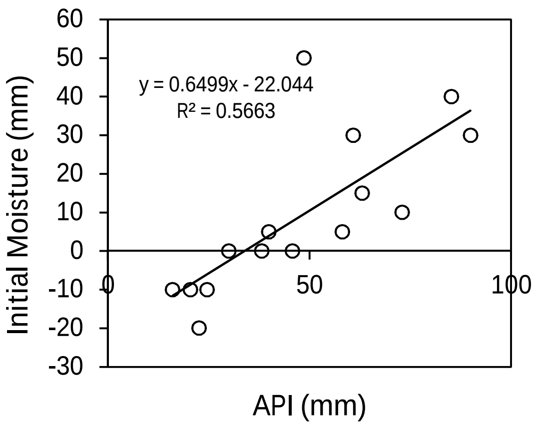




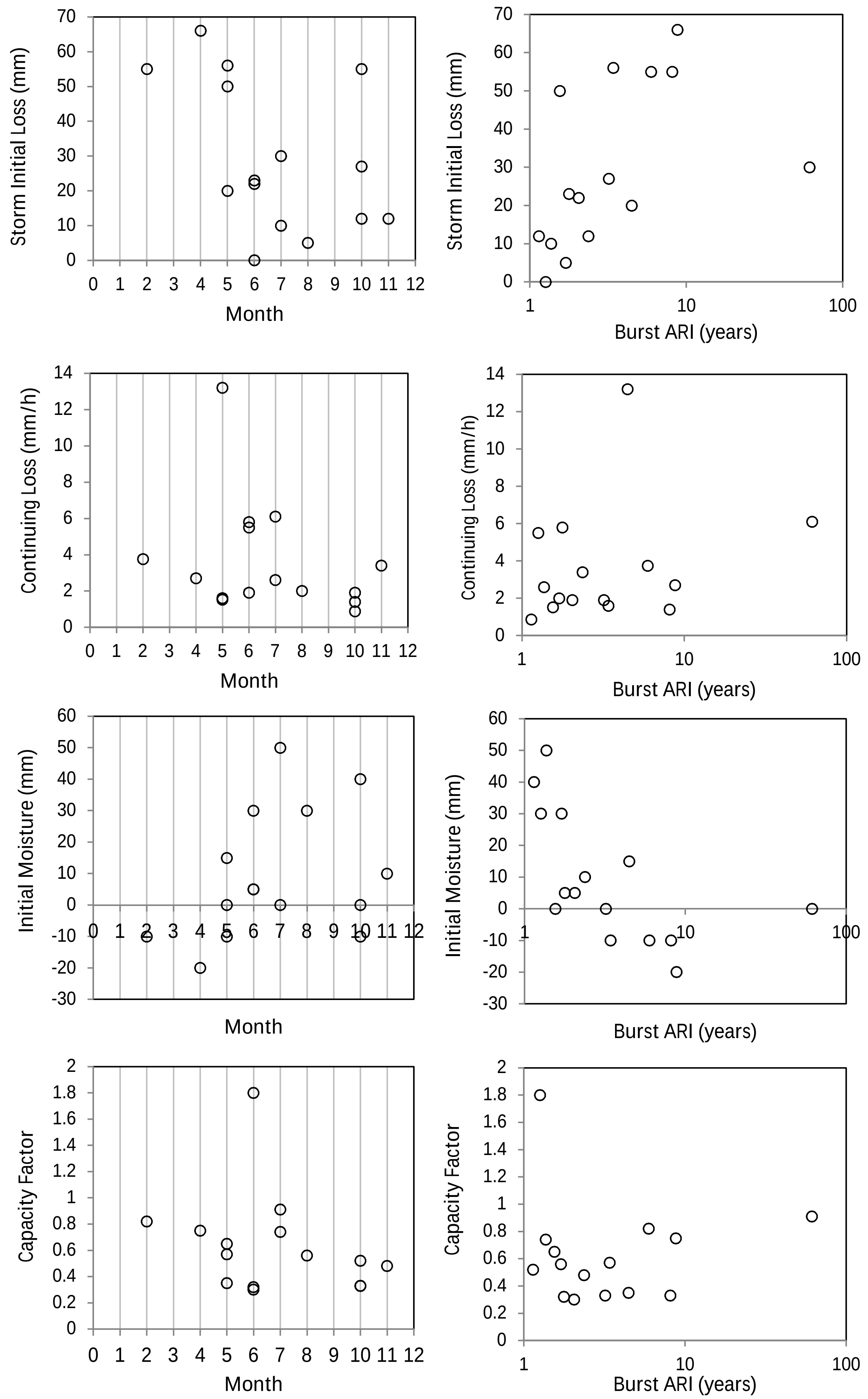




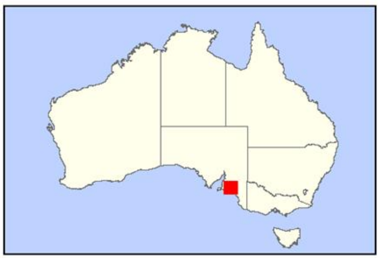


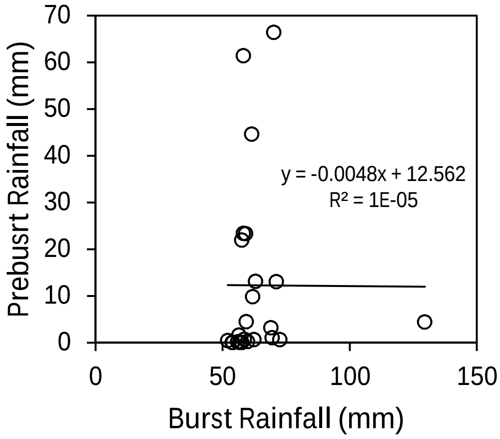


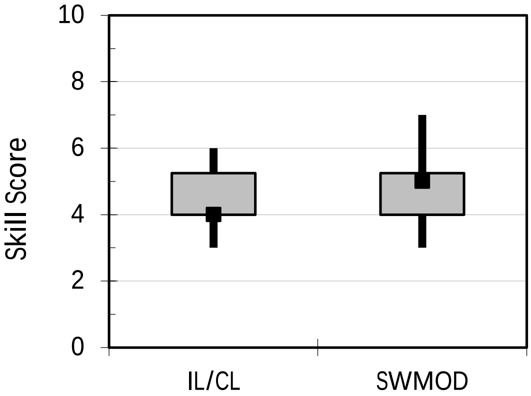
Myponga @ U/S Dam and Rd Br (SA) - 24 hour bursts

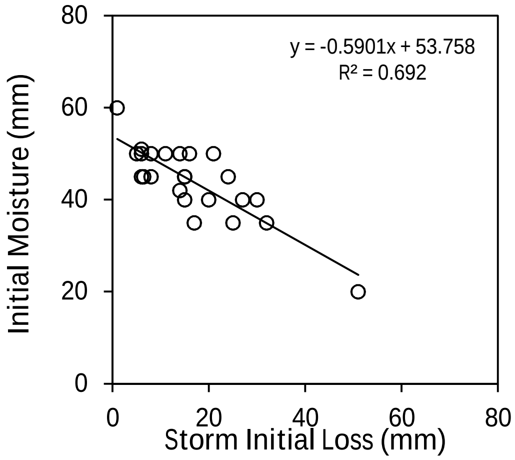


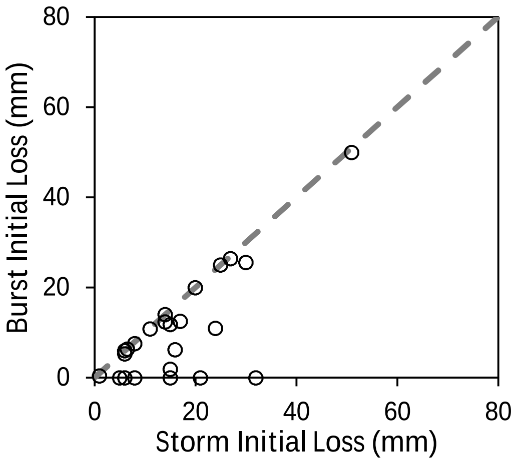
Sixth Ck @ Castambul (SA) - 24 hour bursts

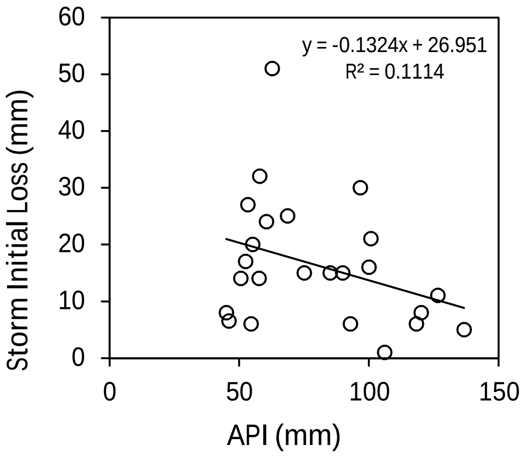


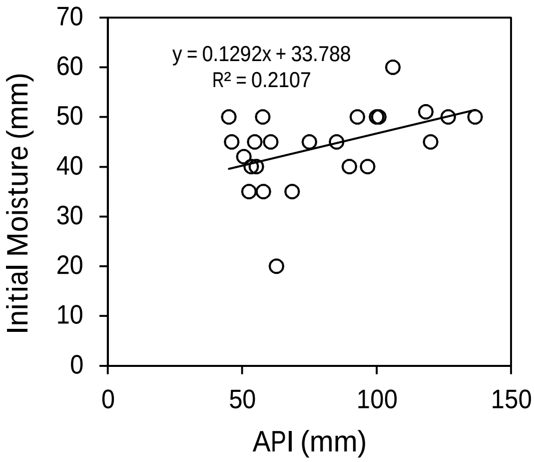




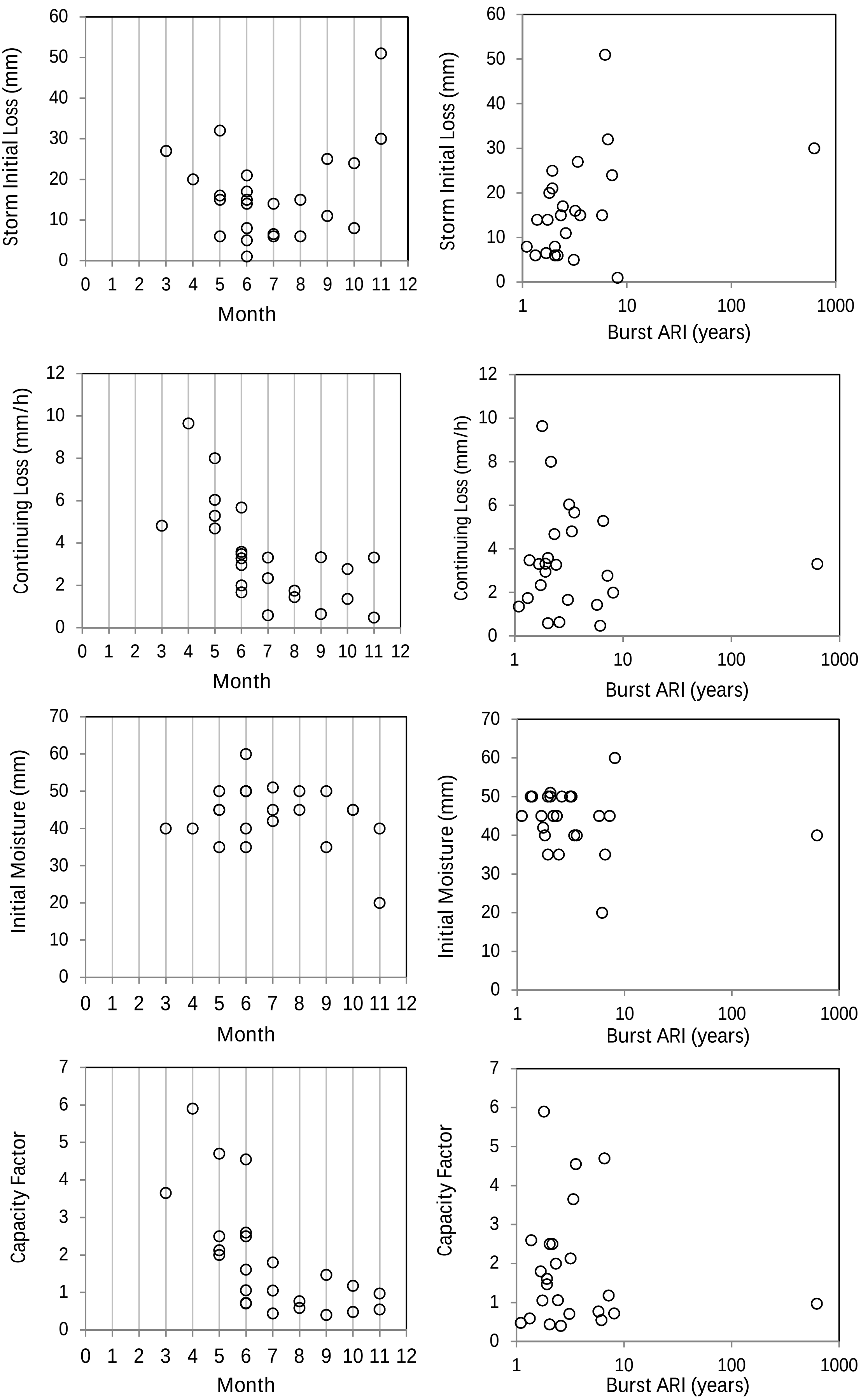




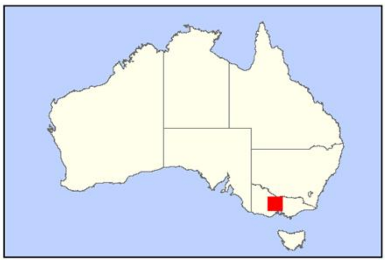


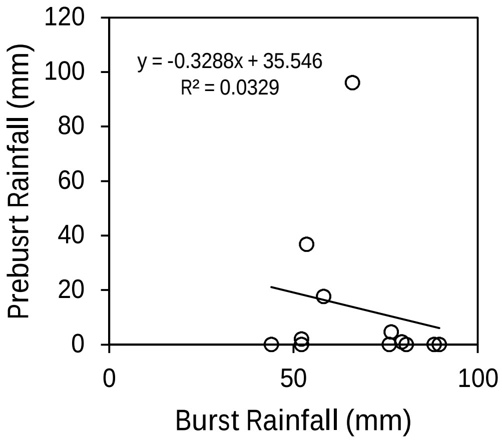


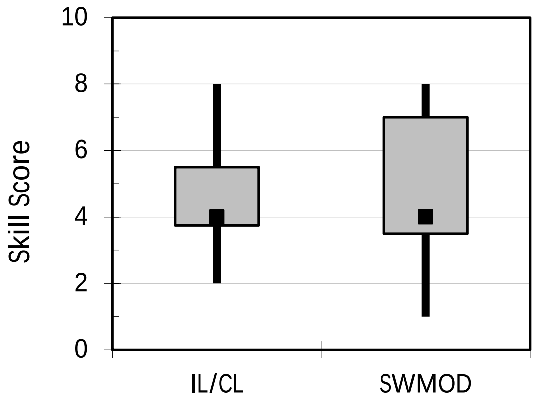
Sixth Ck @ Castambul (SA) - 24 hour bursts

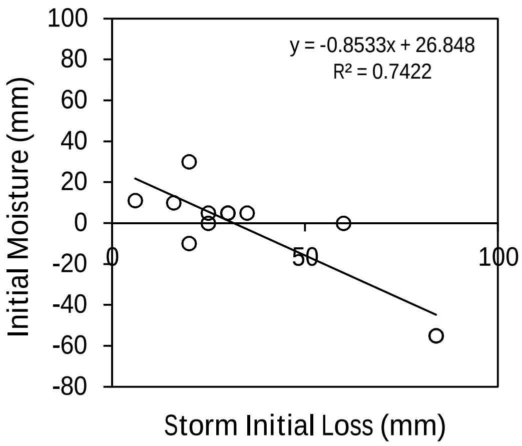


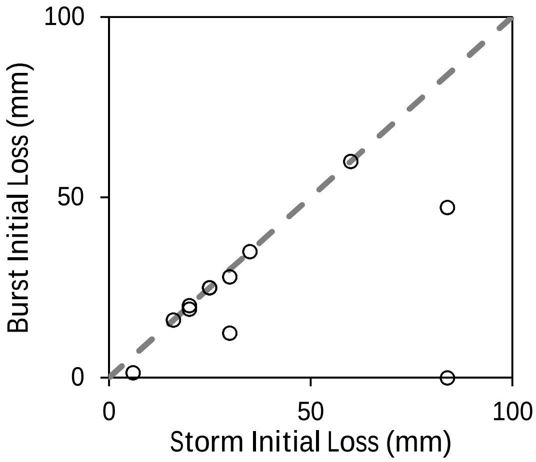
Axe Ck @ Sedgwick (VIC) - 24 hour bursts

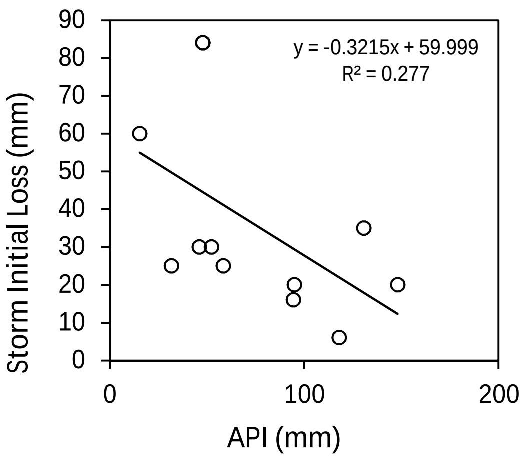


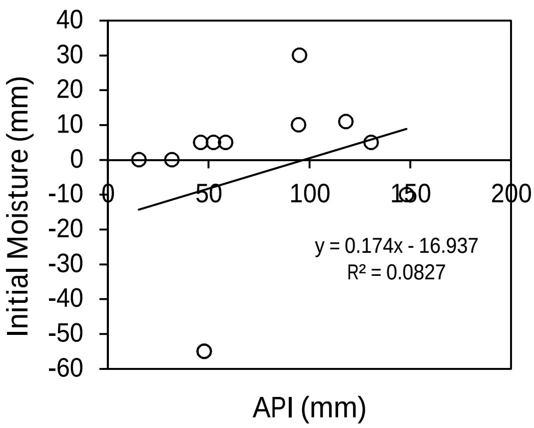




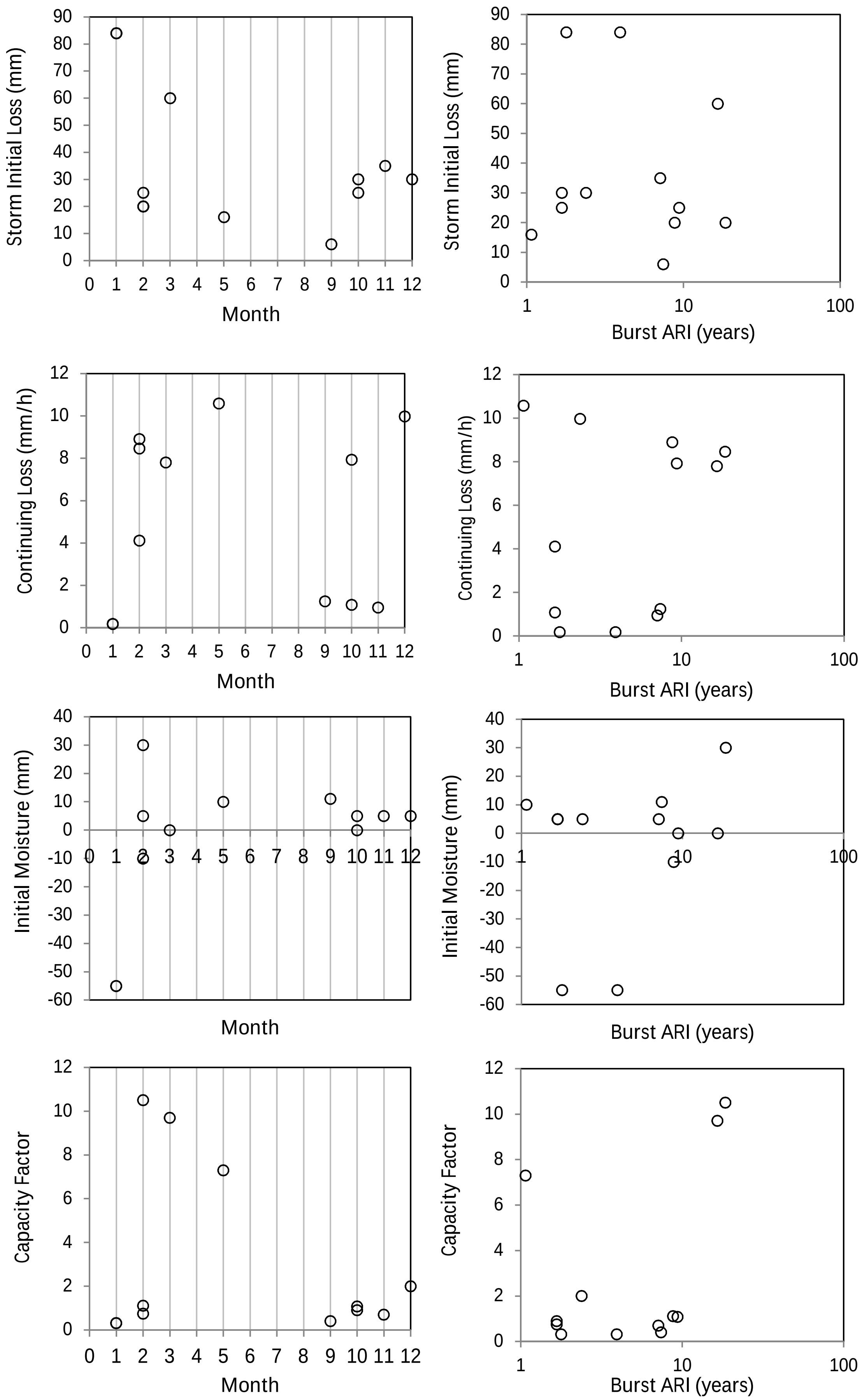




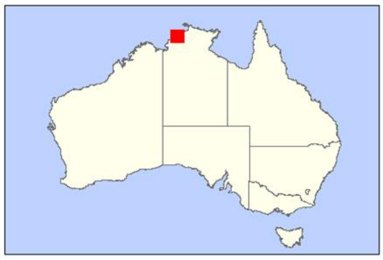


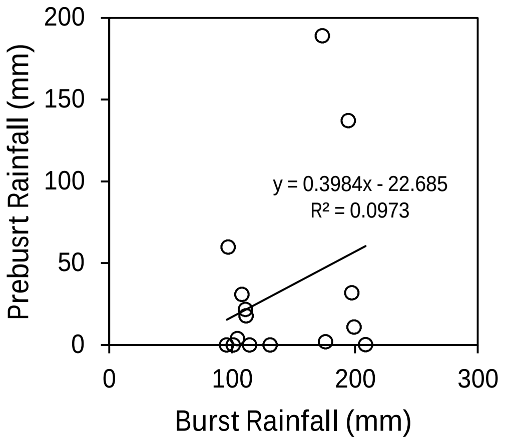


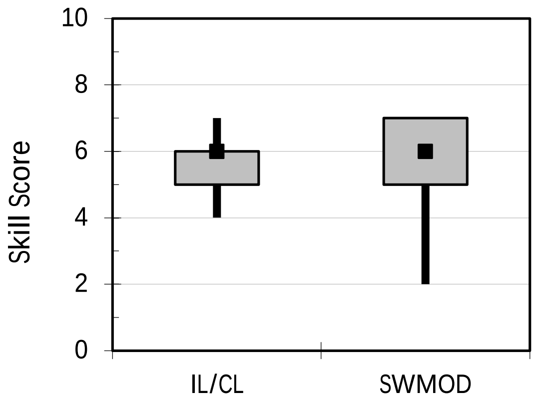
Axe Ck @ Sedgwick (VIC) - 24 hour bursts

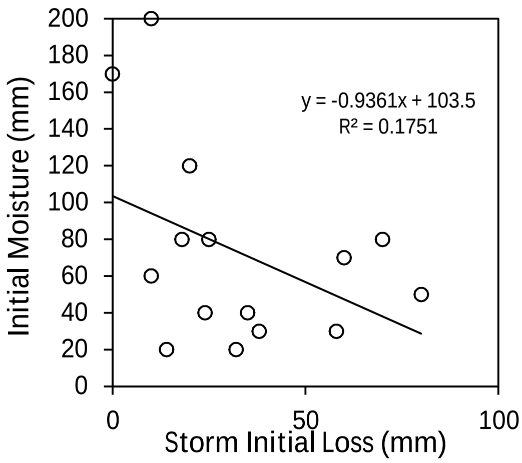


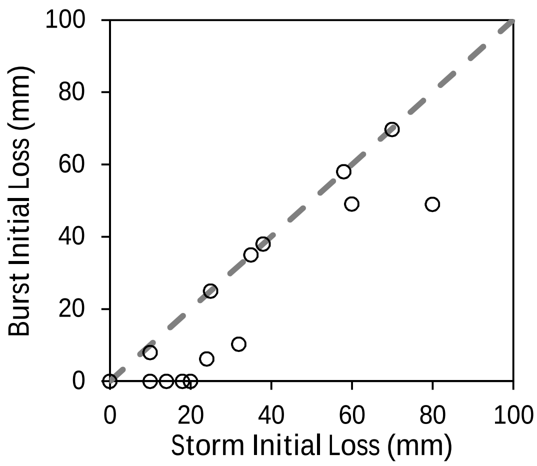
Celia Ck @ U/S Darwin R Dam (NT) - 24 hour bursts

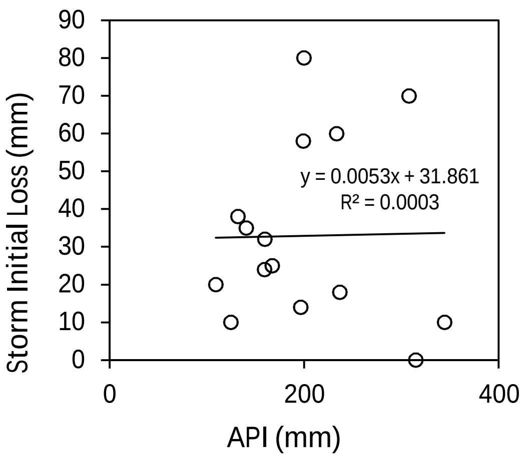


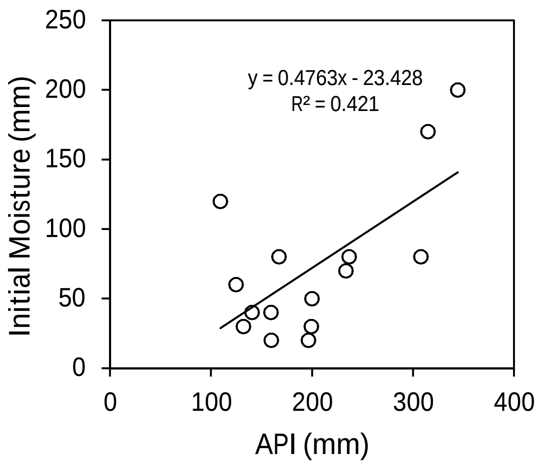




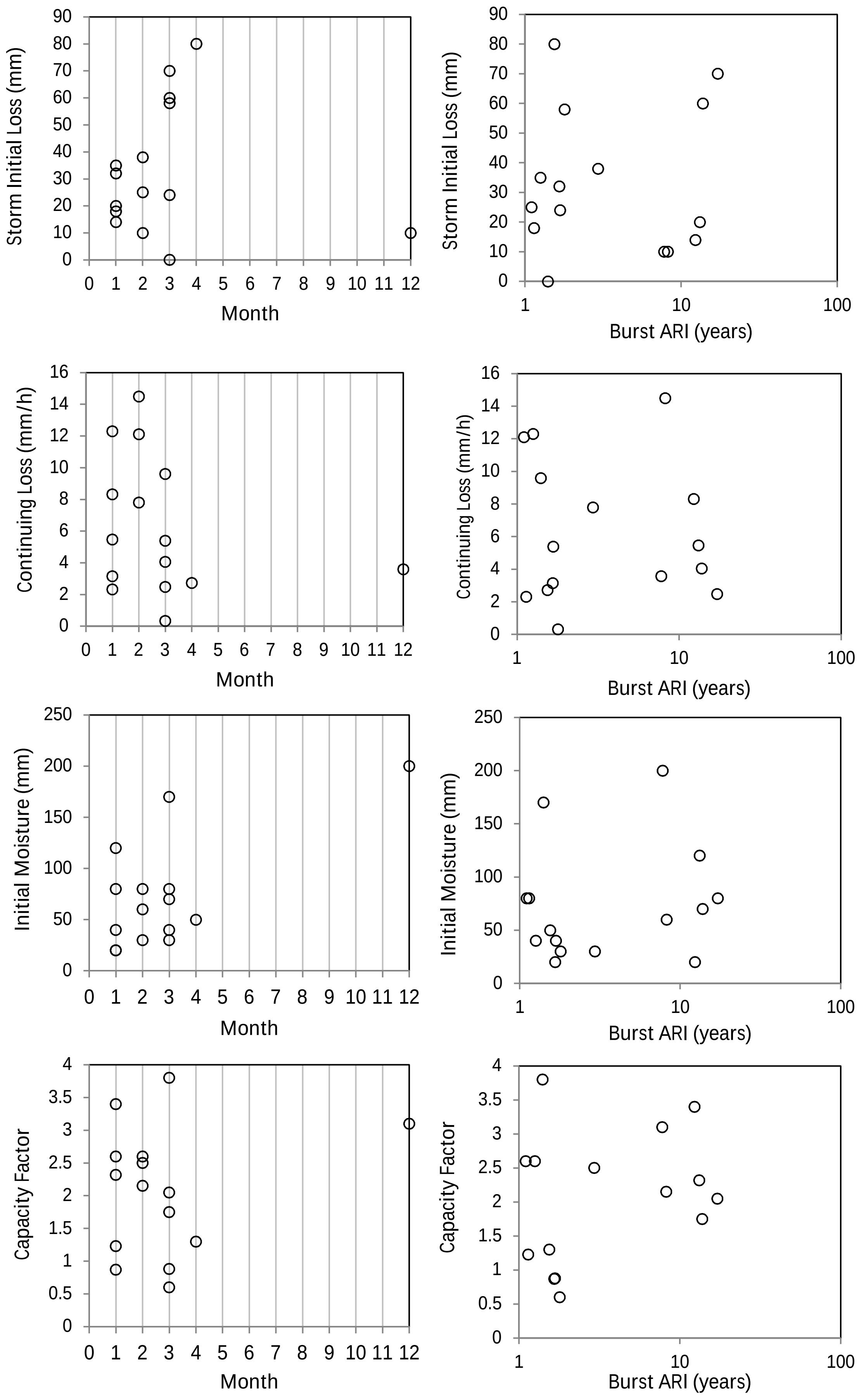




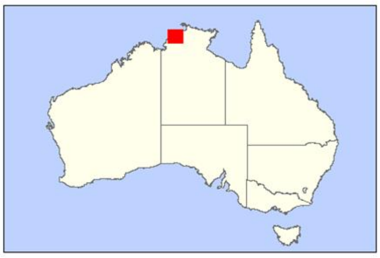


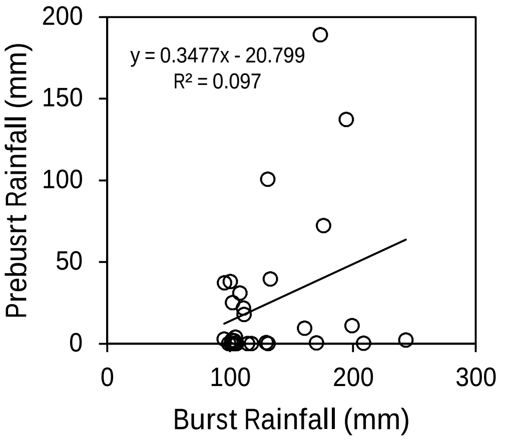


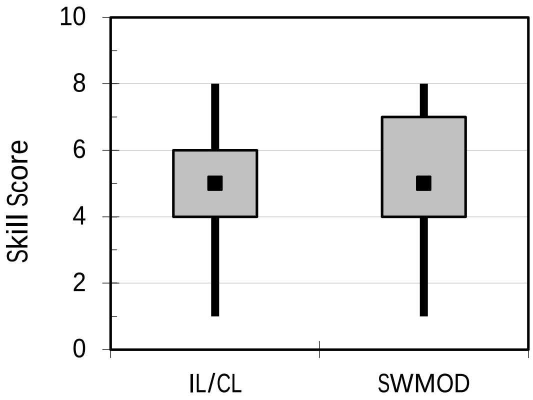
Celia Ck @ U/S Darwin R Dam (NT) - 24 hour bursts

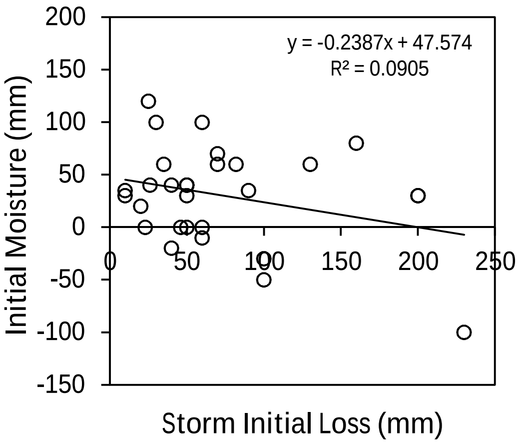


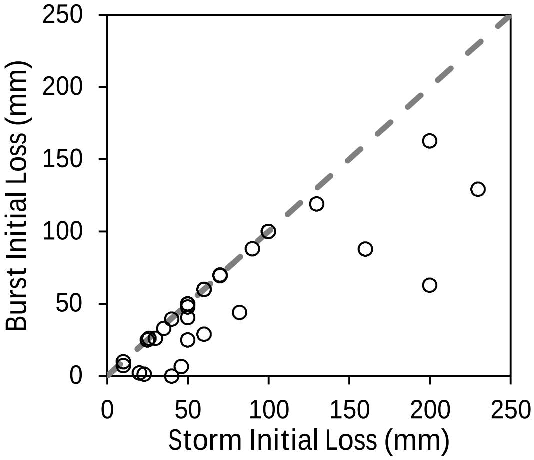
Coomalie Ck @ Stuart HWY (NT) - 24 hour bursts

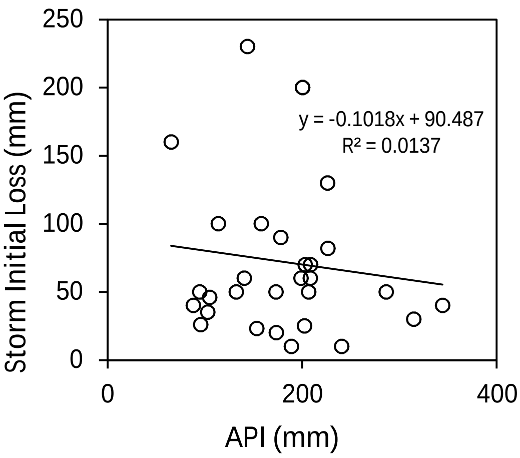


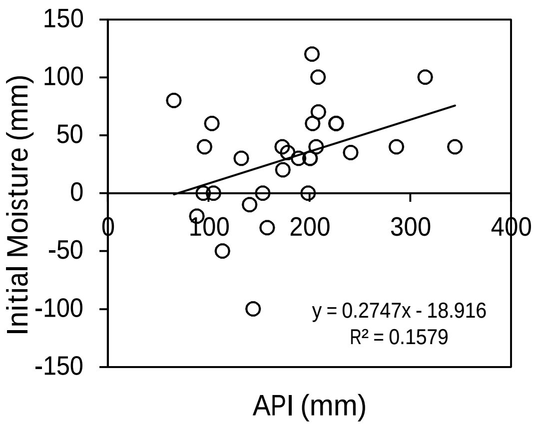




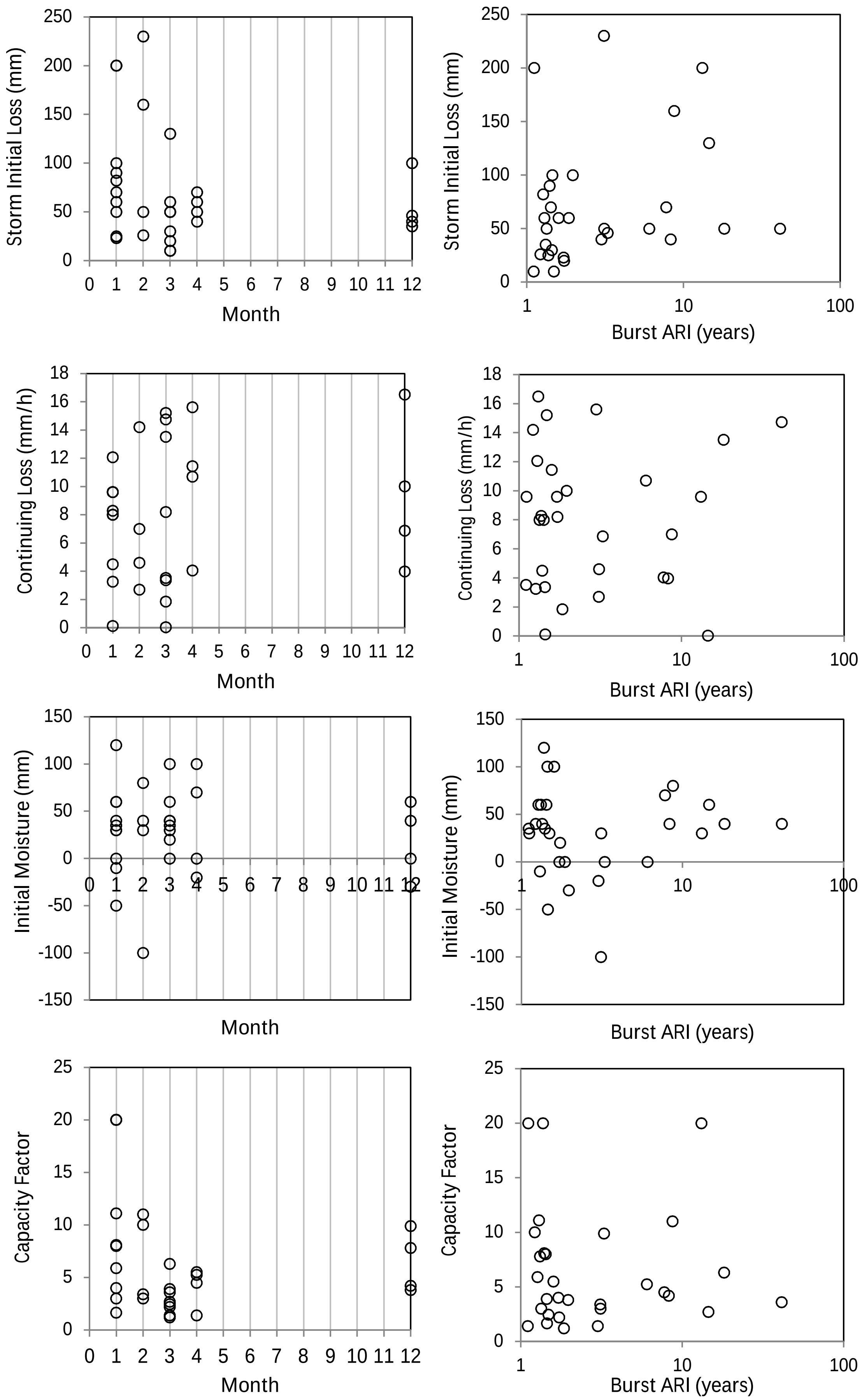




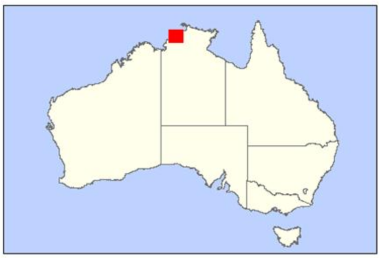


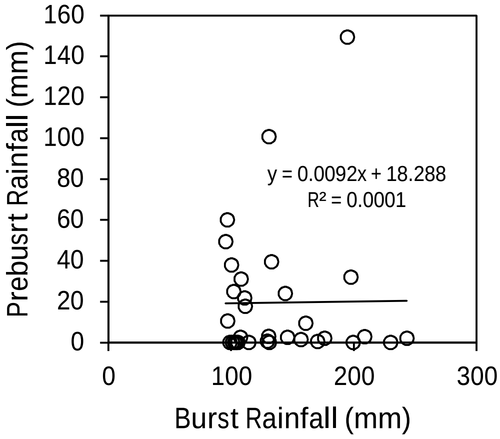


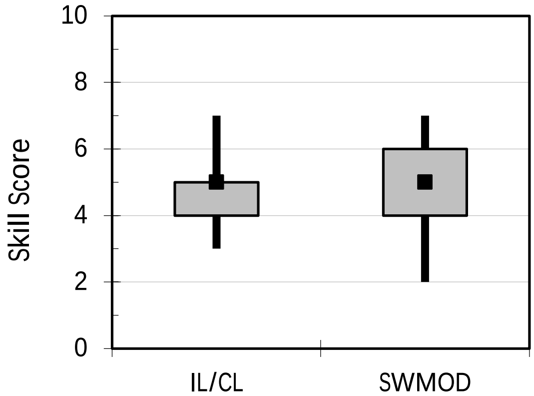
Coomalie Ck @ Stuart HWY (NT) - 24 hour bursts

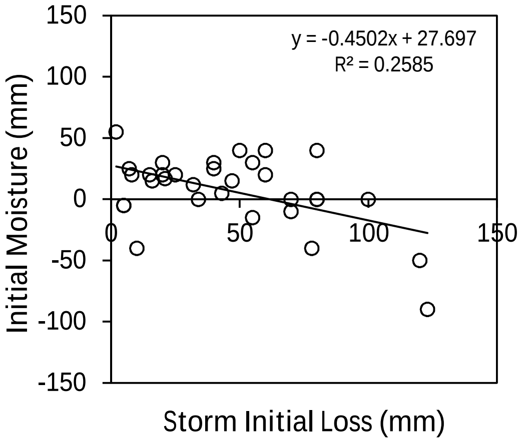


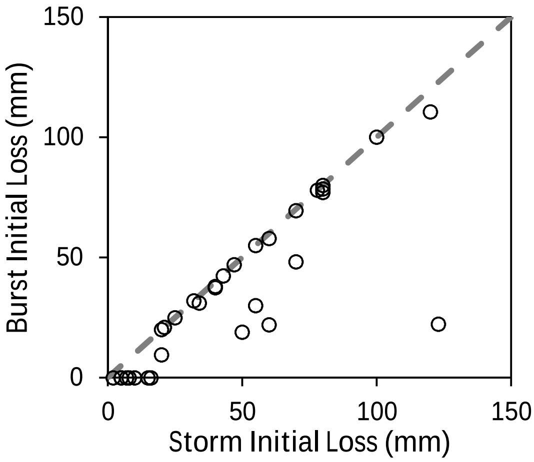
Manton R @ Manton Dam (NT) - 24 hour bursts

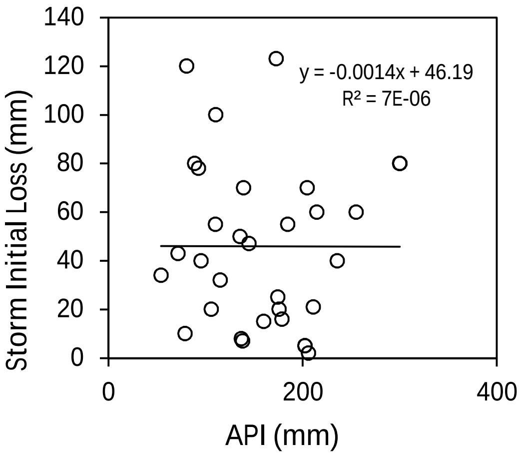


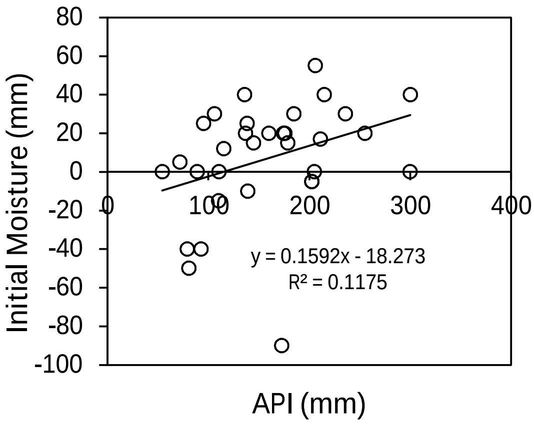




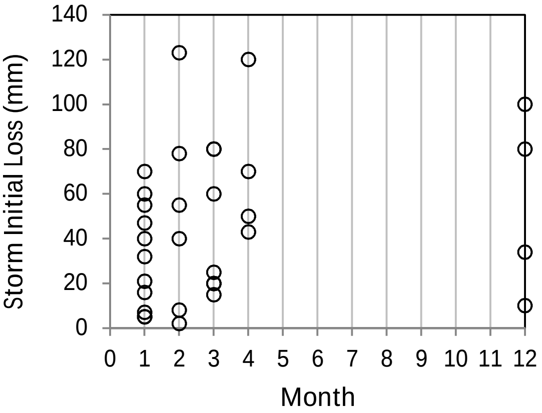


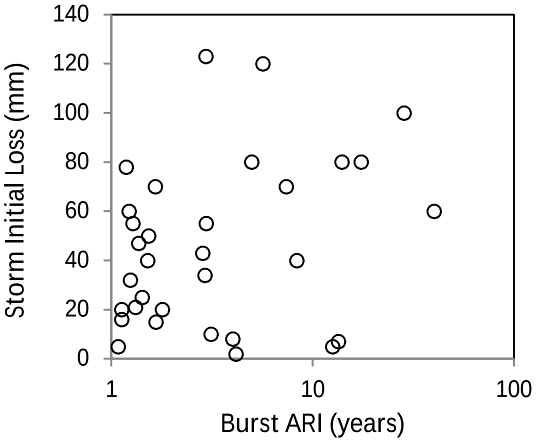


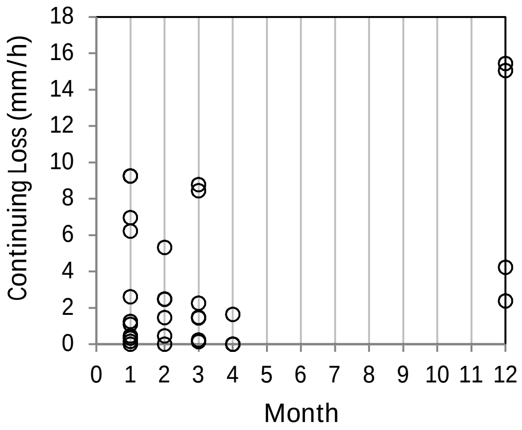


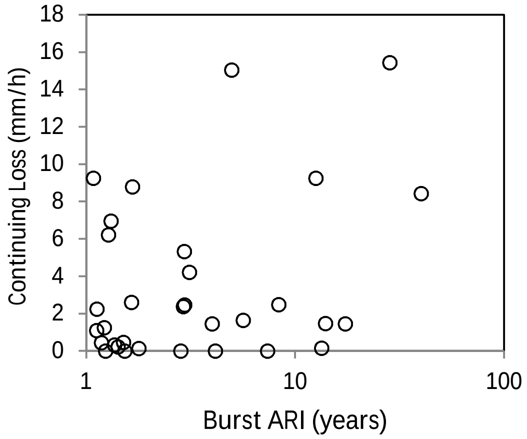


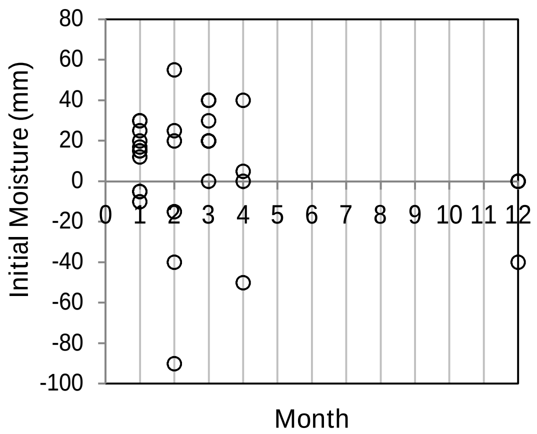
Manton R @ Manton Dam (NT) - 24 hour bursts

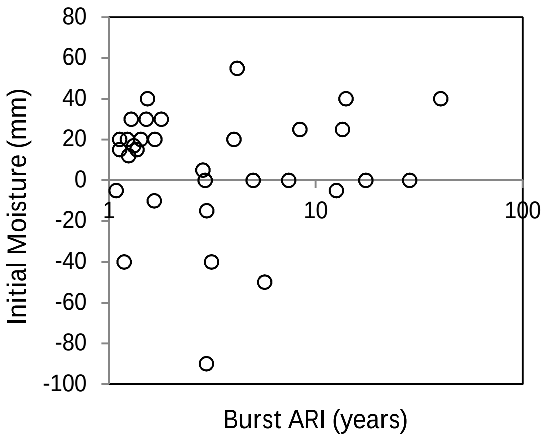


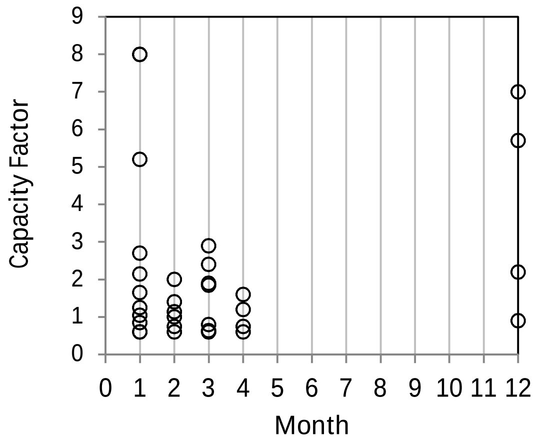


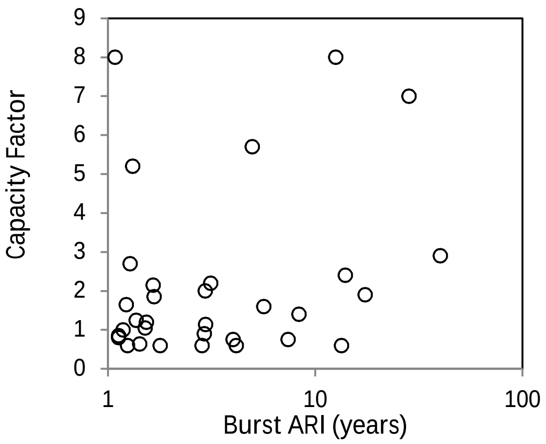




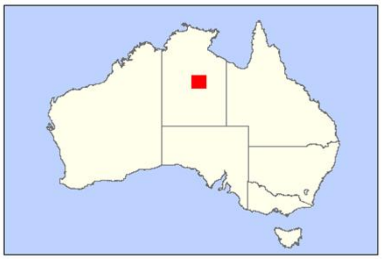


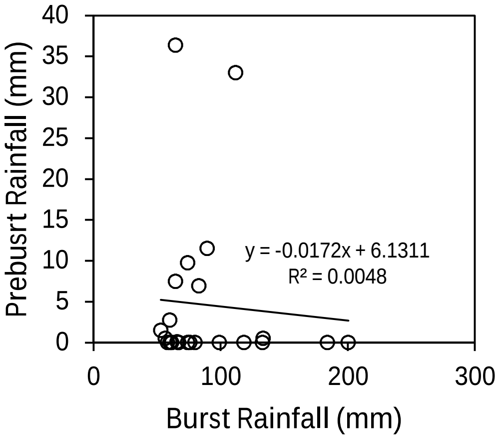


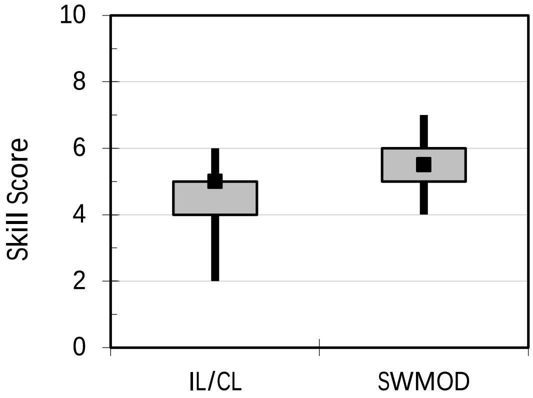


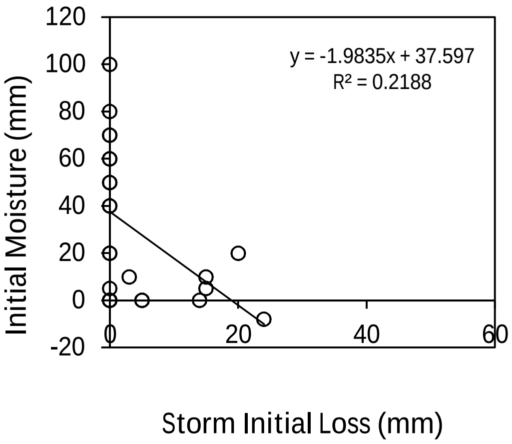


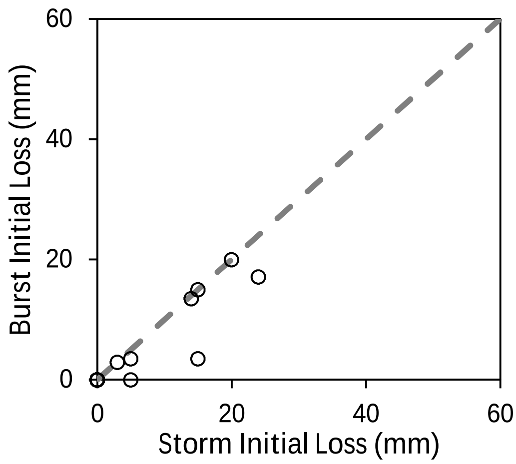
Tennant Ck @ Old Telegraph Stn (NT) - 24 hour bursts

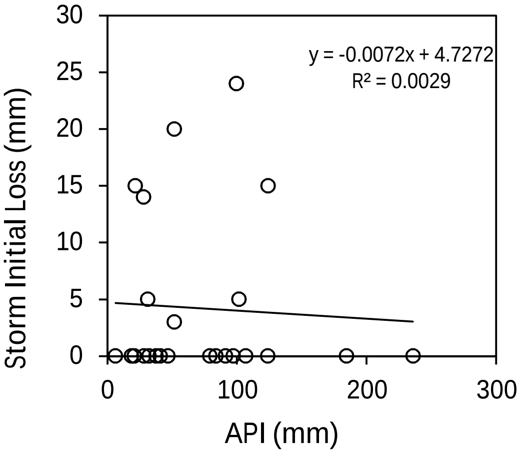


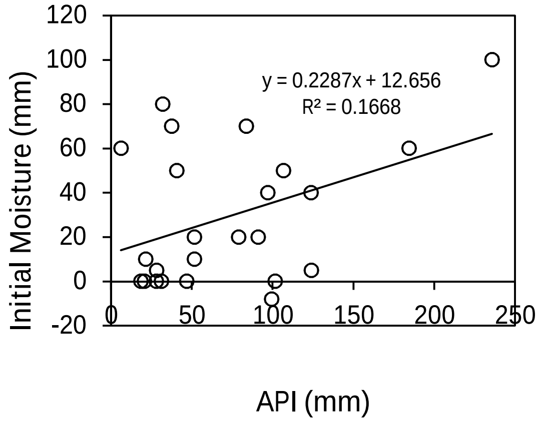




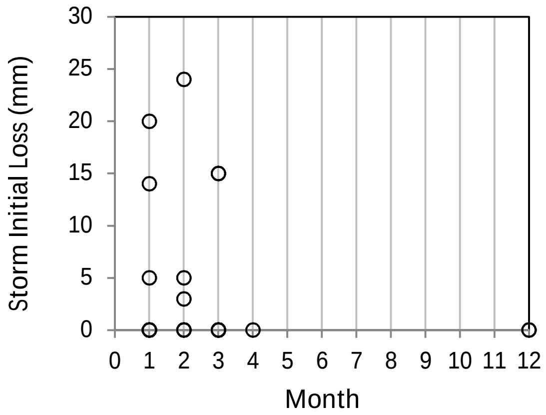


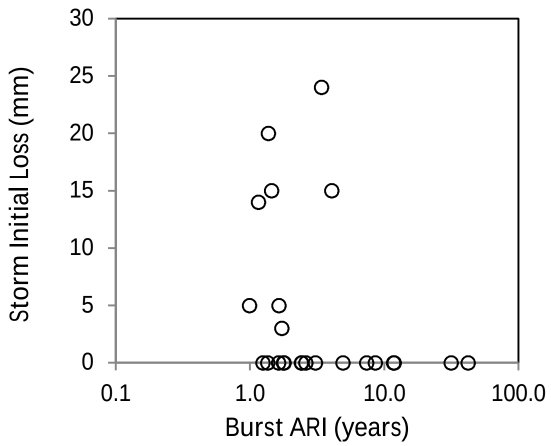


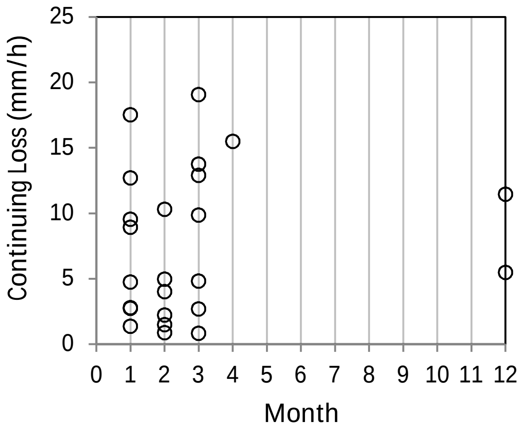


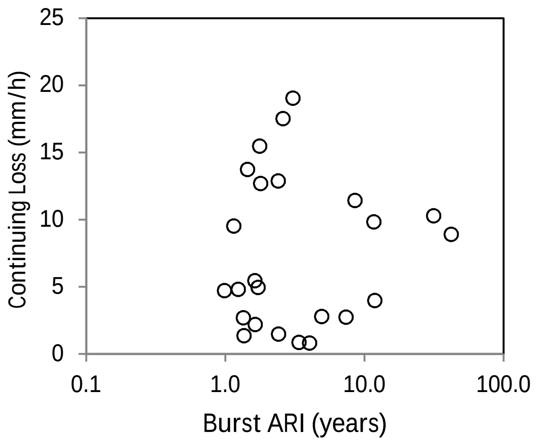


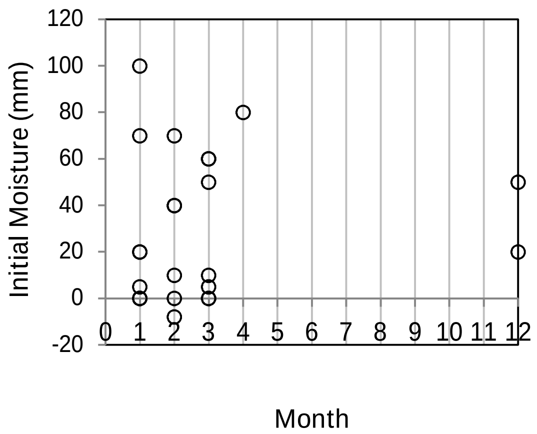
Tennant Ck @ Old Telegraph Stn (NT) - 24 hour bursts

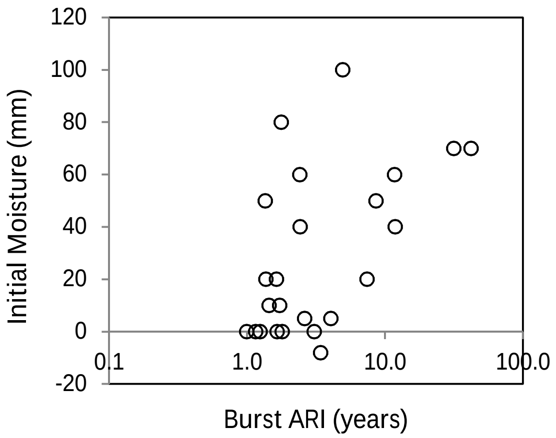


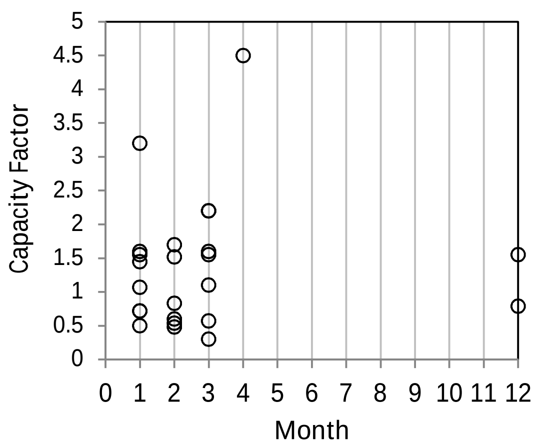


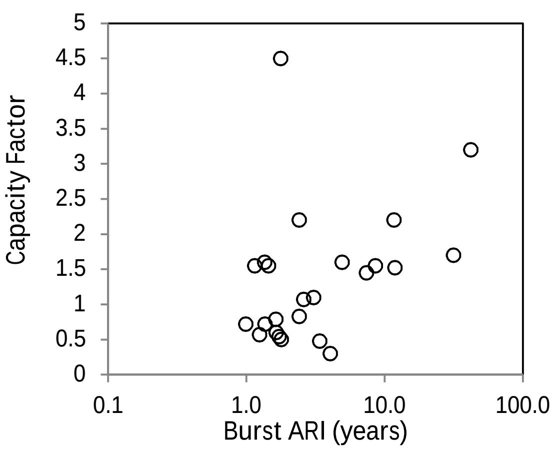




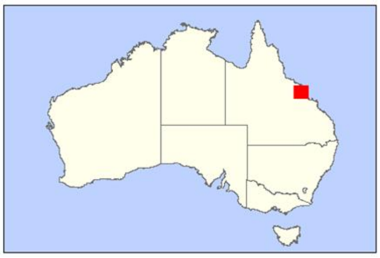


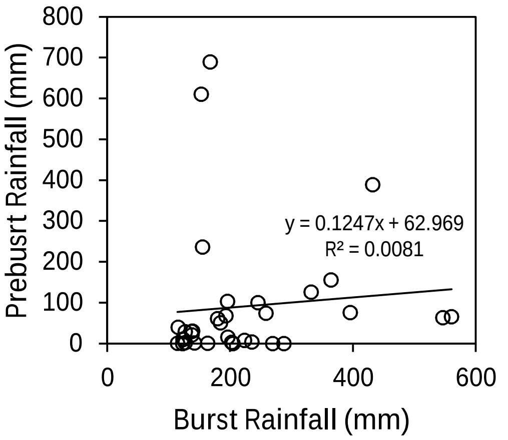


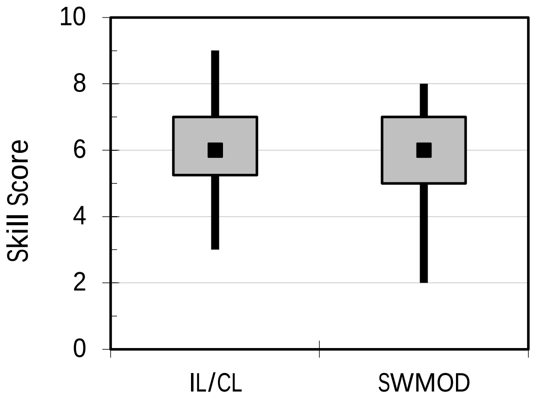


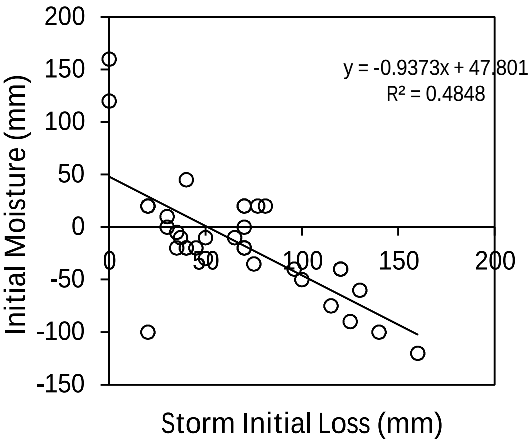


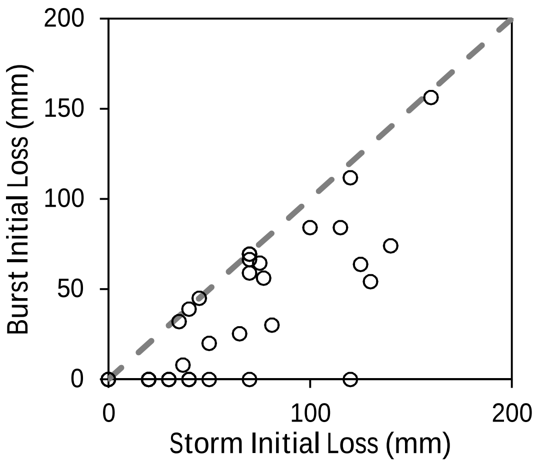
Broken @ Old Racecourse (Qld) - 24 hour bursts

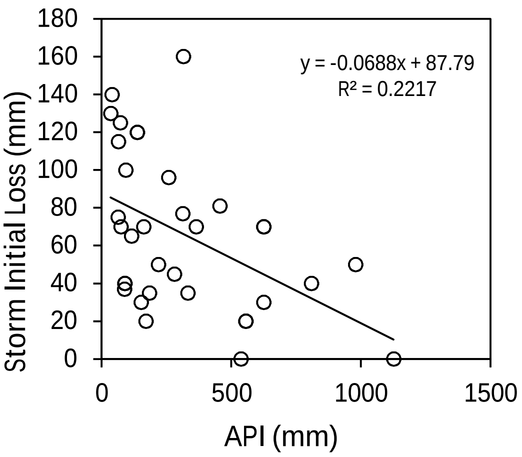


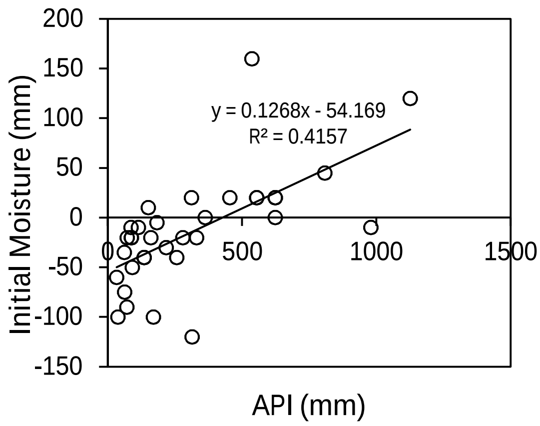




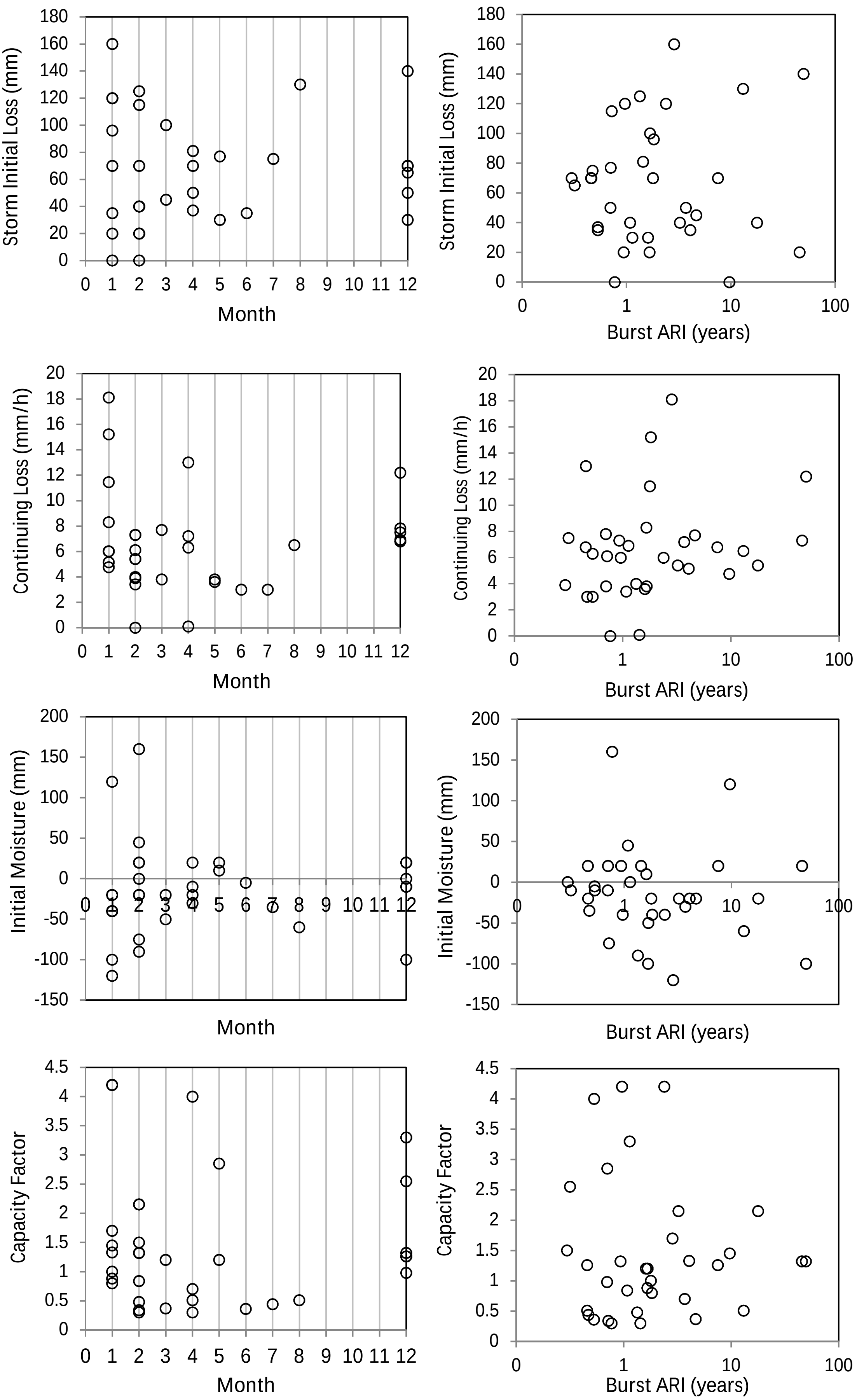




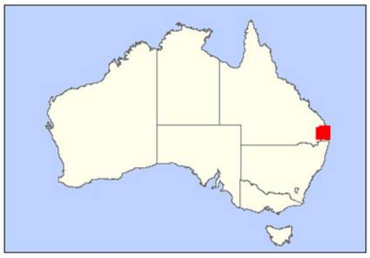


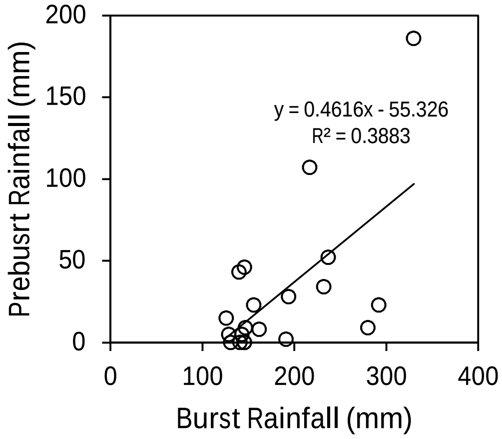


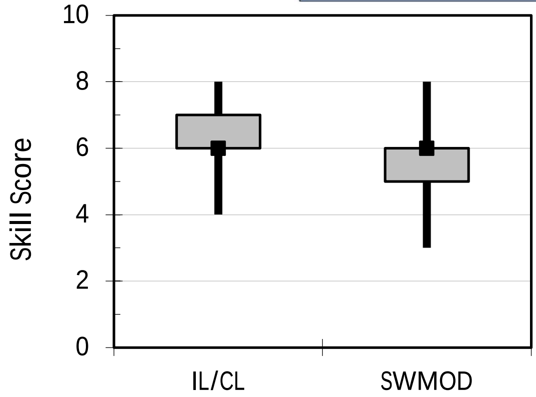
Broken @ Old Racecourse (Qld) - 24 hour bursts

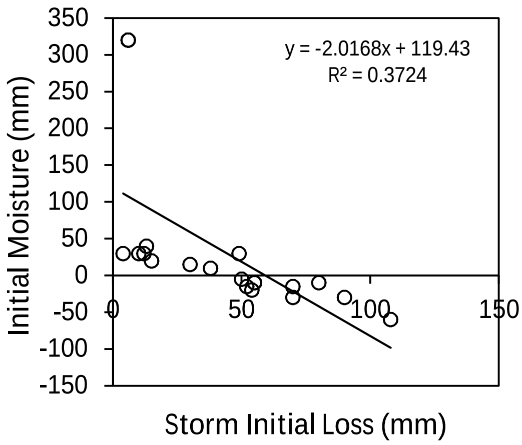


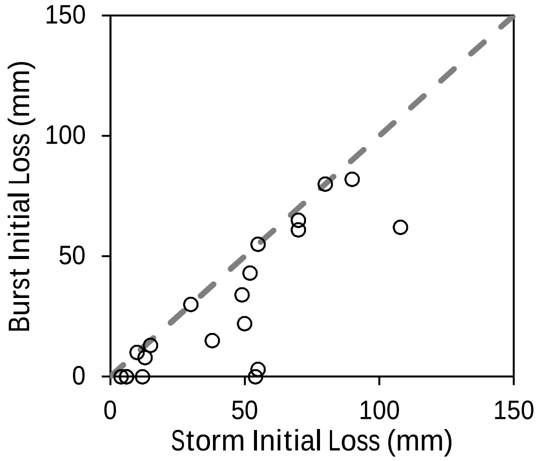
Caboolture @ Upper Caboolture (Qld) - 24 hour bursts

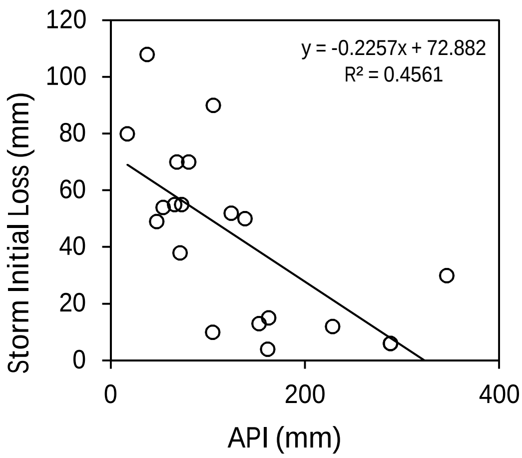


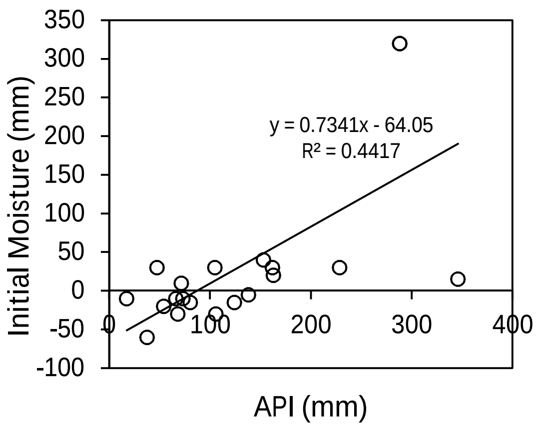




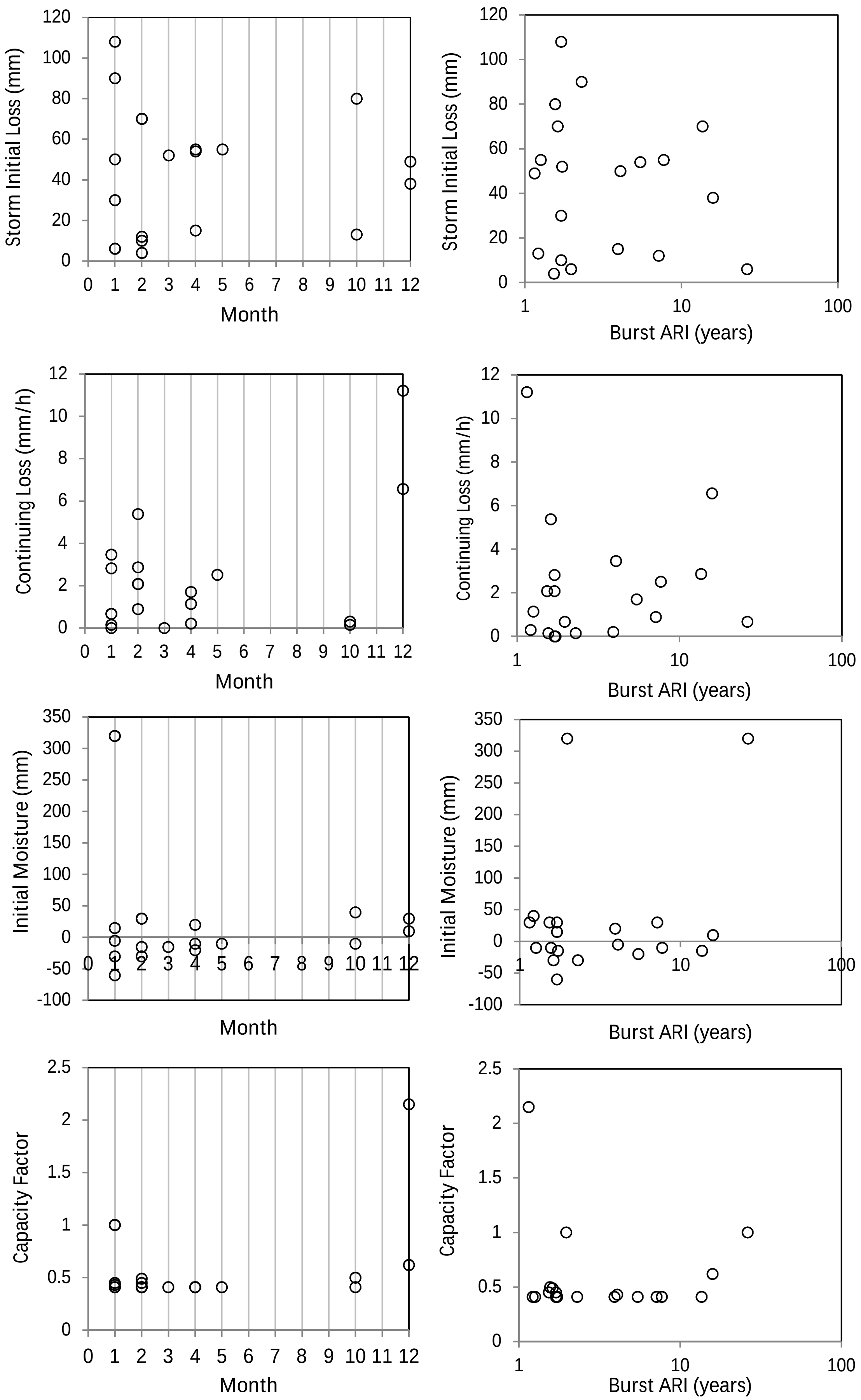




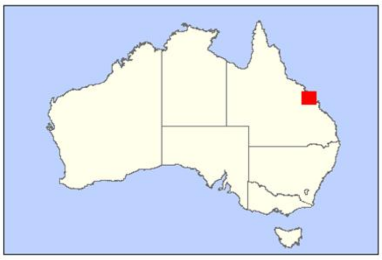


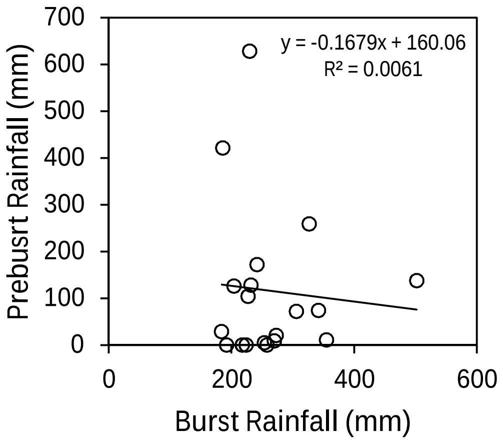


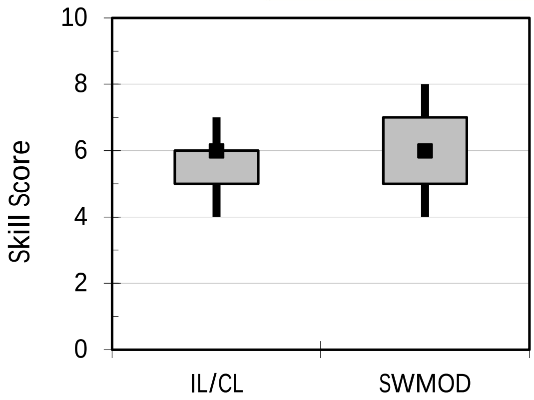
Caboolture @ Upper Caboolture (Qld) - 24 hour bursts

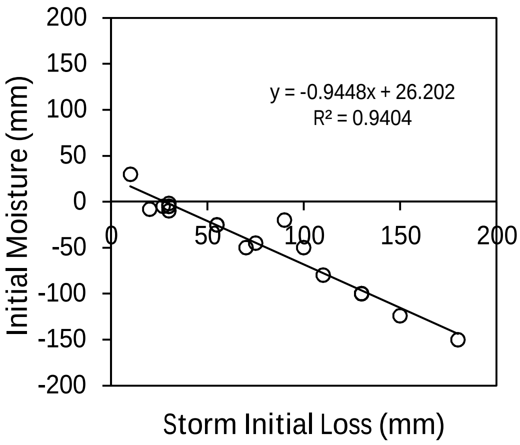


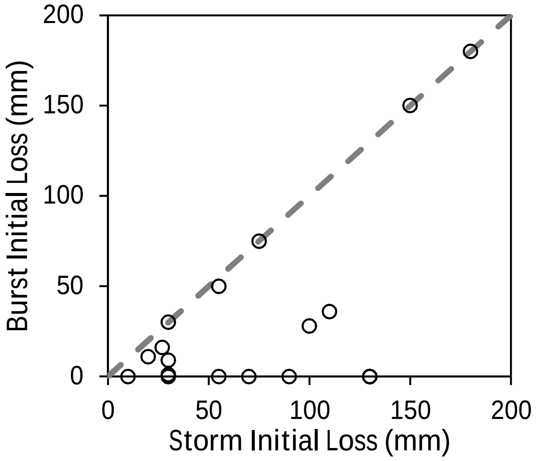
Carmila Ck @ Carmila (Qld) - 24 hour bursts

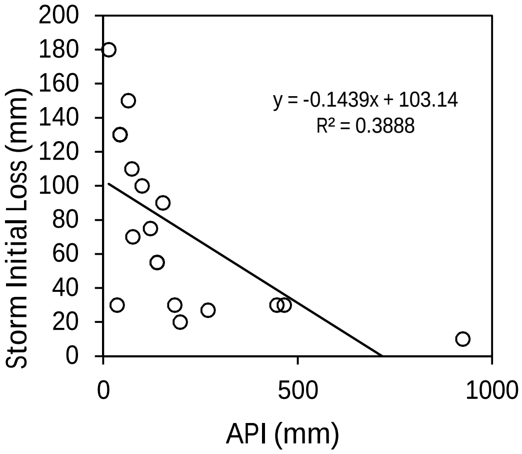


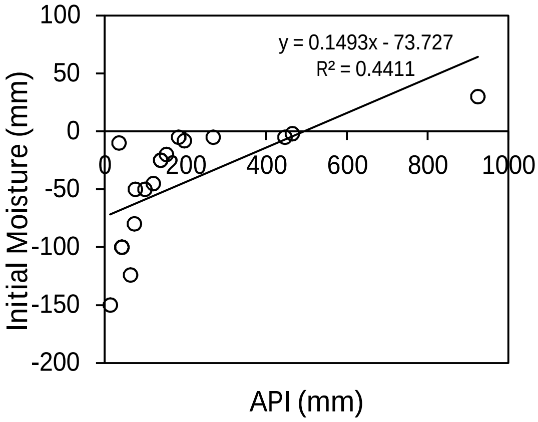




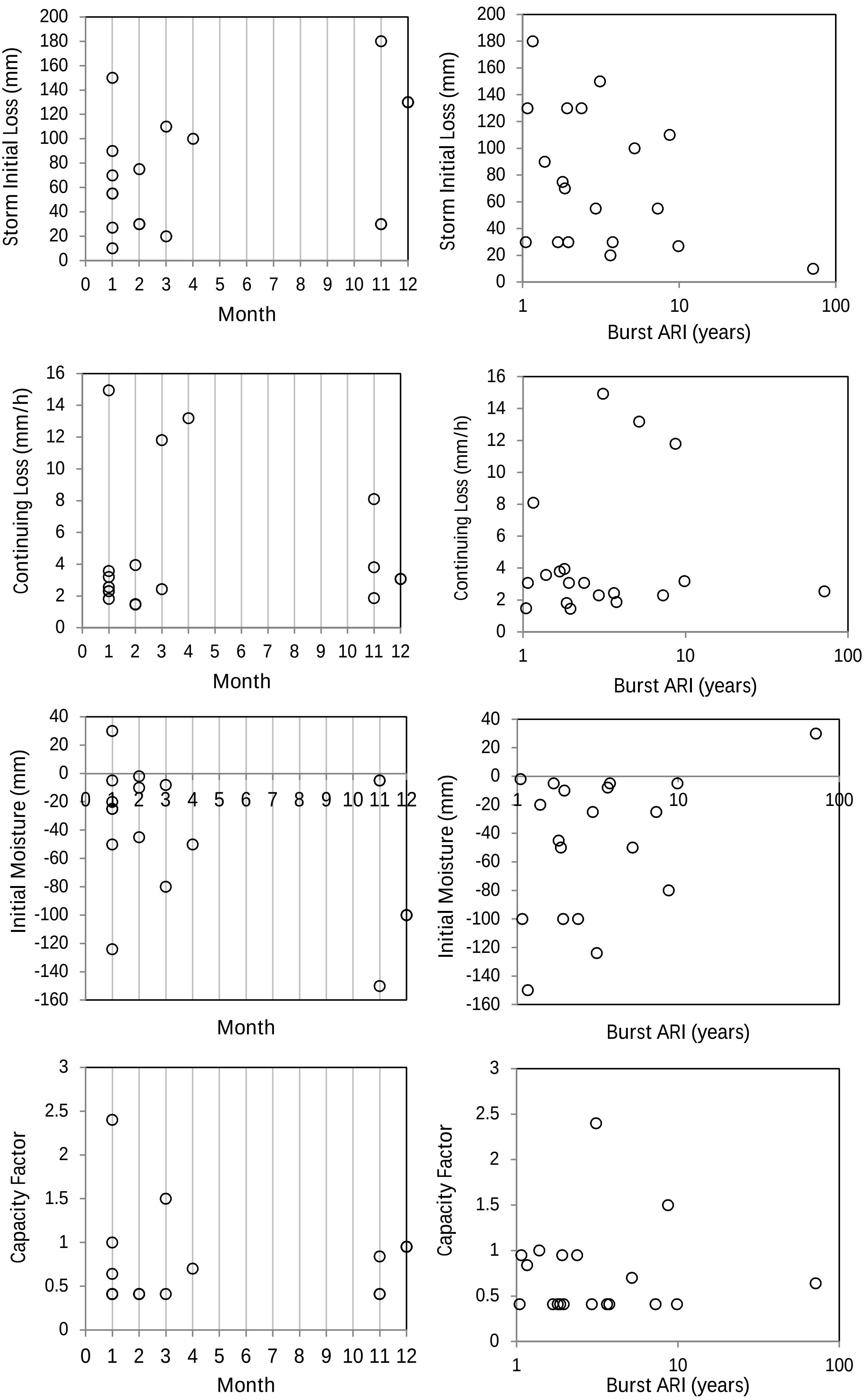




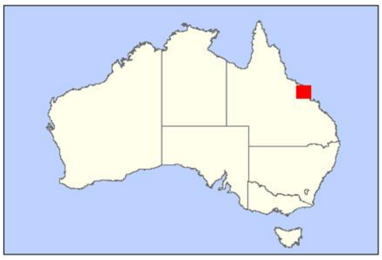


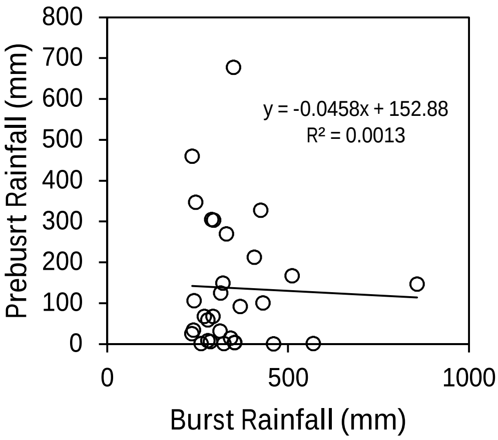


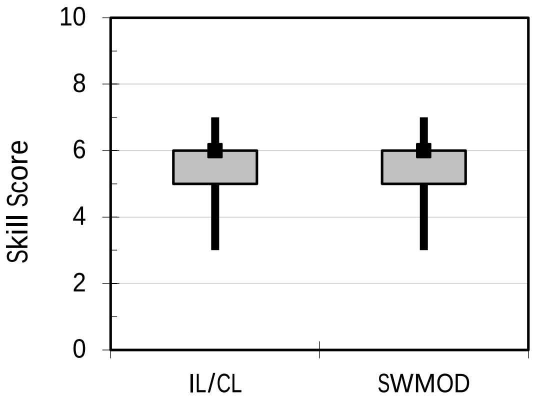
Carmila Ck @ Carmila (Qld) - 24 hour bursts

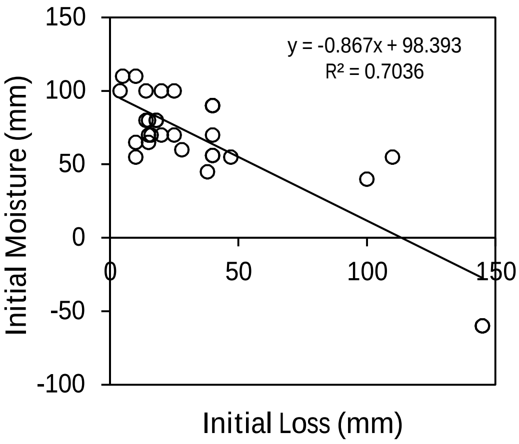


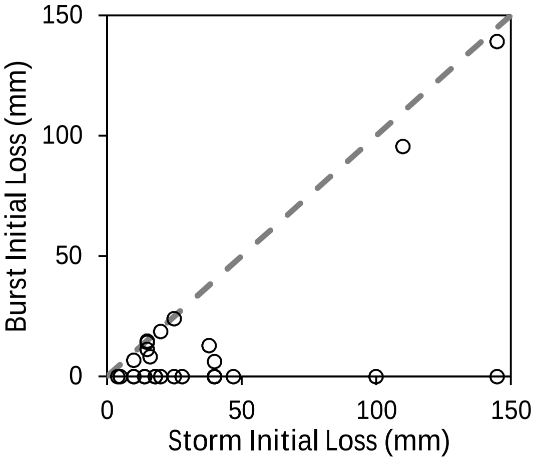
Finch Hatton Ck @ Dam Site (Qld) - 24 hour bursts

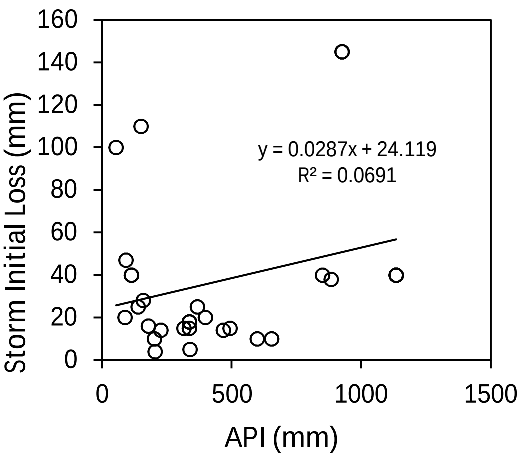


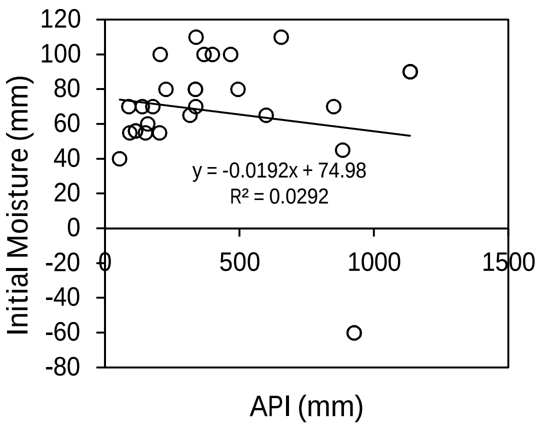




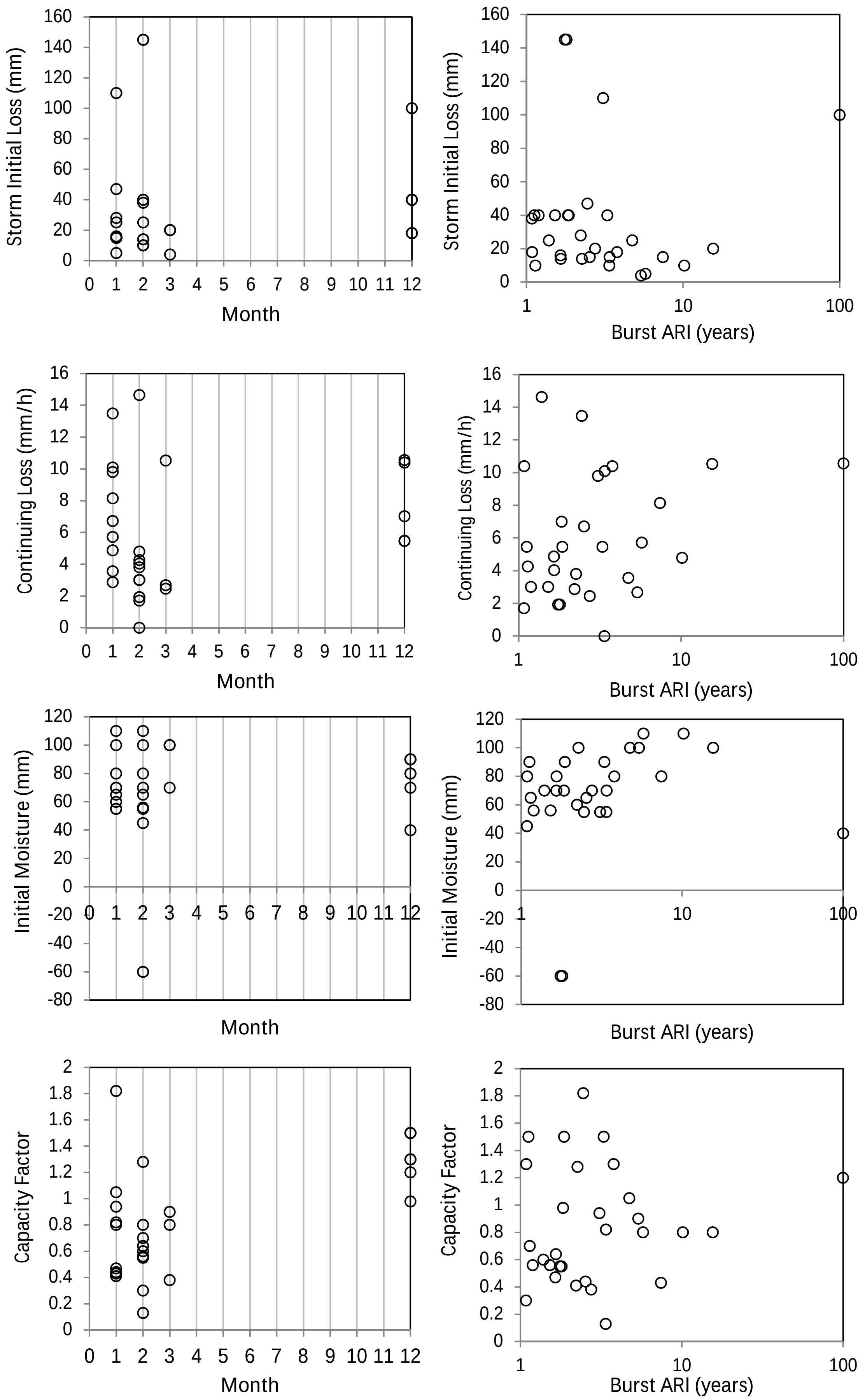




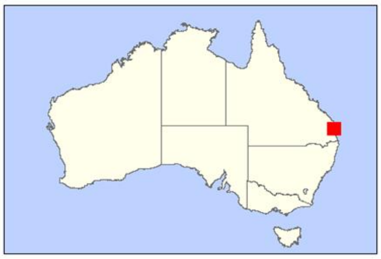


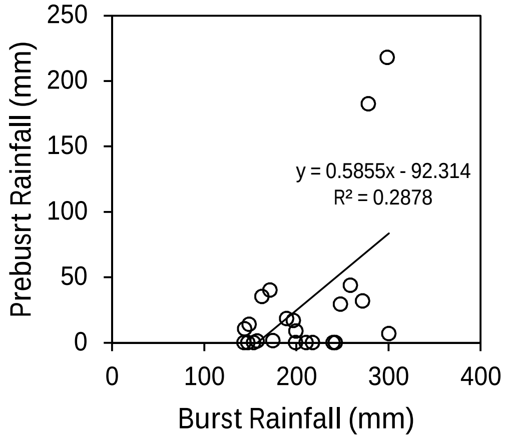


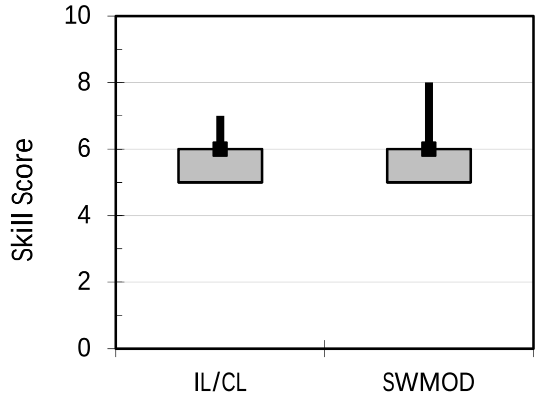
Finch Hatton Ck @ Dam Site (Qld) - 24 hour bursts

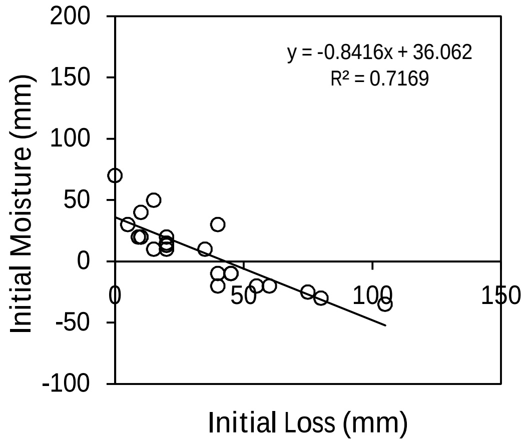


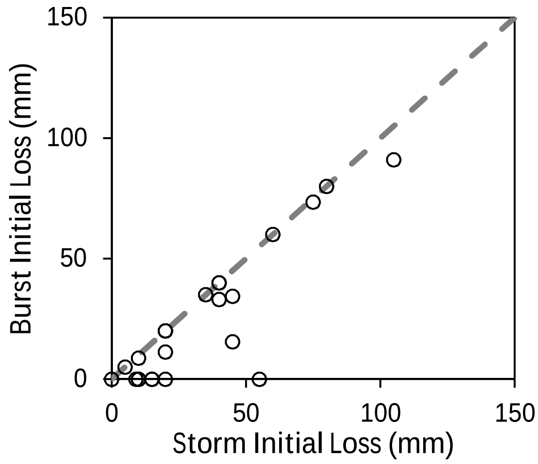
North Maroochy River @ Eumundi (Qld) - 24 hour bursts

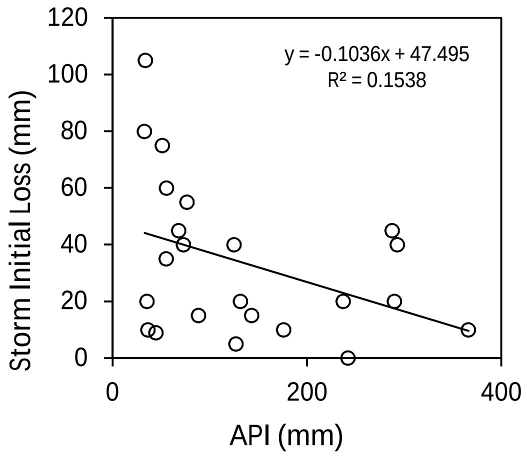


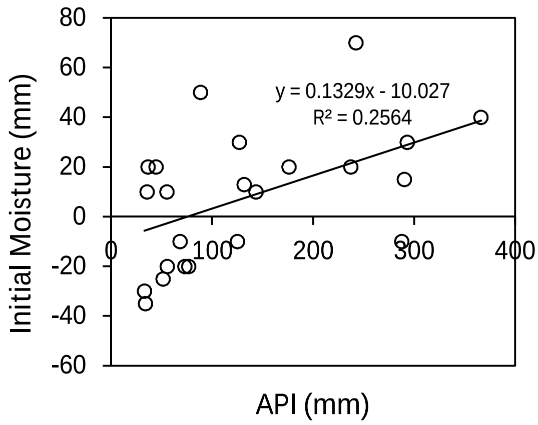




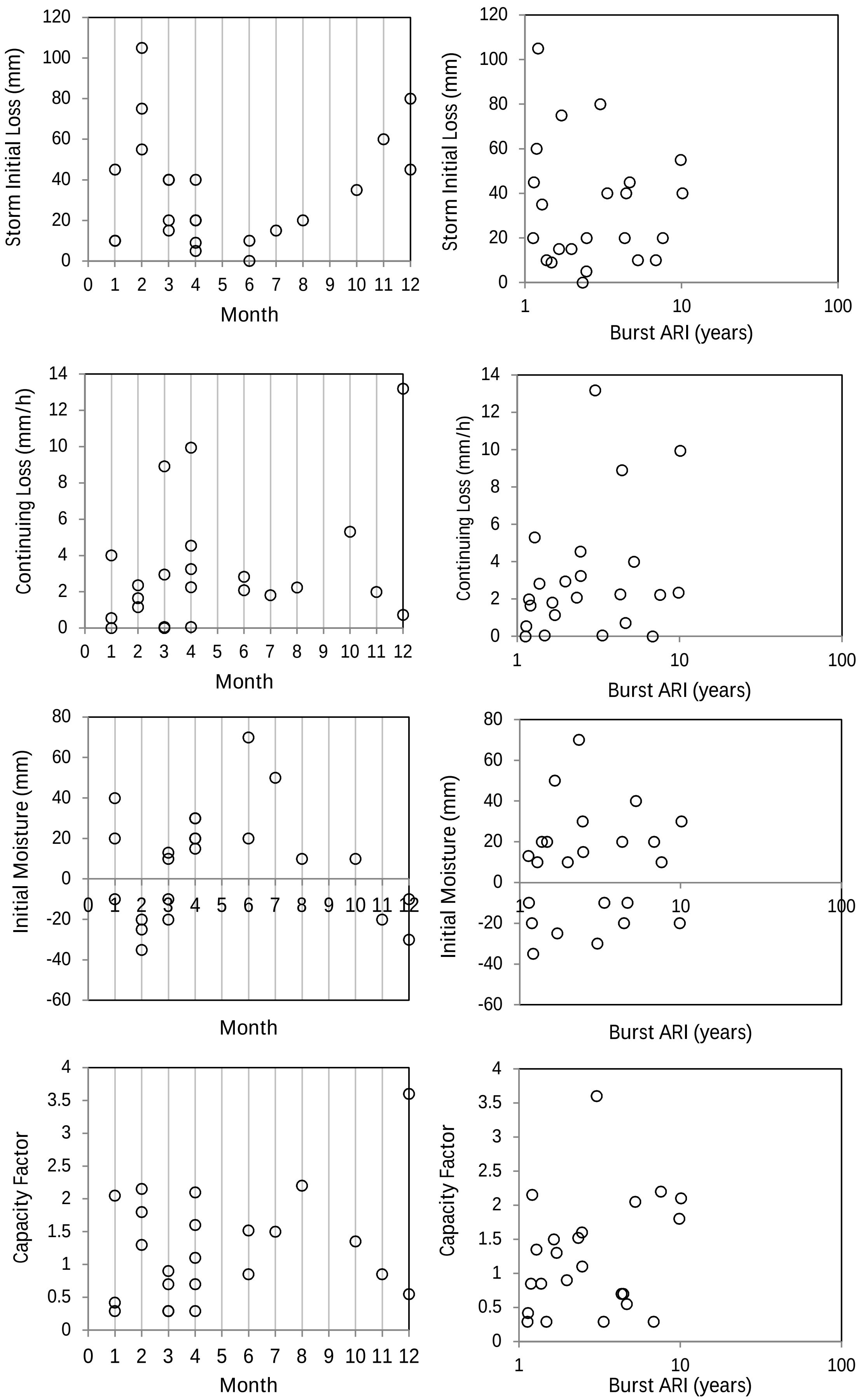




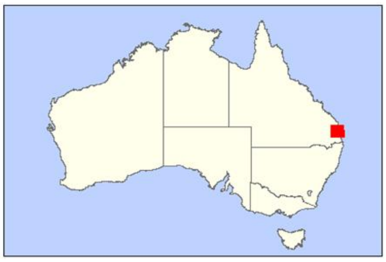


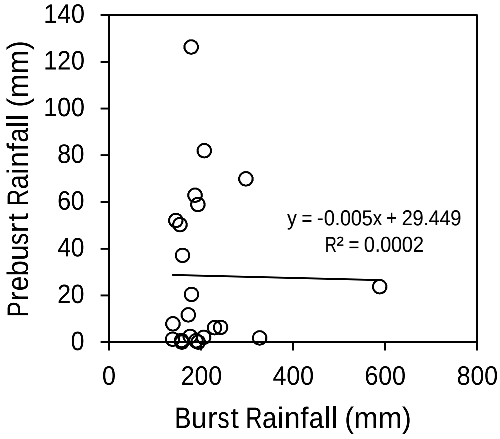


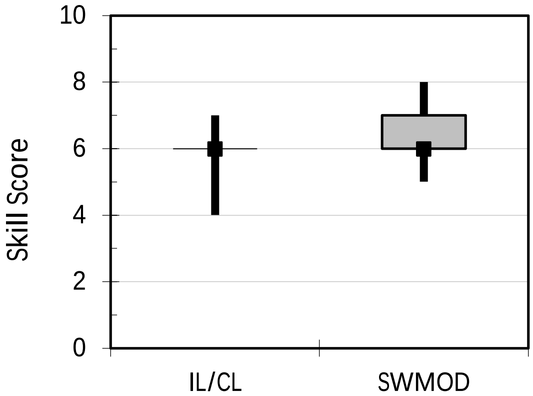
North Maroochy River @ Eumundi (Qld) - 24 hour bursts

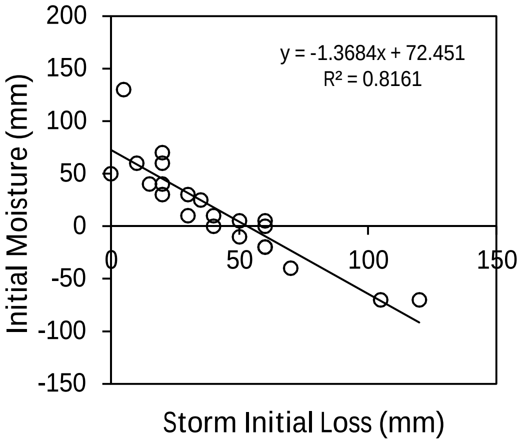


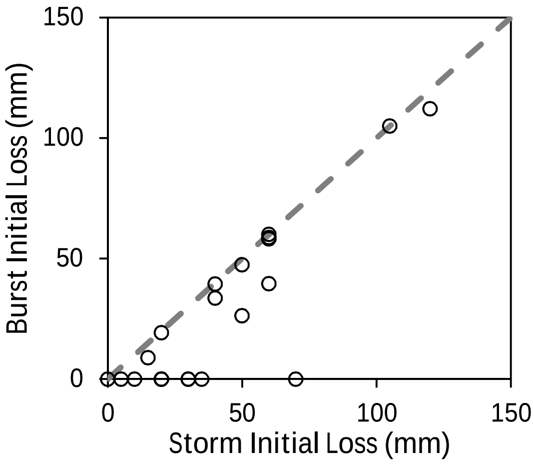
South Maroochy @ Kiamba (QLD) - 24 hour bursts

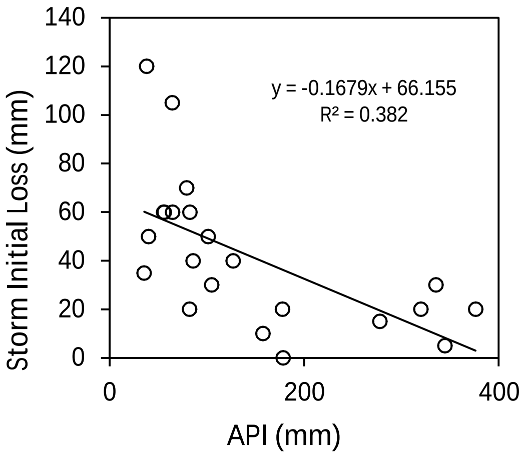


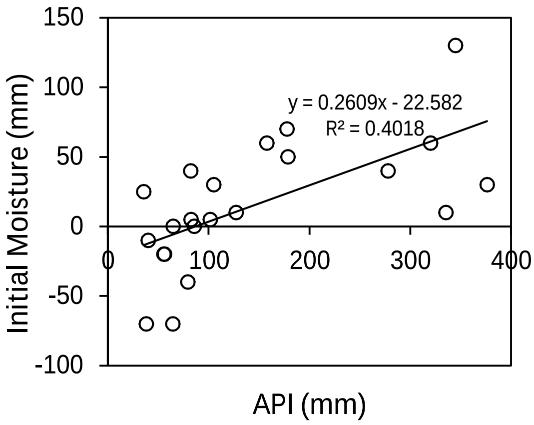




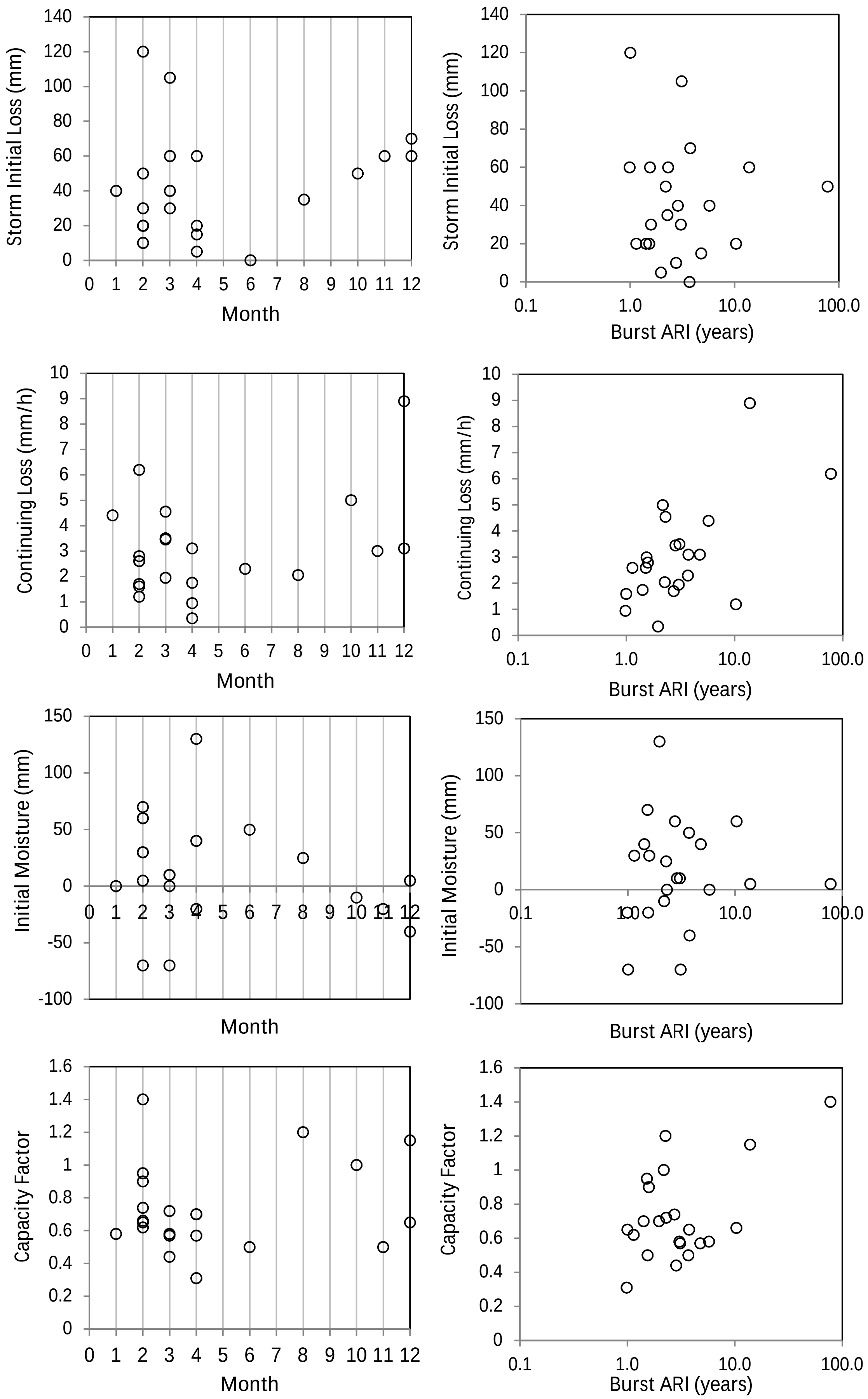




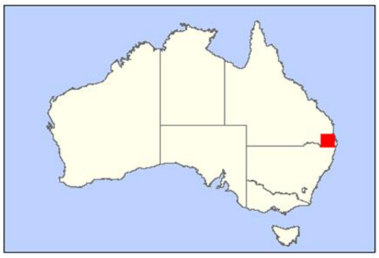


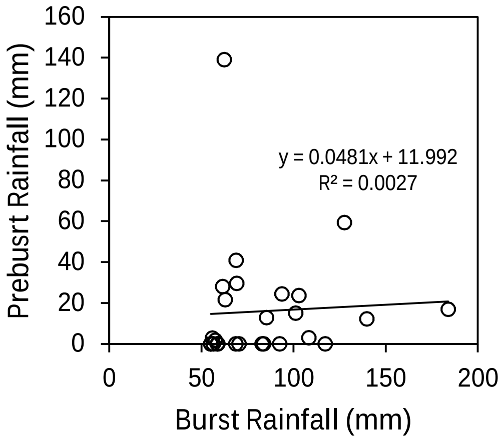


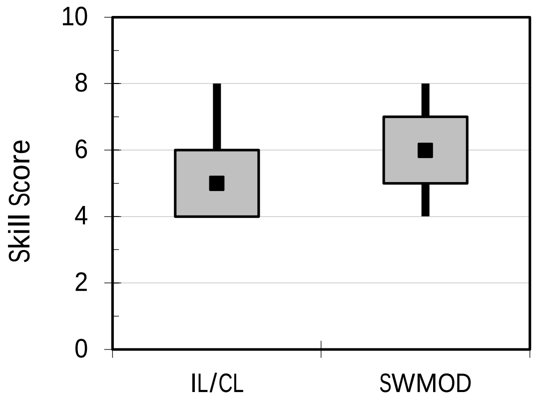
South Maroochy @ Kiamba (QLD) - 24 hour bursts

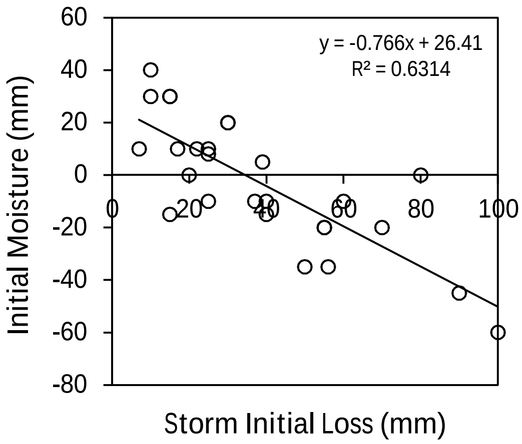


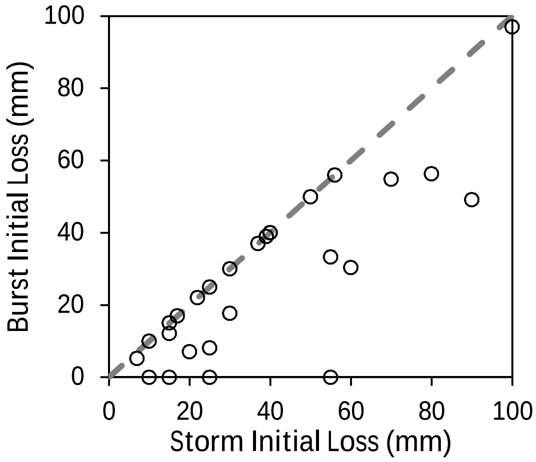
Spring Ck @ Killarney (Qld) - 24 hour bursts

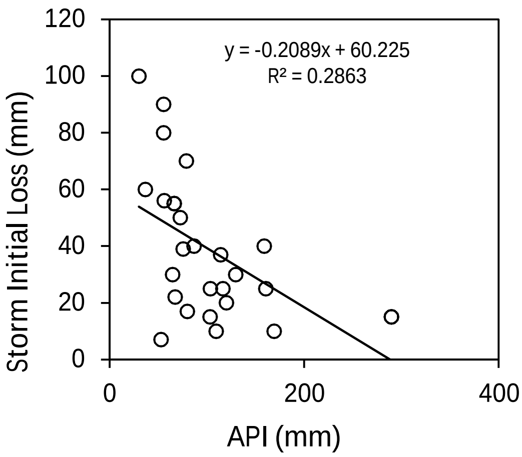


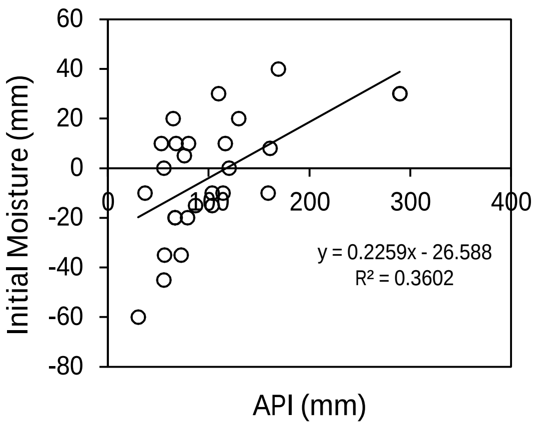




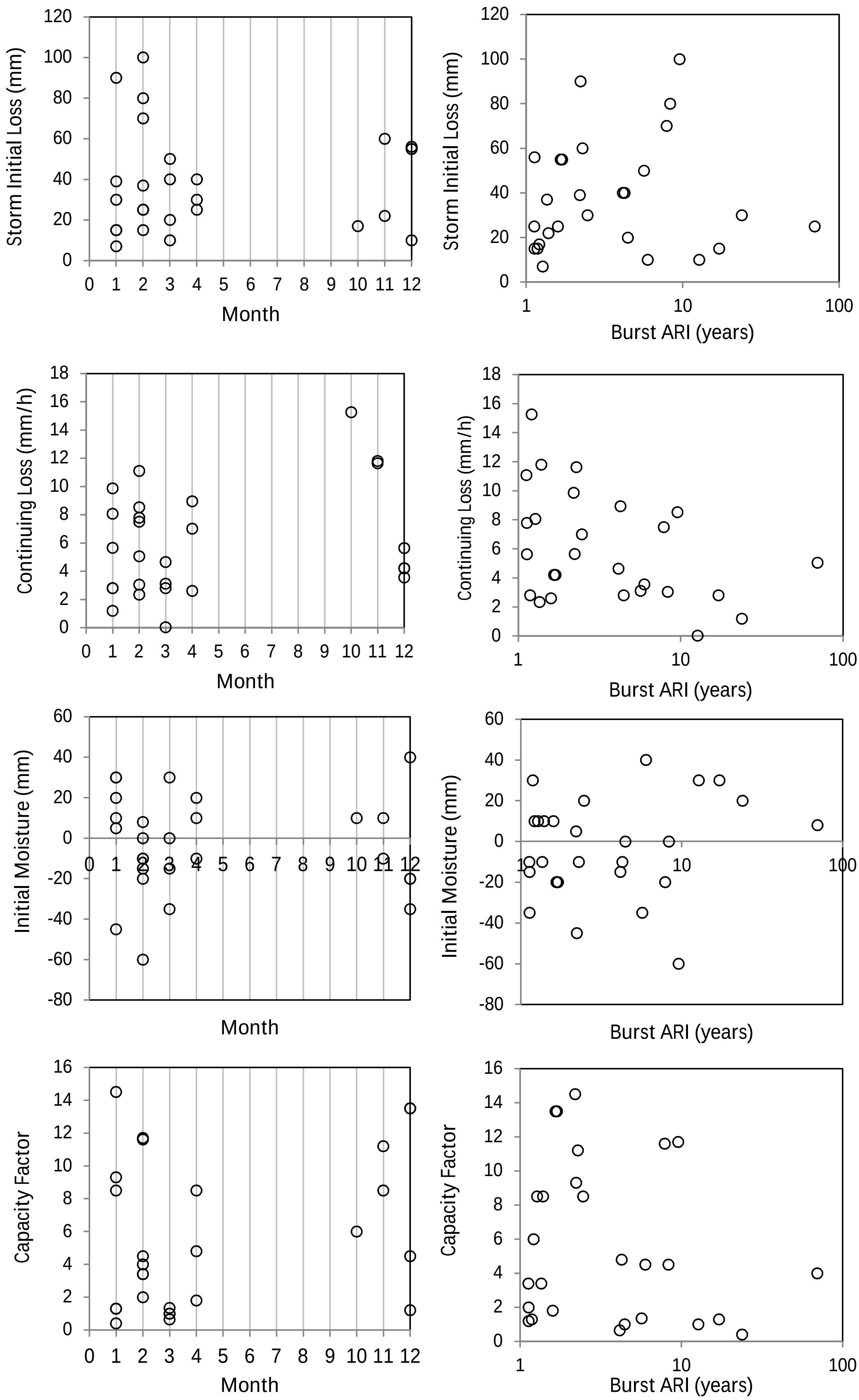




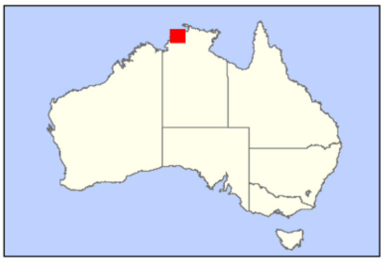


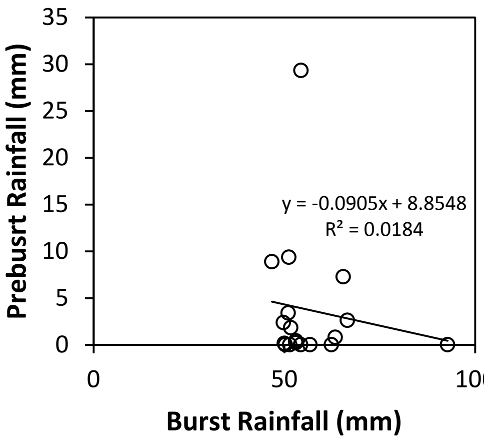


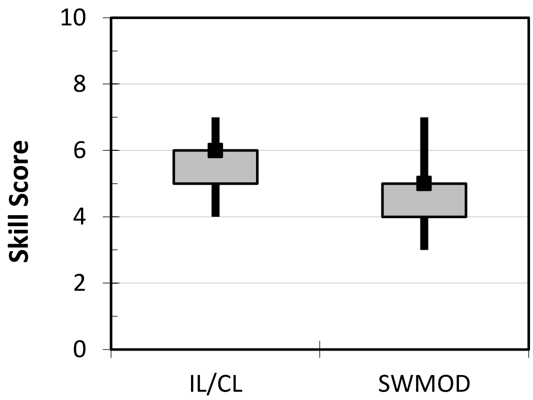
Spring Ck @ Killarney (Qld) - 24 hour bursts

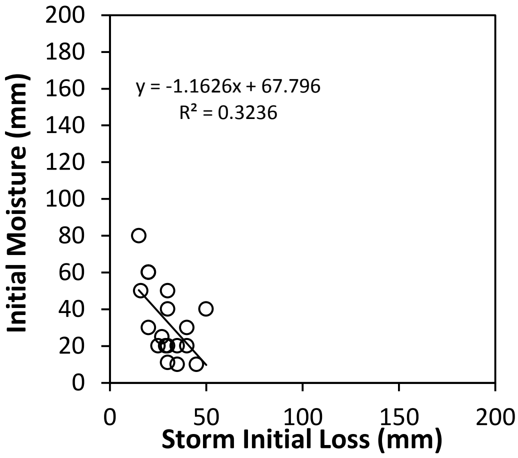


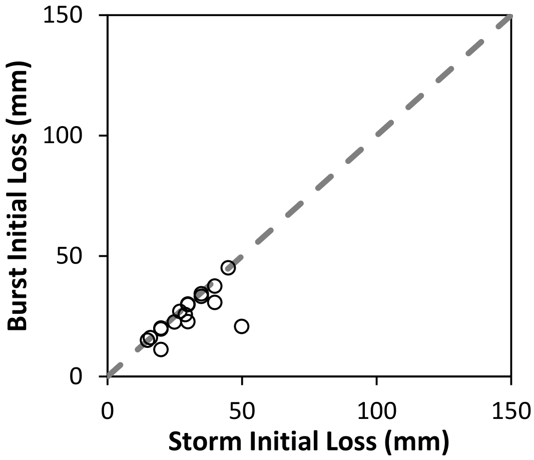
Fletcher Ck @ Frog Hollow (WA) - 3 hour bursts

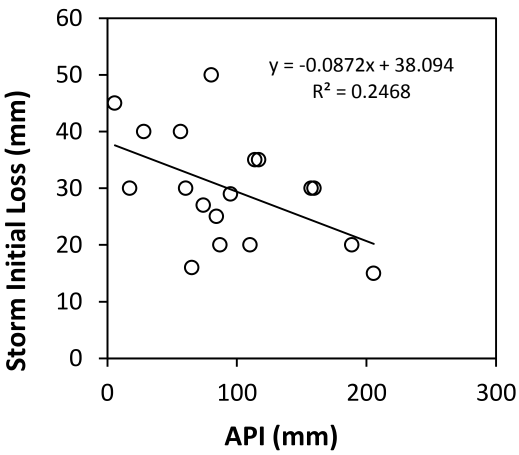


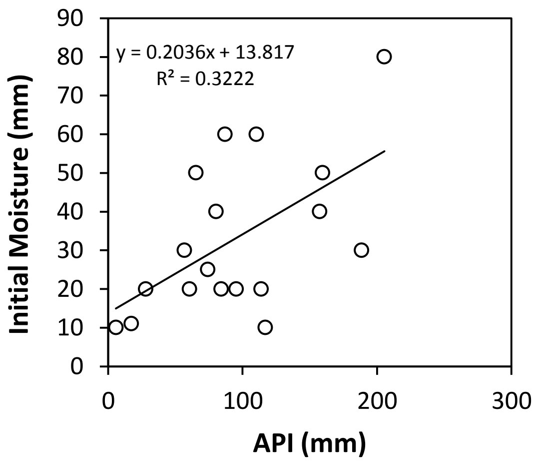




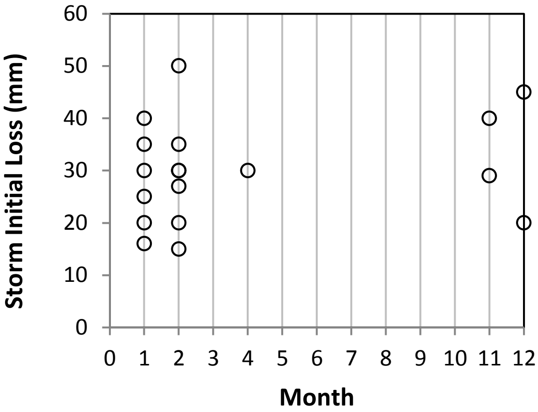


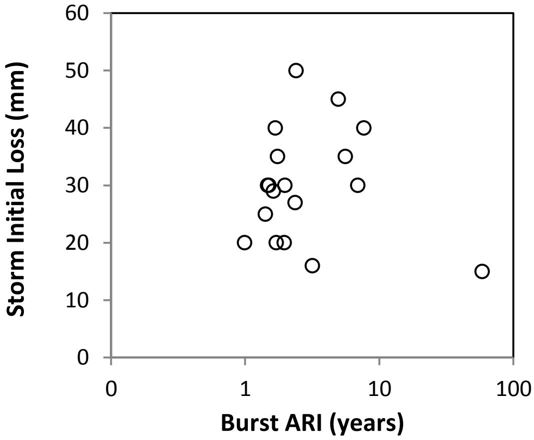


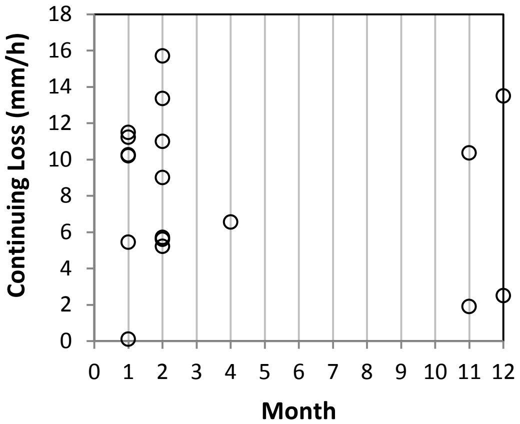


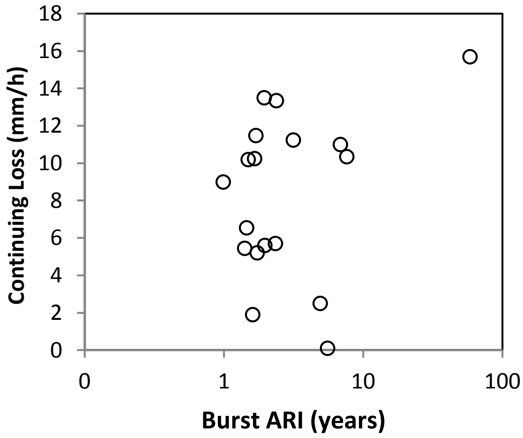


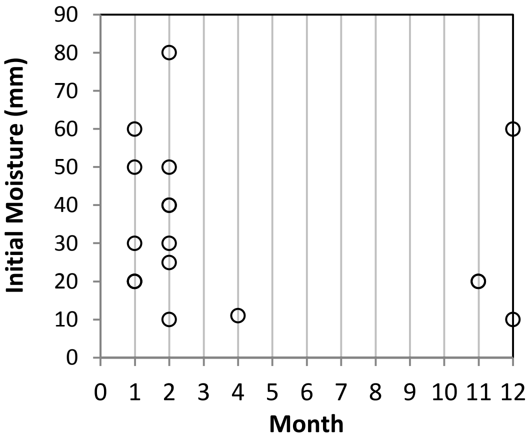
Fletcher Ck @ Frog Hollow (WA) - 3 hour bursts

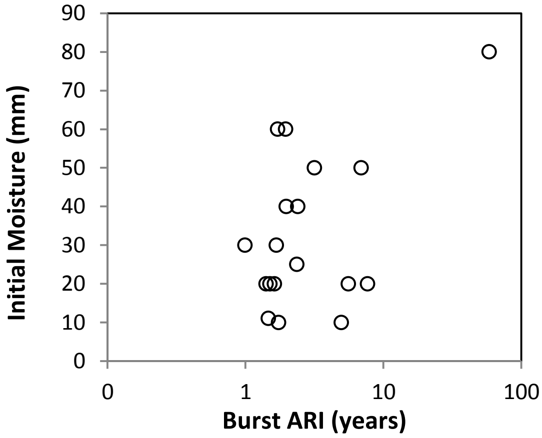


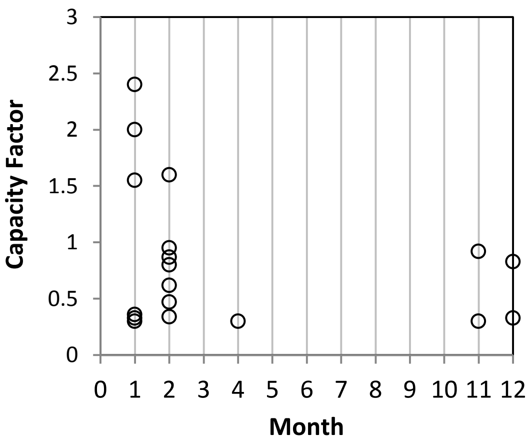


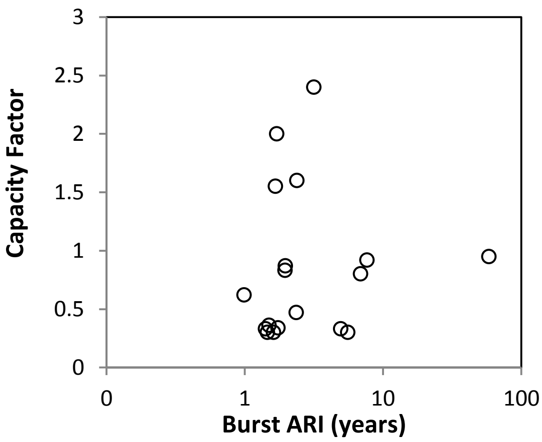




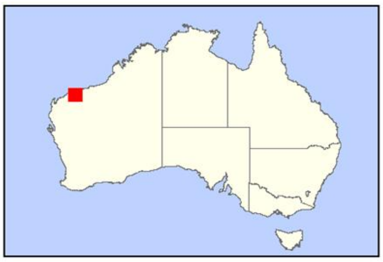


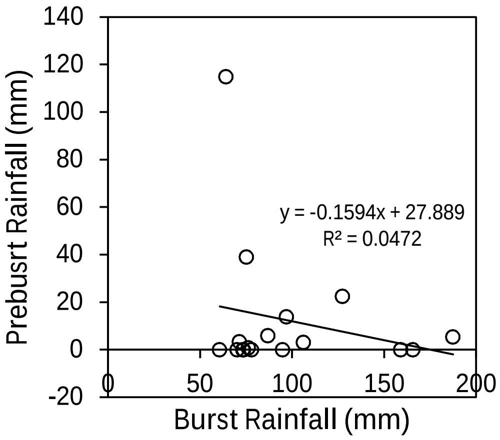


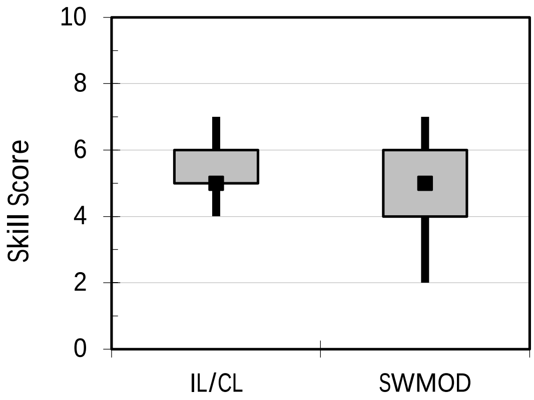


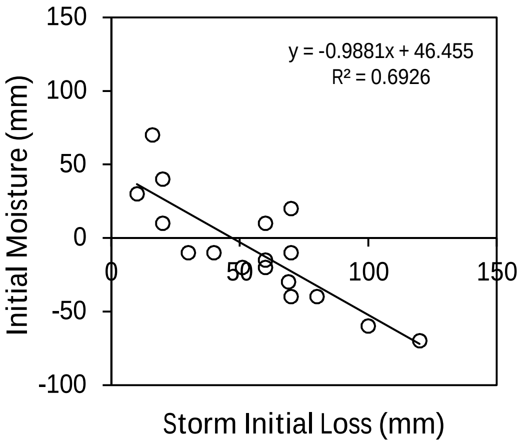


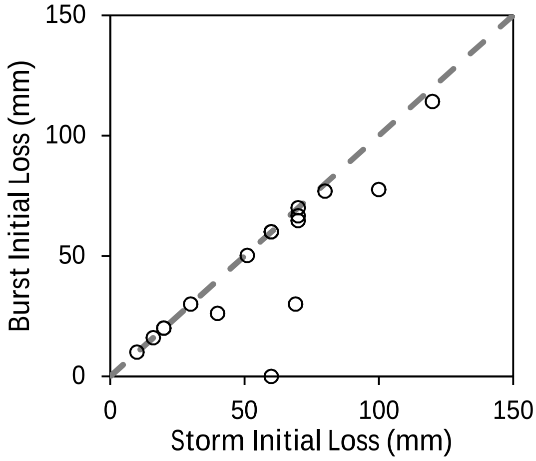
Harding @ Marmurrina Pool U-South (WA) - 24 hour bursts

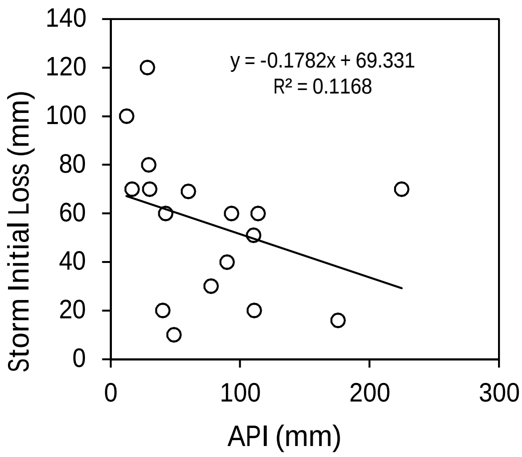


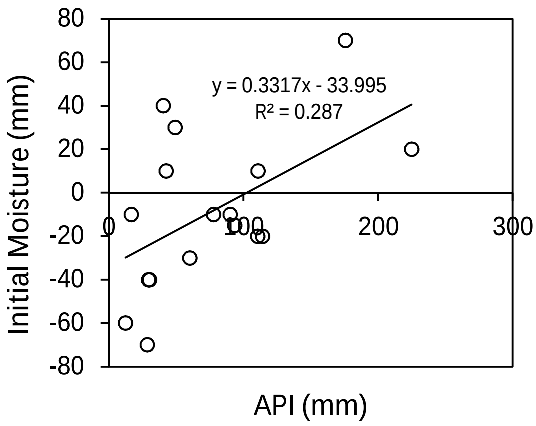




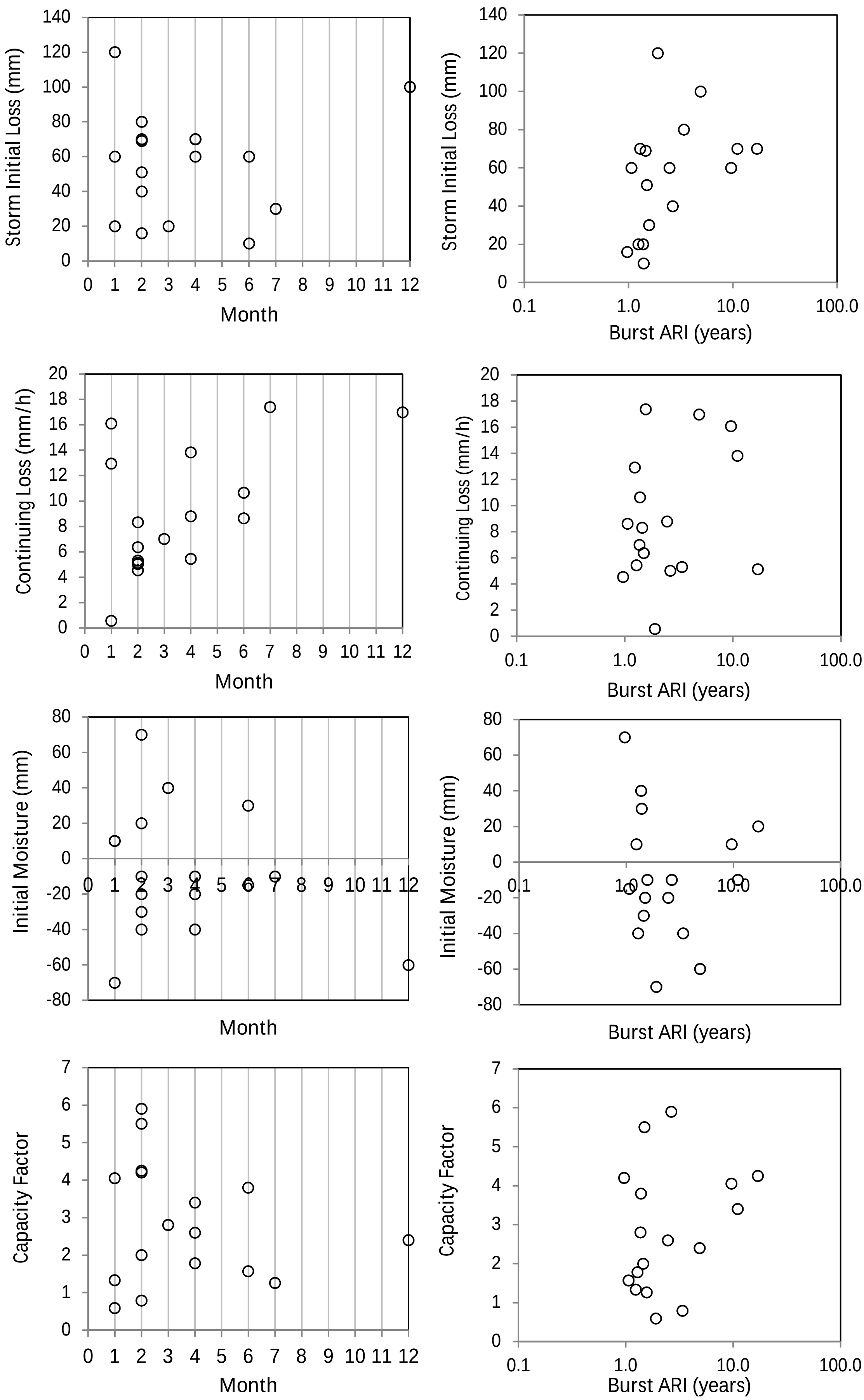




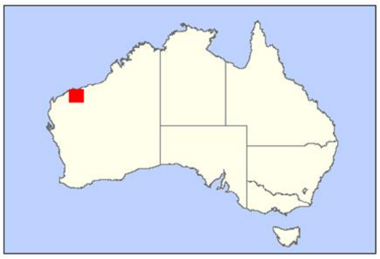


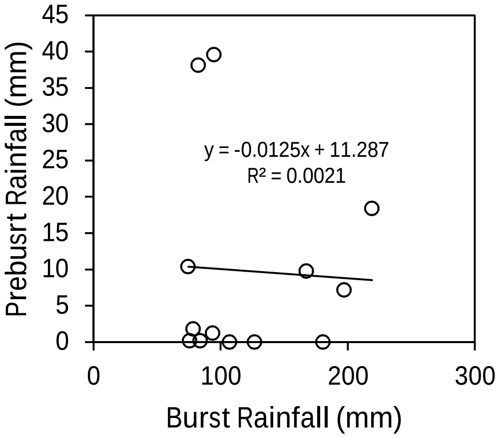


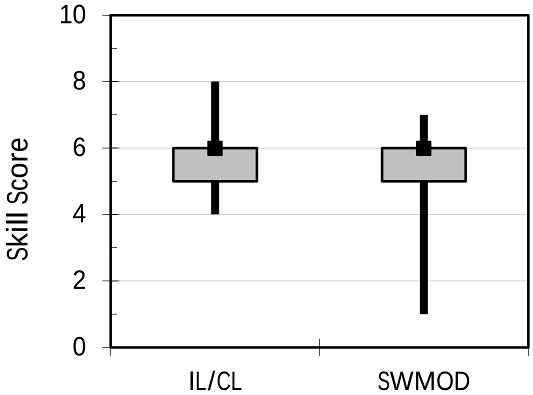
Harding @ Marmurrina Pool U-South (WA) - 24 hour bursts

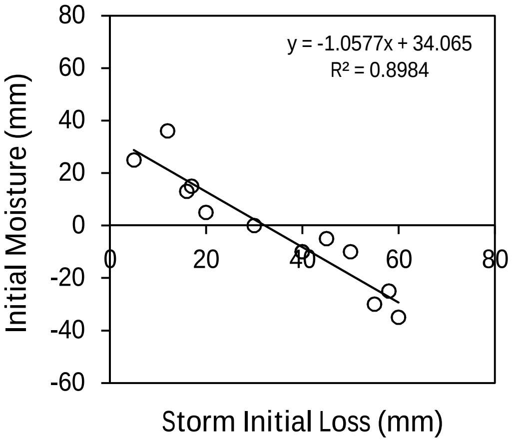


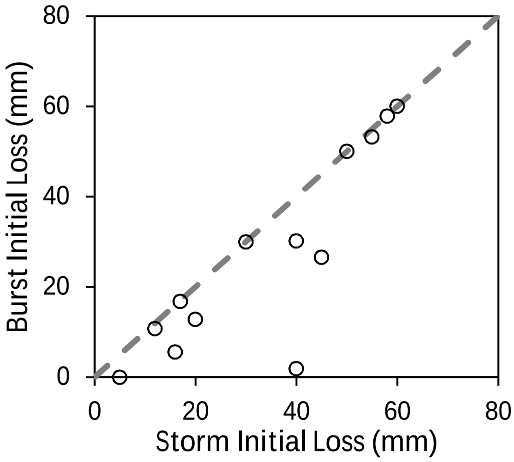
Kanjenjie Ck Trib. @ Fish Pool (WA) - 24 hour bursts

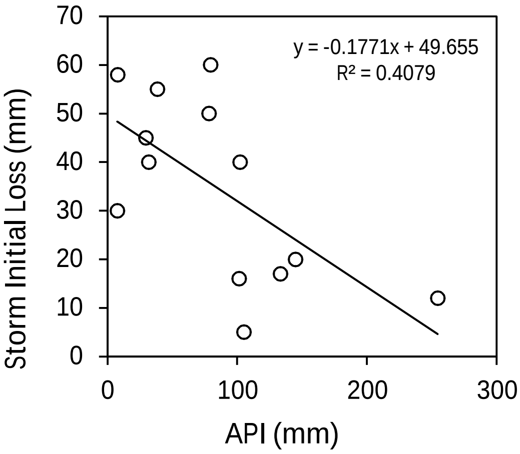


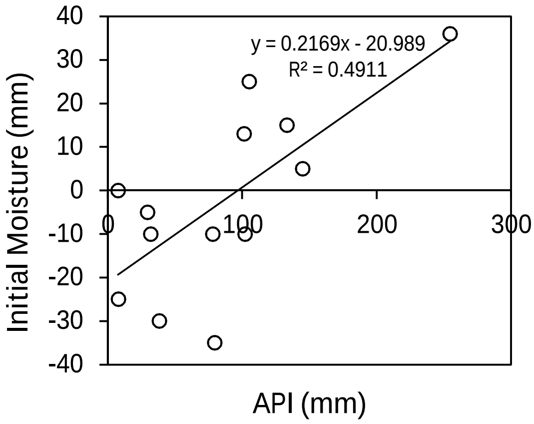




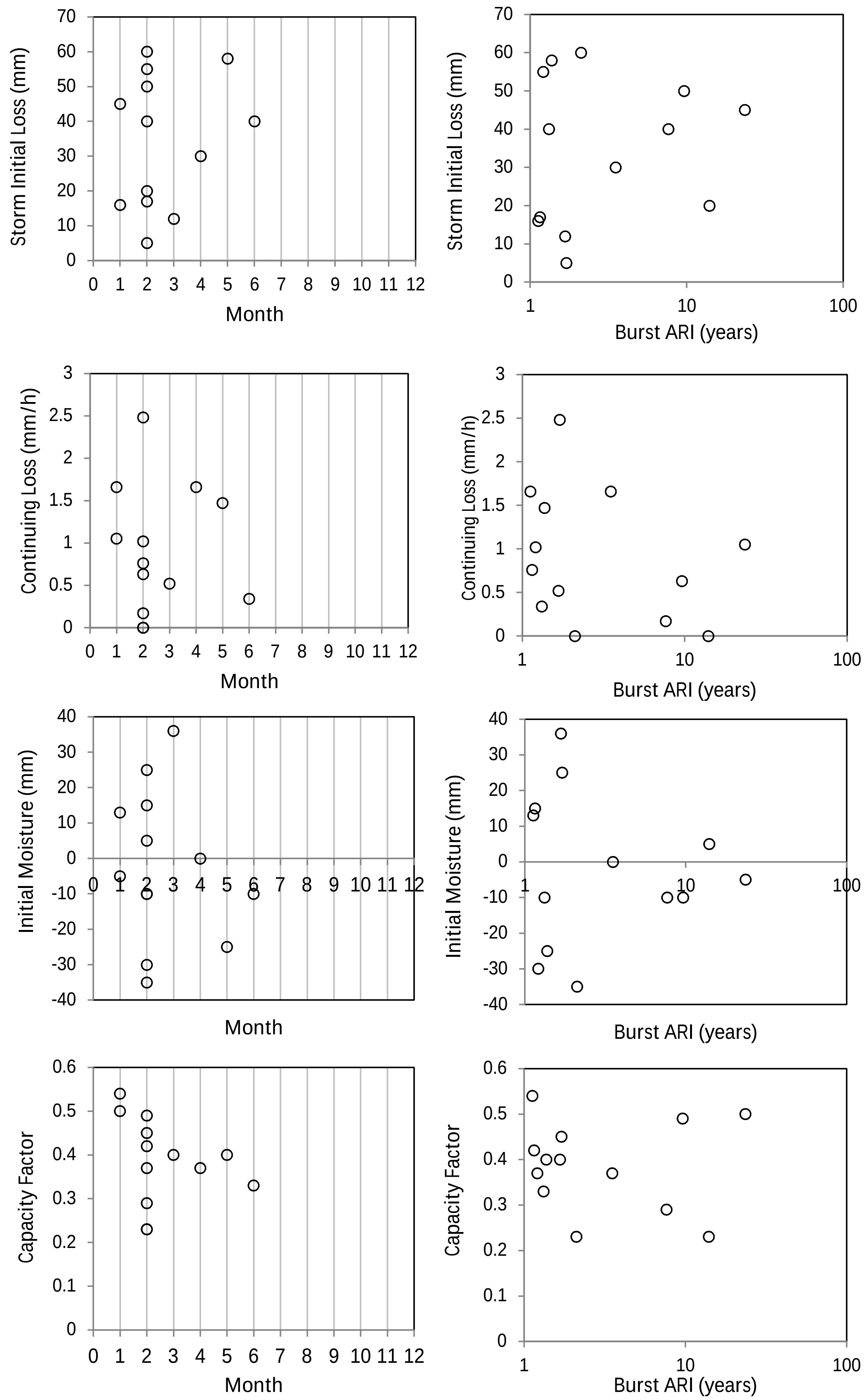




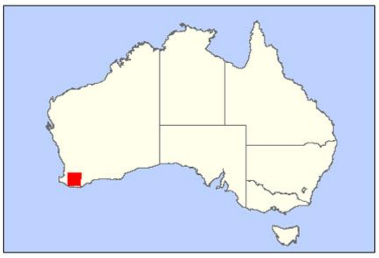


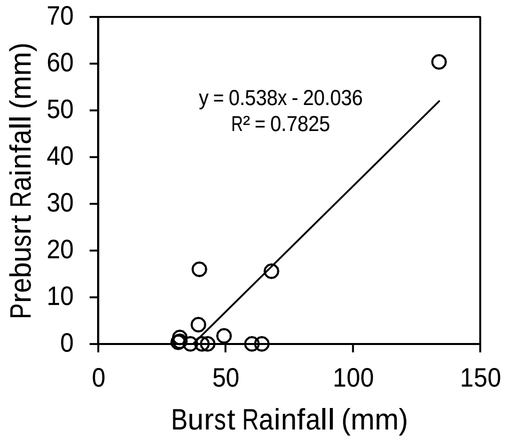


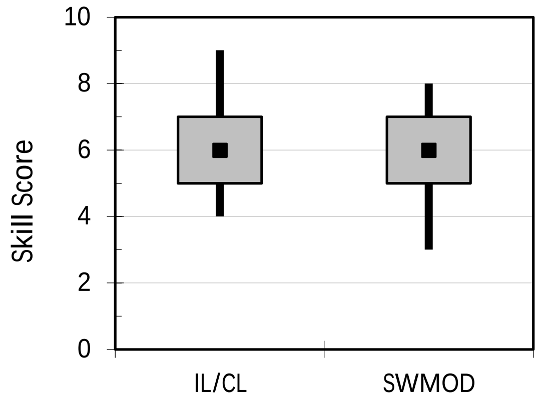
Kanjenjie Ck Trib. @ Fish Pool (WA) - 24 hour bursts

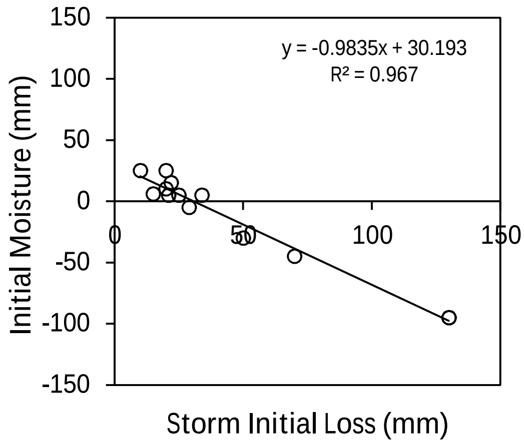


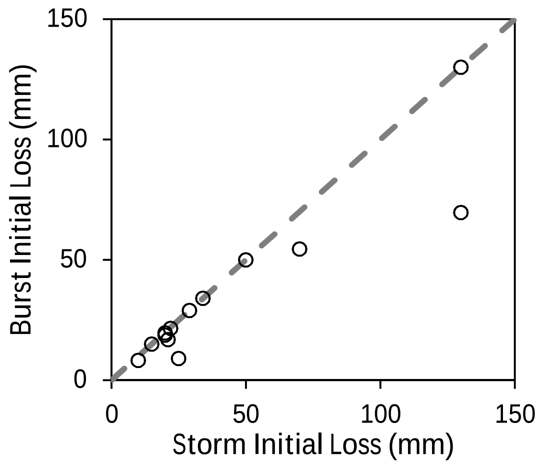
Balgarup @ Mandelup Pool (WA) - 24 hour bursts

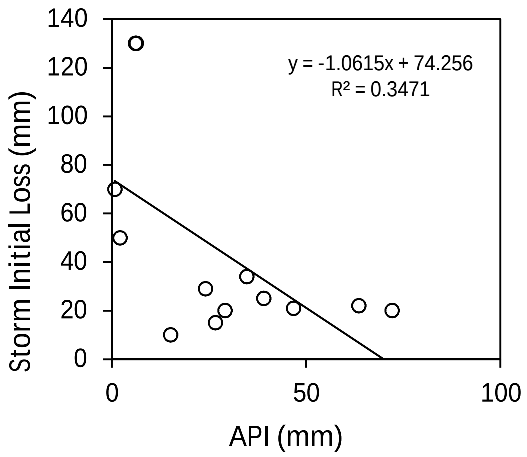


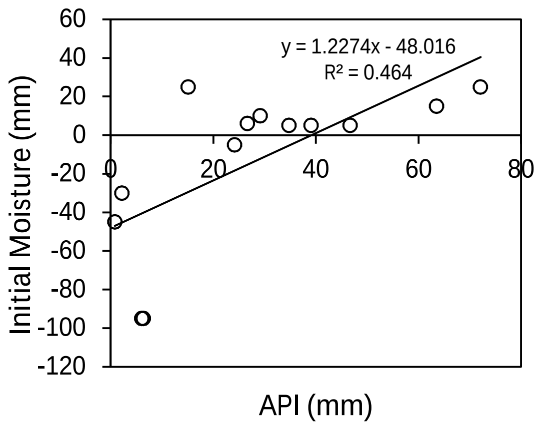




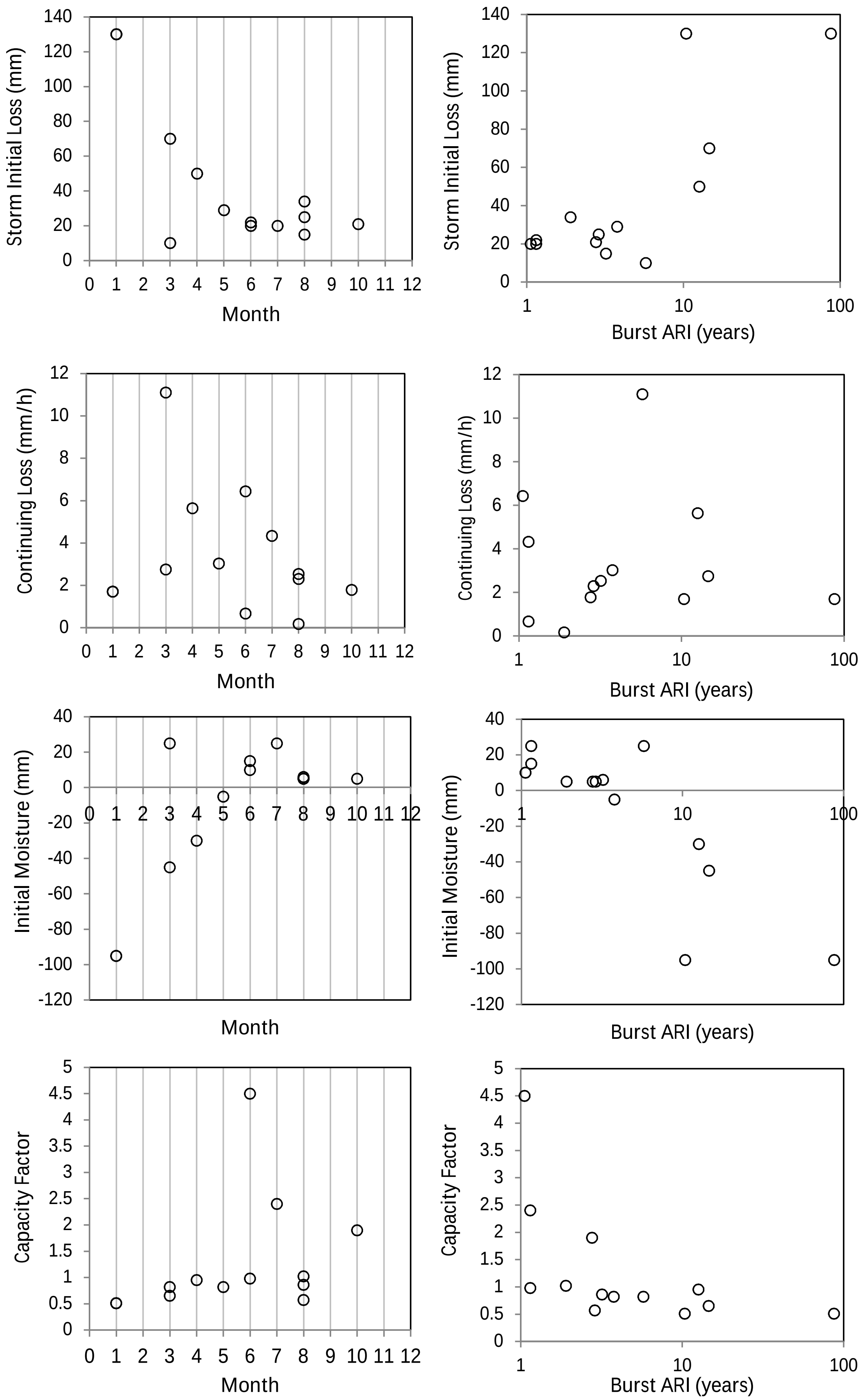




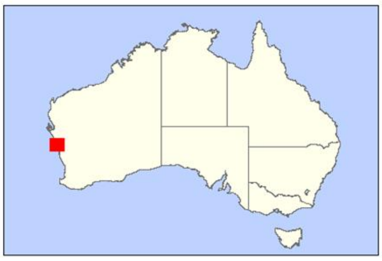


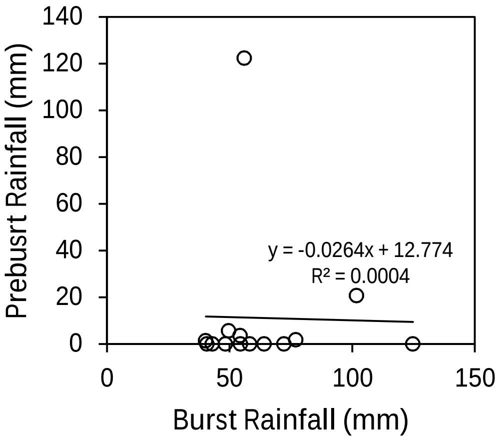


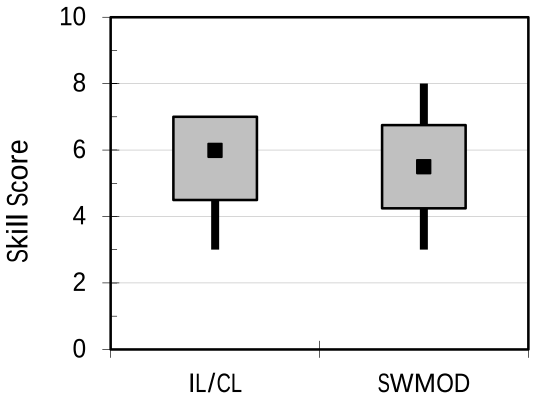
Balgarup @ Mandelup Pool (WA) - 24 hour bursts

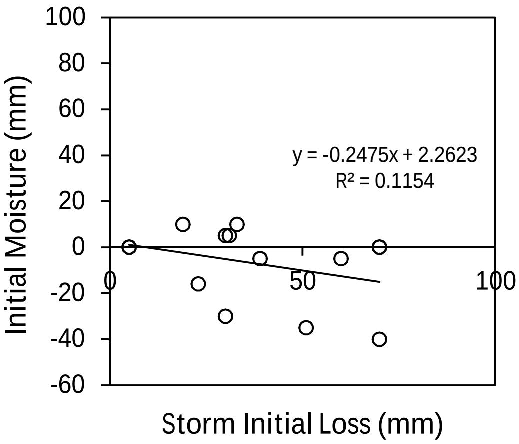


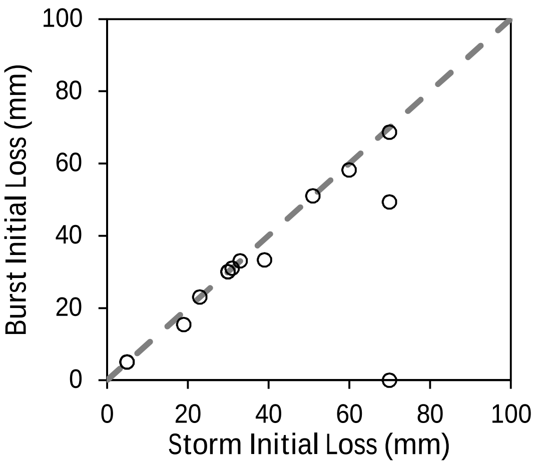
Buller @ Buller (WA) - 24 hour bursts

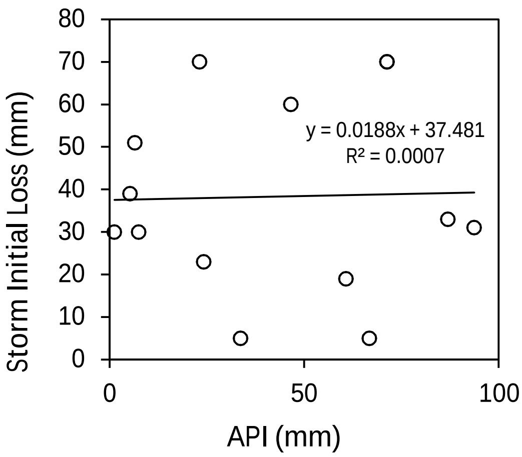


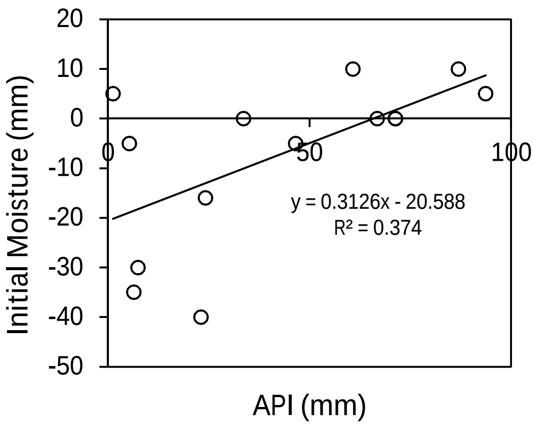




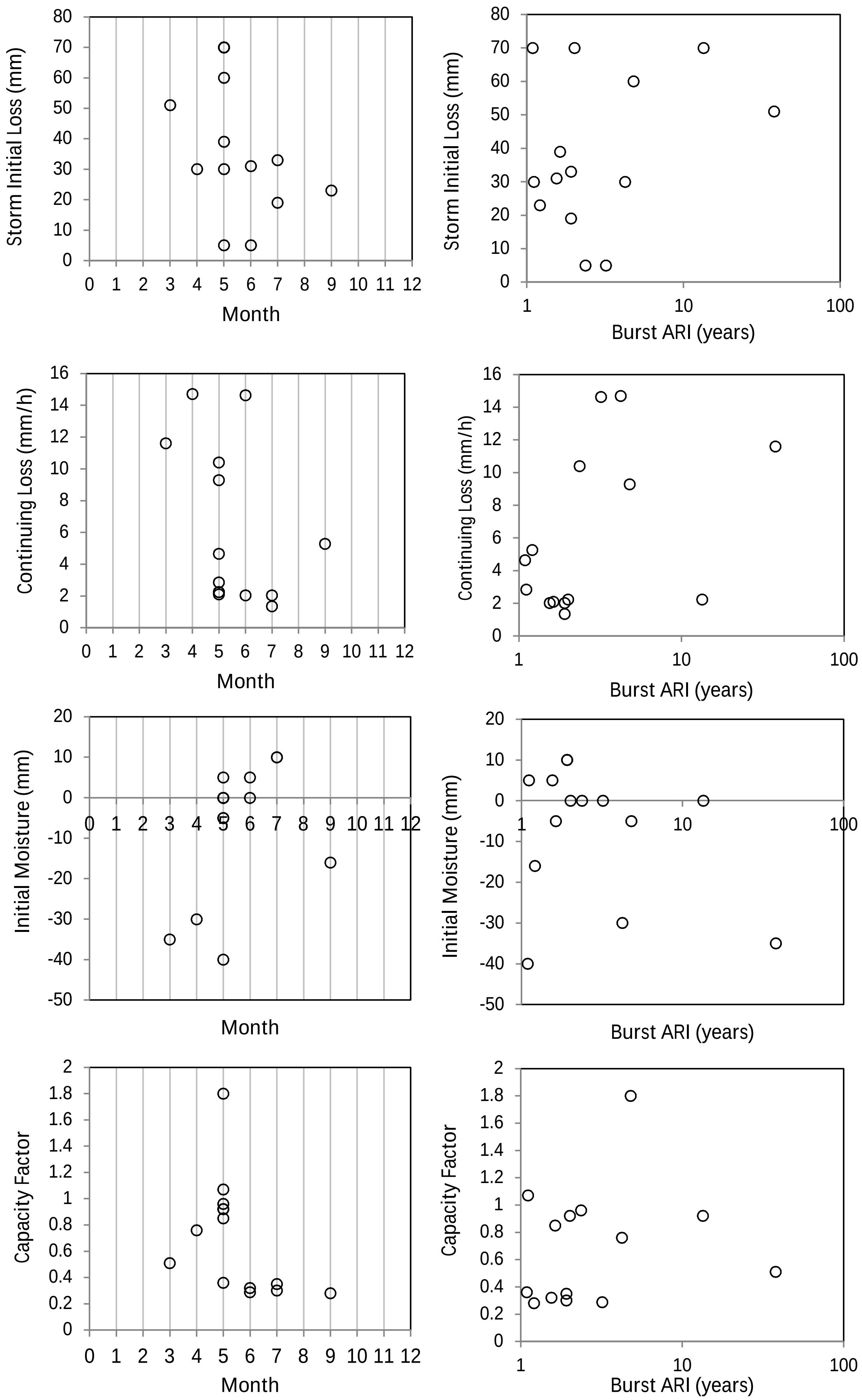




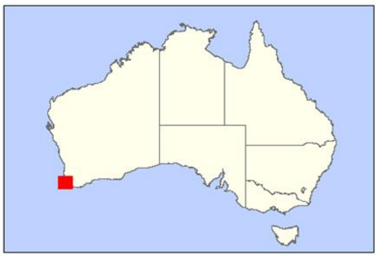


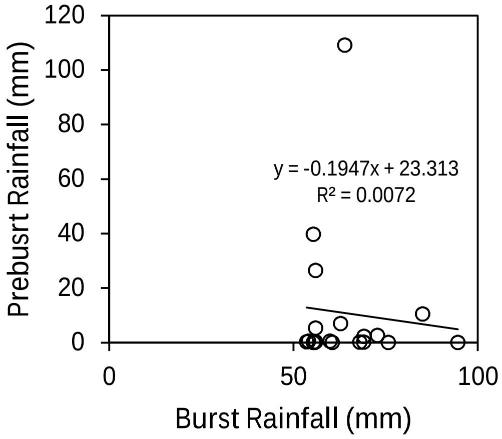


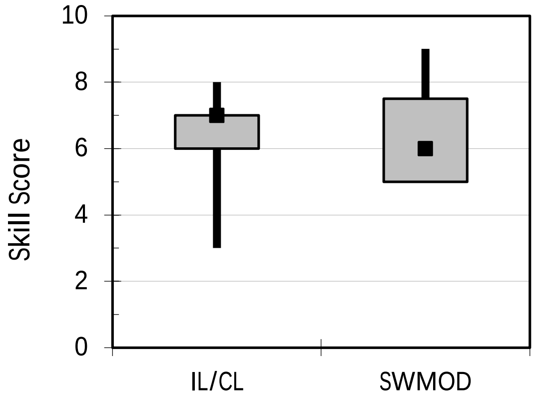
Buller @ Buller (WA) - 24 hour bursts

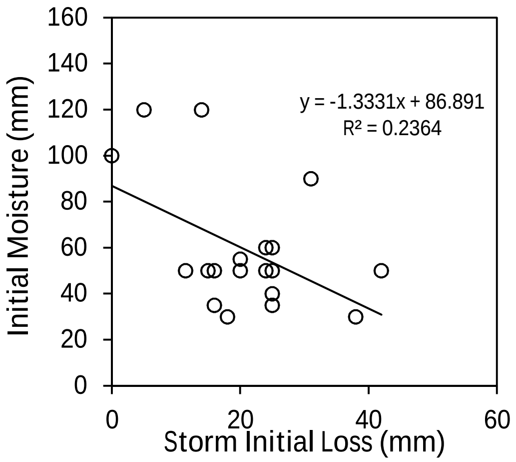


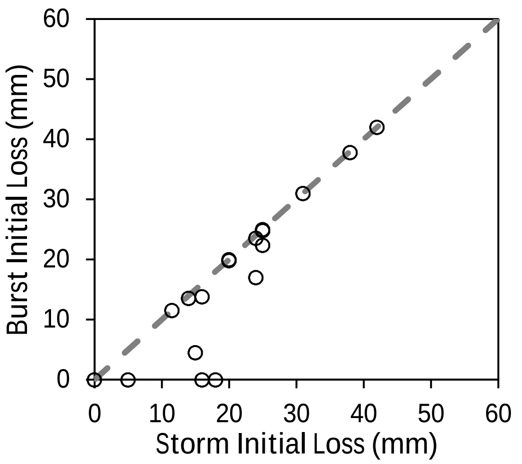
Carey Brook @ Staircase Rd (WA) - 24 hour bursts

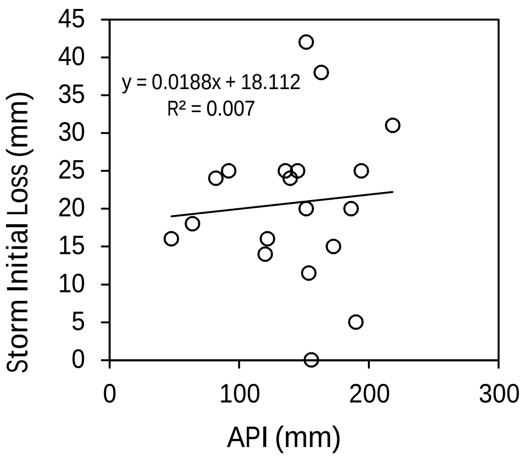


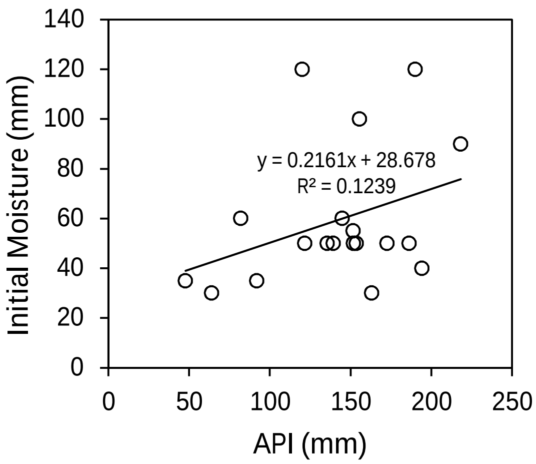




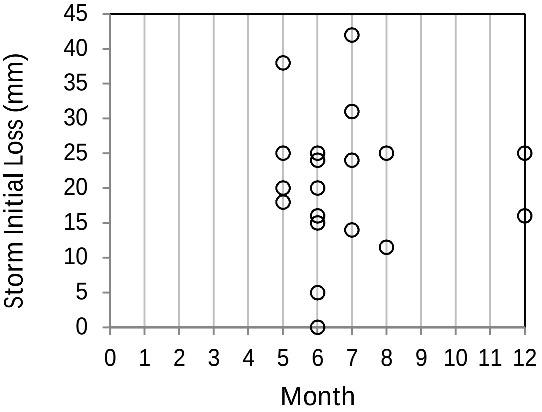


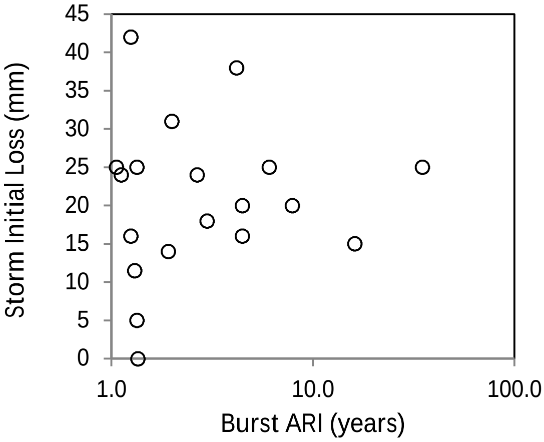


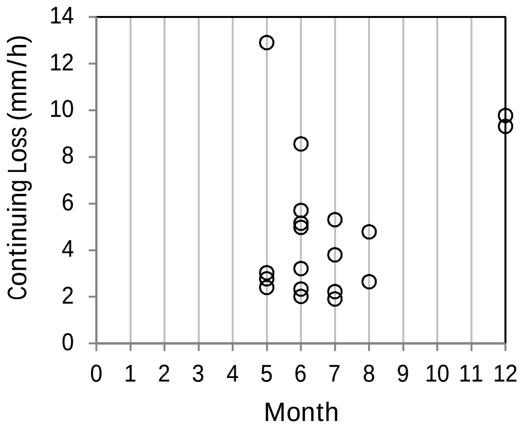


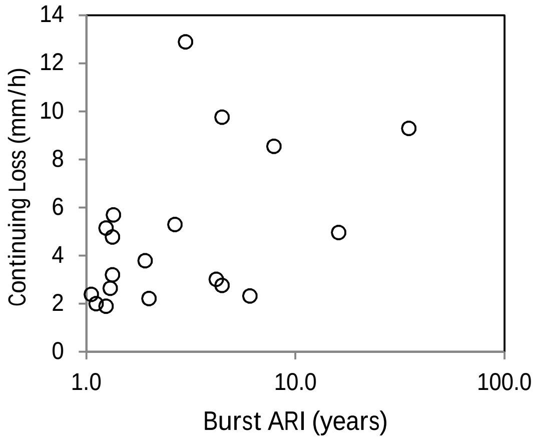


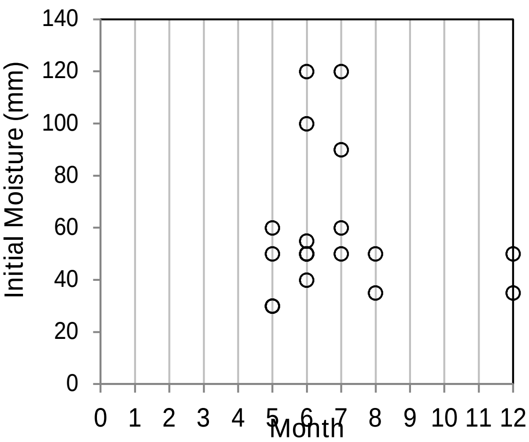
Carey Brook @ Staircase Rd (WA) - 24 hour bursts

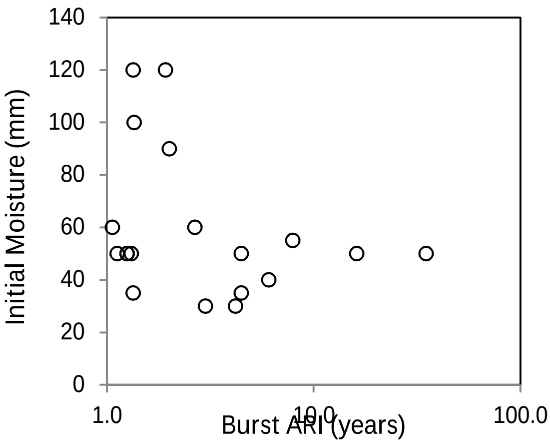


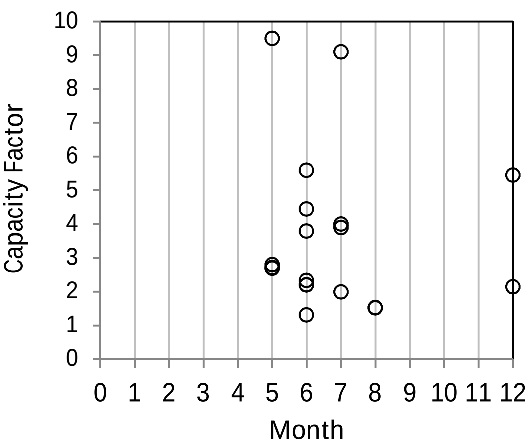


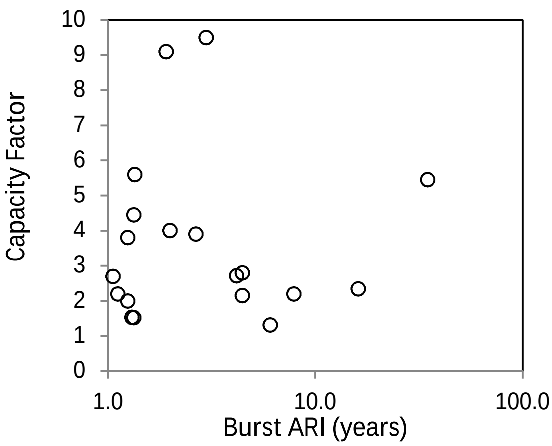




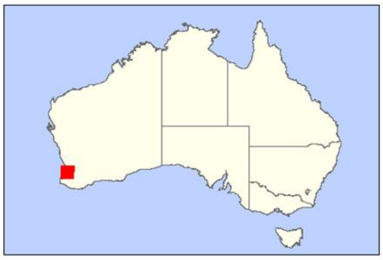


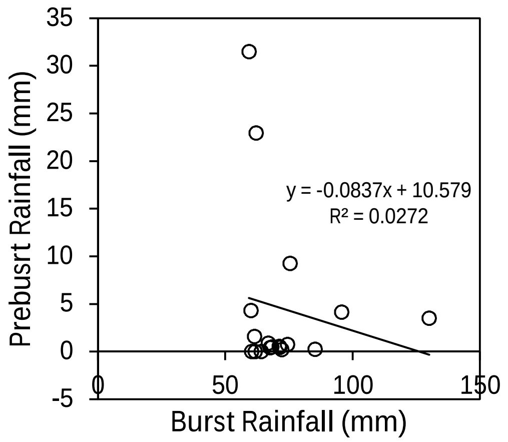


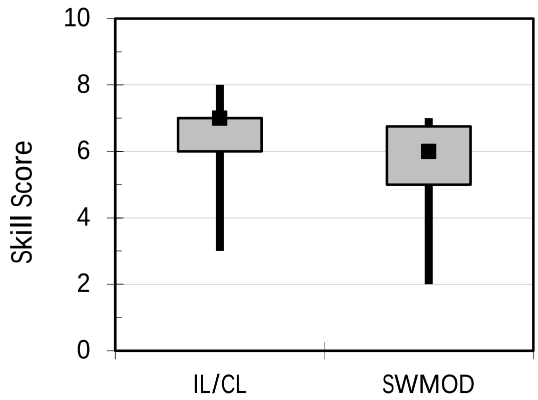


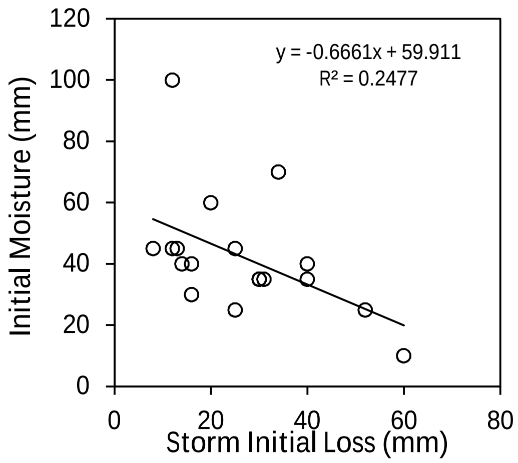


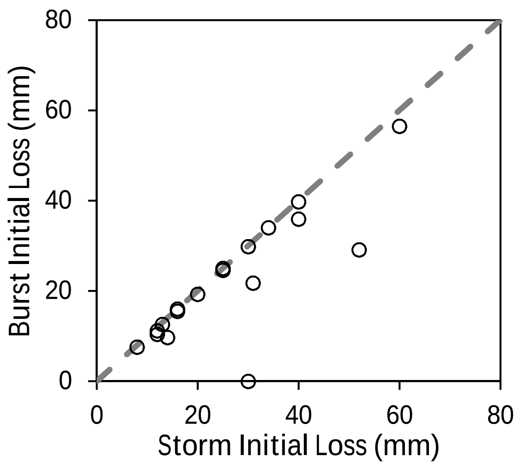
Davis Brook @ Murray Valley Plntn (WA) - 24 hour bursts

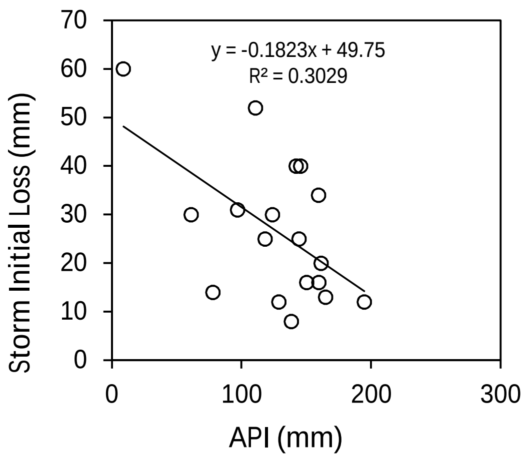


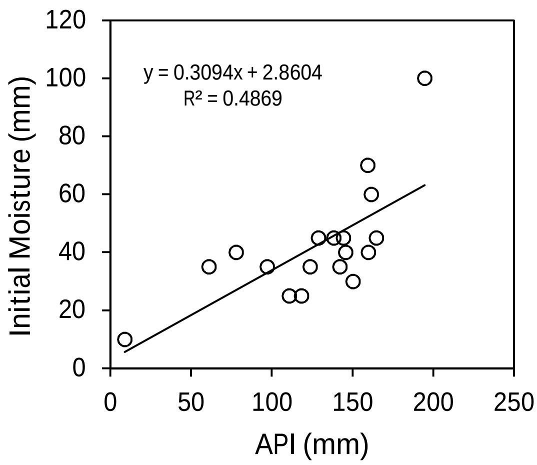




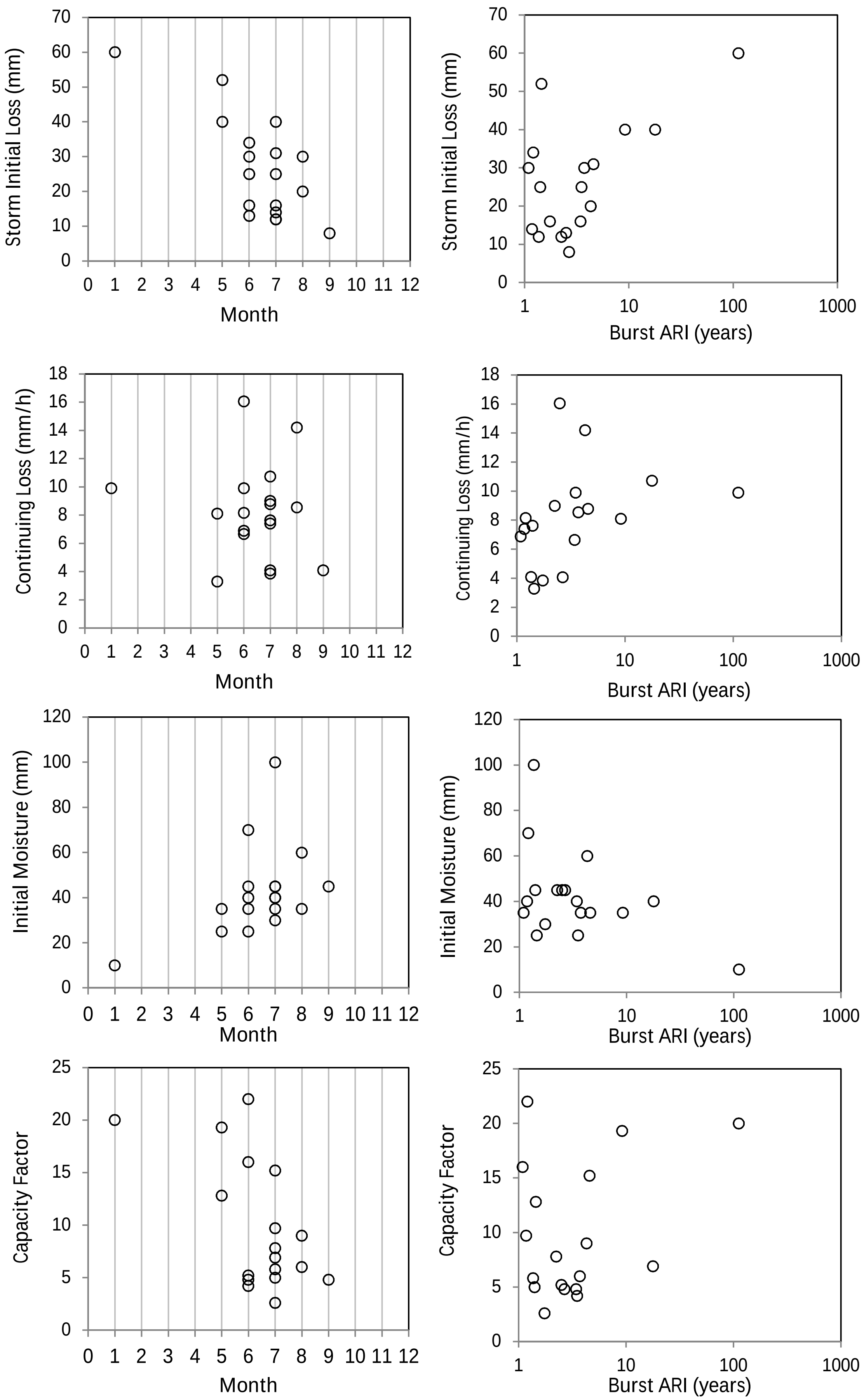




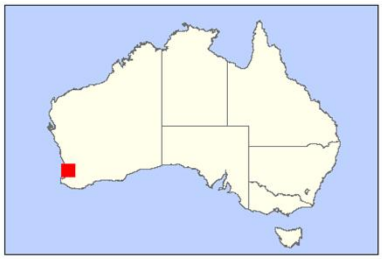


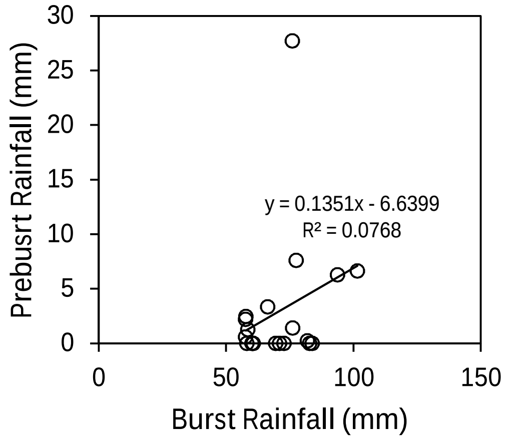


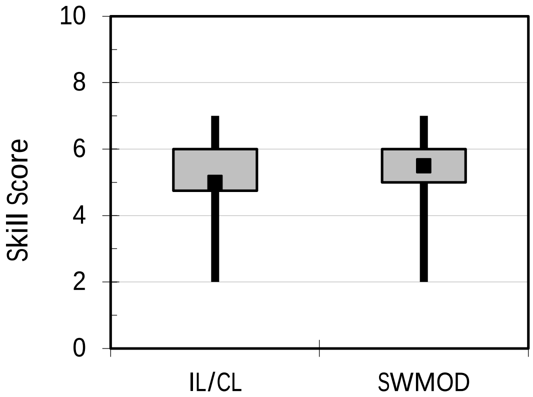
Davis Brook @ Murray Valley Plntn (WA) - 24 hour bursts

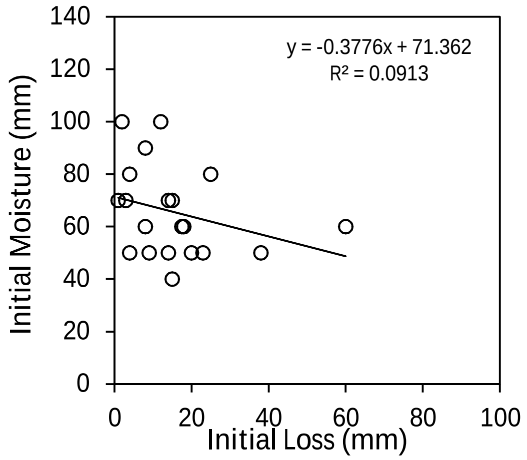


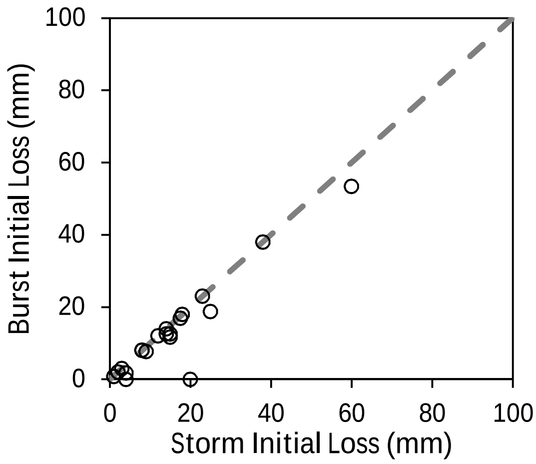
Dirk Brook @ Kentish Farm (WA) - 24 hour bursts

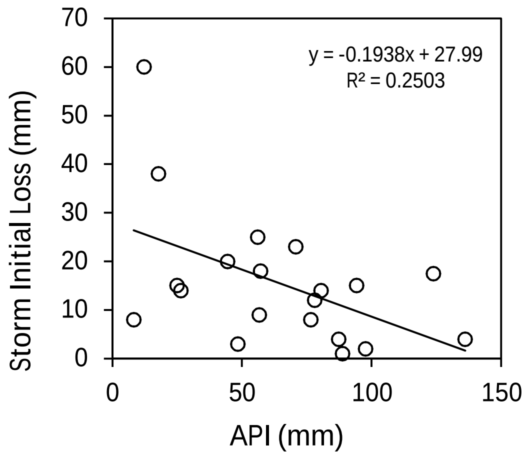


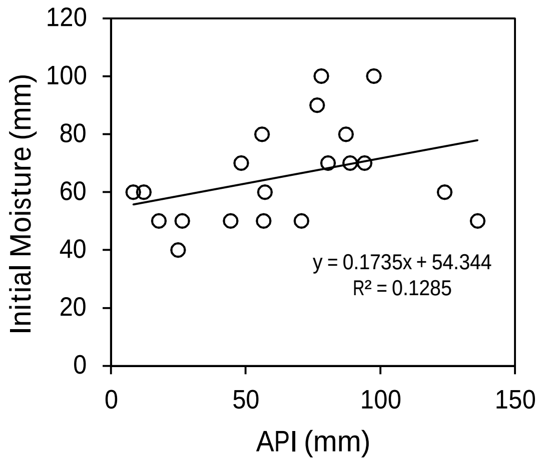




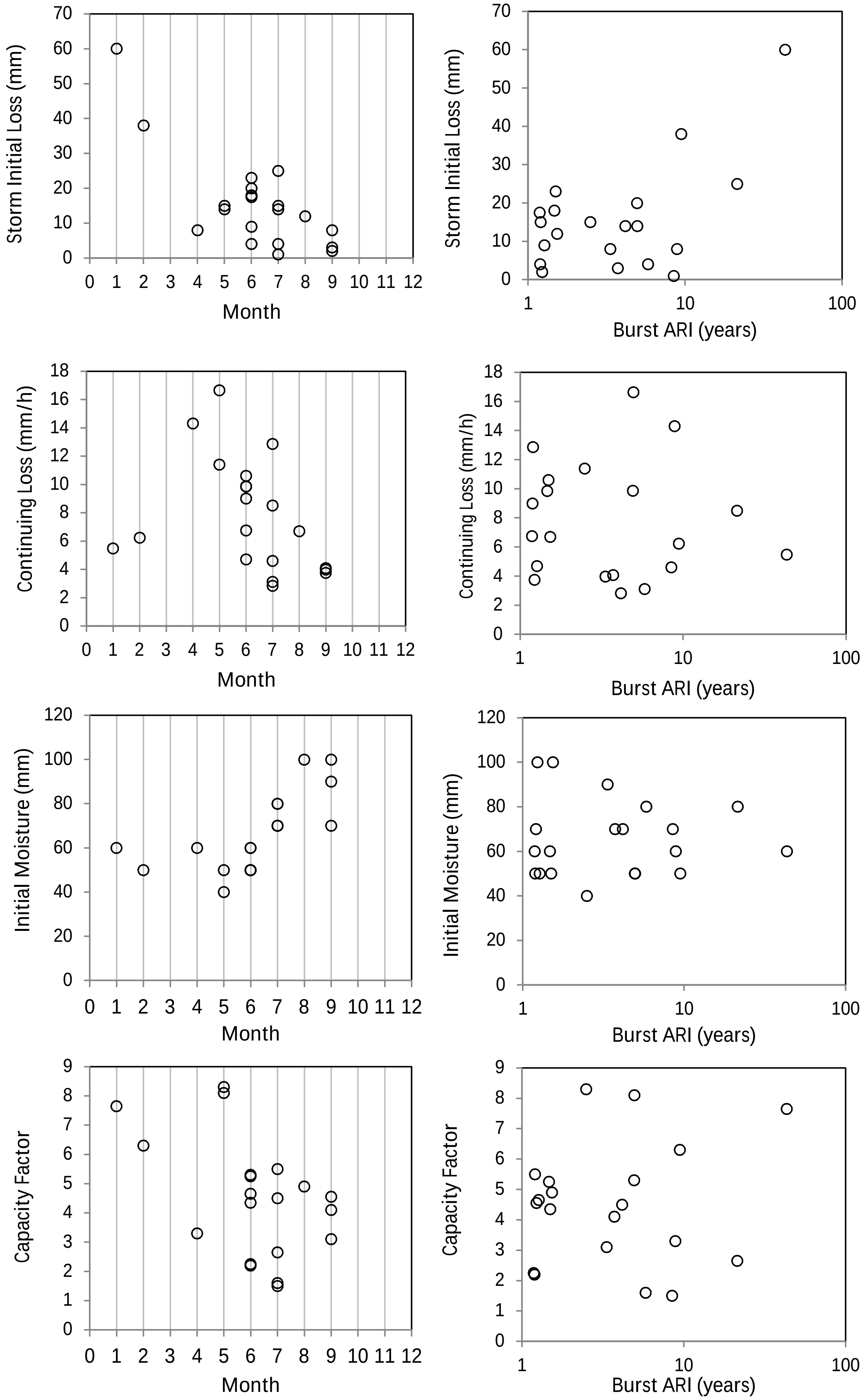




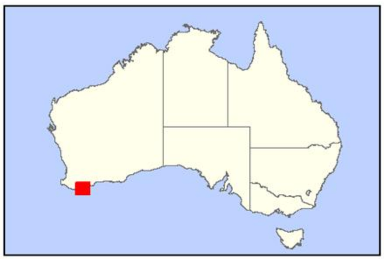


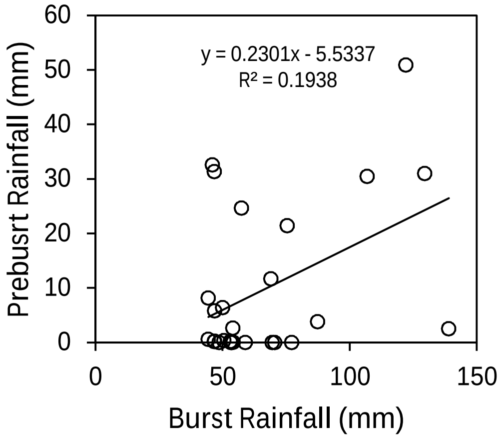


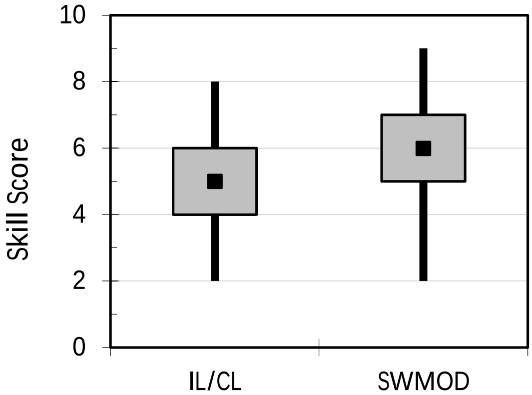
Dirk Brook @ Kentish Farm (WA) - 24 hour bursts

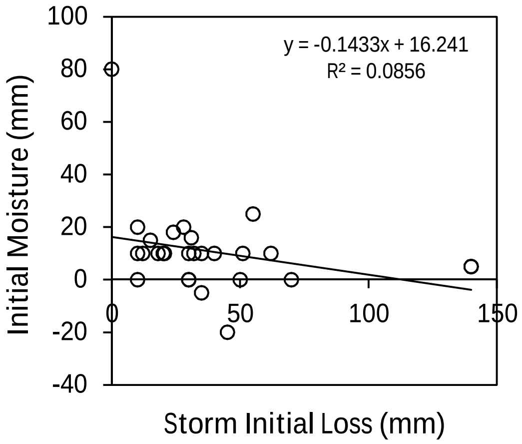


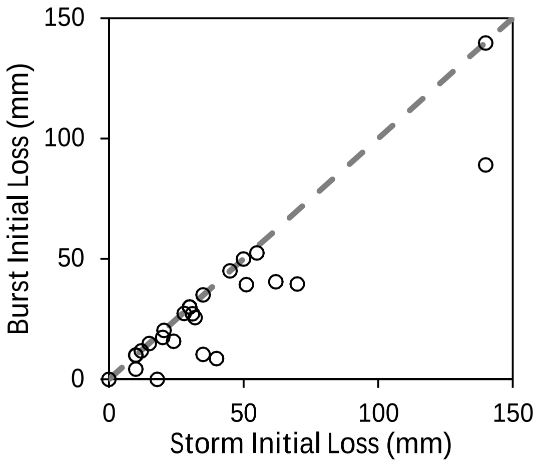
Goodga @ Black Cat (WA) - 24 hour bursts

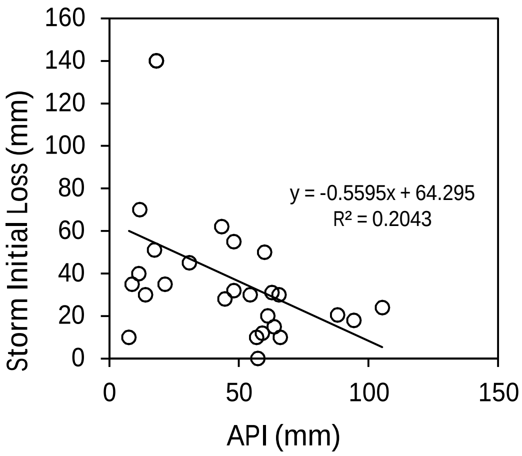


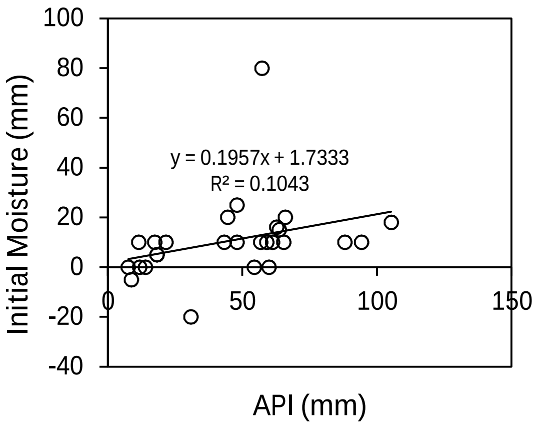




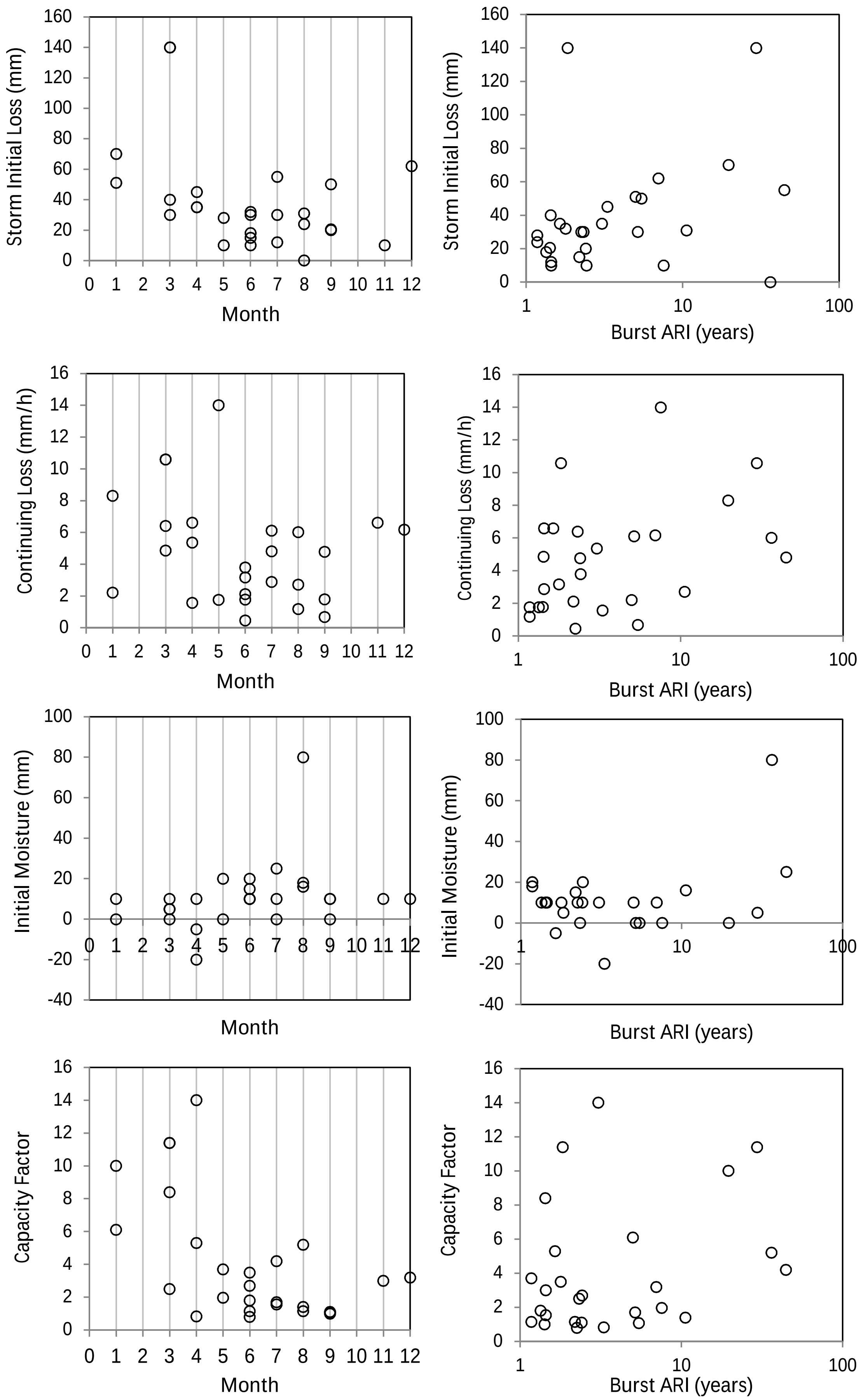




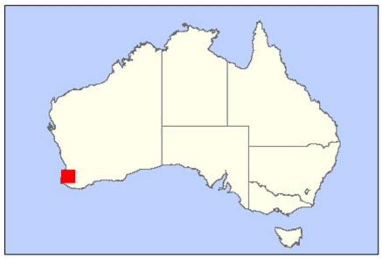


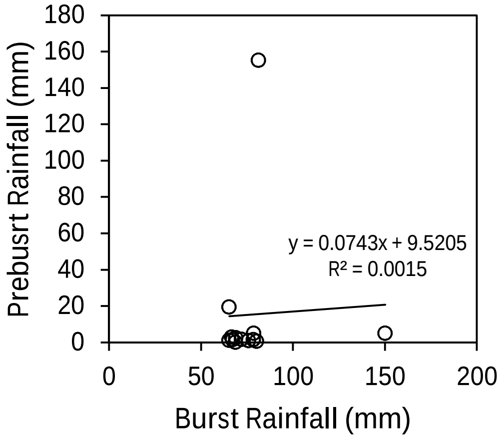


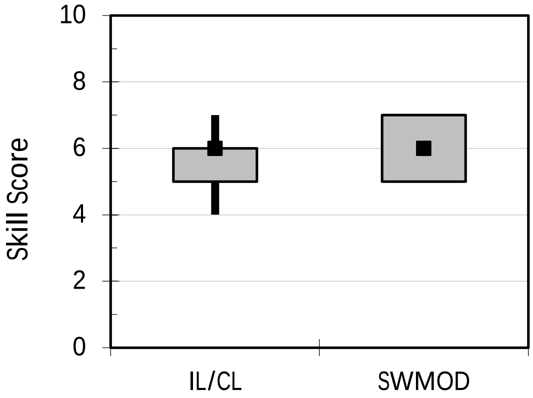
Goodga @ Black Cat (WA) - 24 hour bursts

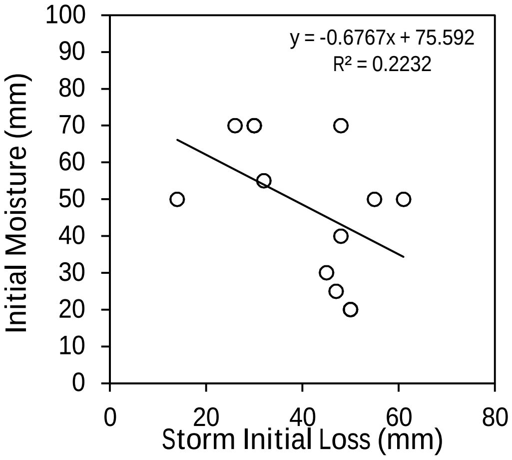


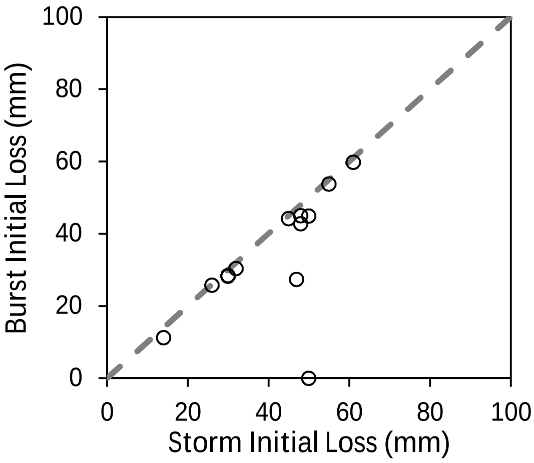
Hamilton @ Worsley (WA) - 24 hour bursts

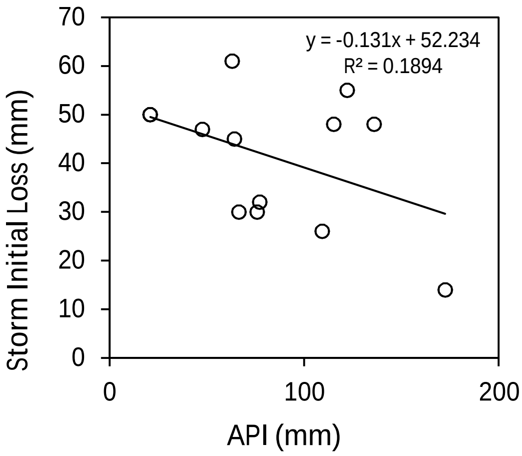


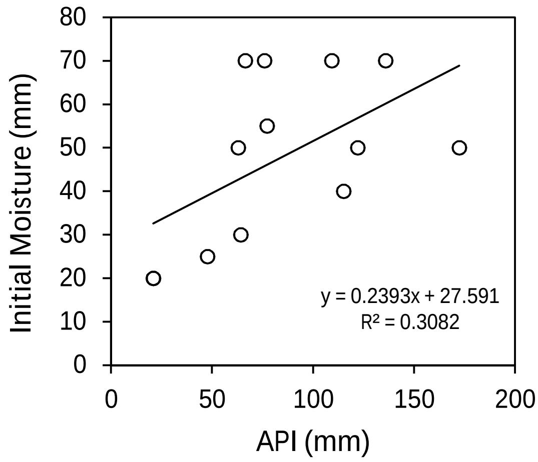




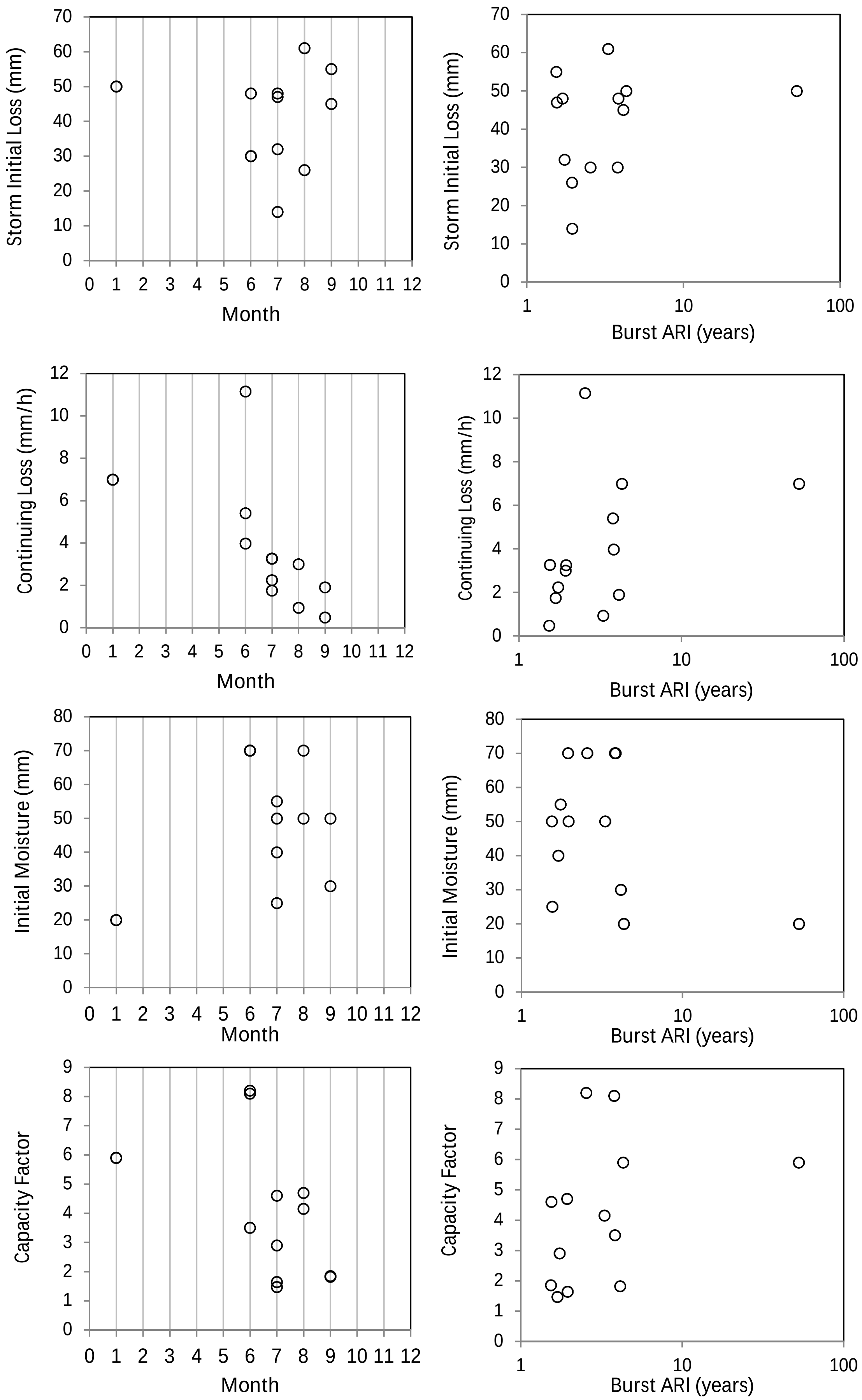




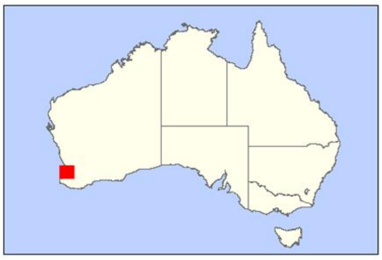


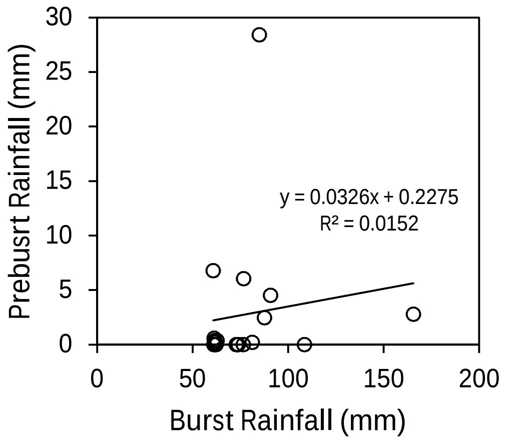


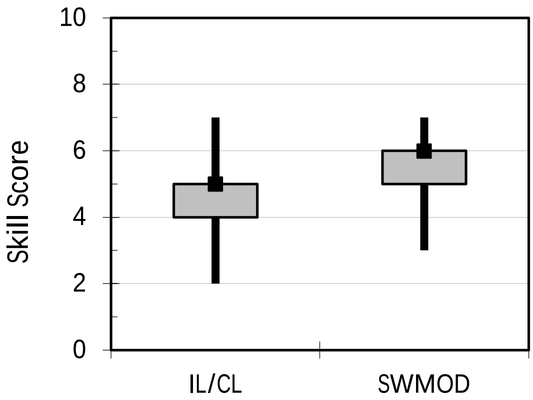
Hamilton @ Worsley (WA) - 24 hour bursts

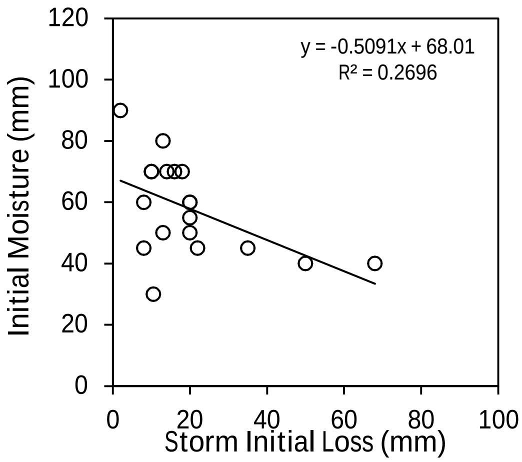


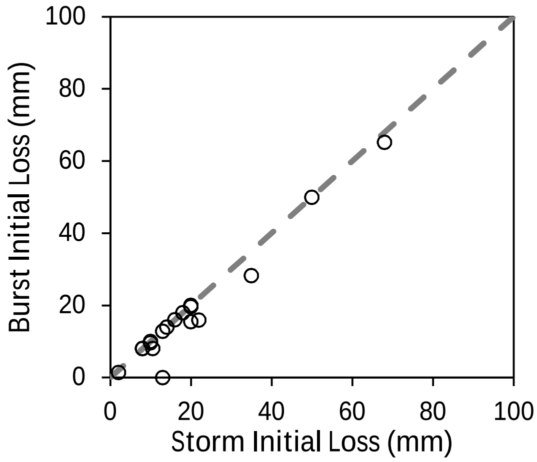
Marrinup Bk @ Brookdale Siding (WA) - 24 hour bursts

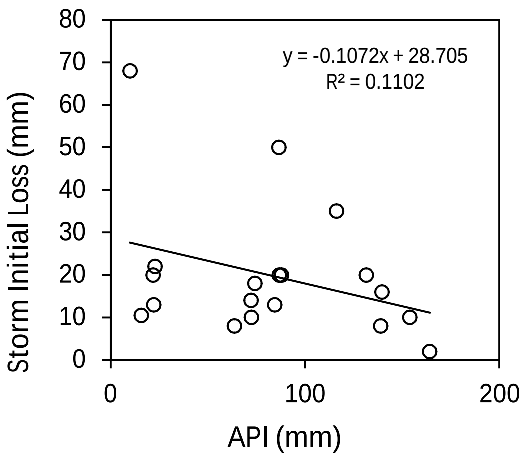


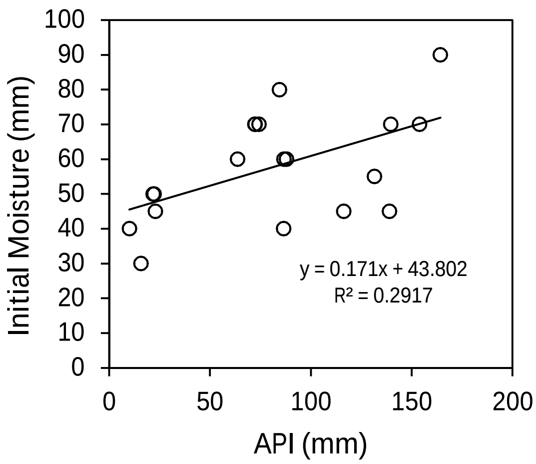




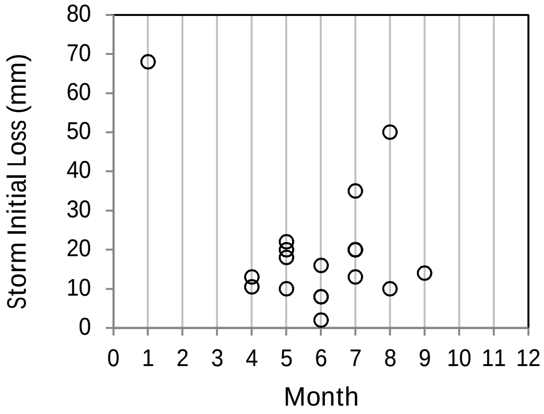


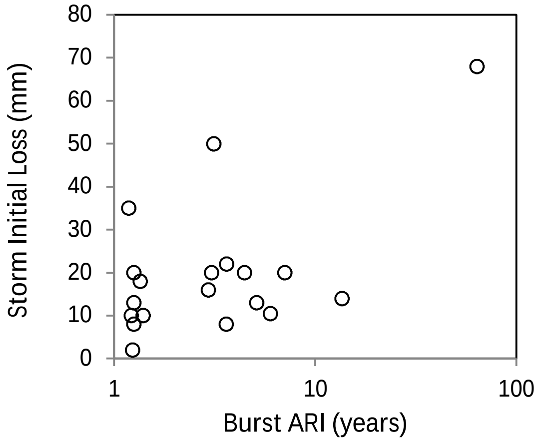


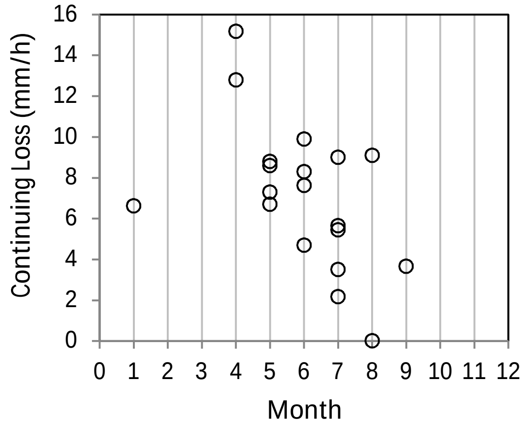


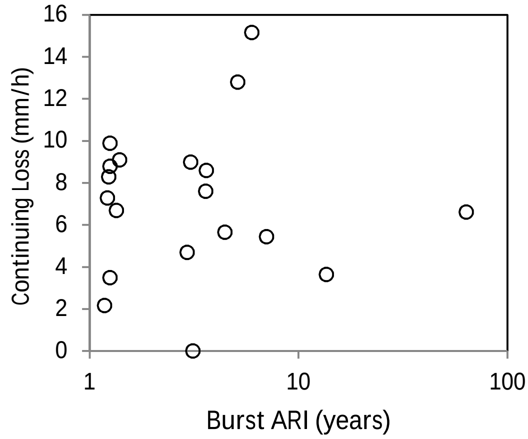


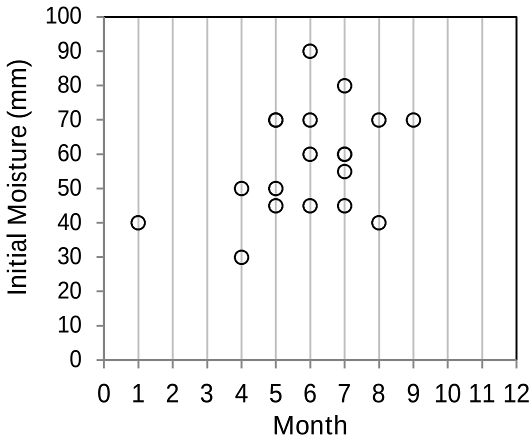
Marrinup Bk @ Brookdale Siding (WA) - 24 hour bursts

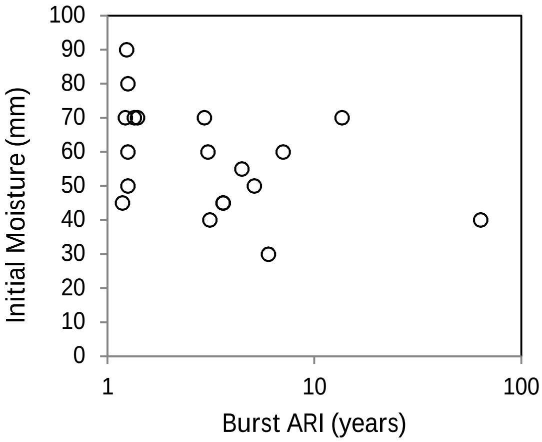


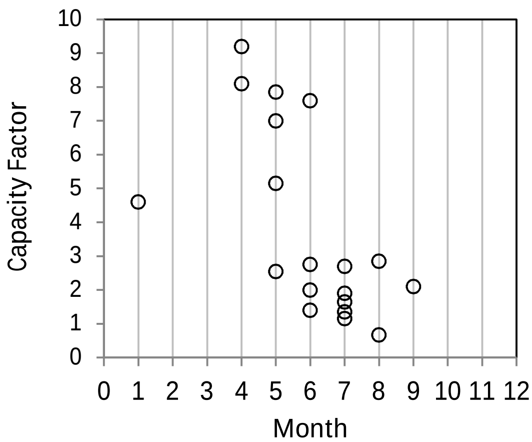


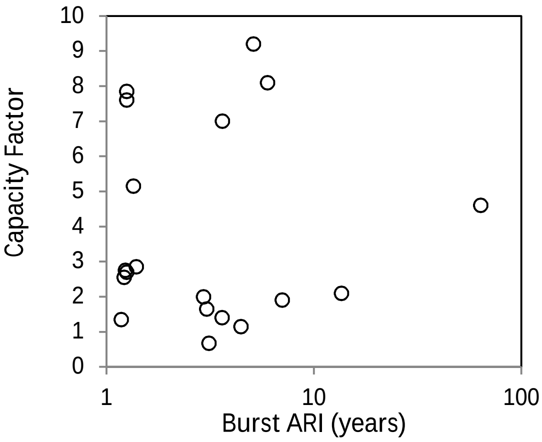




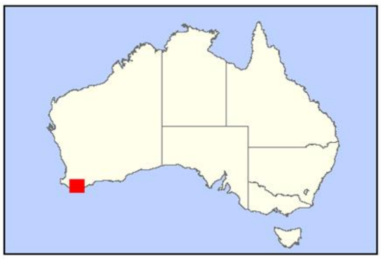


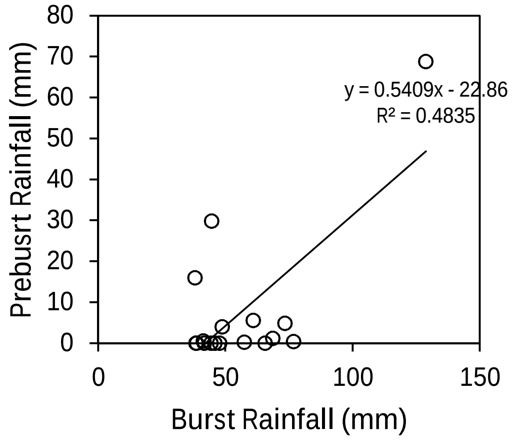


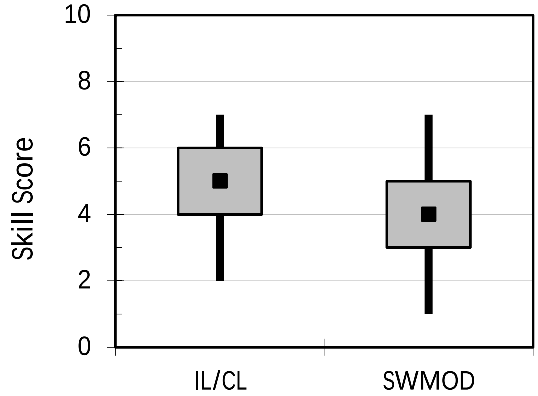


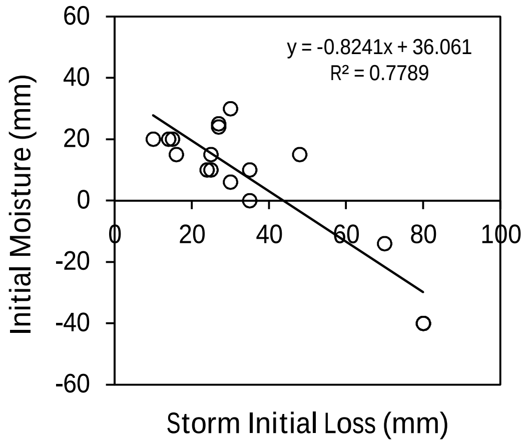


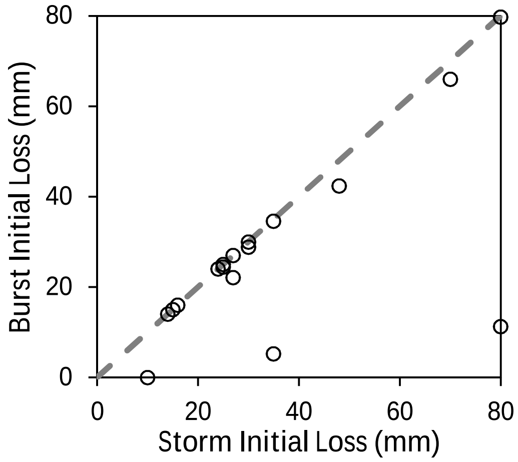
Yates Flat Ck @ Woonanup (WA) - 24 hour bursts

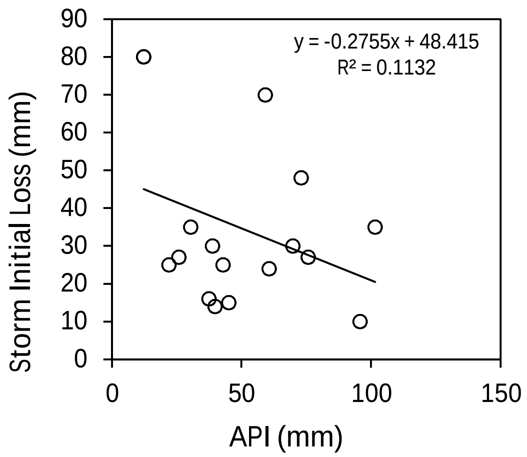


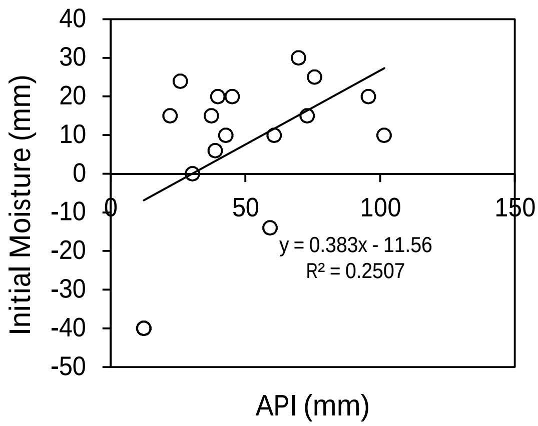




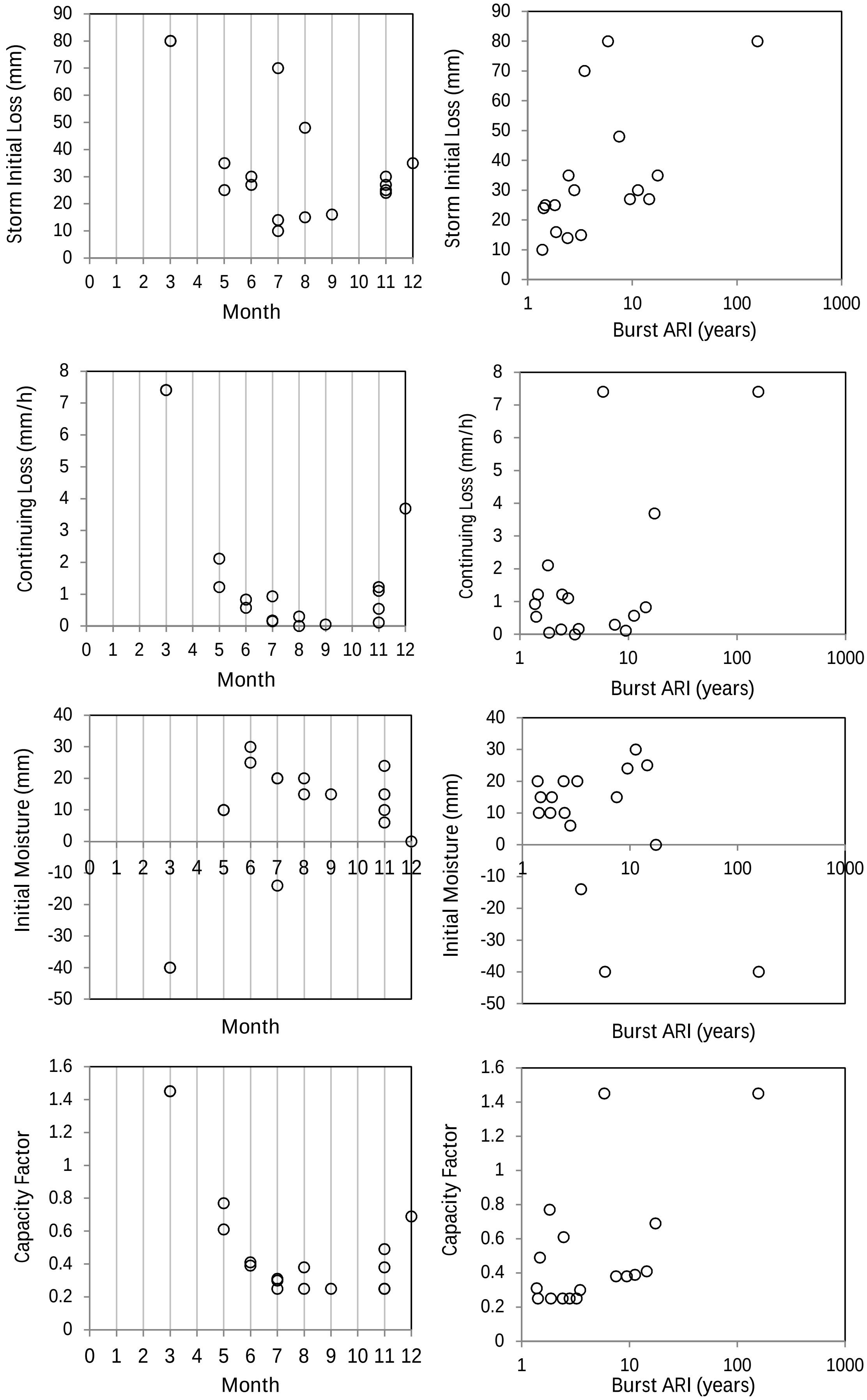






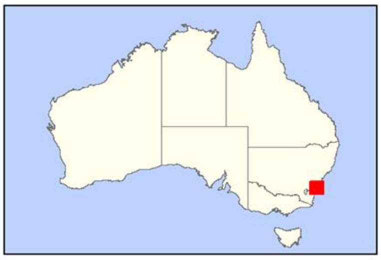


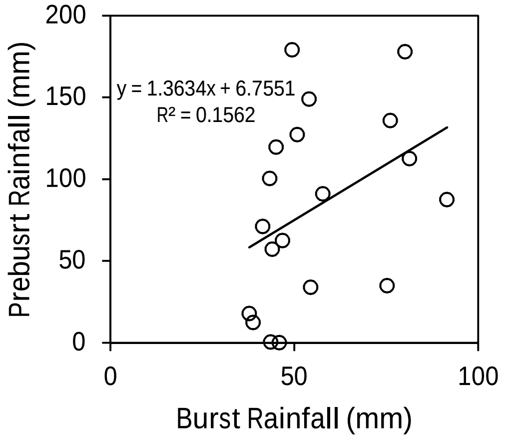
Yates Flat Ck @ Woonanup (WA) - 24 hour bursts

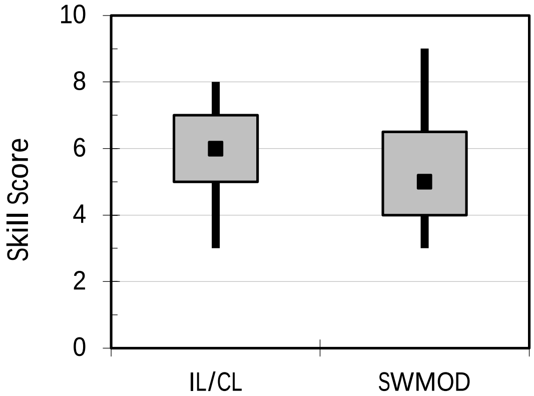


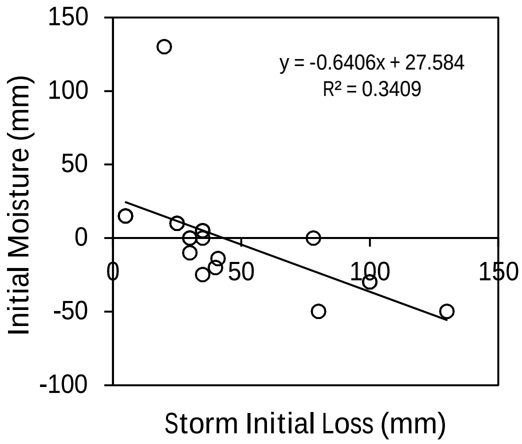
Appendix J Loss summaries for 3h bursts

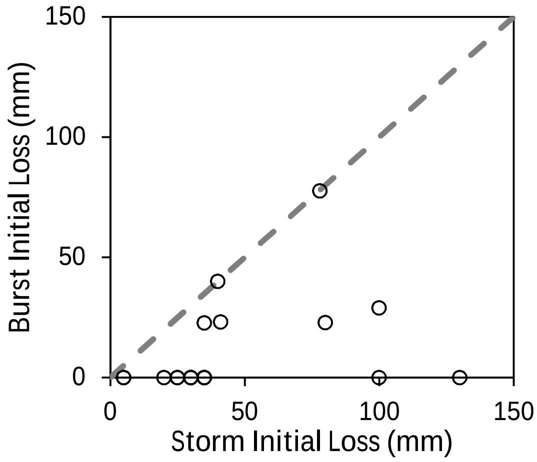
Currambene Ck @ Falls Ck (NSW) - 3 hour bursts

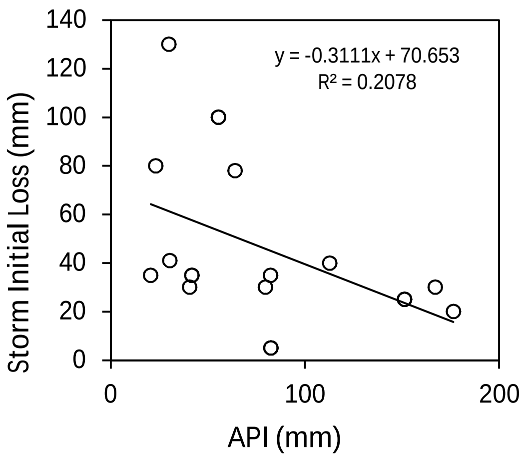


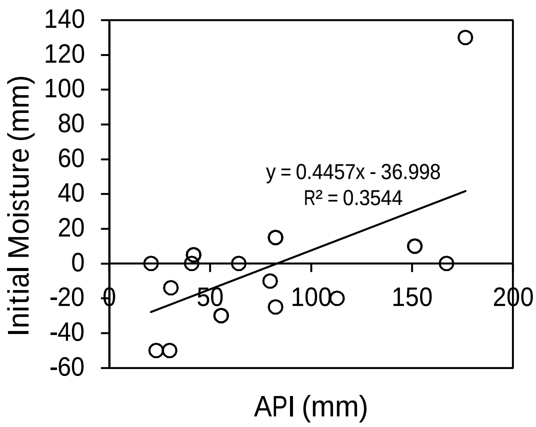




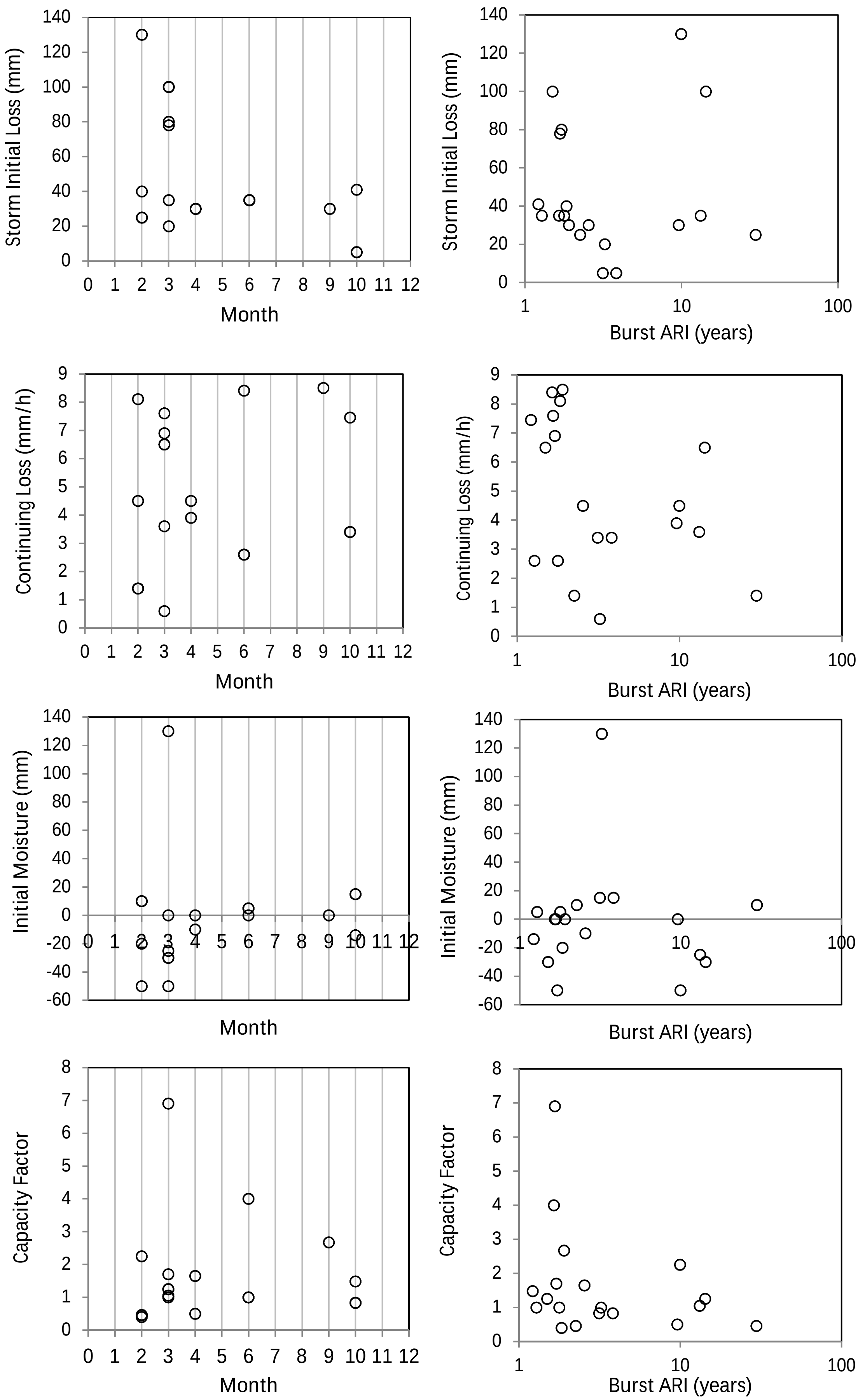




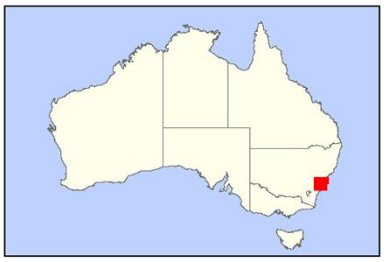


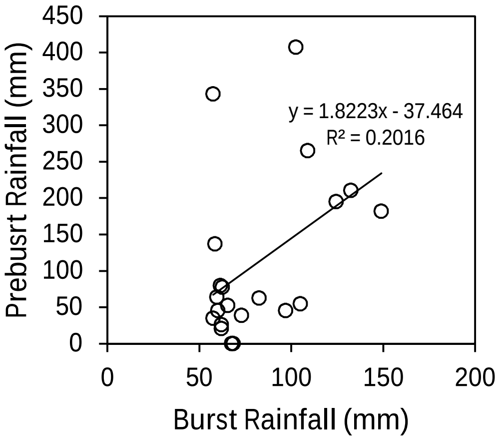


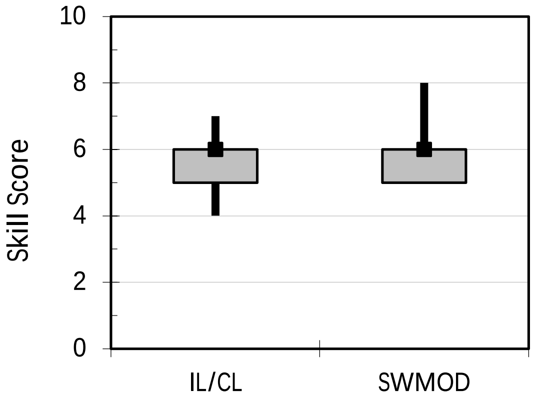
Currambene Ck @ Falls Ck (NSW) - 3 hour bursts

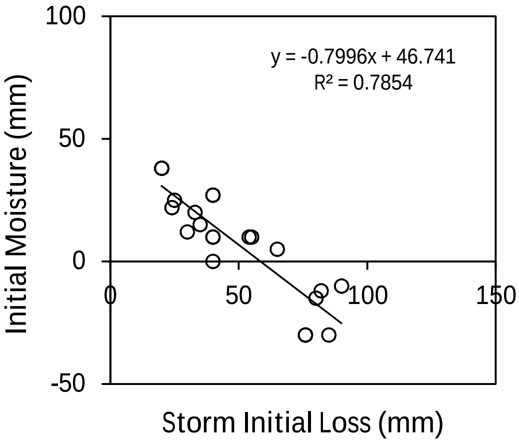


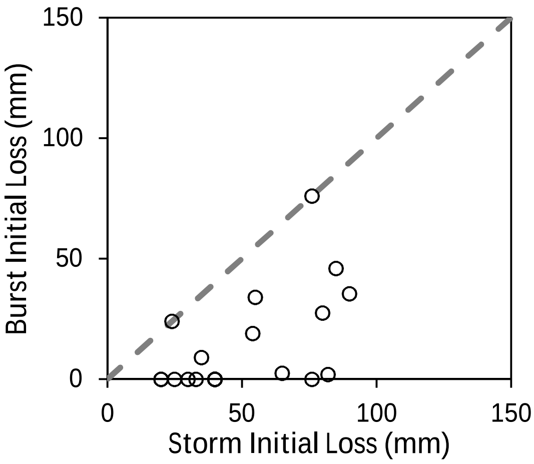
O'Hares Ck @ Wedderburn (NSW) - 3 hour bursts

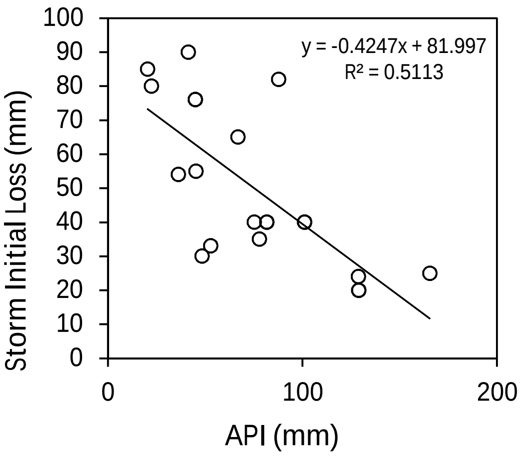


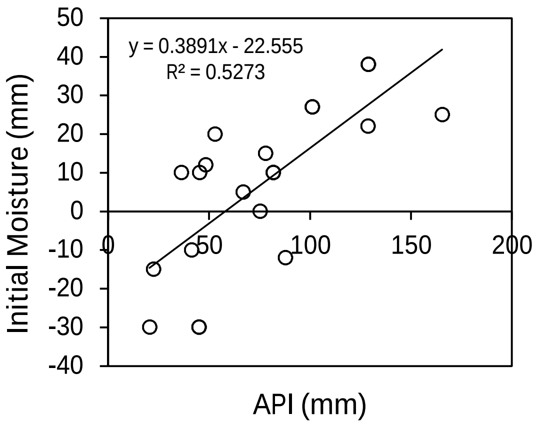




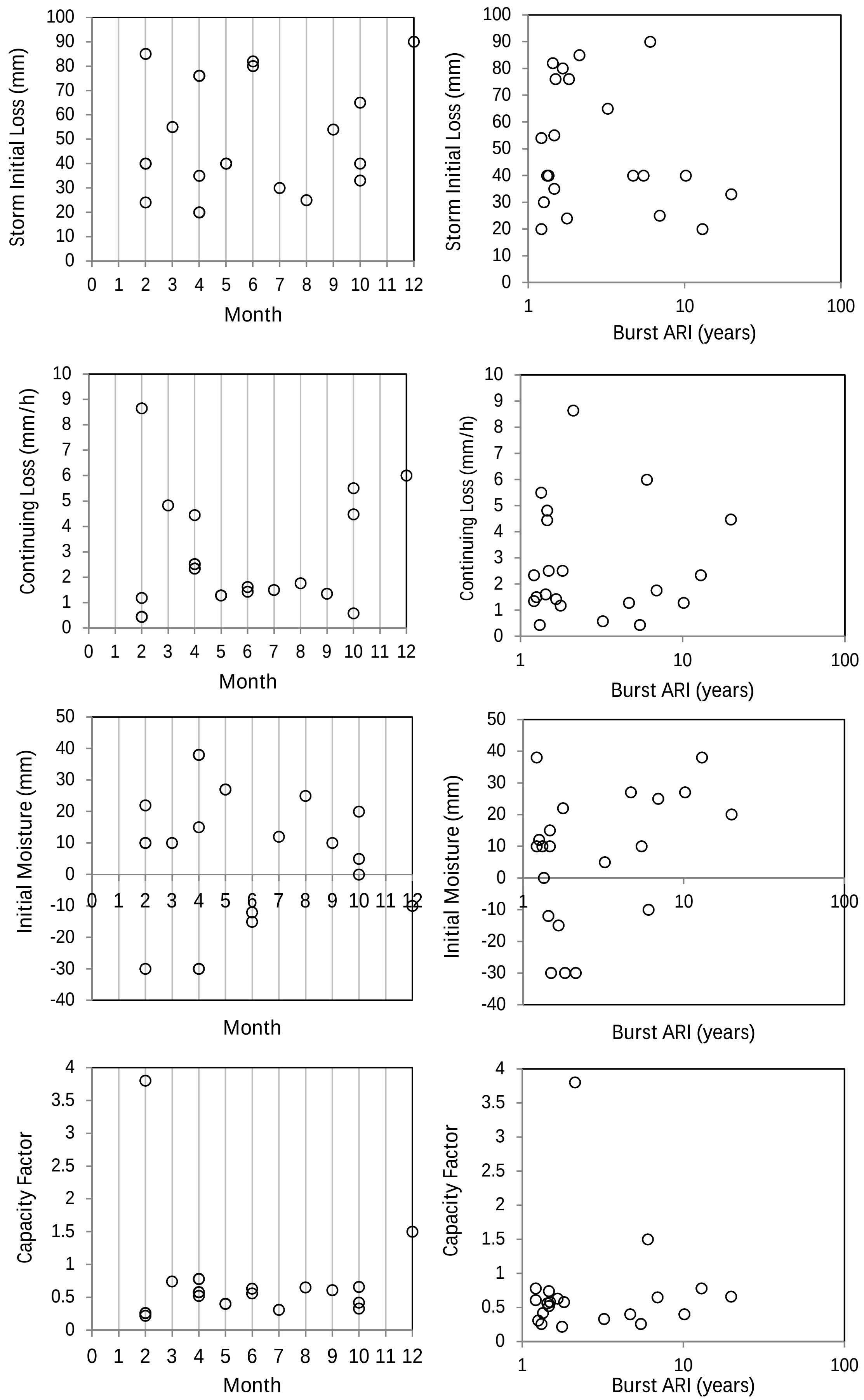




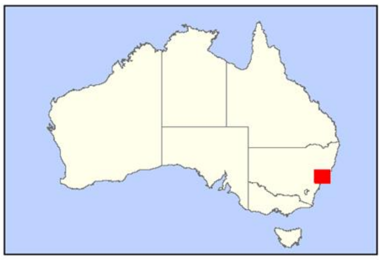


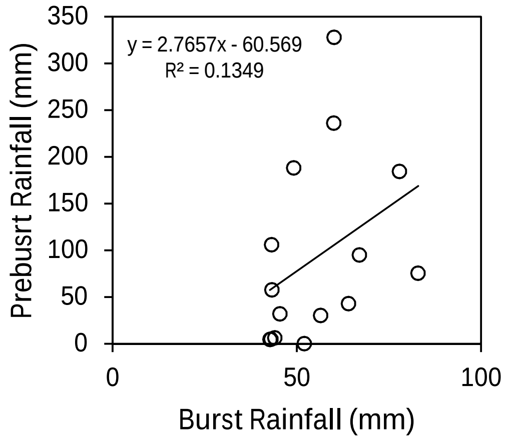


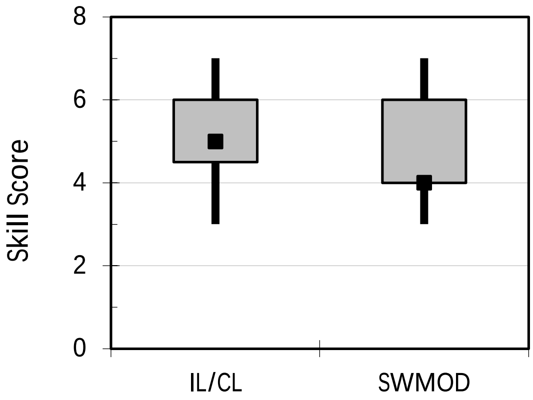
O'Hares Ck @ Wedderburn (NSW) - 3 hour bursts

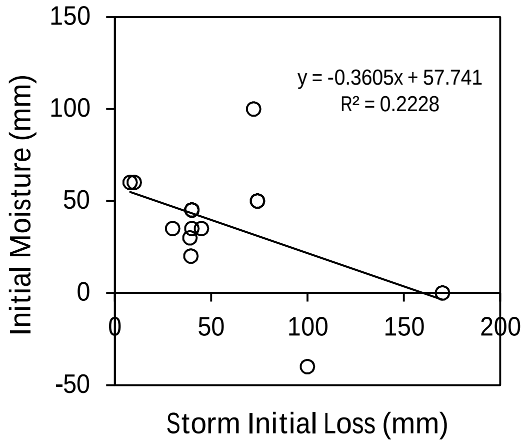


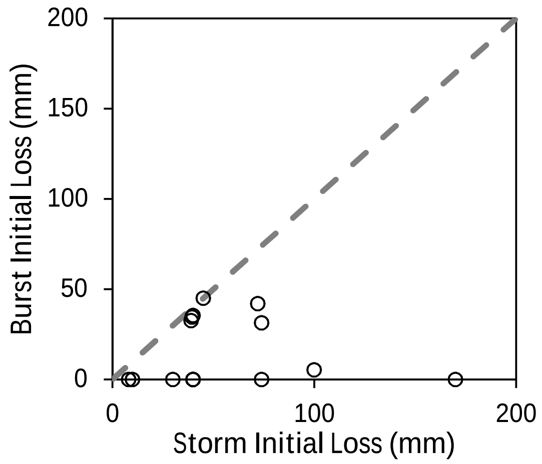
Ourimbah Ck @ U/S Weir (NSW) - 3 hour bursts

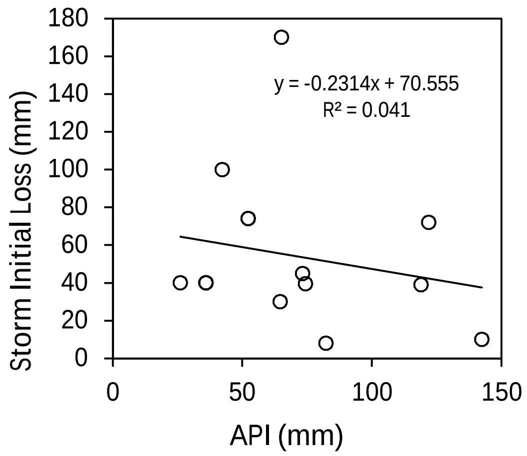


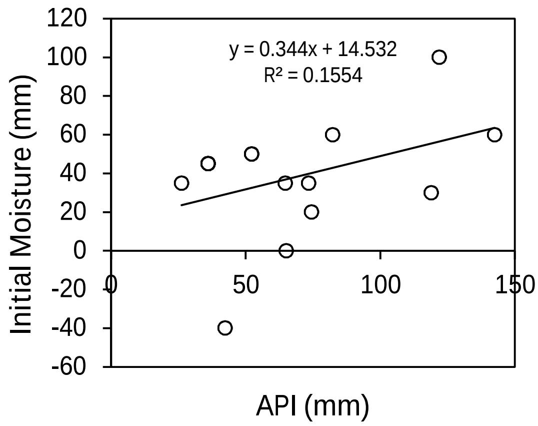




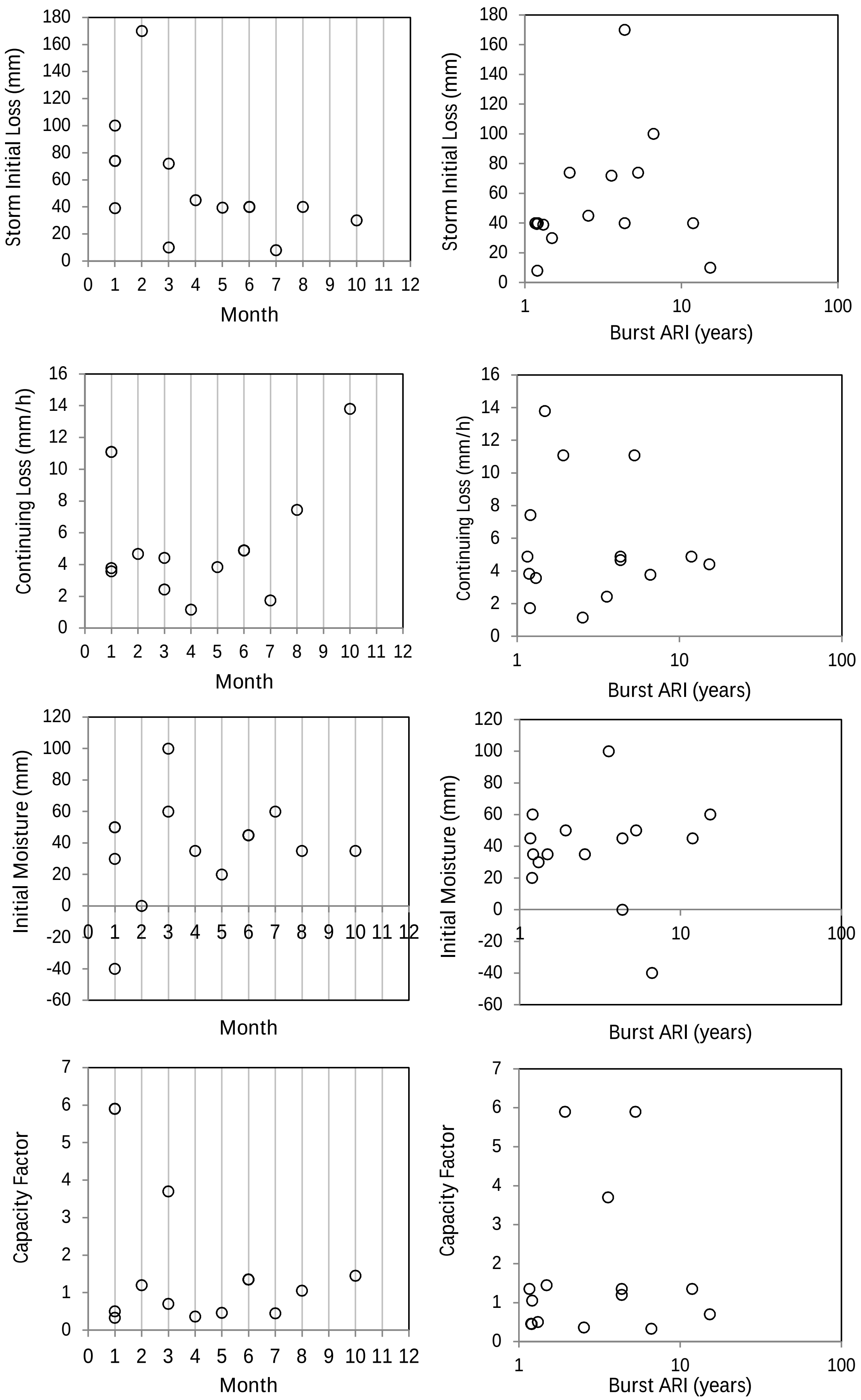




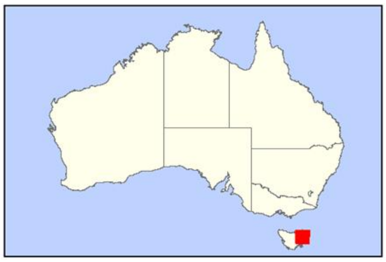


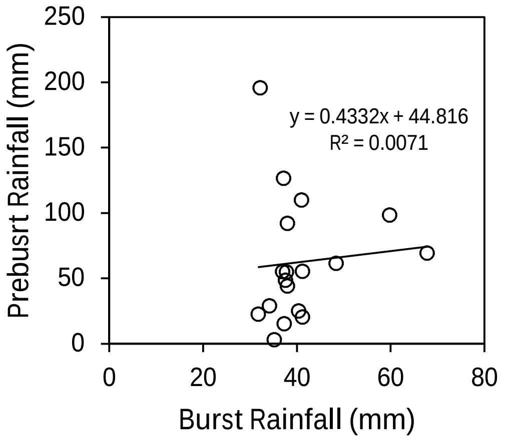


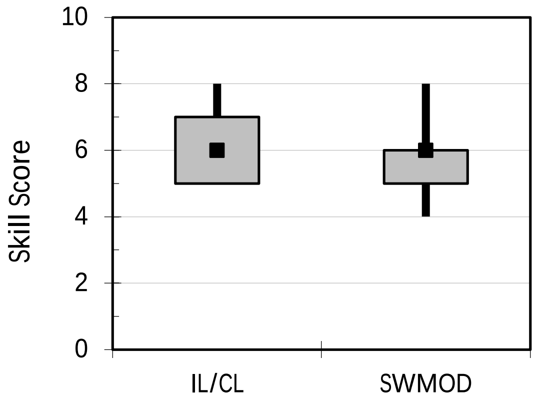
Ourimbah Ck @ U/S Weir (NSW) - 3 hour bursts

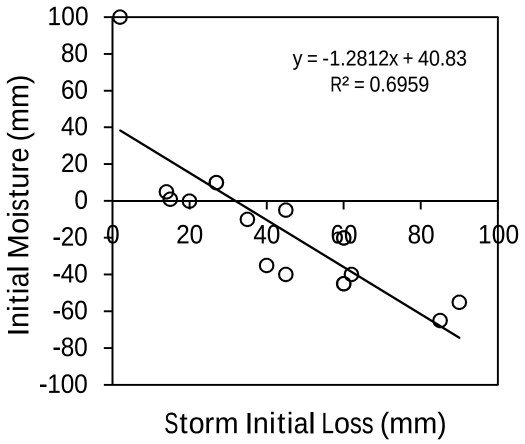


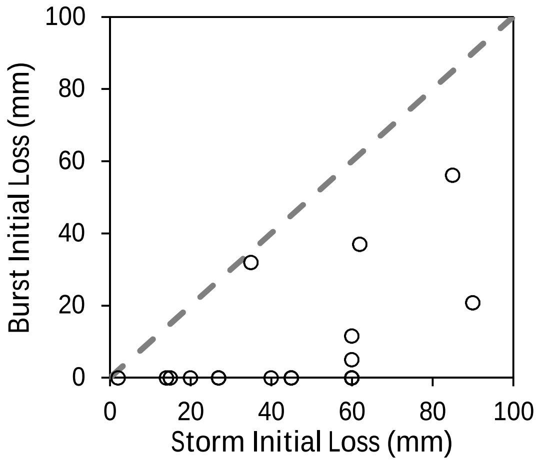
Swan River @ Harding Falls (Tas) - 3 hour bursts

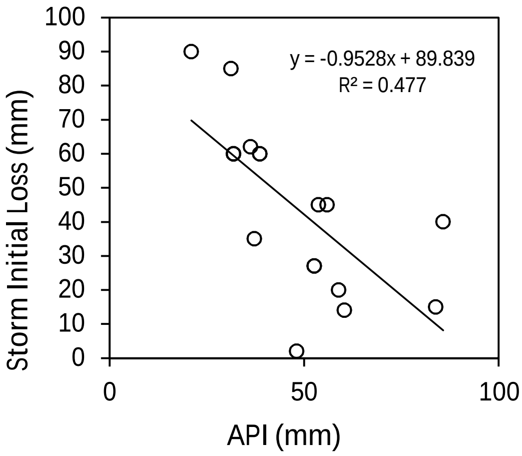


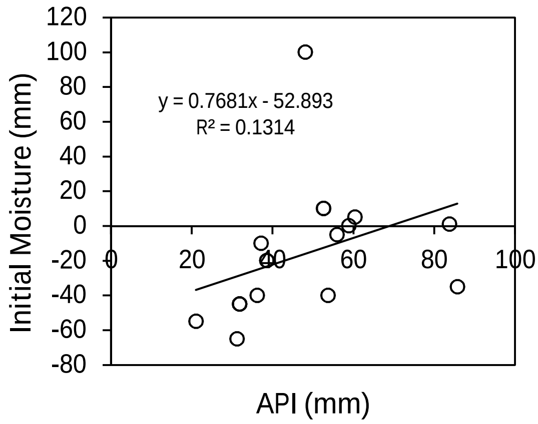




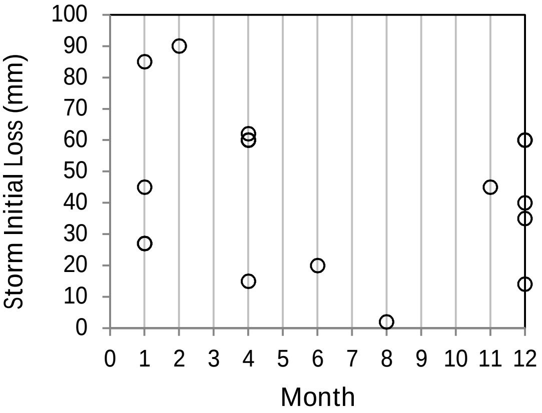


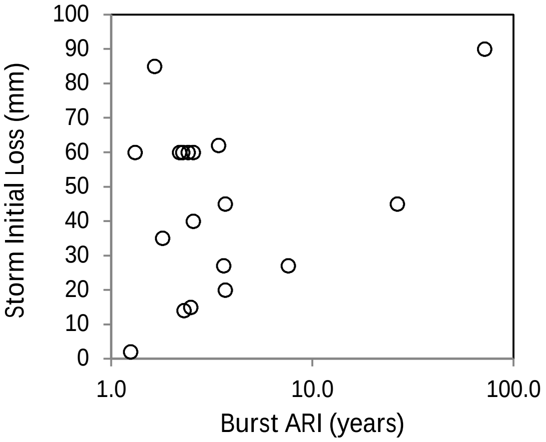


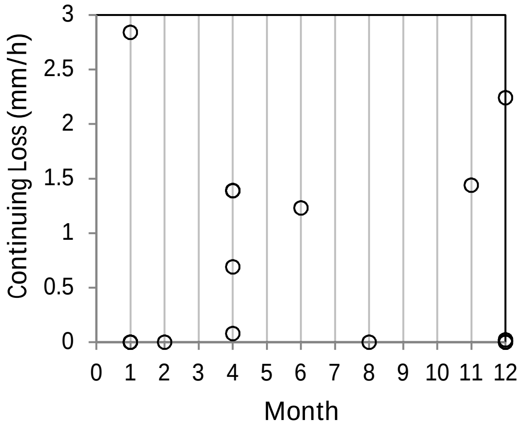


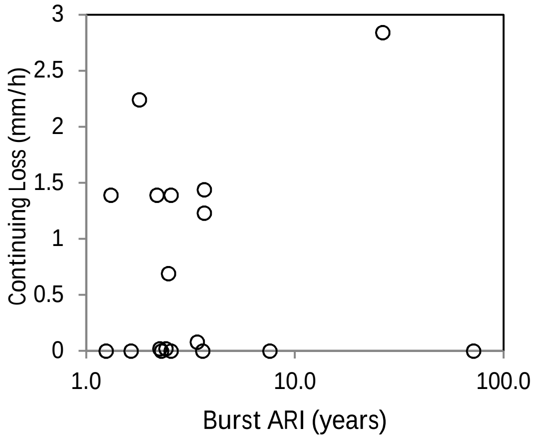


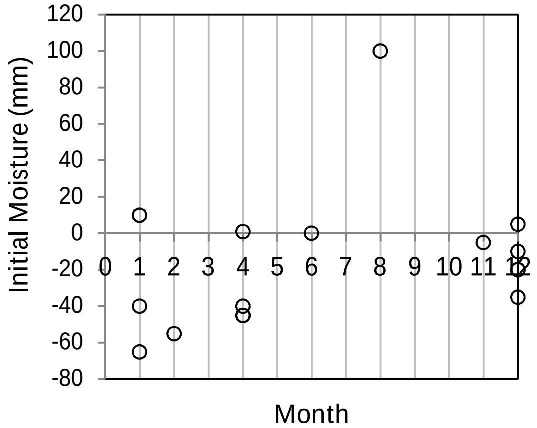
Swan River @ Harding Falls (Tas) - 3 hour bursts

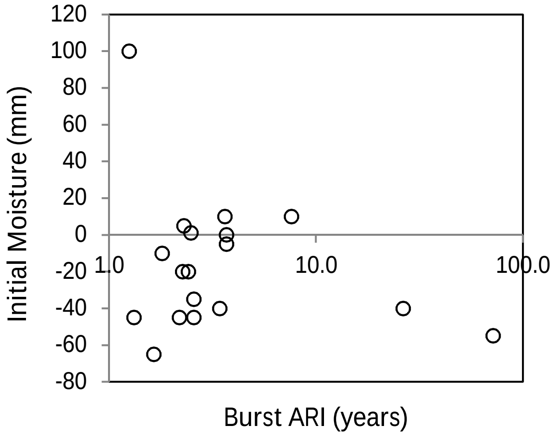


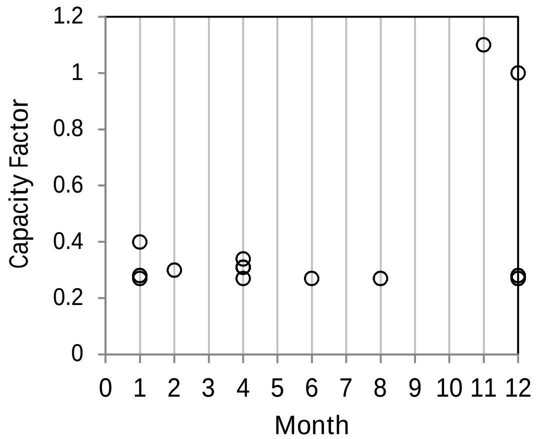


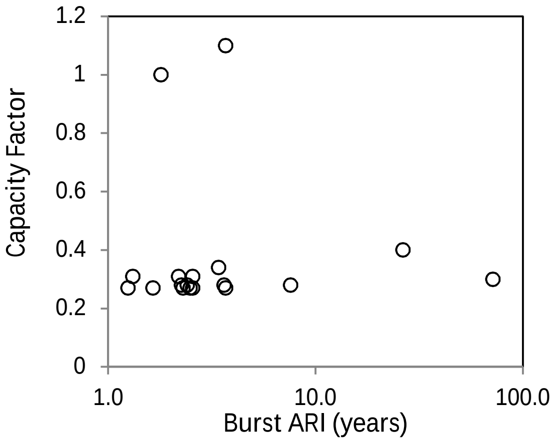




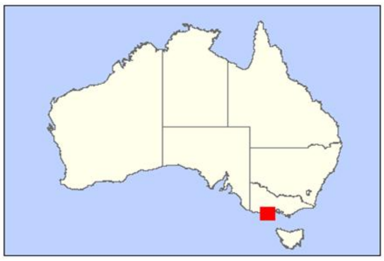


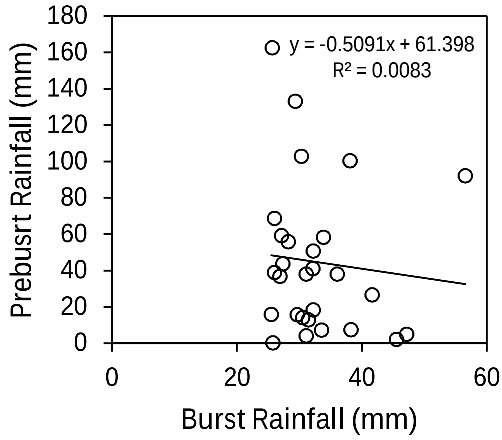


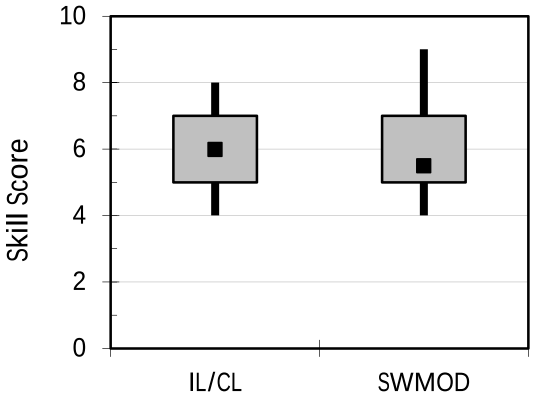


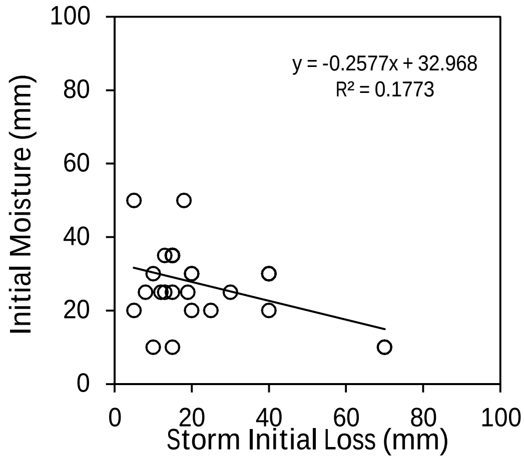


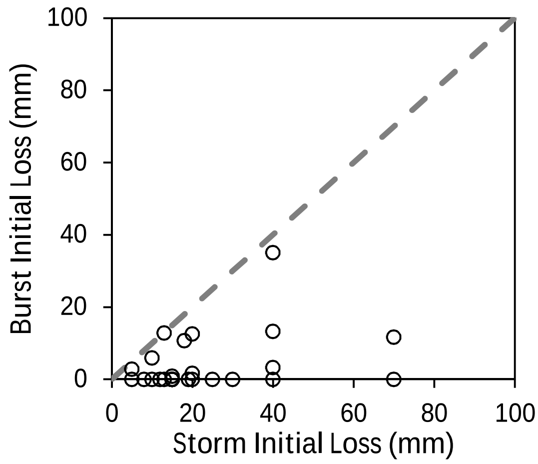
Aire @ Wyelangta (VIC) - 3 hour bursts

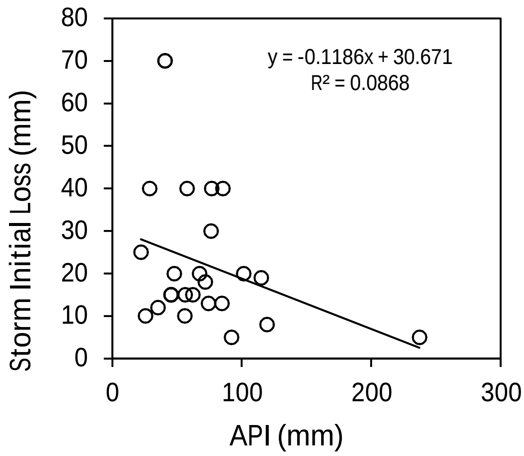


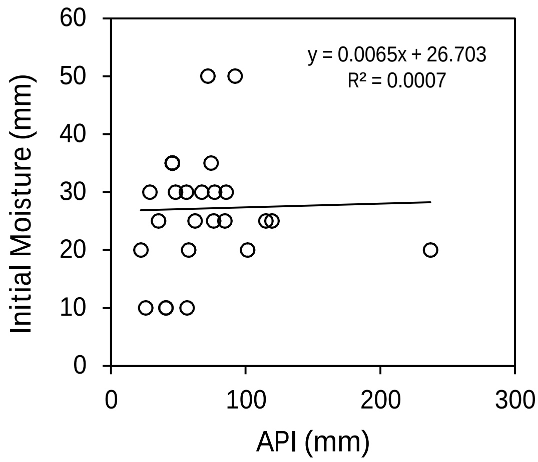




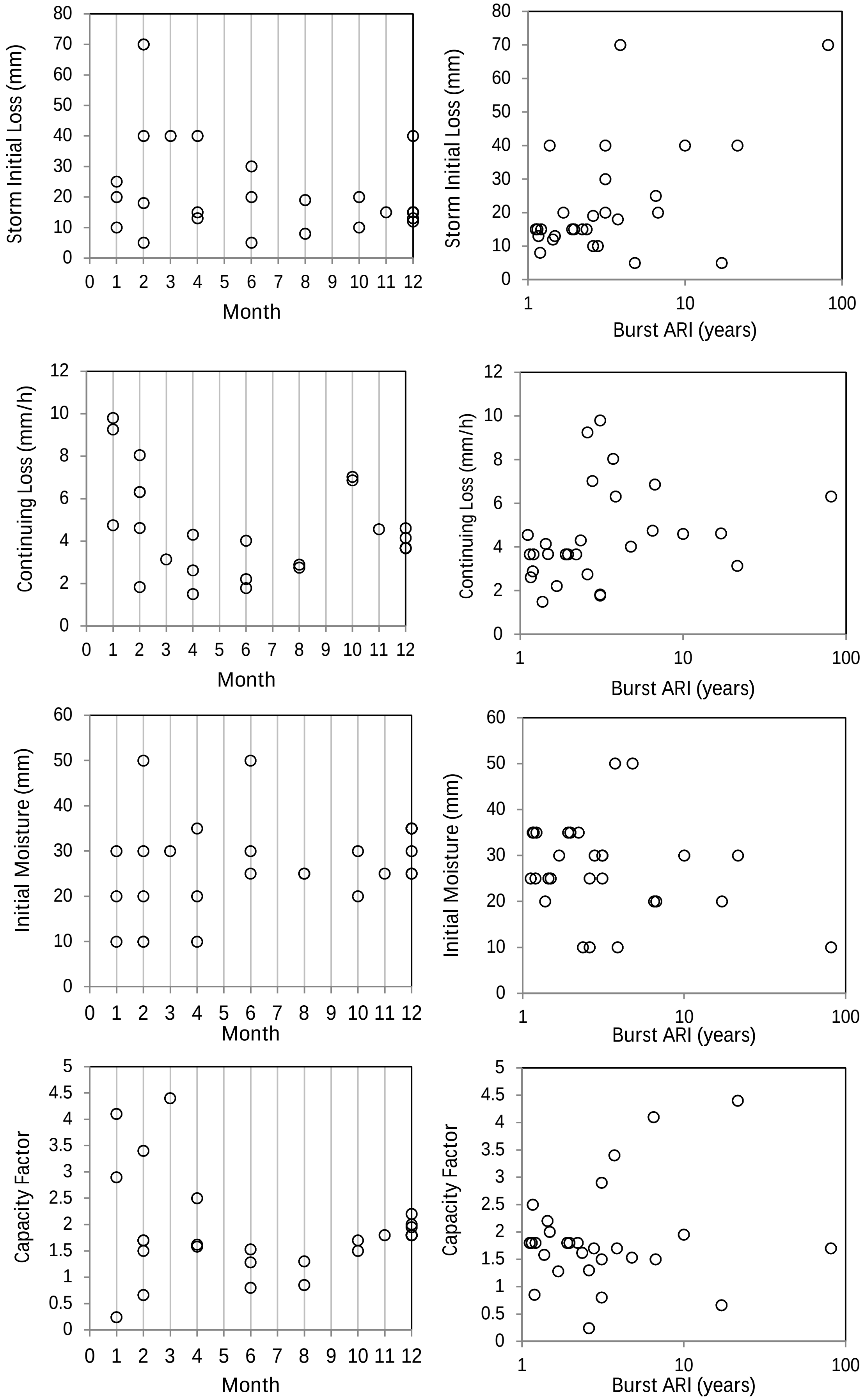




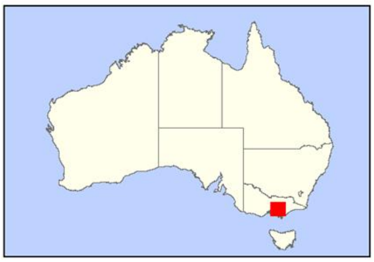


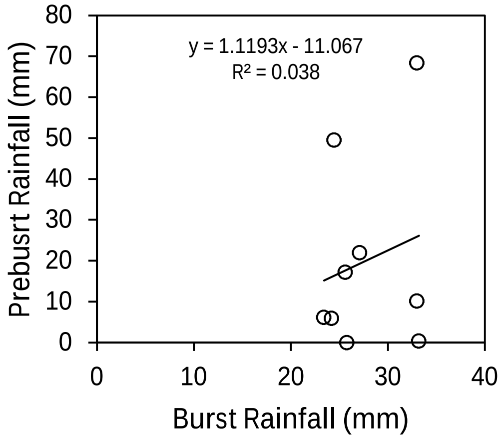


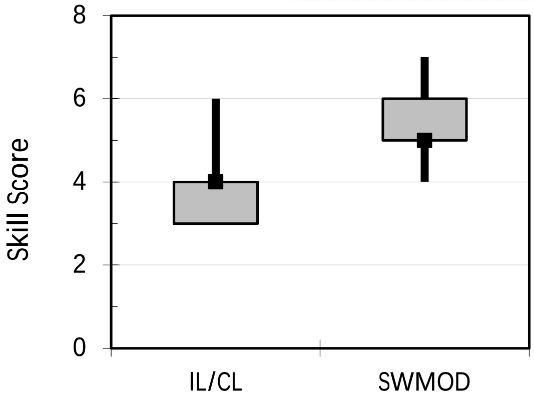
Aire @ Wyelangta (VIC) - 3 hour bursts

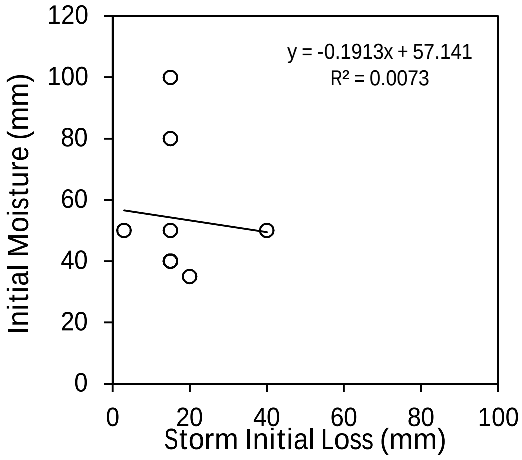


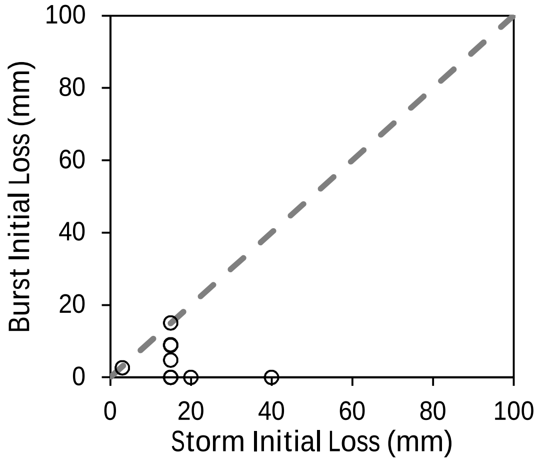
McMahons Ck @ Upstreams Weir (VIC) - 3 hour bursts

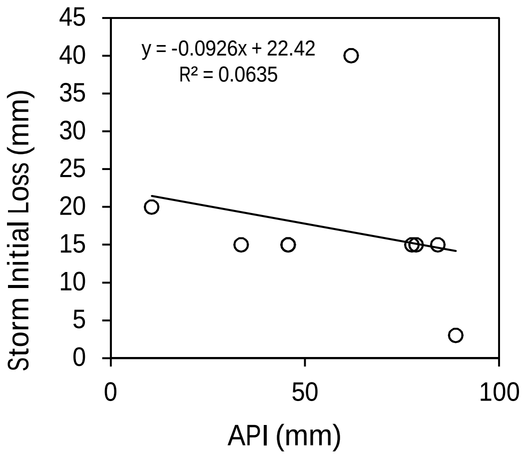


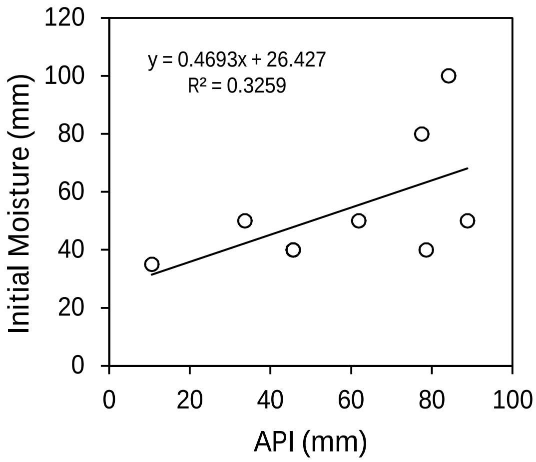




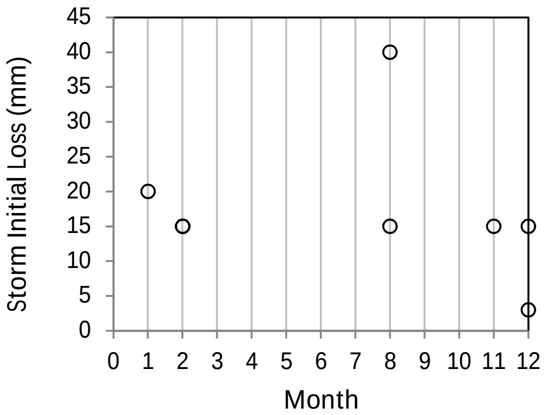


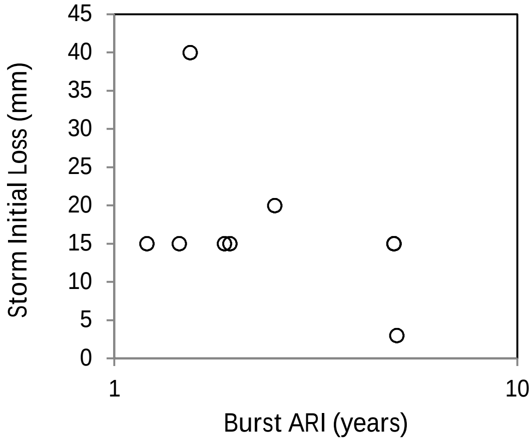


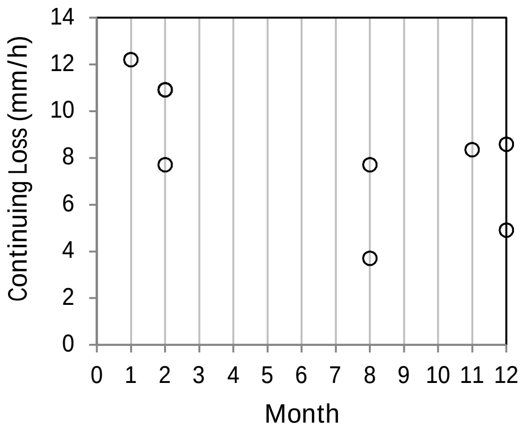


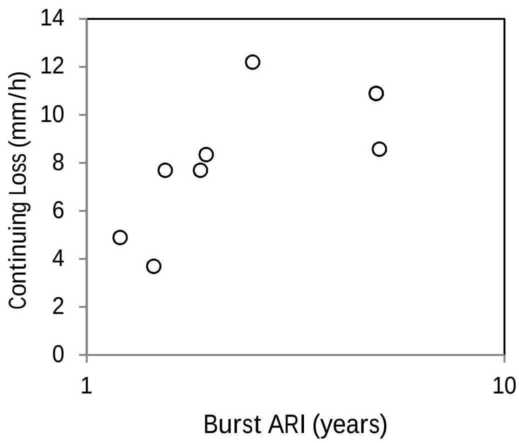


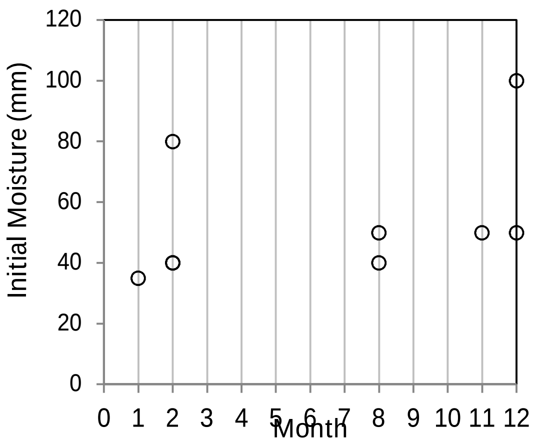
McMahons Ck @ Upstreams Weir (VIC) - 3 hour bursts

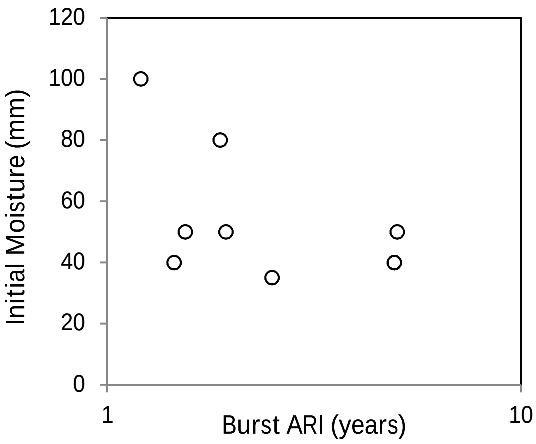


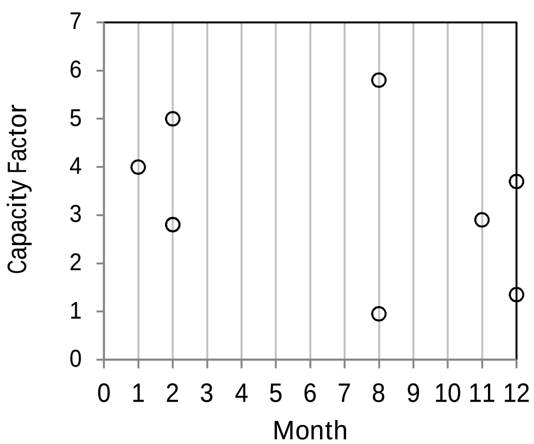


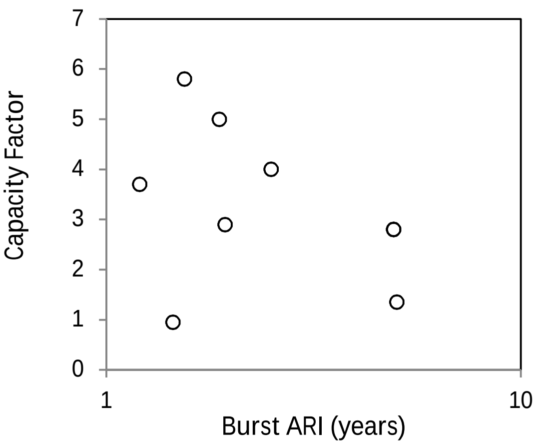




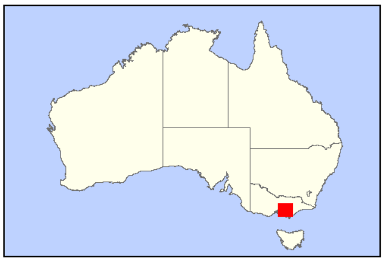


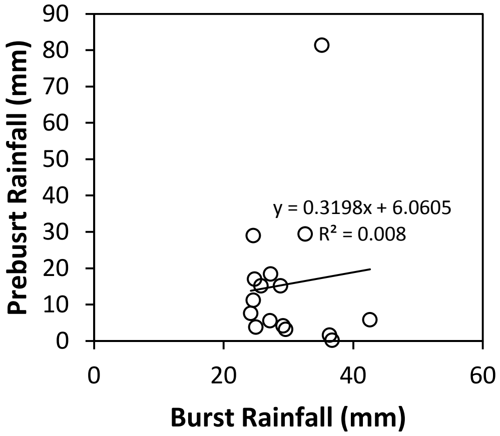


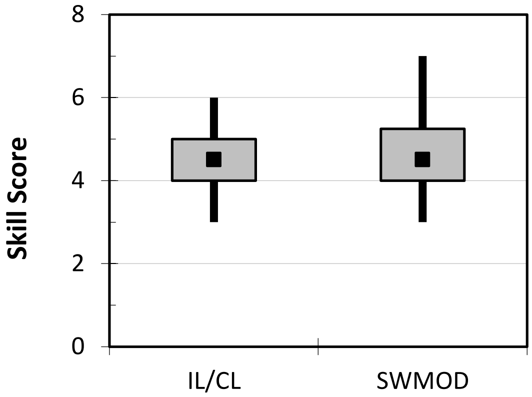


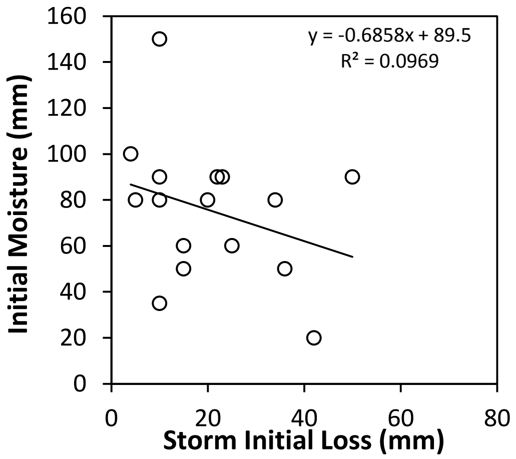


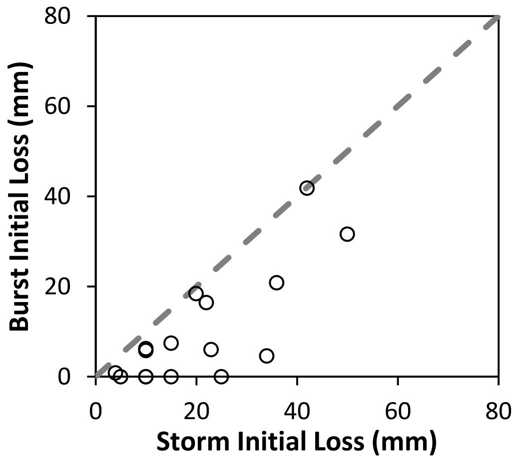
Tarago @ Neerim (VIC) - 3 hour bursts

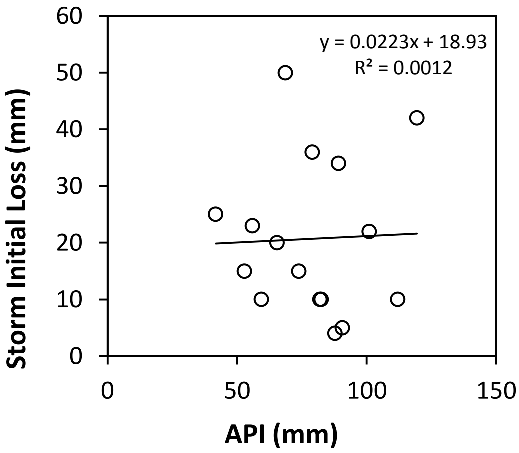


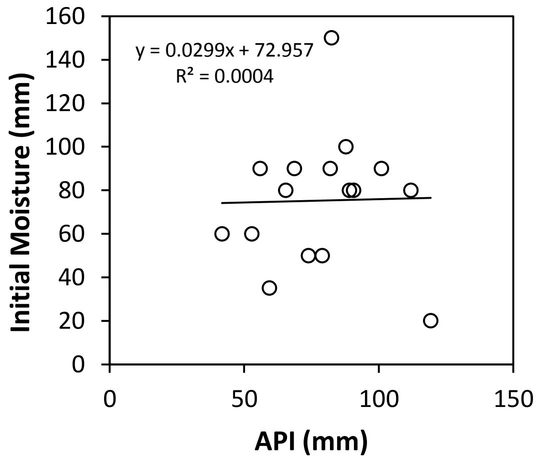




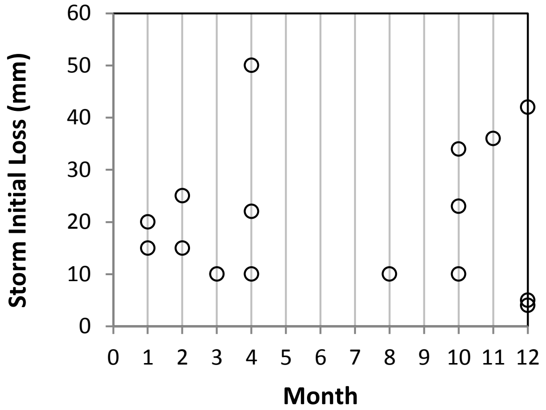


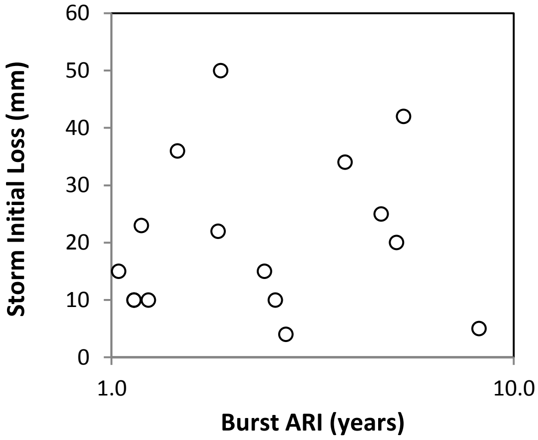


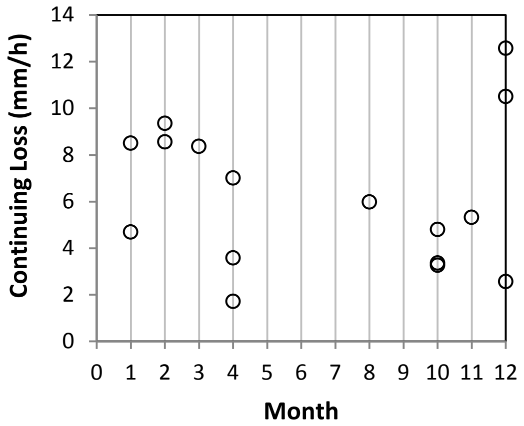


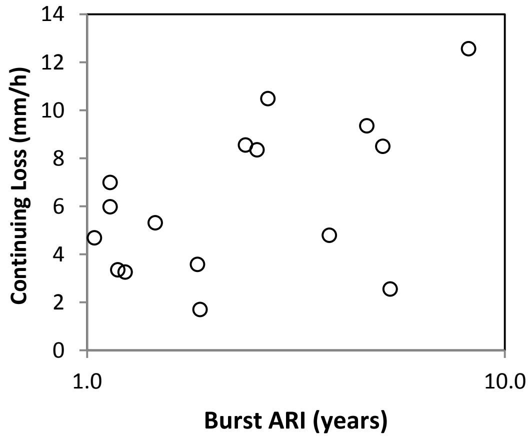


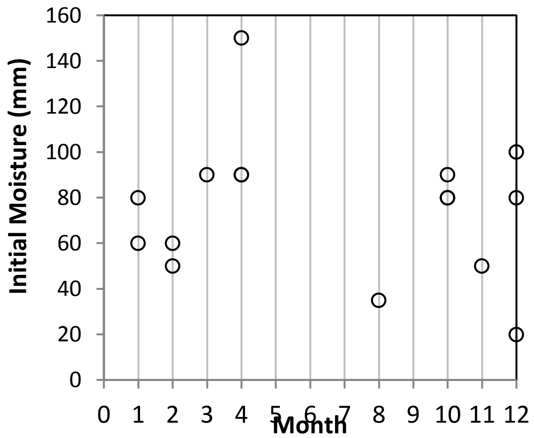
Tarago @ Neerim (VIC) - 3 hour bursts

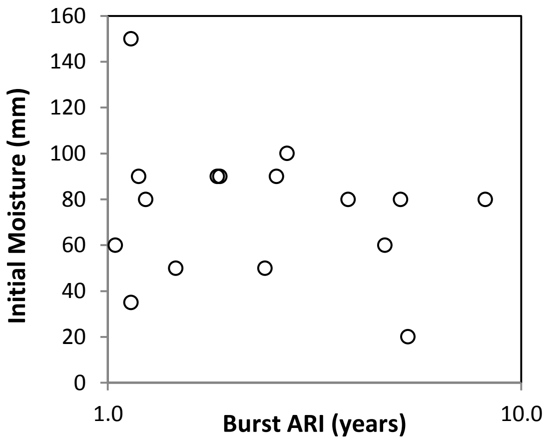


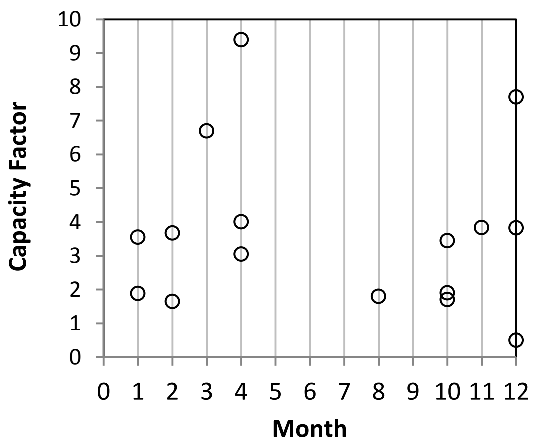


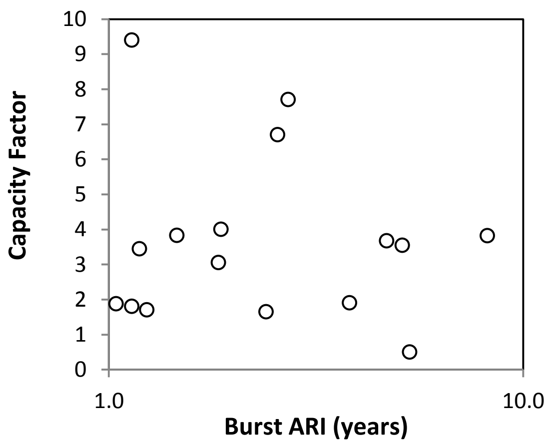




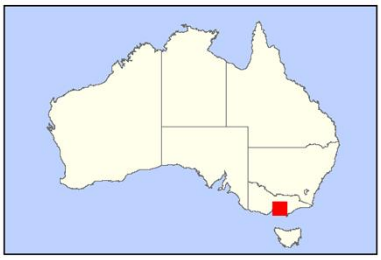


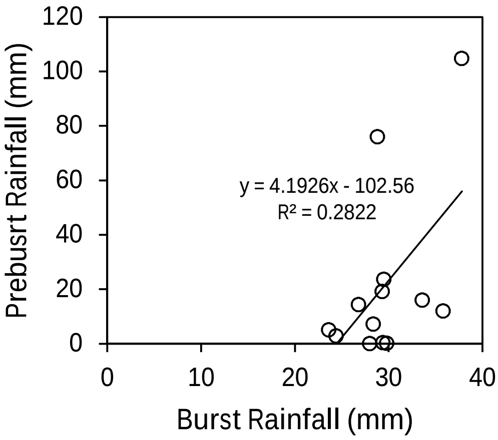


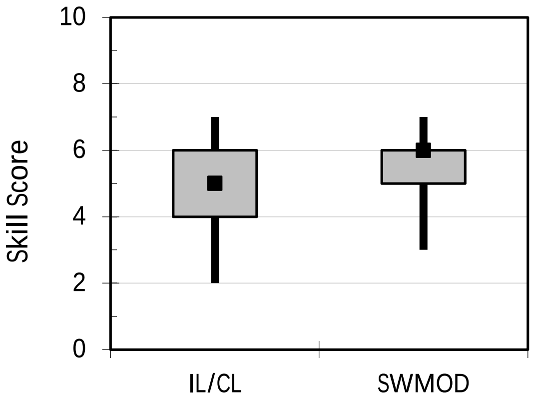


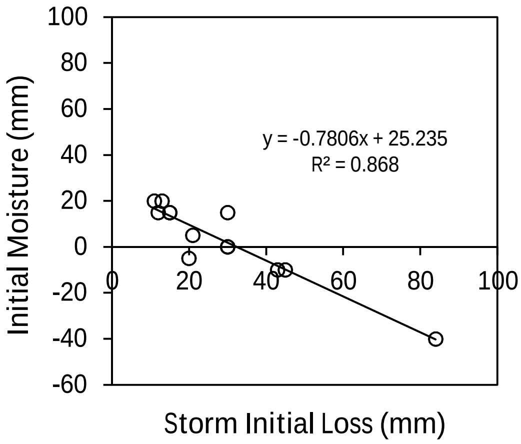


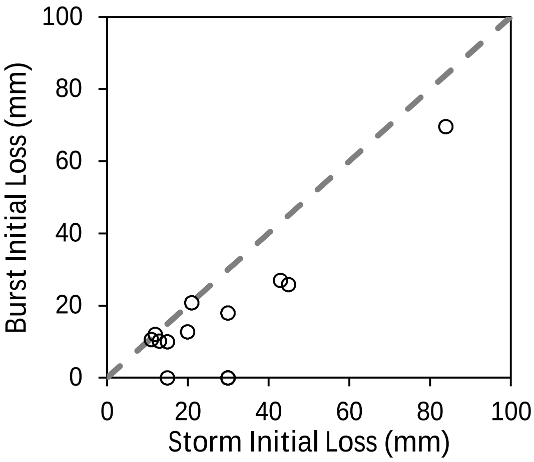
Toomuc Ck @ Pakenham (VIC) - 3 hour bursts

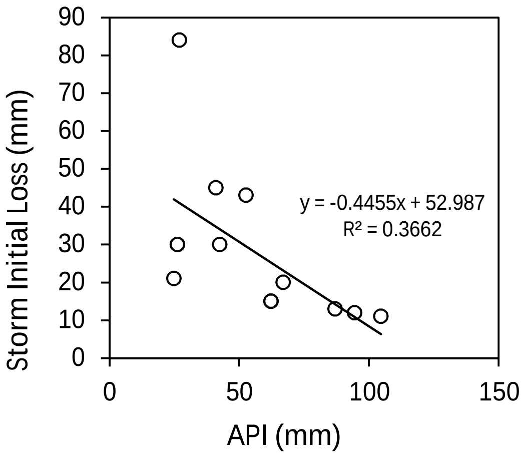


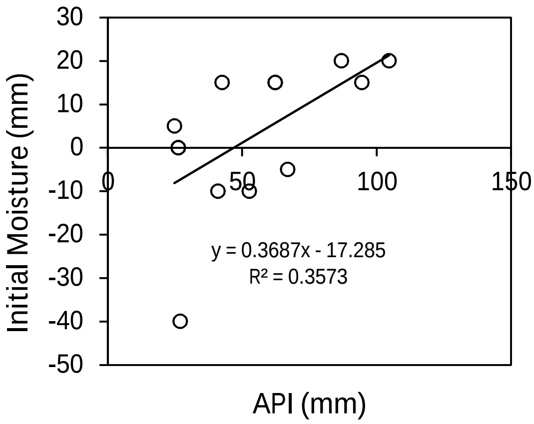




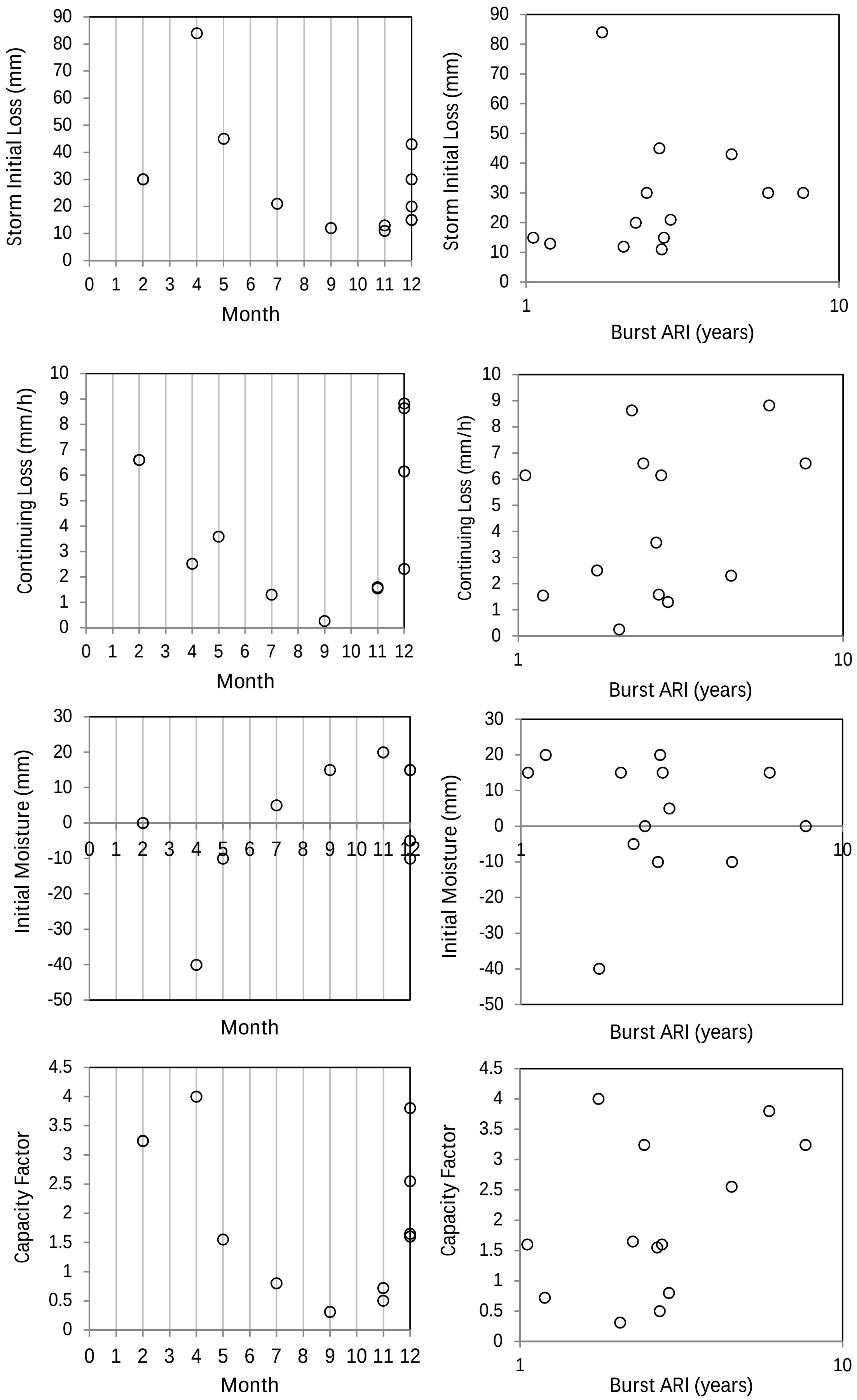




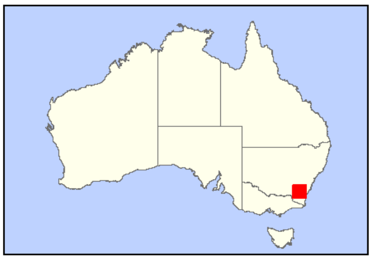


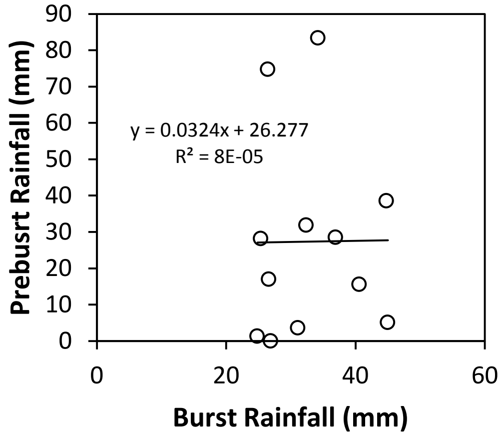


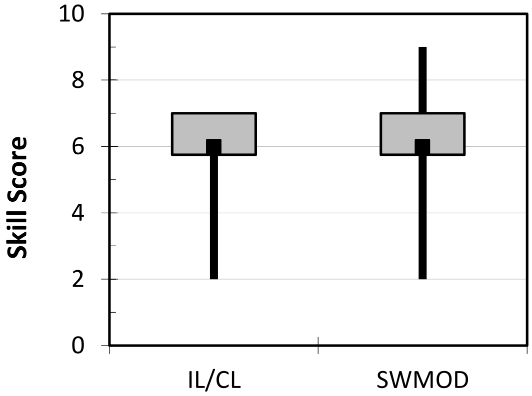
Toomuc Ck @ Pakenham (VIC) - 3 hour bursts

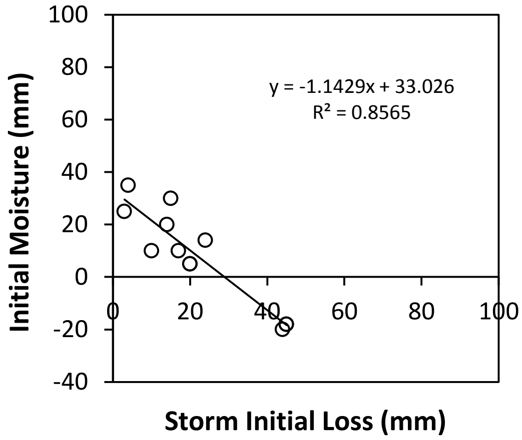


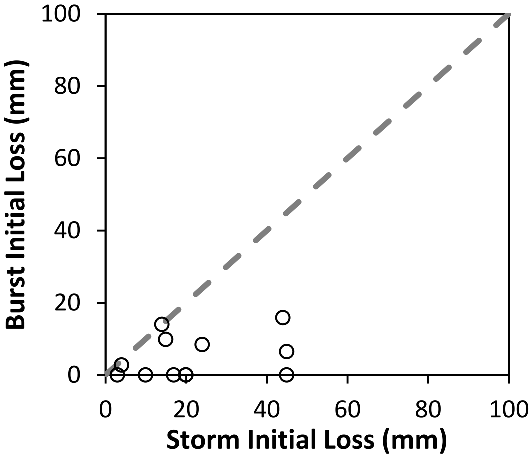
Jerrabomberra Ck @ Four Mile Ck (ACT) - 3 hour bursts

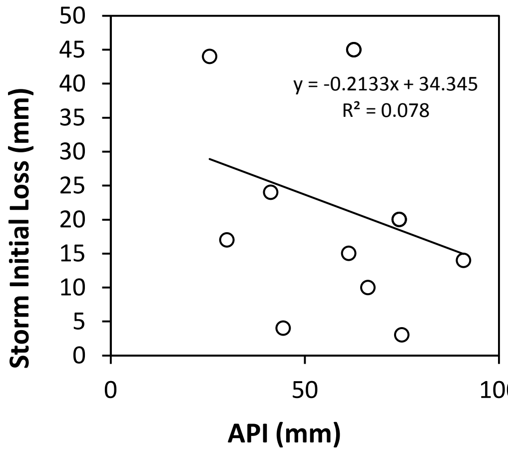


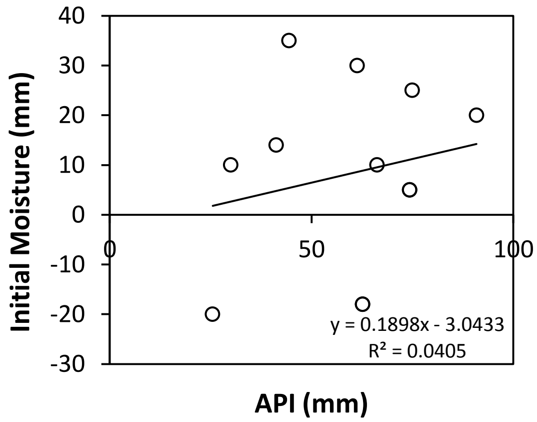




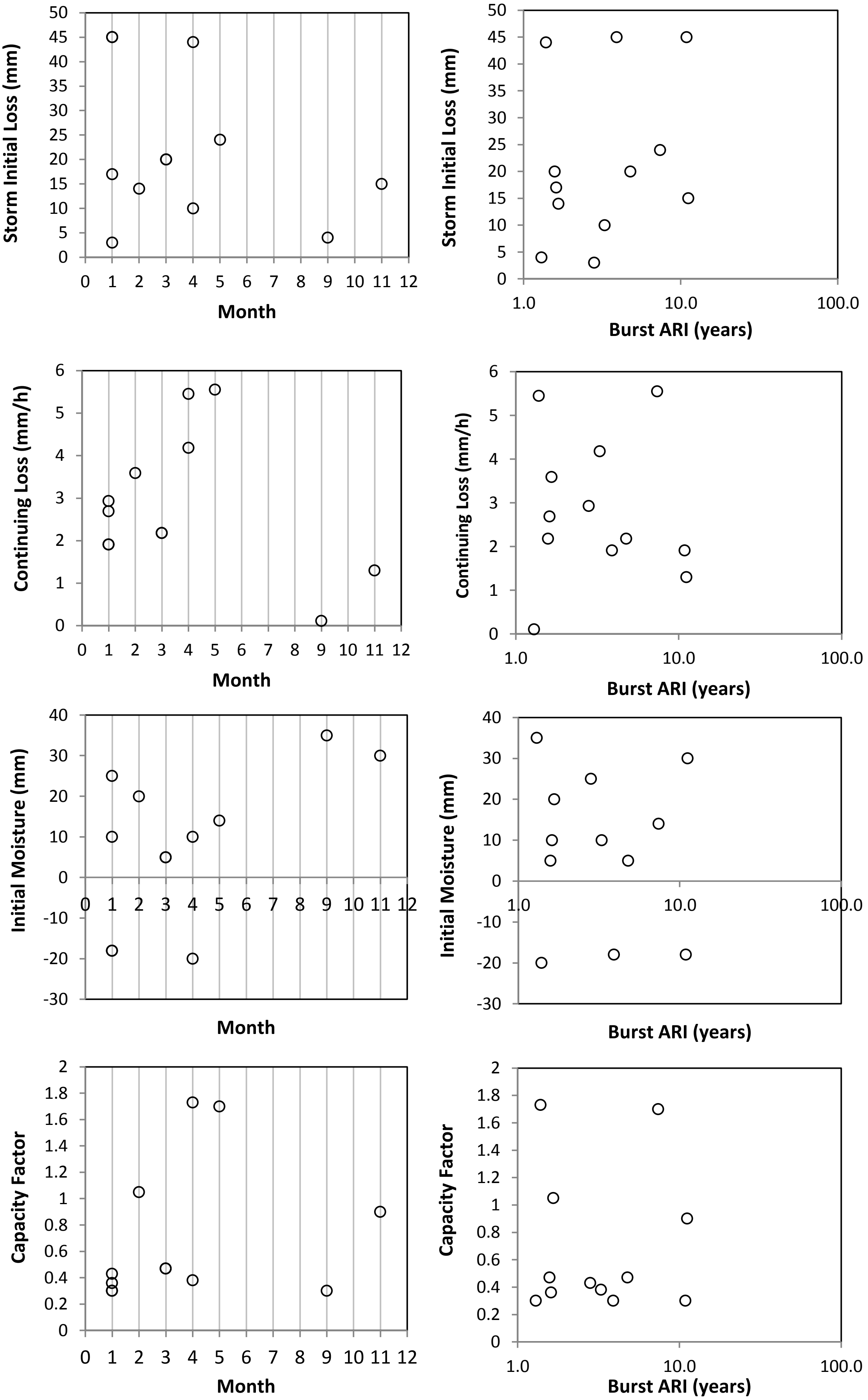




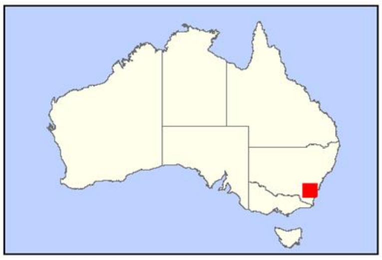


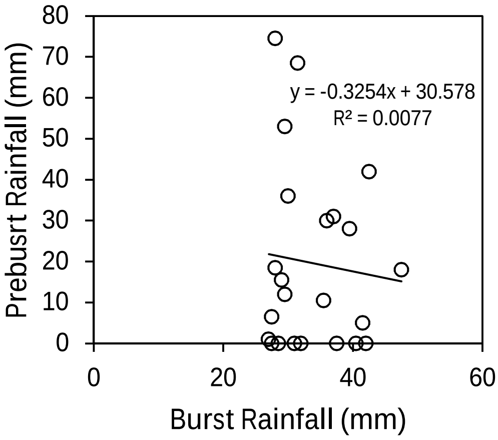


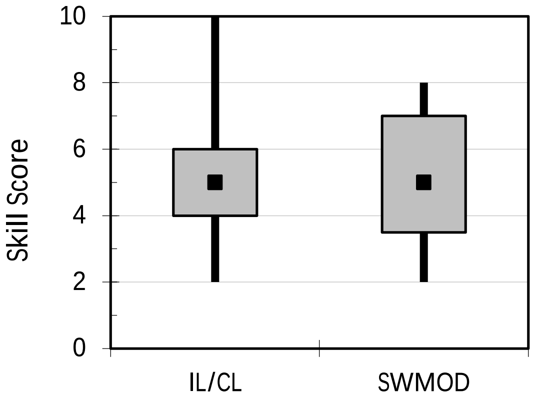
Jerrabomberra Ck @ Four Mile Ck (ACT) - 3 hour bursts

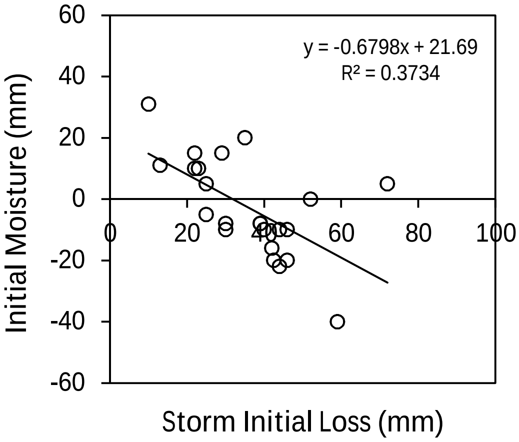


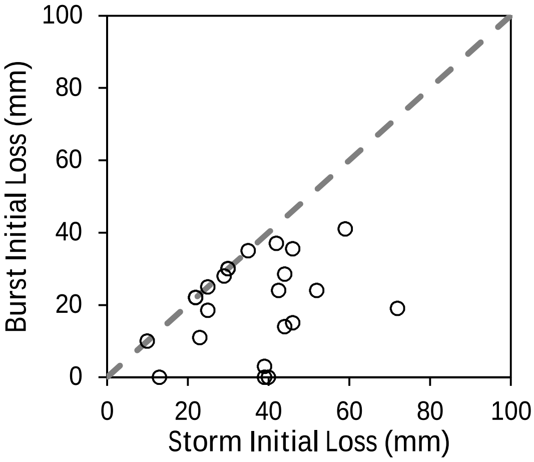
Butmaroo Ck @ Butmaroo (NSW) - 3 hour bursts

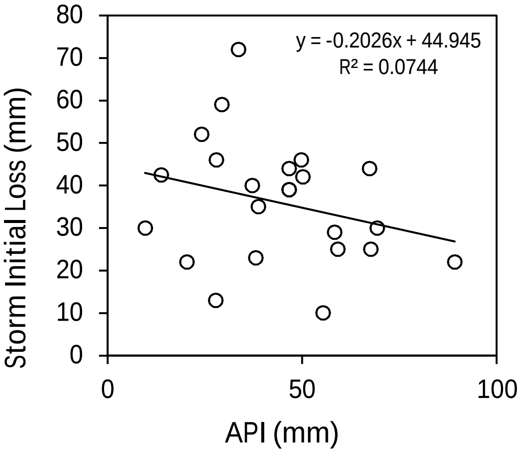


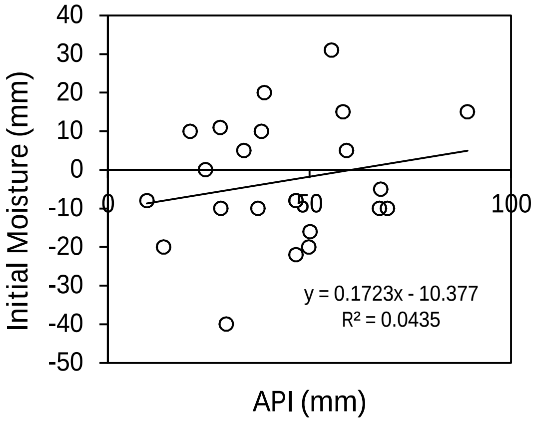




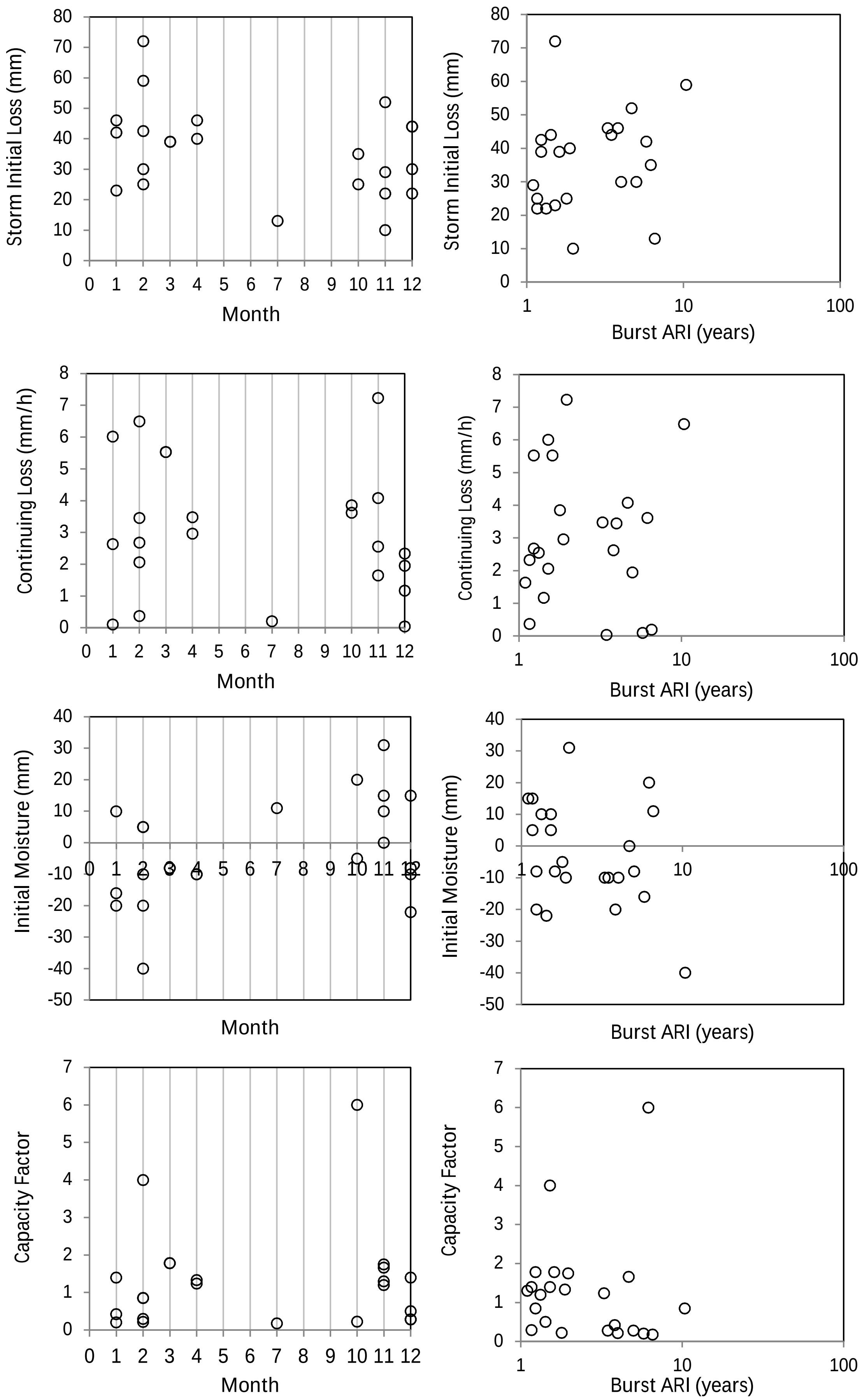




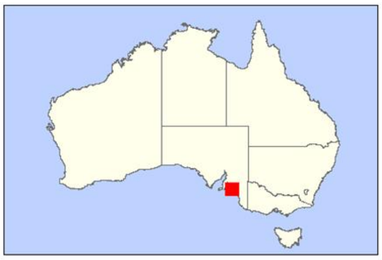


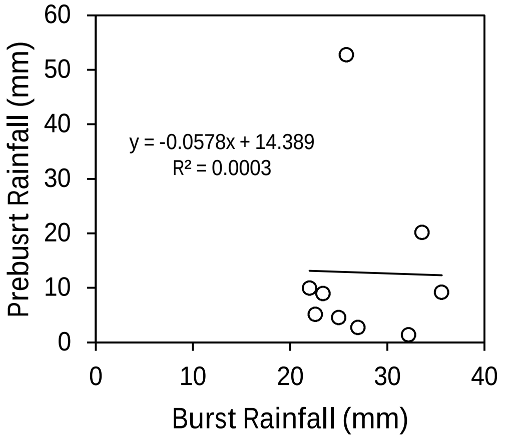


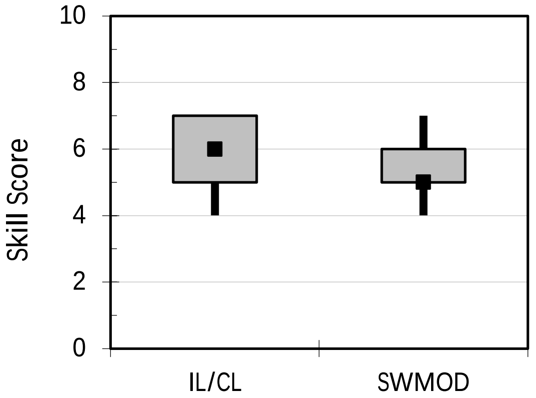
Butmaroo Ck @ Butmaroo (NSW) - 3 hour bursts

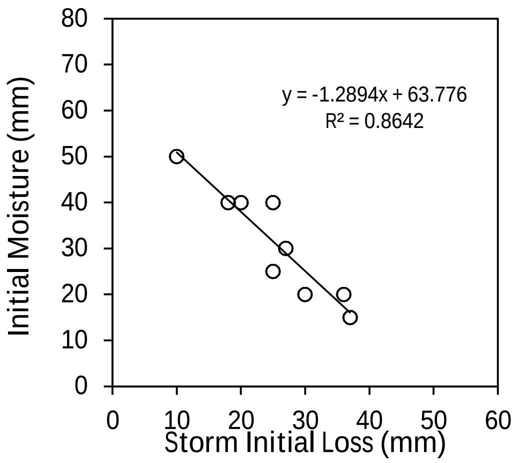


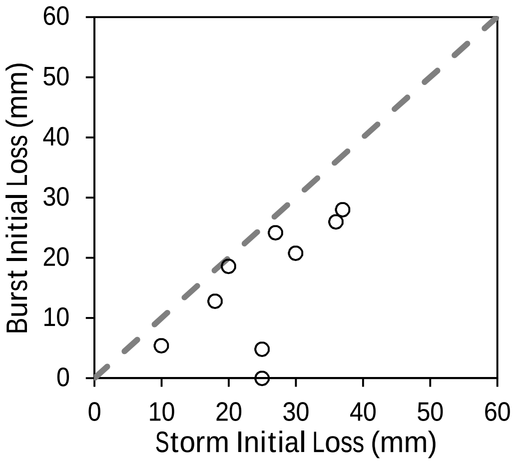
Echunga Ck @ U/S Mt Bold Res. (SA) - 3 hour bursts

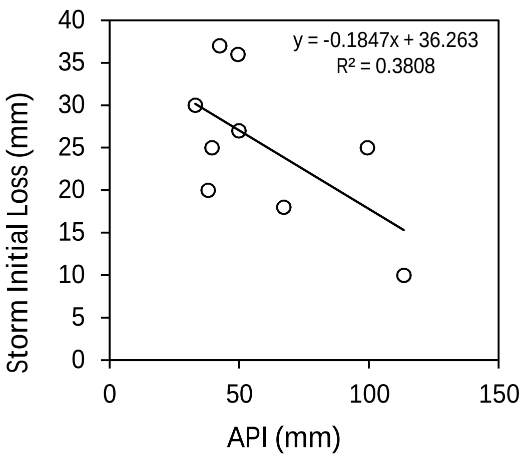


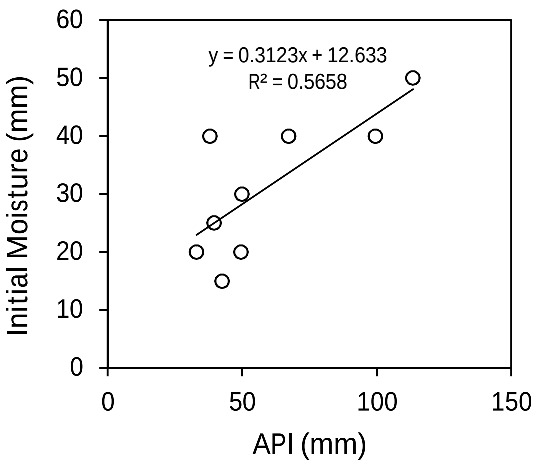




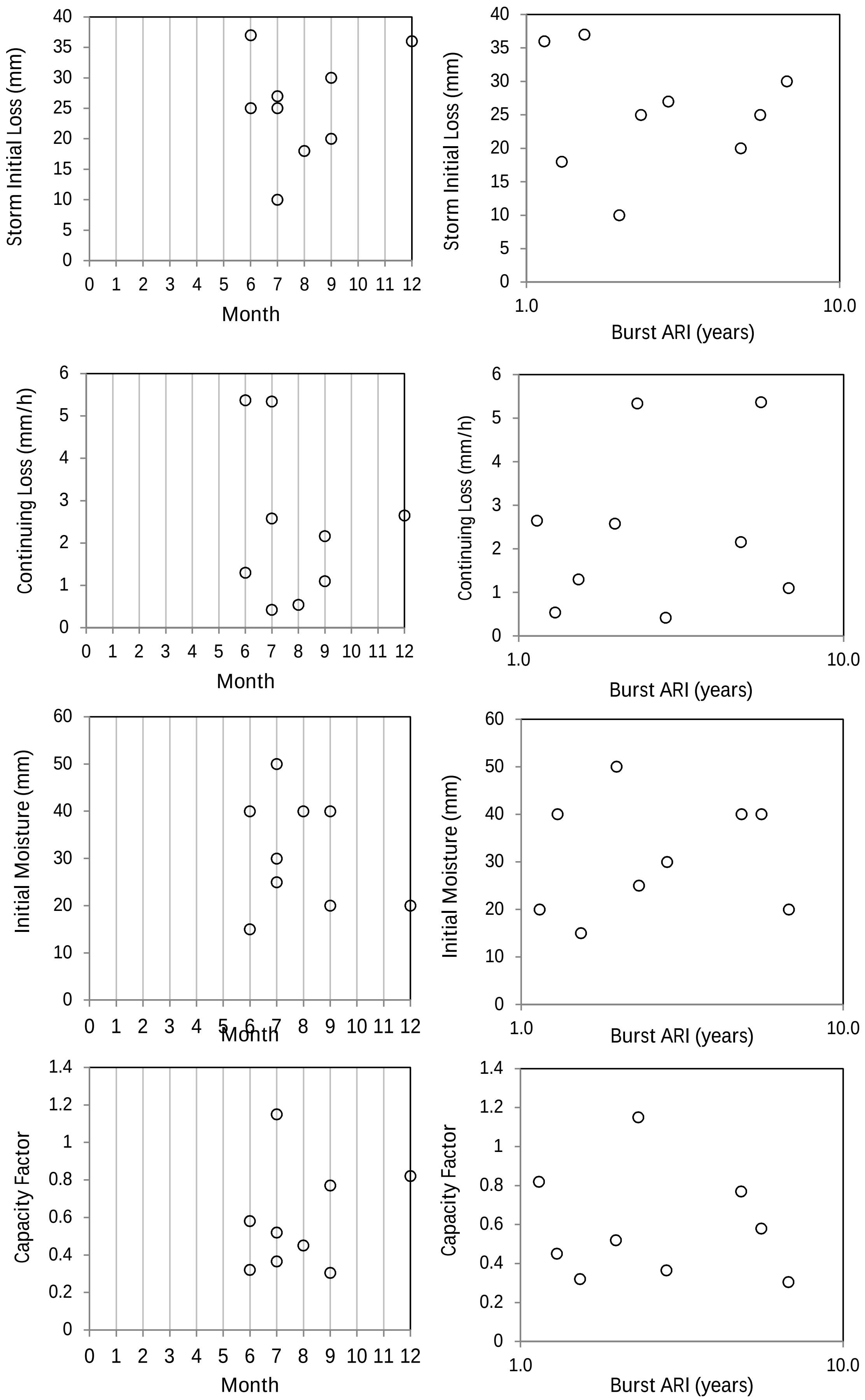




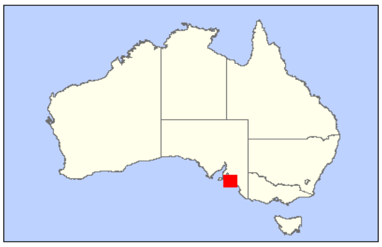


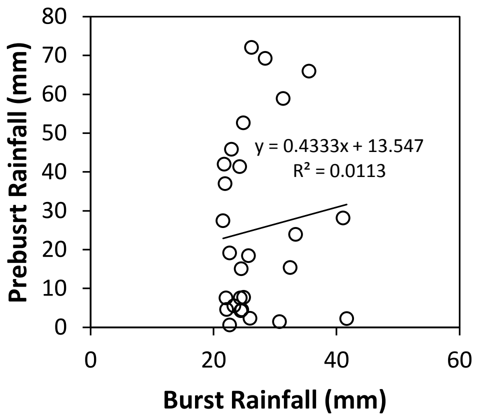


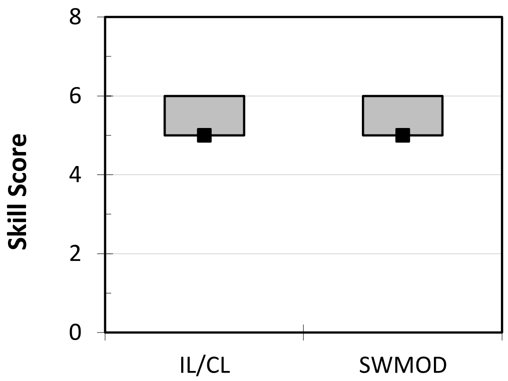
Echunga Ck @ U/S Mt Bold Res. (SA) - 3 hour bursts

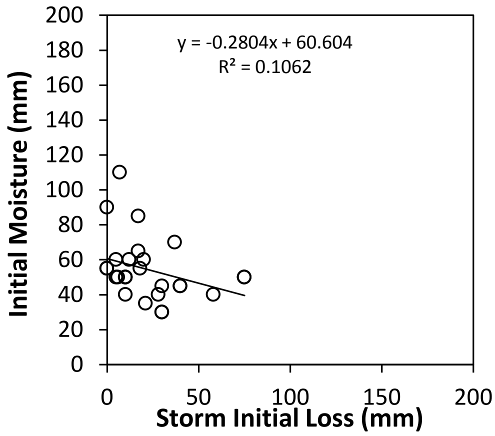


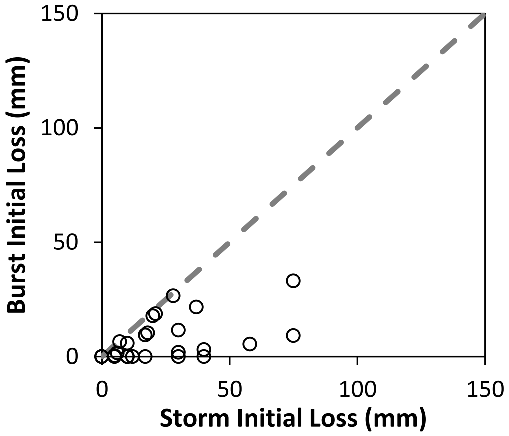
Hindmarsh @ Hindmarsh Vy Res Offtake W (SA) - 3 hour bursts

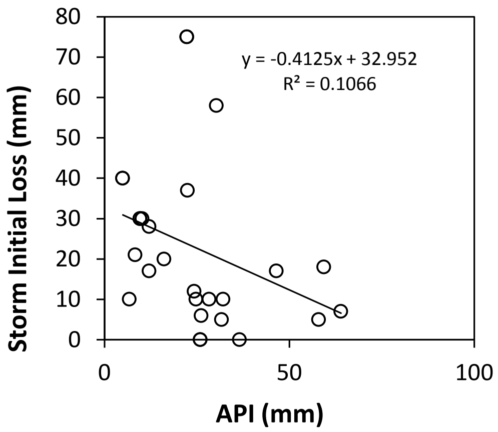


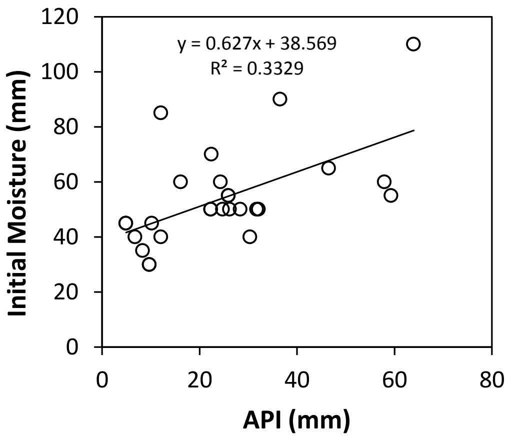




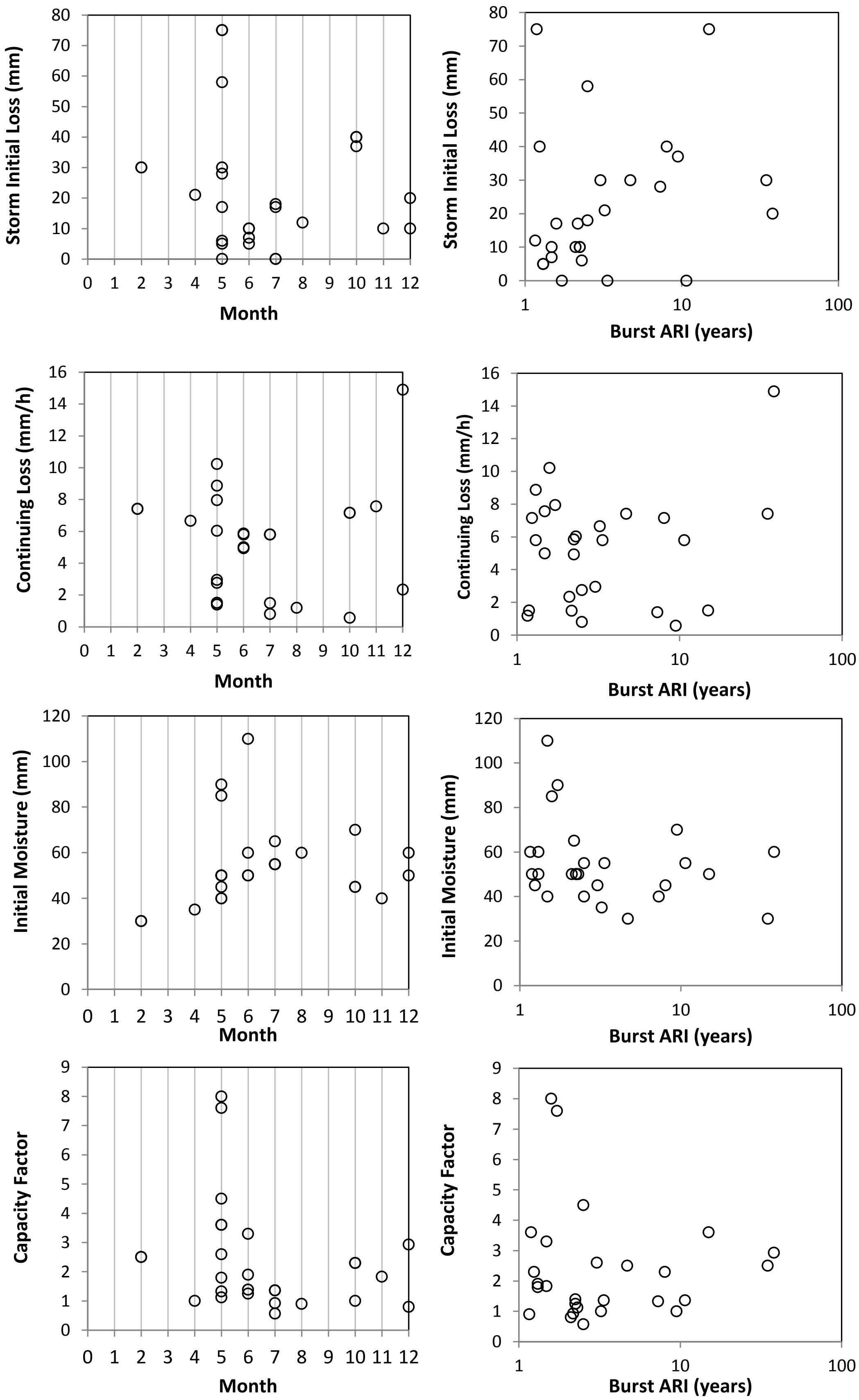




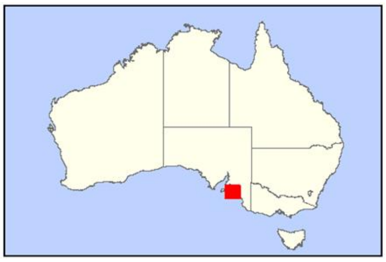


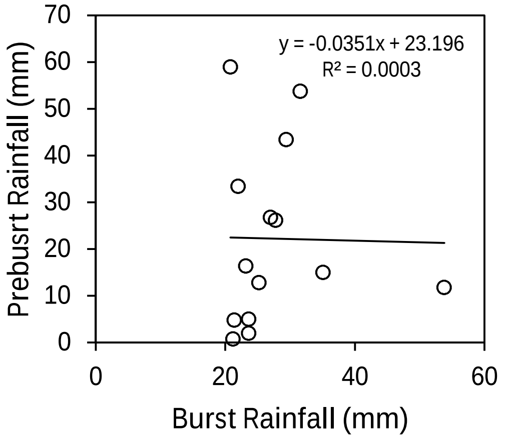


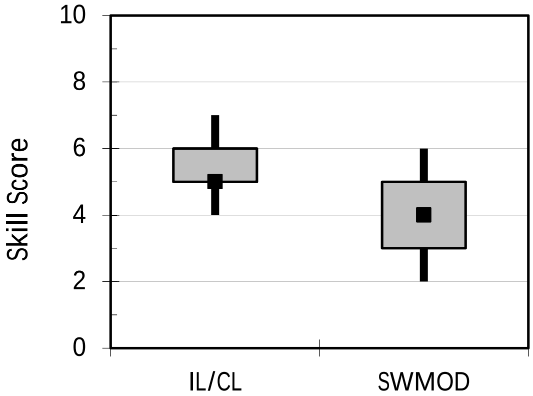
Hindmarsh @ Hindmarsh Vy Res Offtake W (SA) - 3 hour bursts

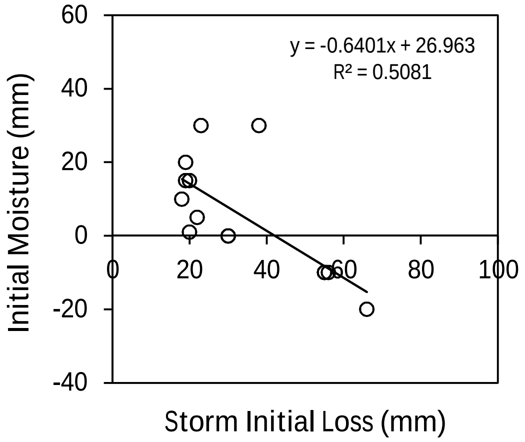


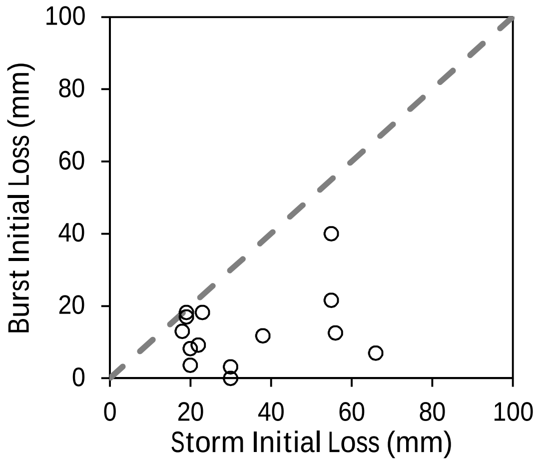
Myponga @ U/S Dam and Rd Br (SA) - 3 hour bursts

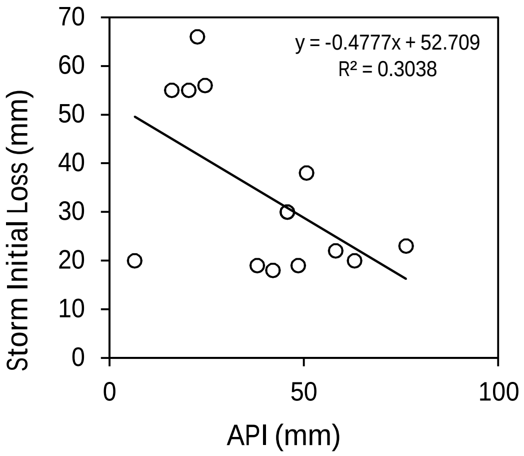


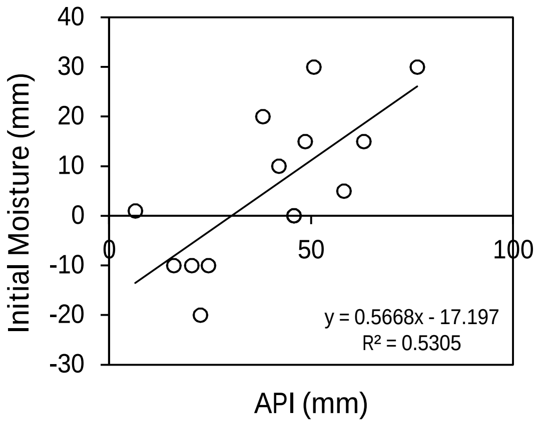




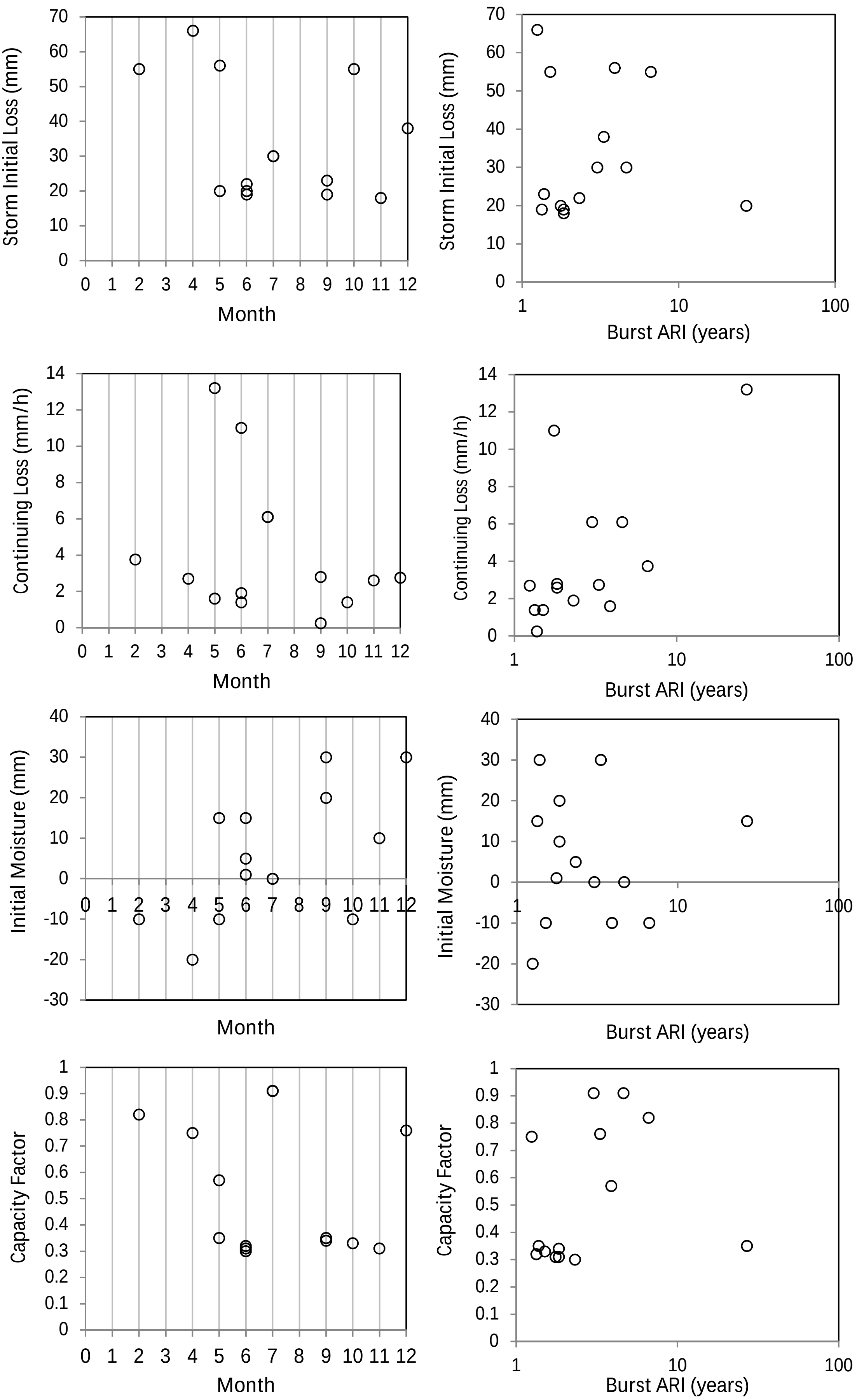




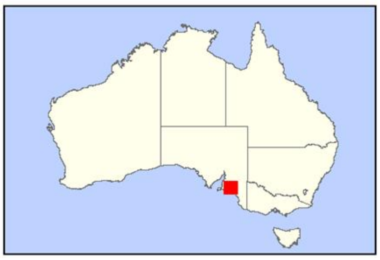


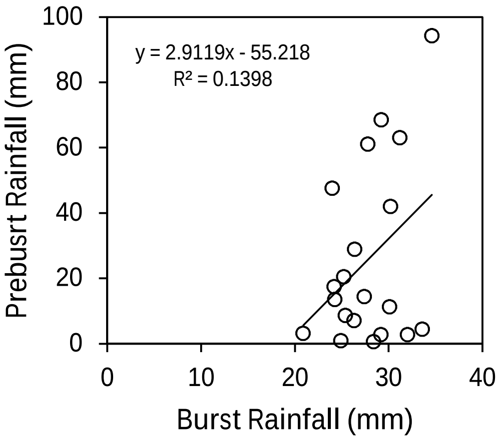


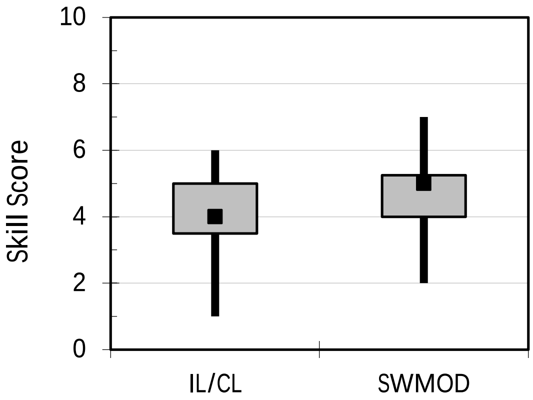
Myponga @ U/S Dam and Rd Br (SA) - 3 hour bursts

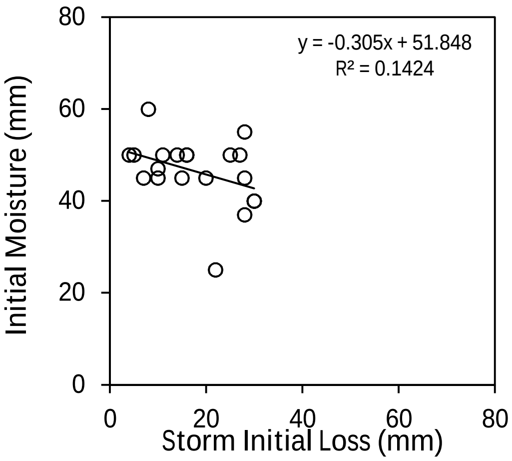


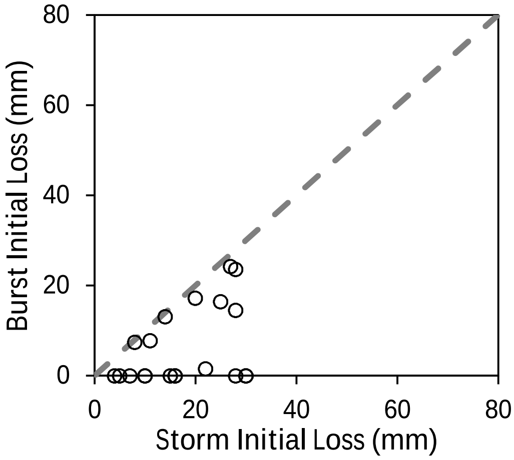
Sixth Ck @ Castambul (SA) - 3 hour bursts

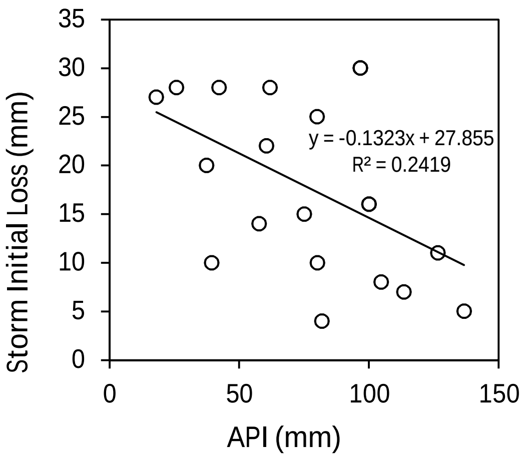


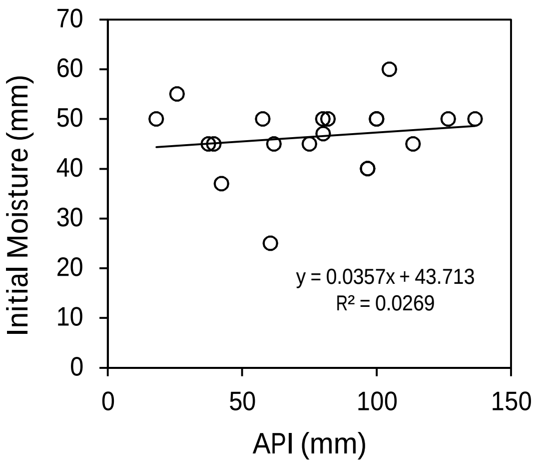




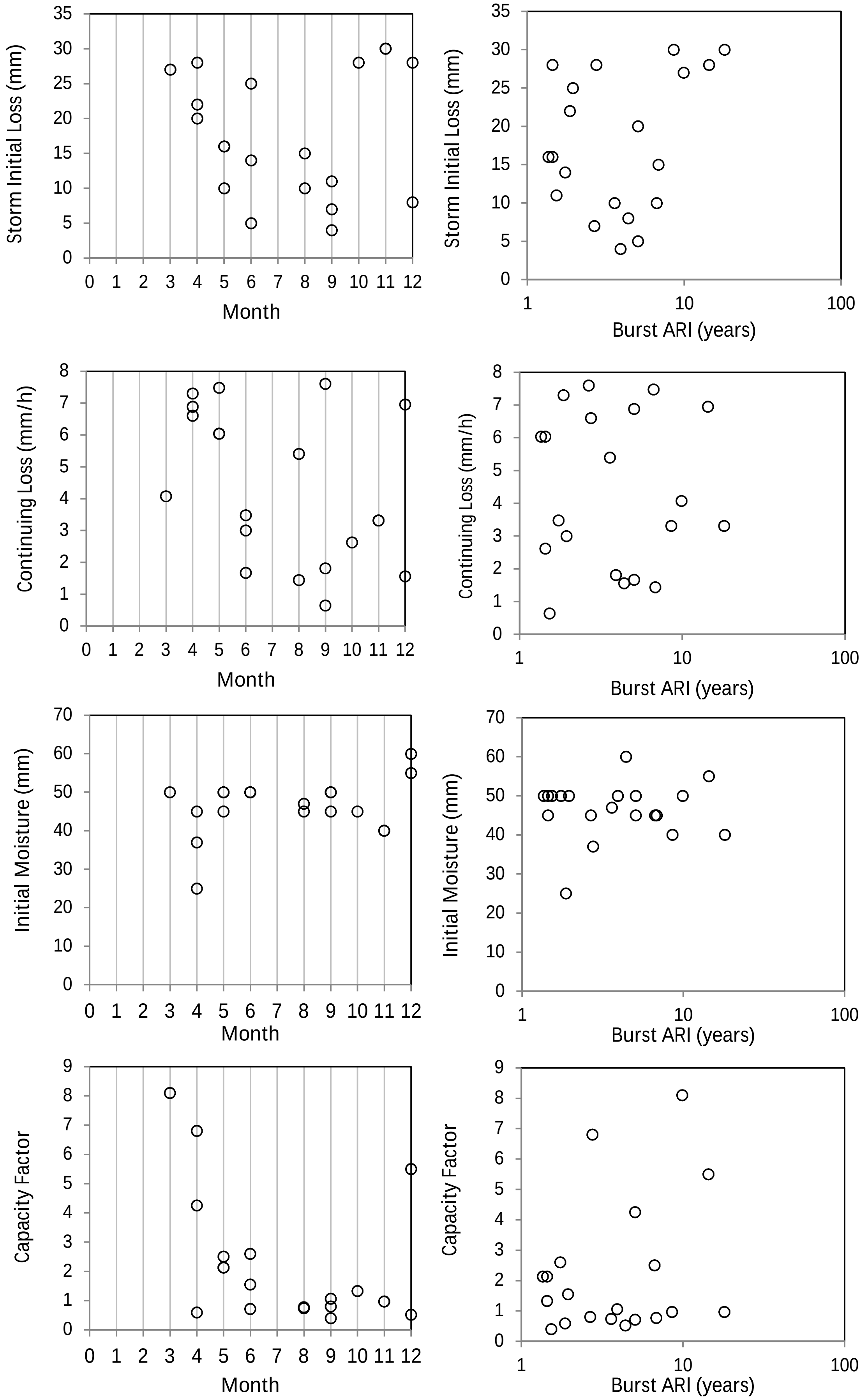




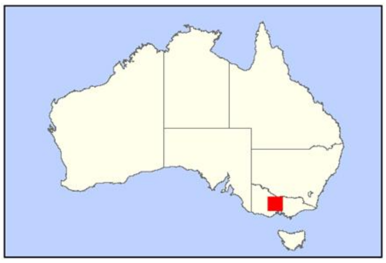


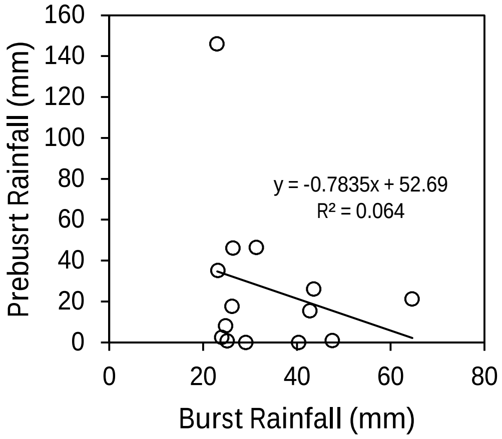


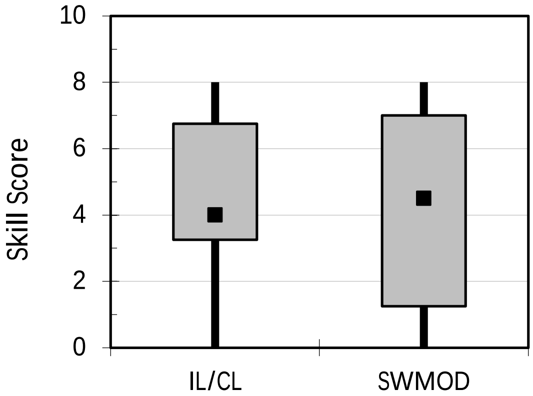
Sixth Ck @ Castambul (SA) - 3 hour bursts

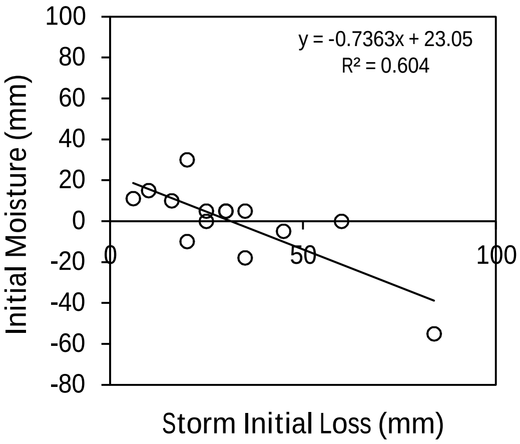


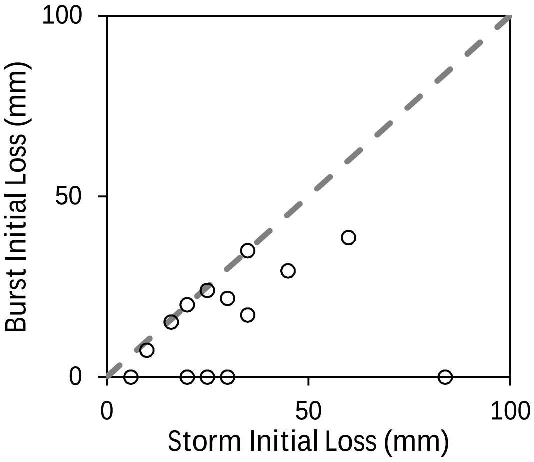
Axe Ck @ Sedgwick (VIC) - 3 hour bursts

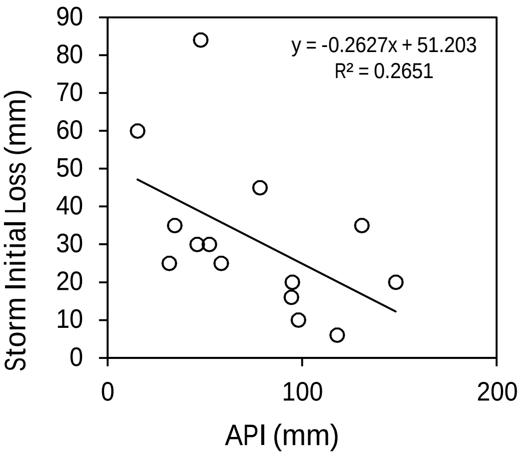


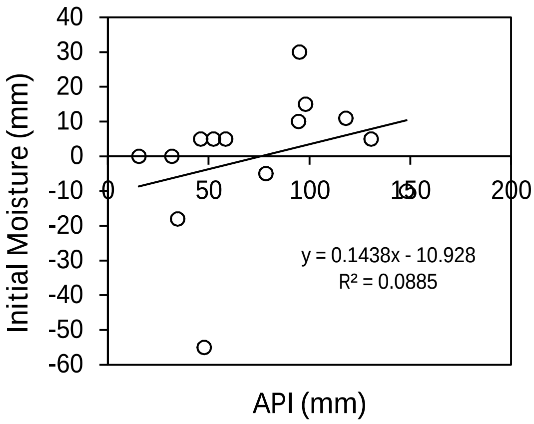




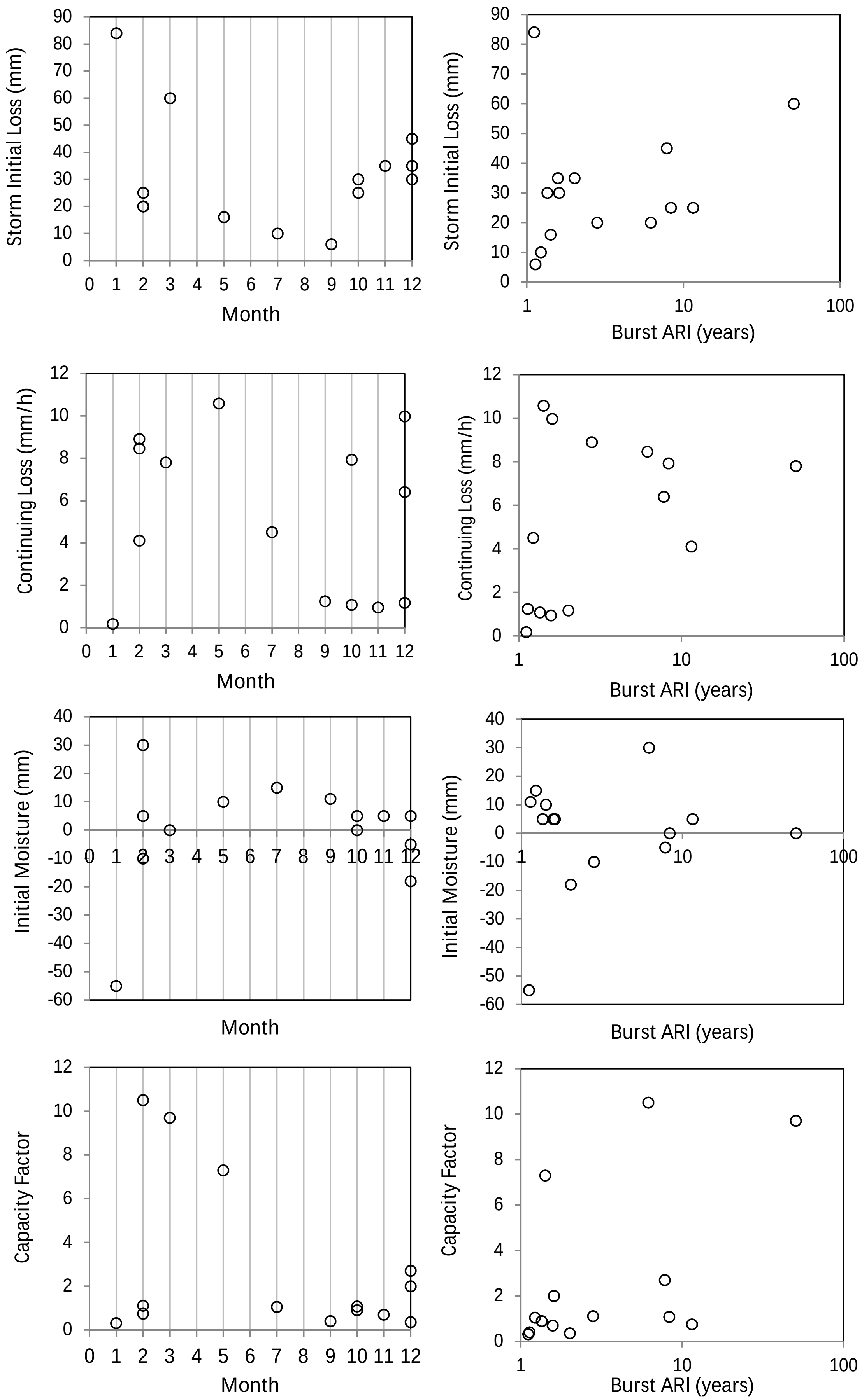




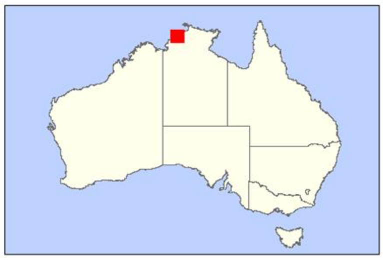


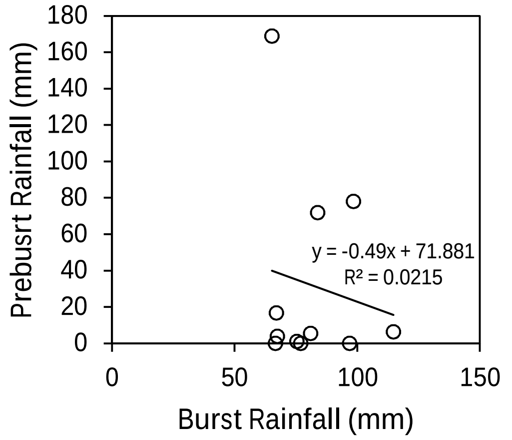


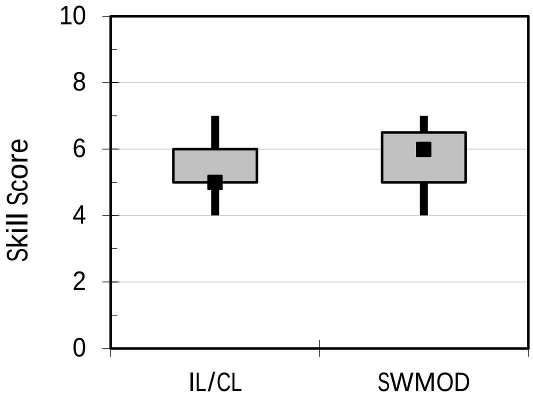
Axe Ck @ Sedgwick (VIC) - 3 hour bursts

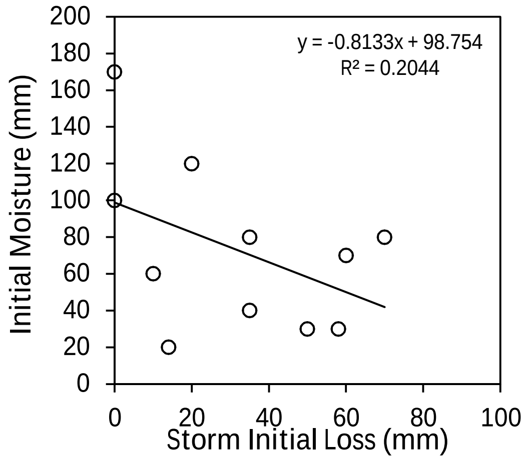


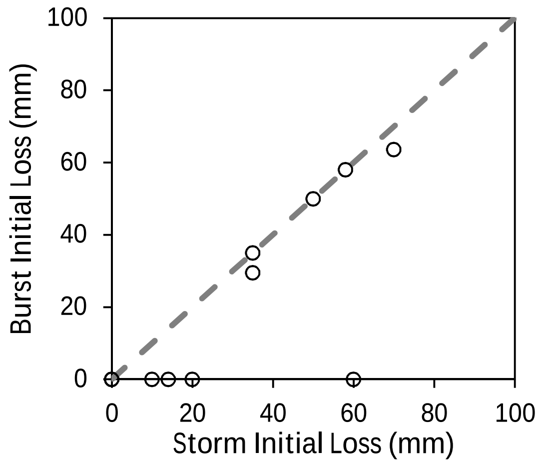
Celia Ck @ U/S Darwin R Dam (NT) - 3 hour bursts

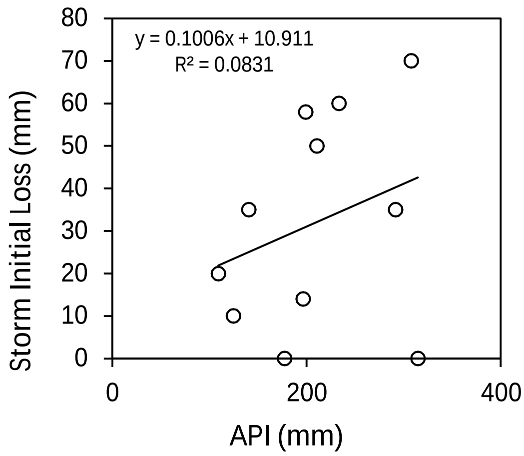


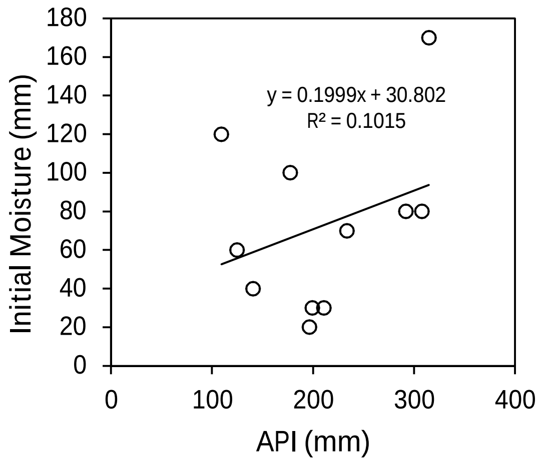




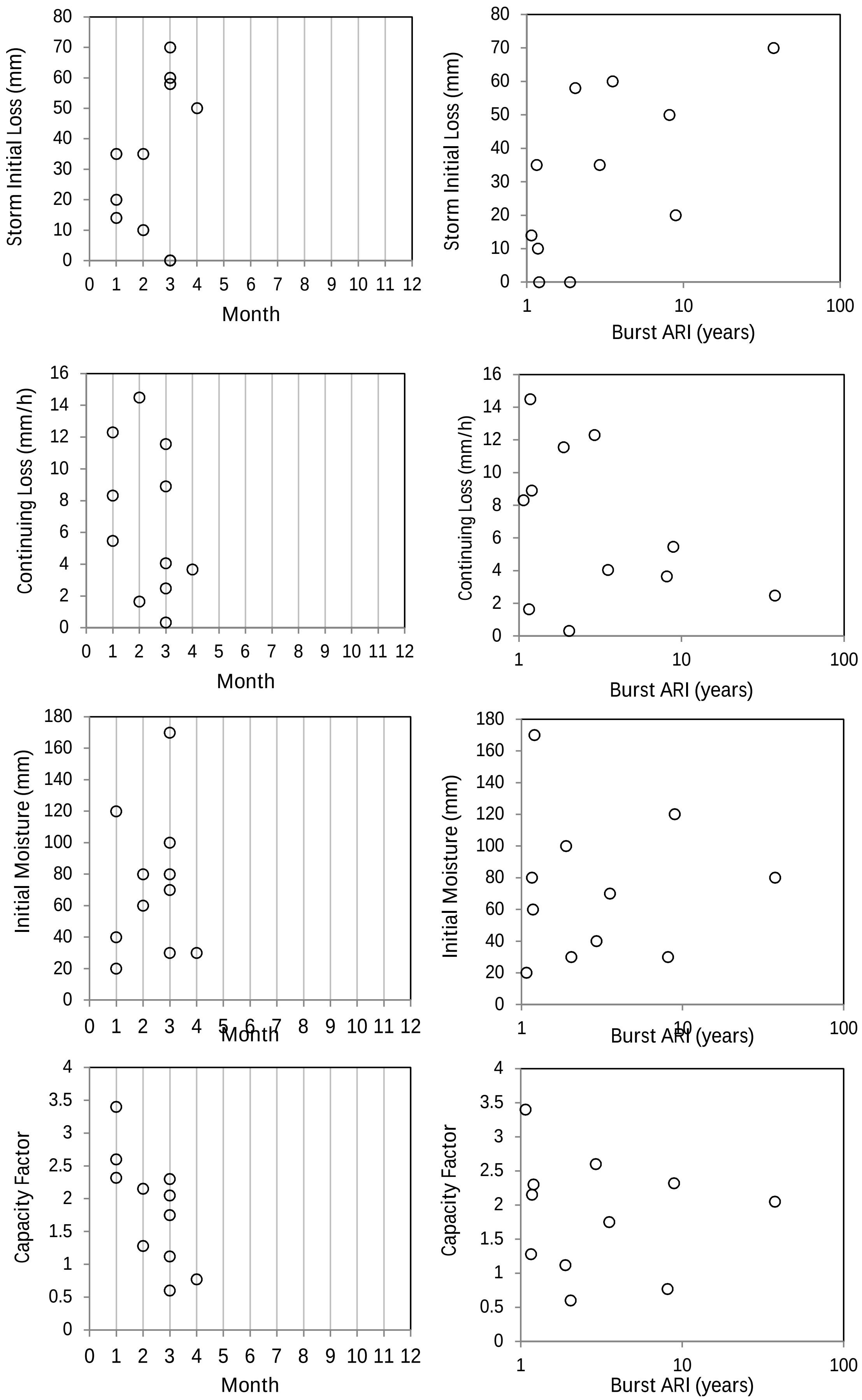




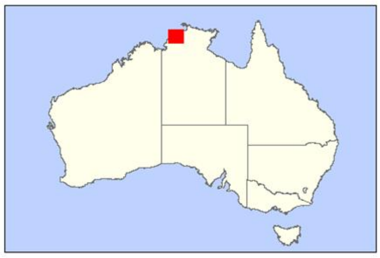


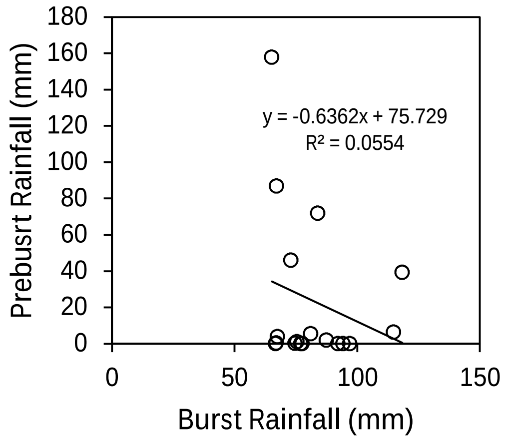


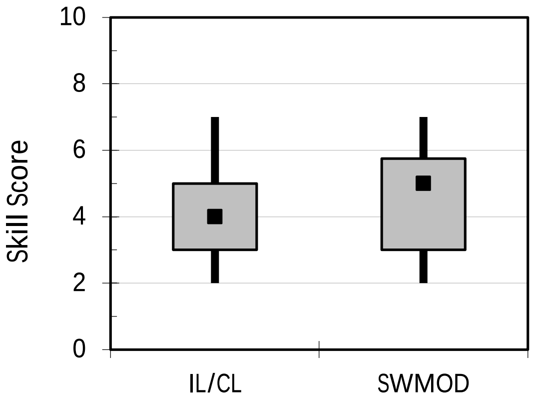
Celia Ck @ U/S Darwin R Dam (NT) - 3 hour bursts

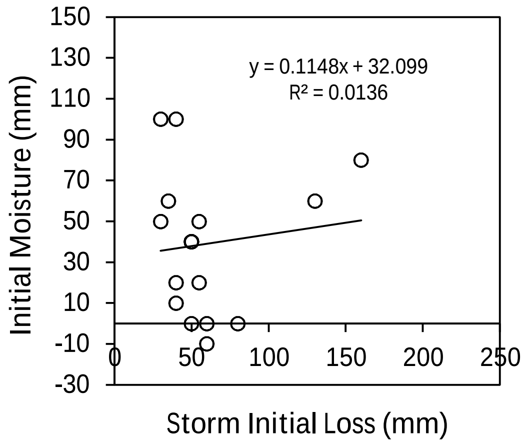


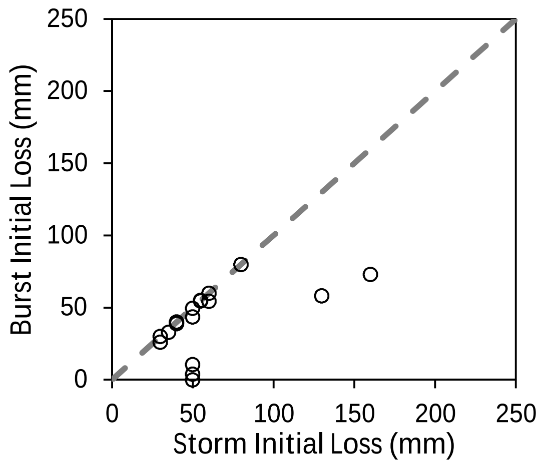
Coomalie Ck @ Stuart HWY (NT) - 3 hour bursts

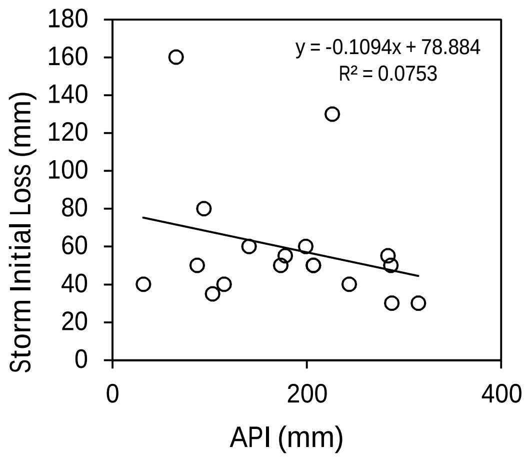


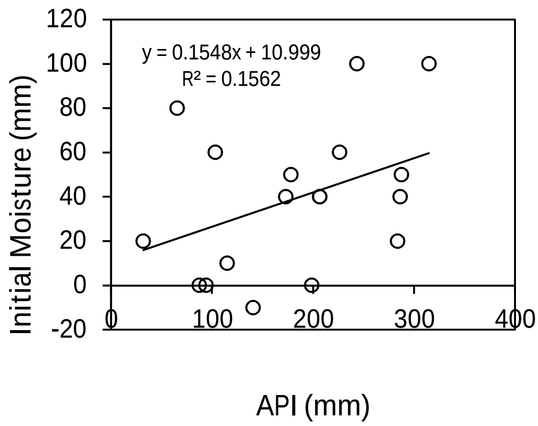




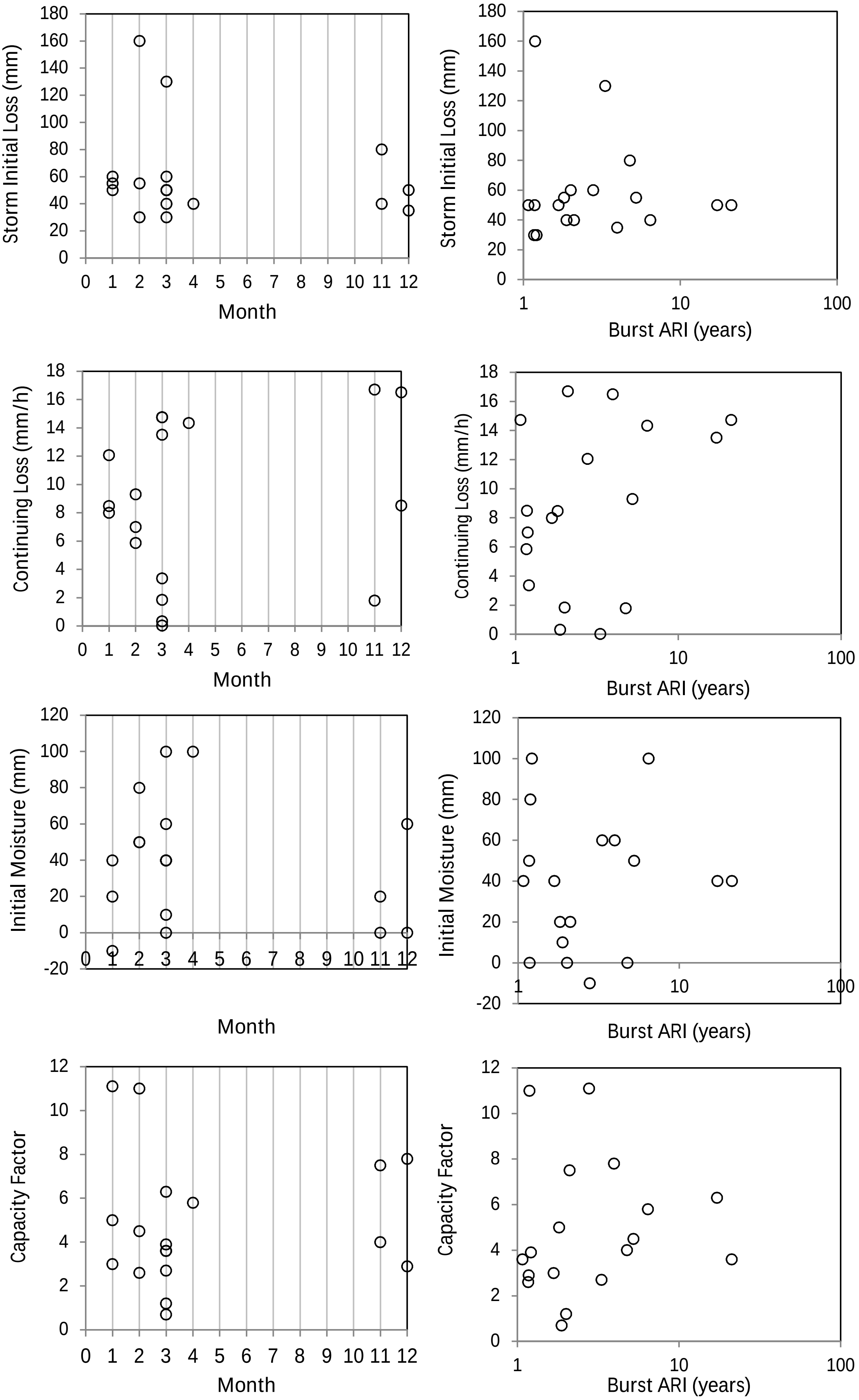




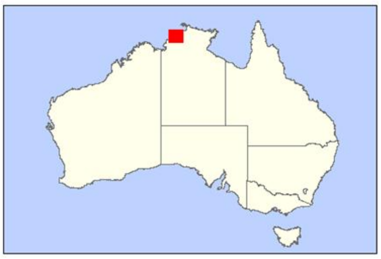


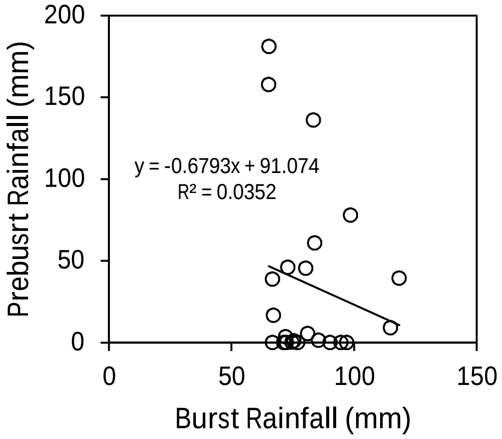


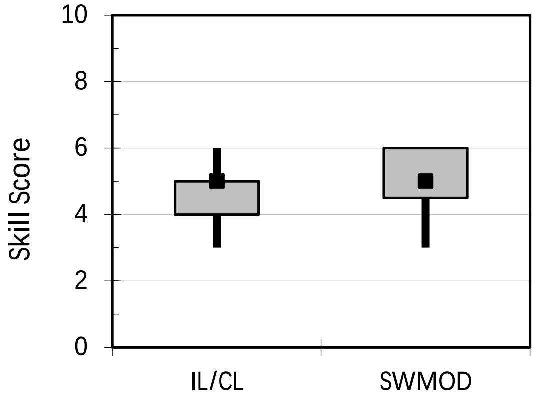
Coomalie Ck @ Stuart HWY (NT) - 3 hour bursts

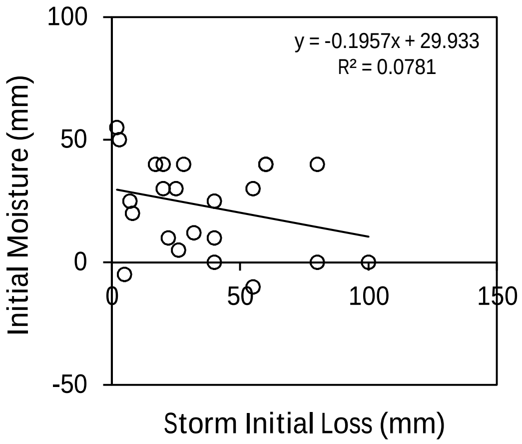


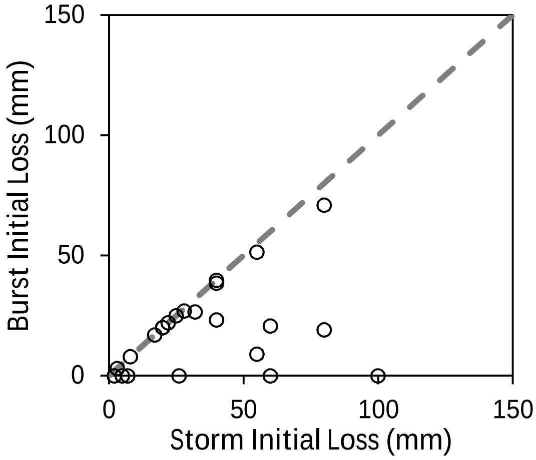
Manton R @ Manton Dam (NT) - 3 hour bursts

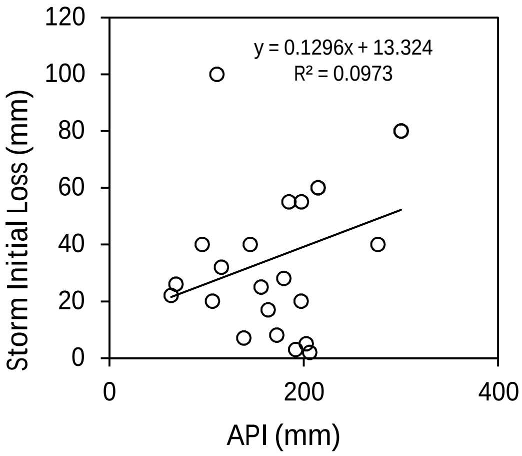


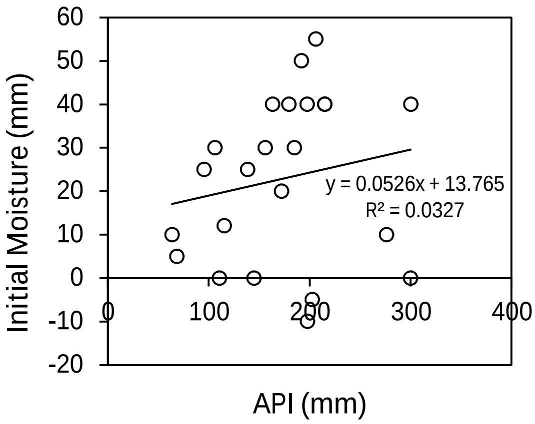




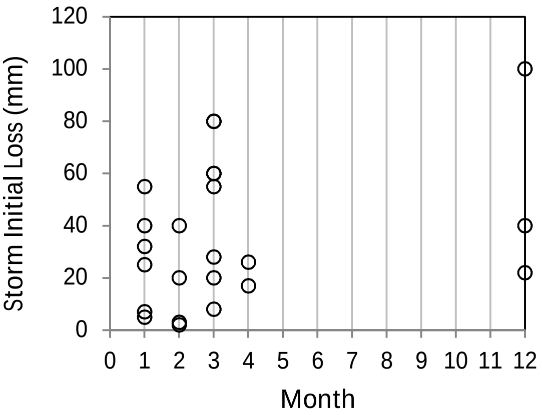


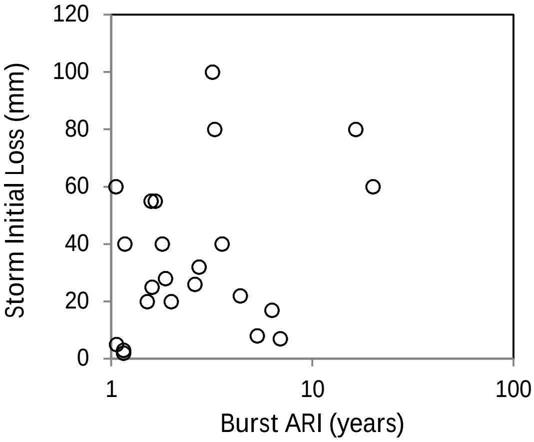


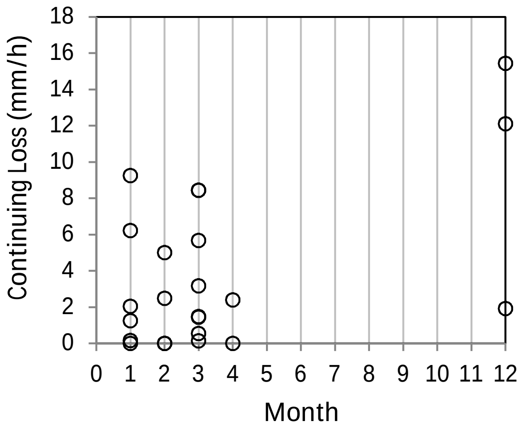


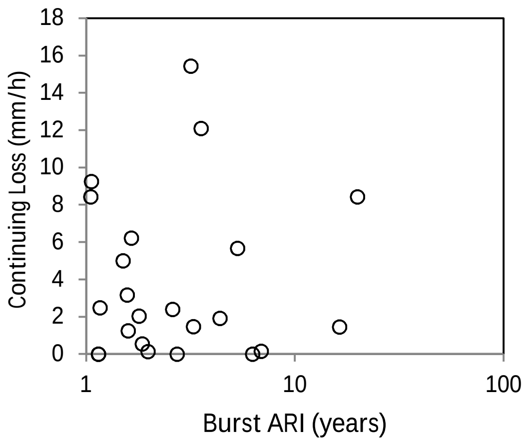


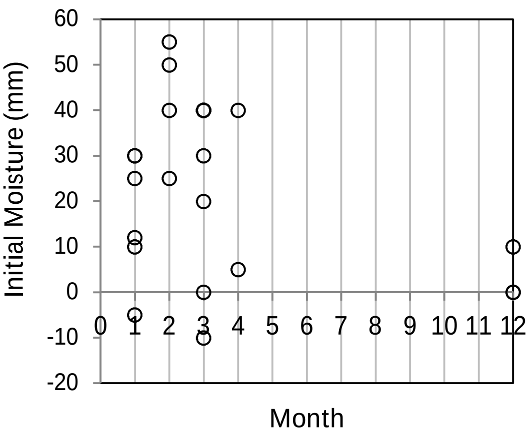
Manton R @ Manton Dam (NT) - 3 hour bursts

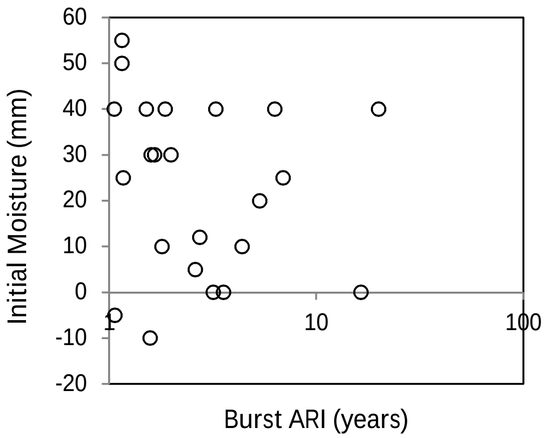


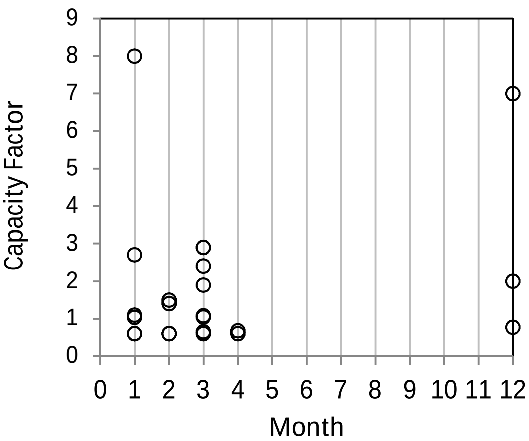


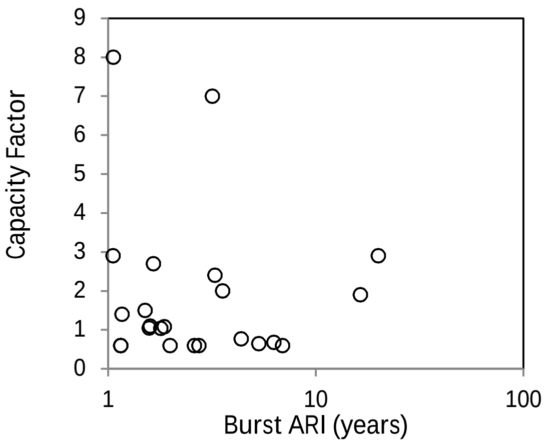




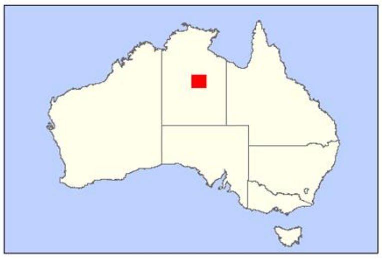


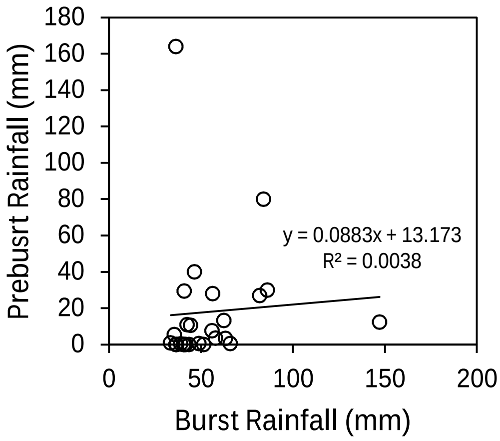


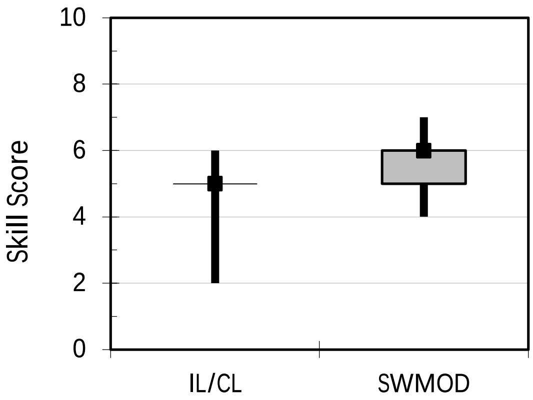


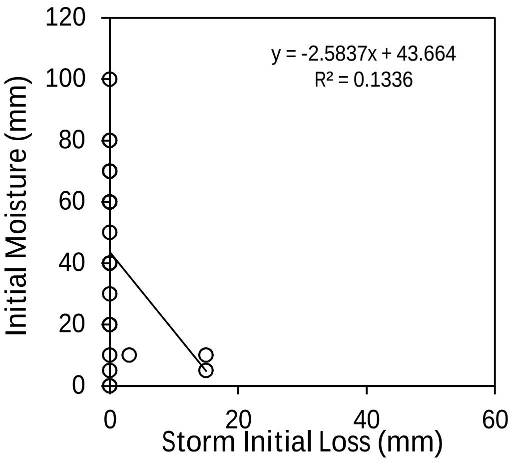


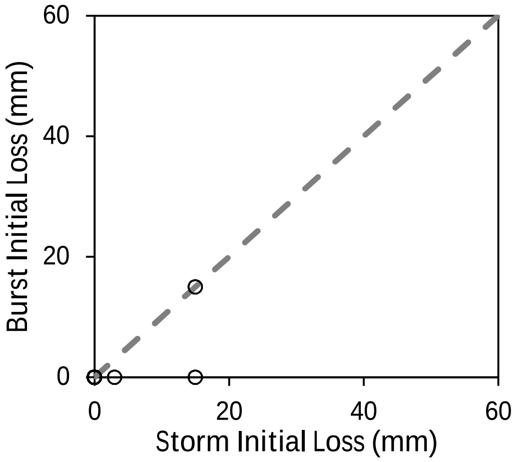
Tennant Ck @ Old Telegraph Stn (NT) - 3 hour bursts

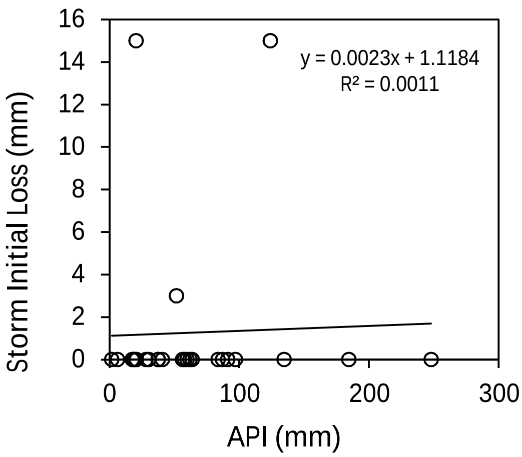


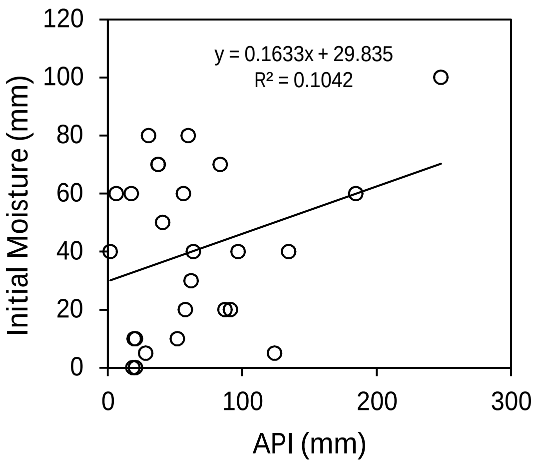




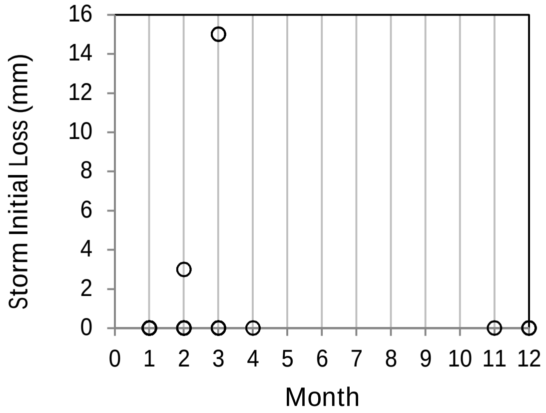


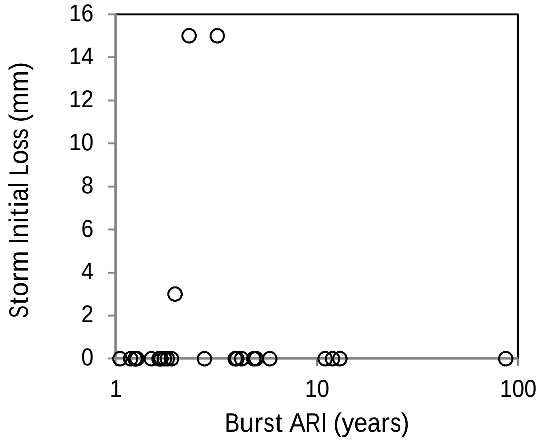


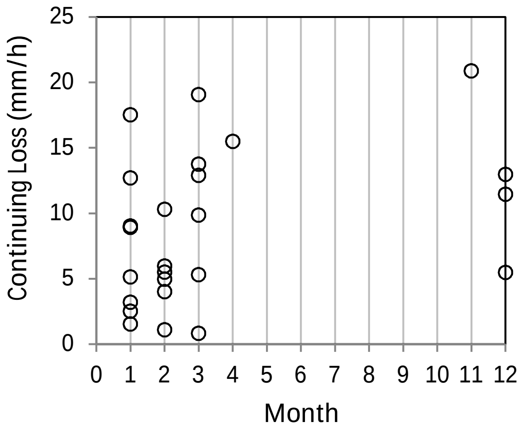


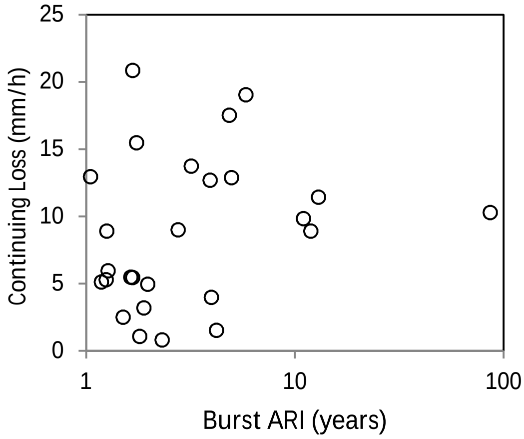


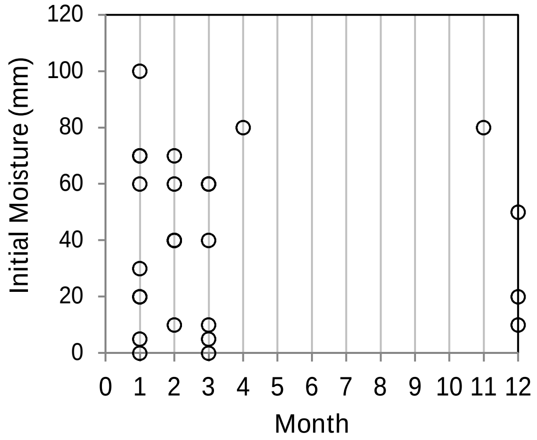
Tennant Ck @ Old Telegraph Stn (NT) - 3 hour bursts

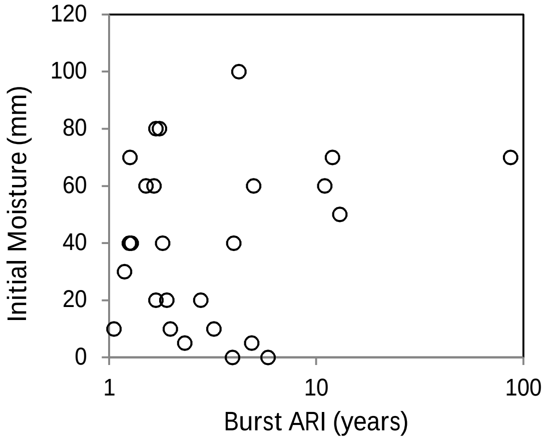


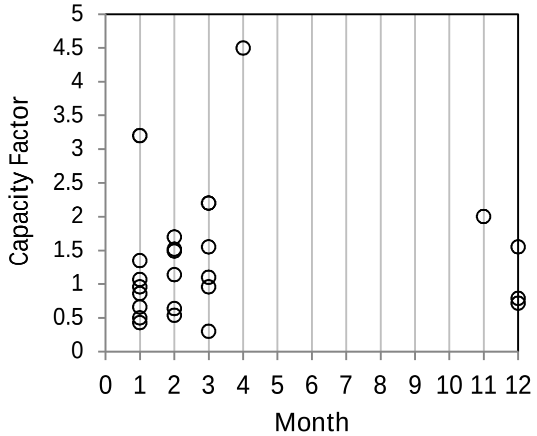


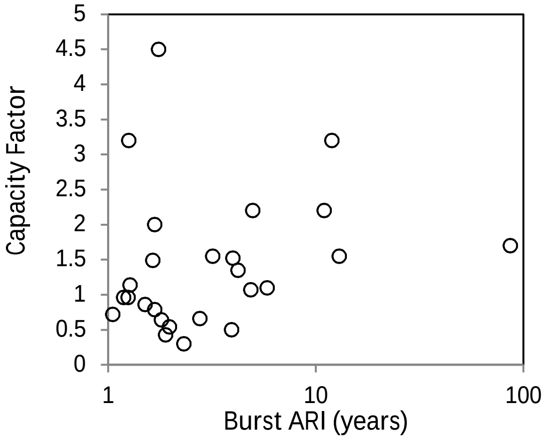




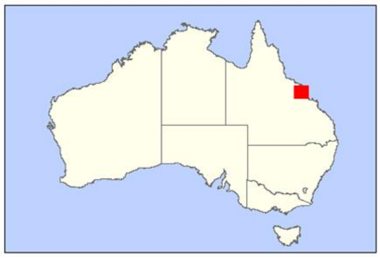


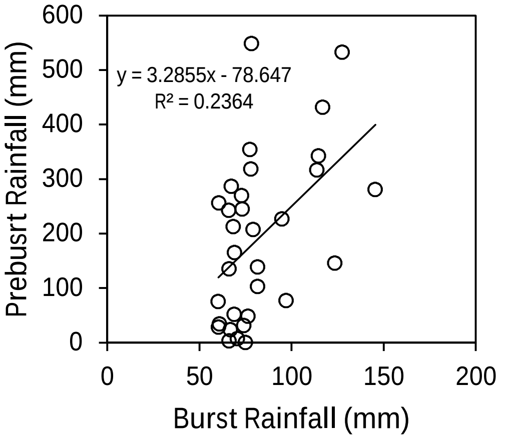


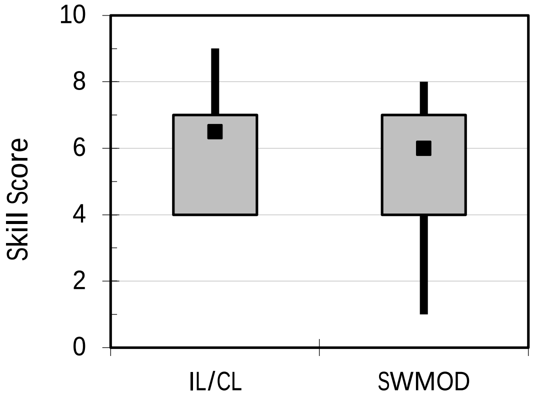


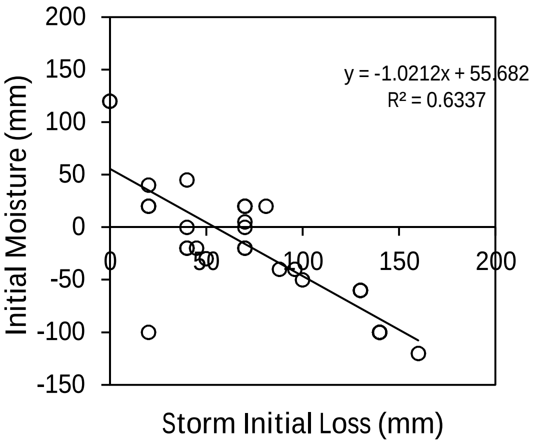


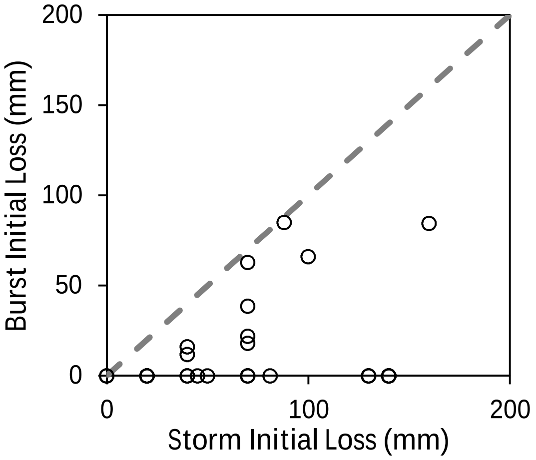
Broken @ Old Racecourse (Qld) - 3 hour bursts

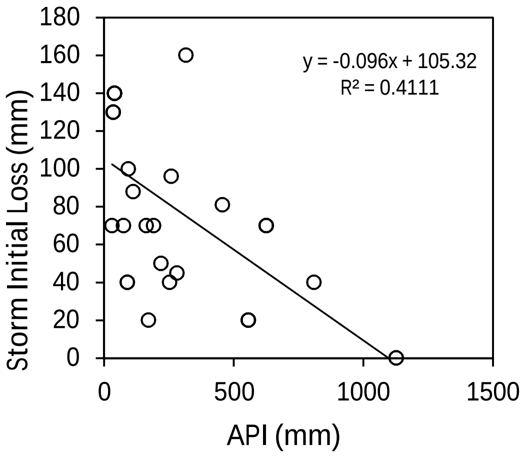


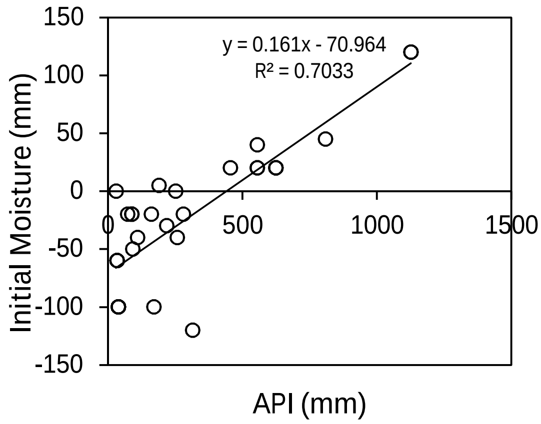




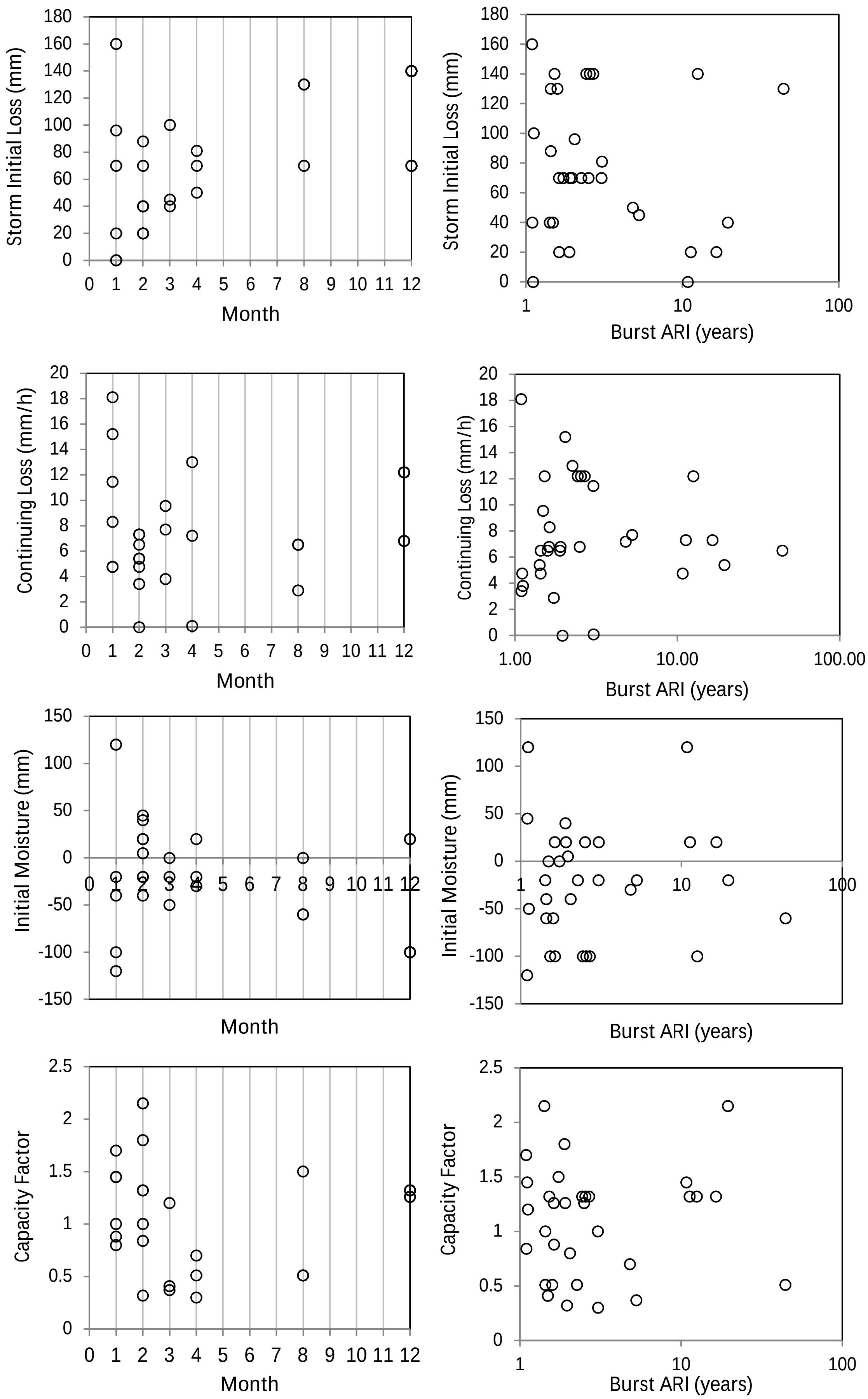




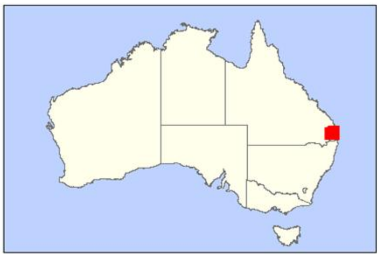


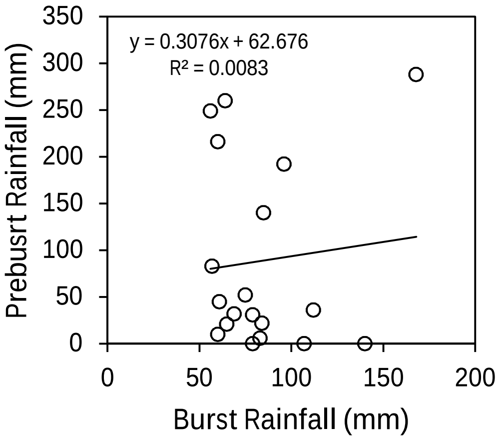


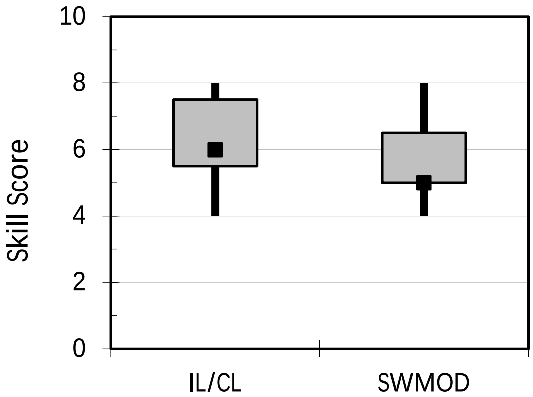
Broken @ Old Racecourse (Qld) - 3 hour bursts

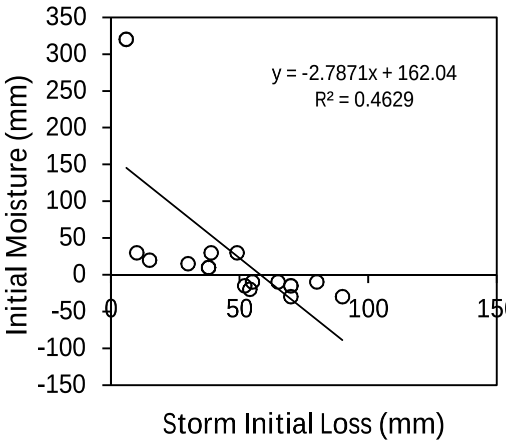


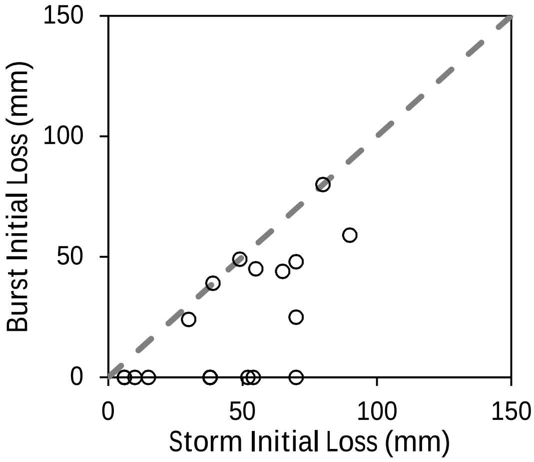
Caboolture @ Upper Caboolture (Qld) - 3 hour bursts

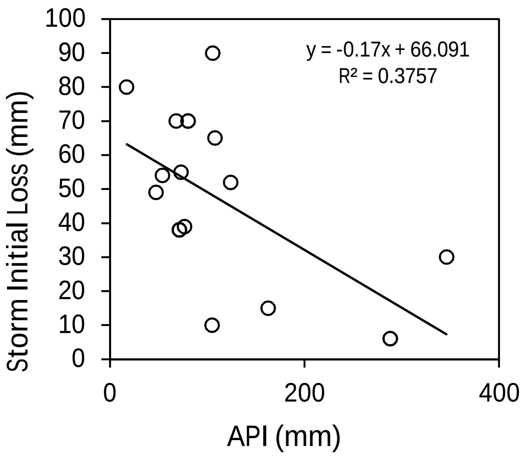


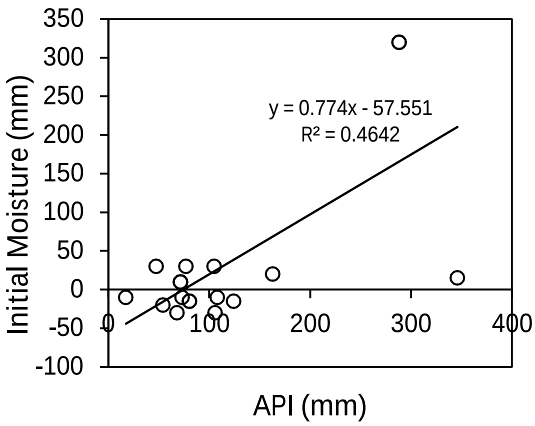




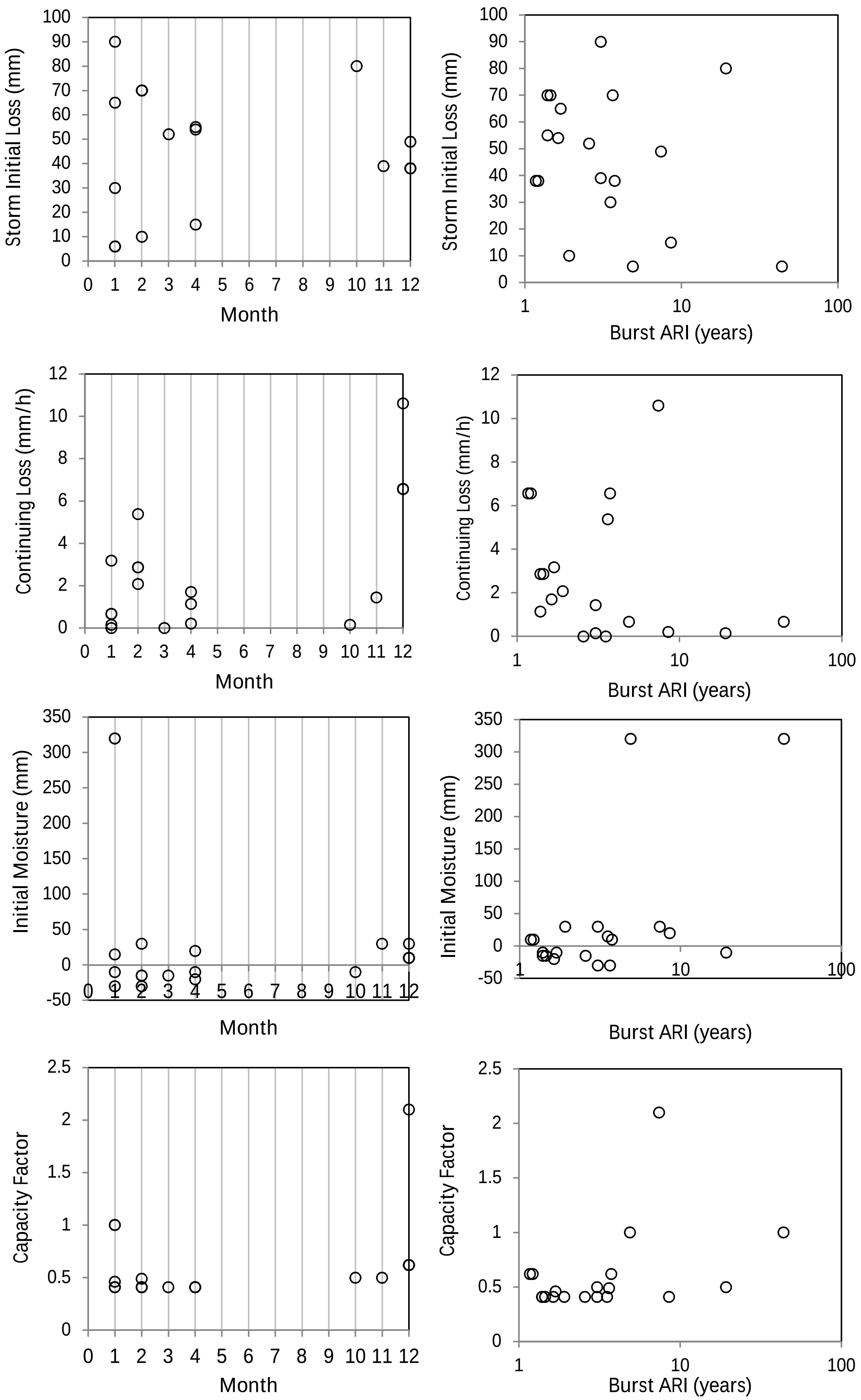




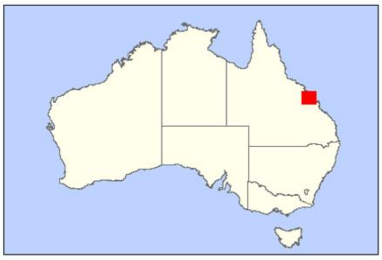


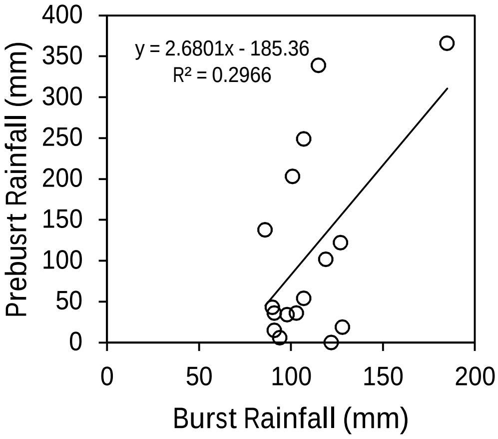


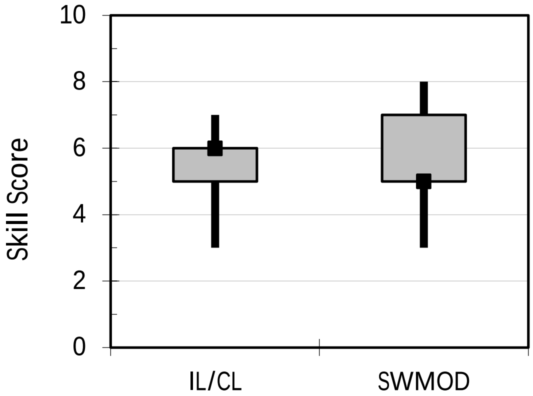
Caboolture @ Upper Caboolture (Qld) - 3 hour bursts

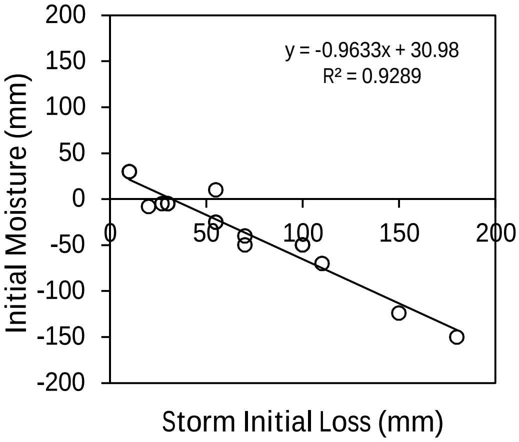


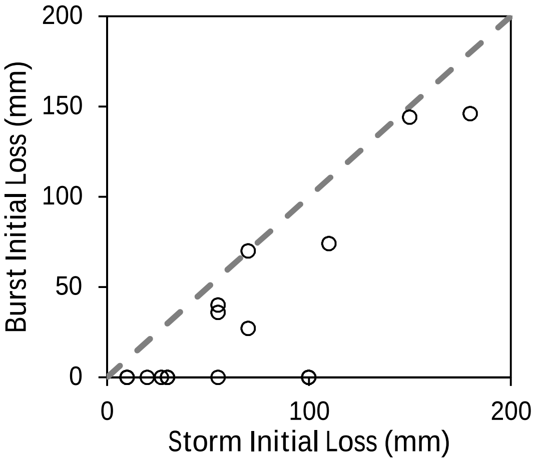
Carmila Ck @ Carmila (Qld) - 3 hour bursts

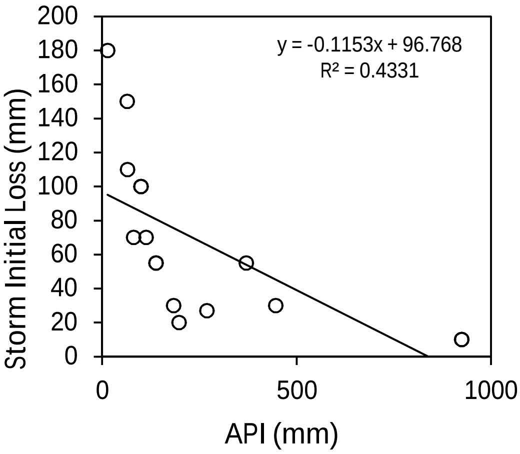


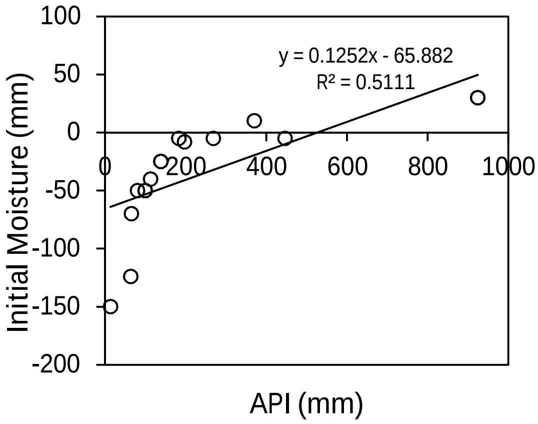




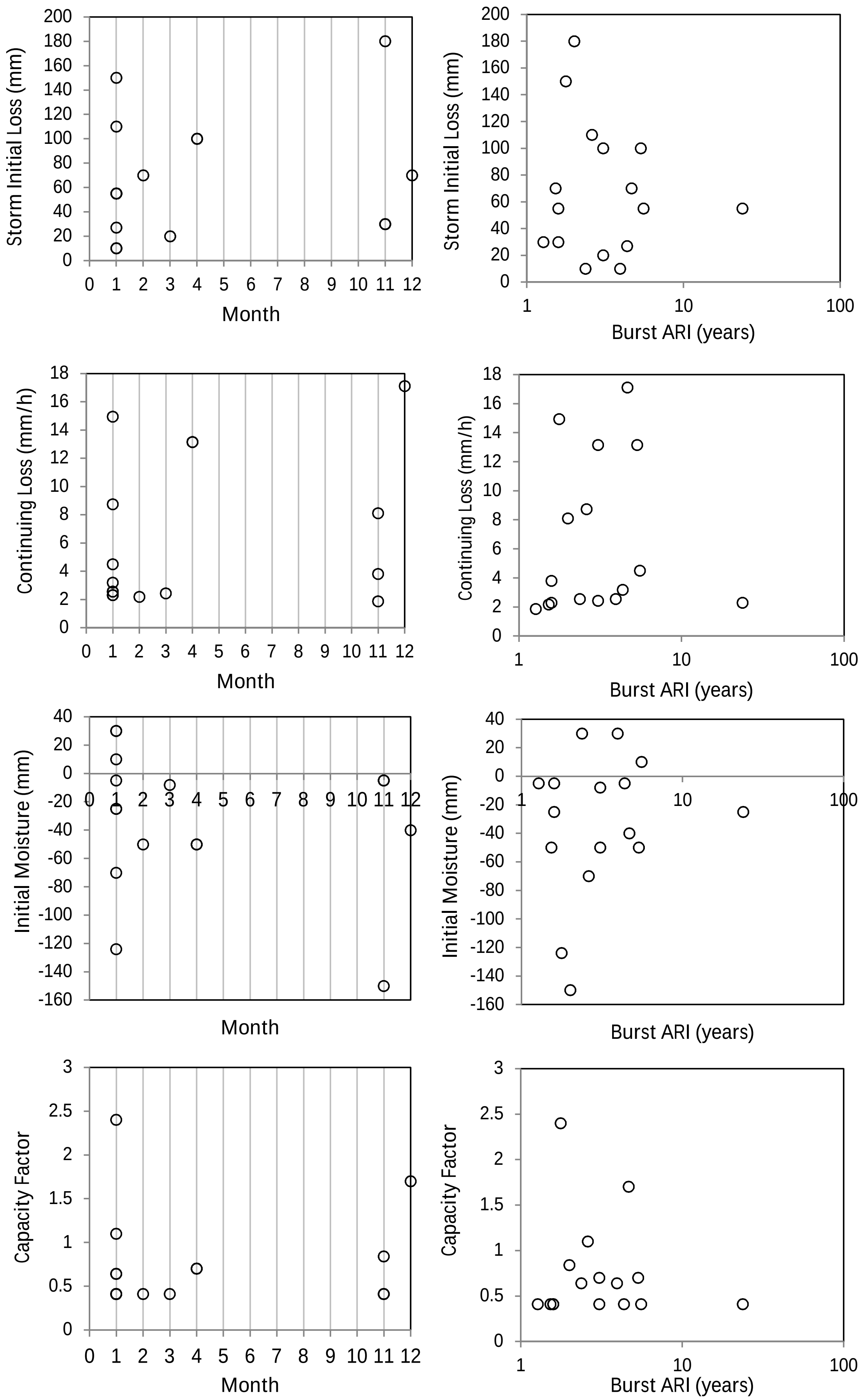




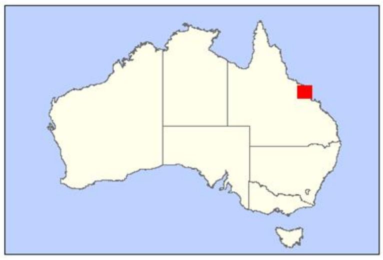


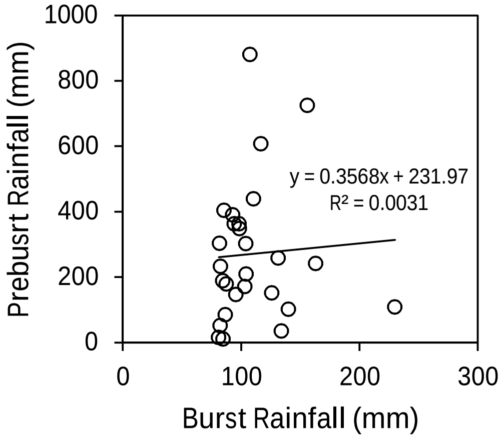


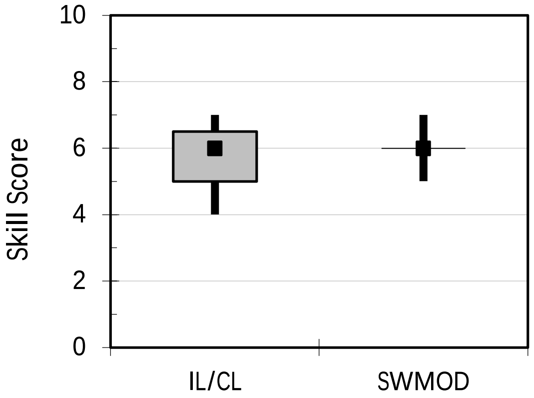
Carmila Ck @ Carmila (Qld) - 3 hour bursts

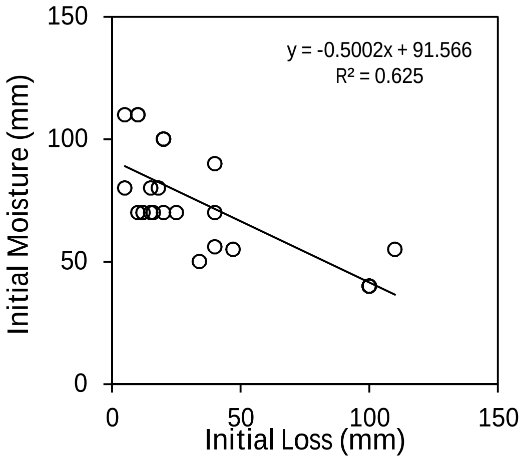


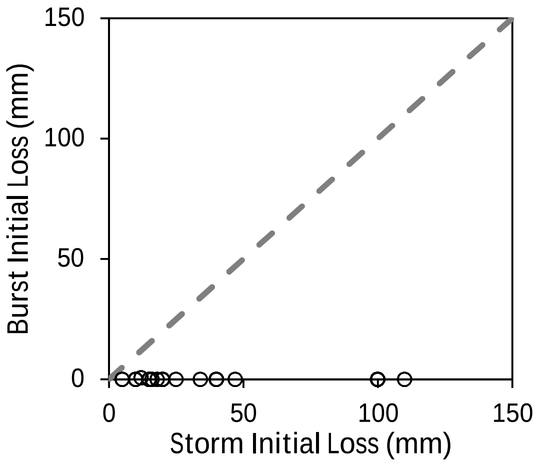
Finch Hatton Ck @ Dam Site (Qld) - 3 hour bursts

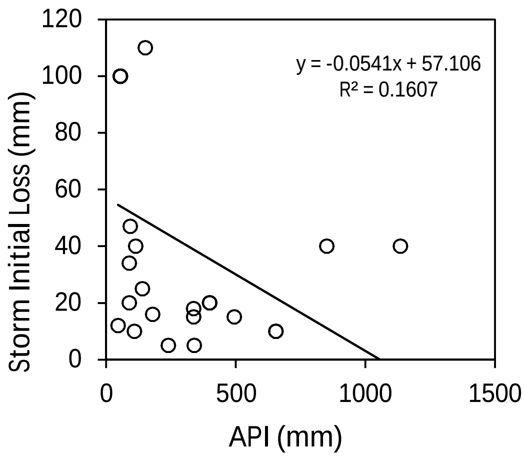


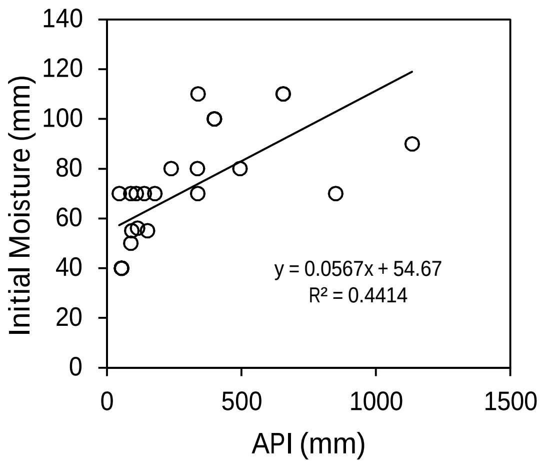




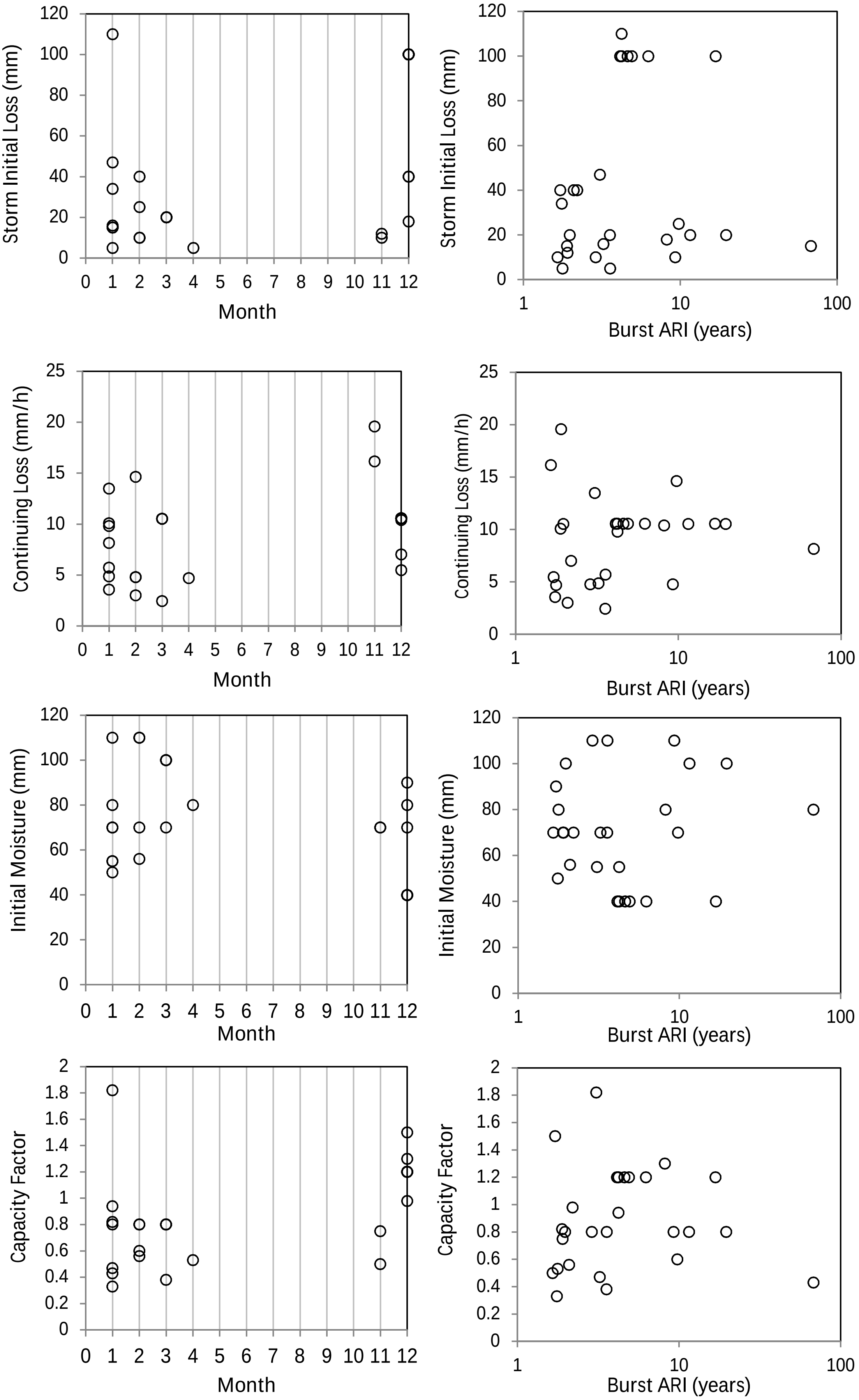




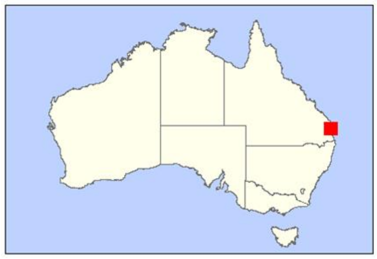


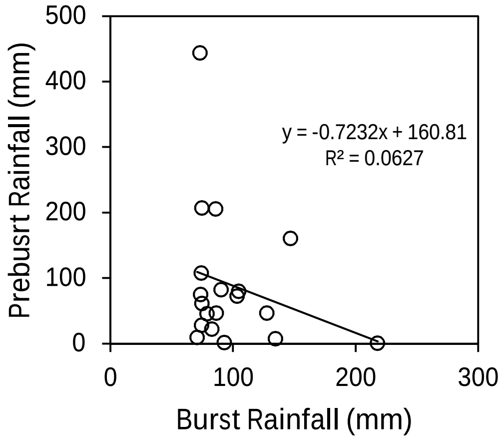


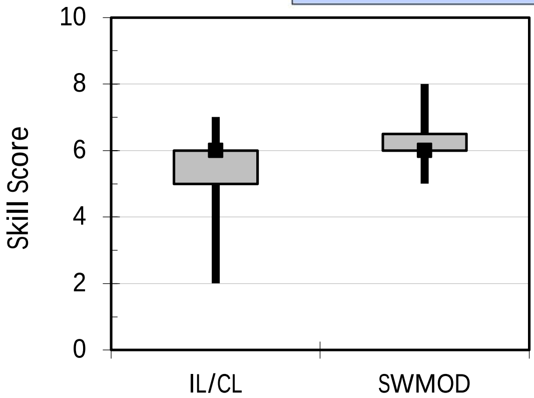
Finch Hatton Ck @ Dam Site (Qld) - 3 hour bursts

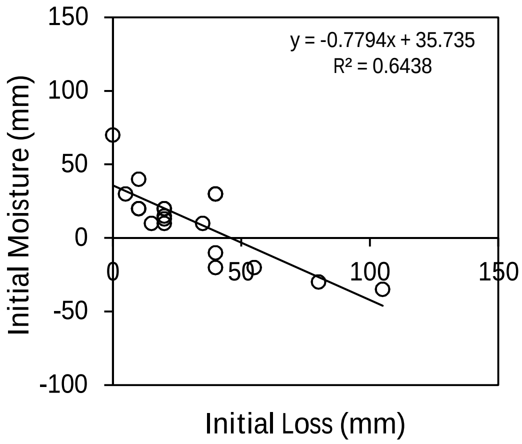


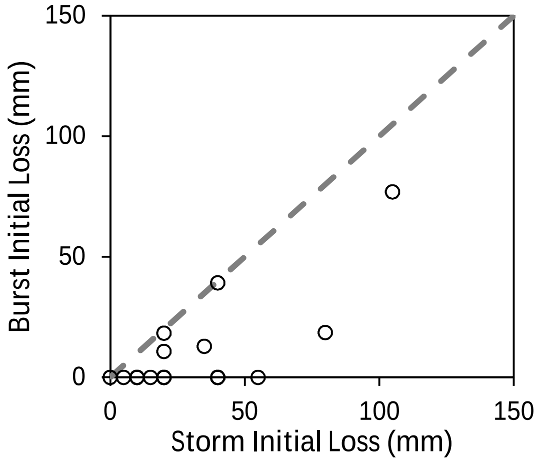
North Maroochy River @ Eumundi (Qld) - 3 hour bursts

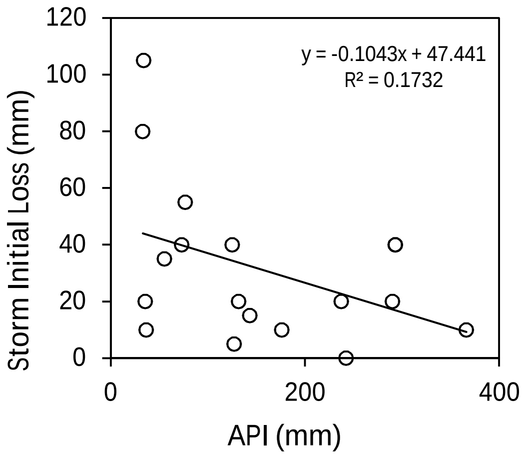


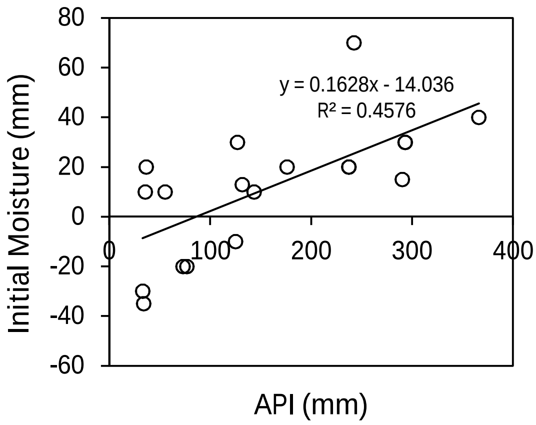




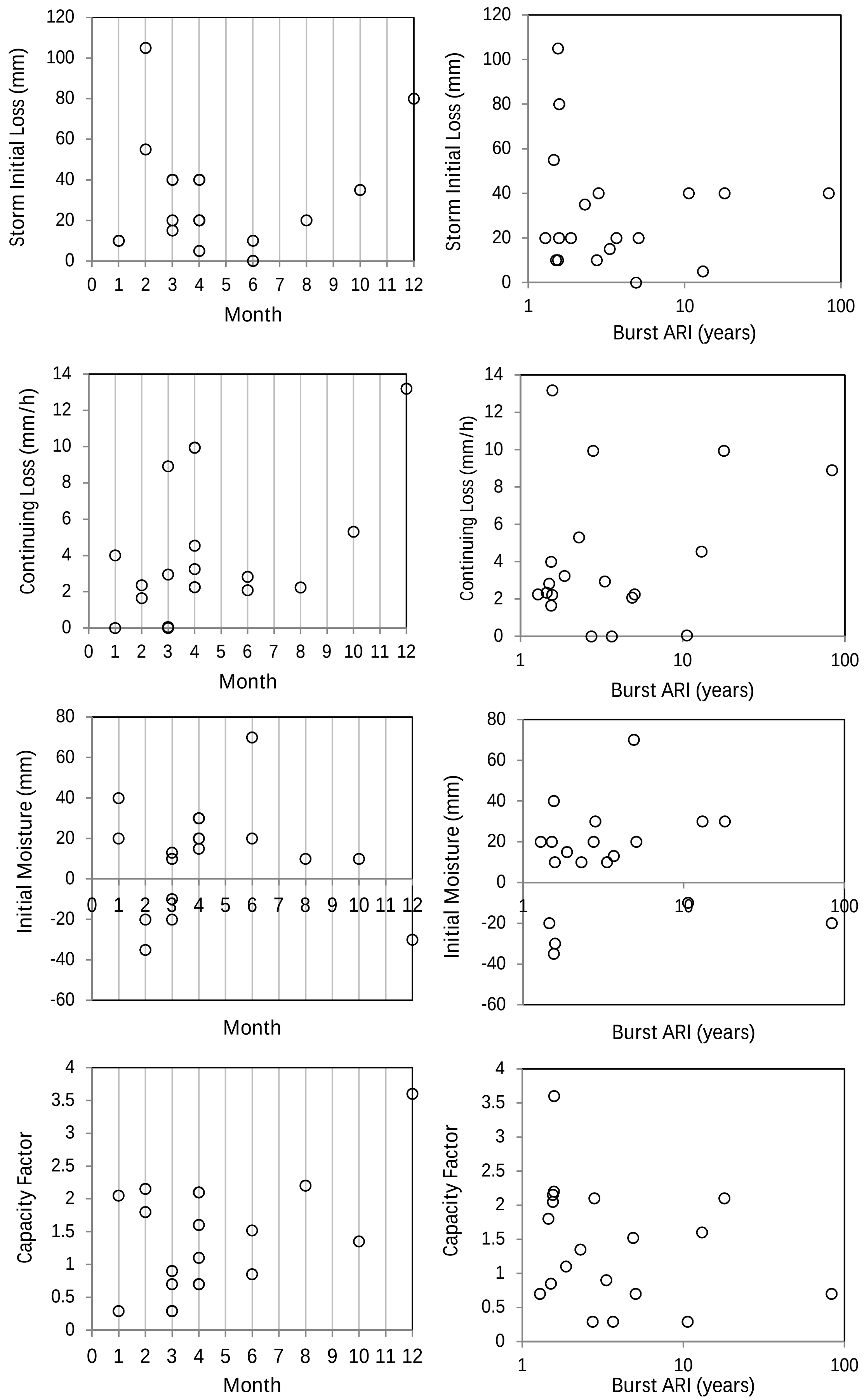




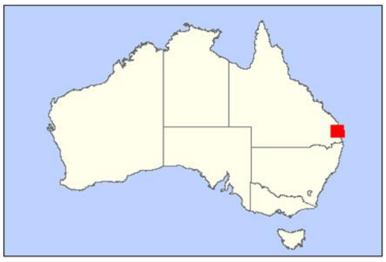


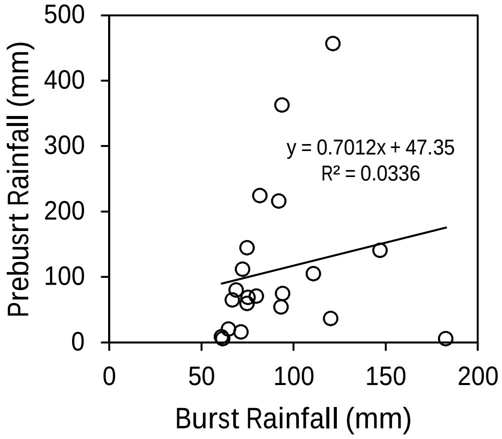


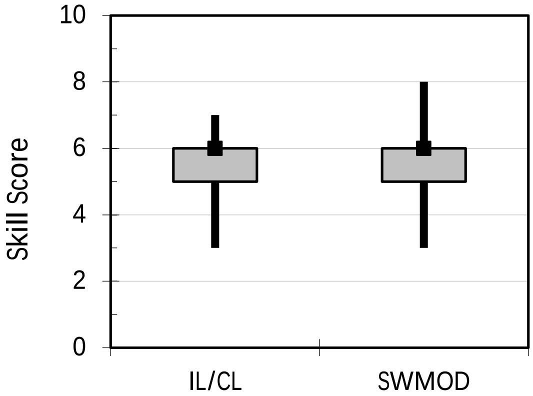
North Maroochy River @ Eumundi (Qld) - 3 hour bursts

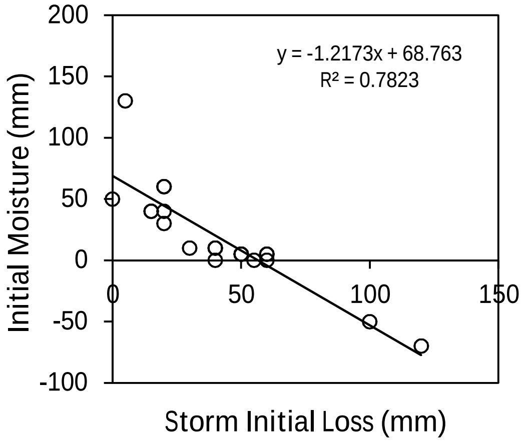


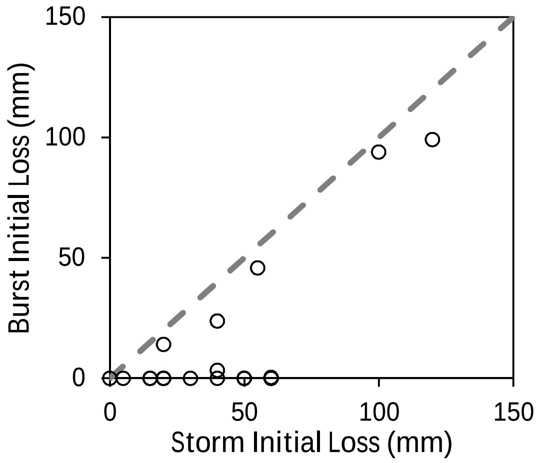
South Maroochy @ Kiamba (QLD) - 3 hour bursts

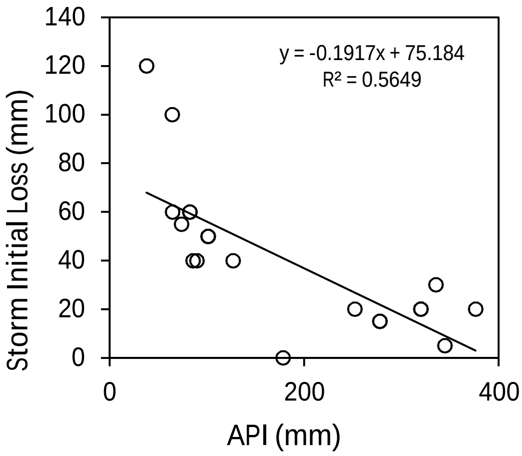


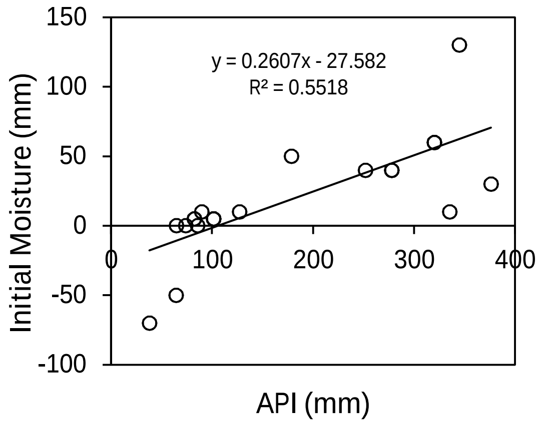




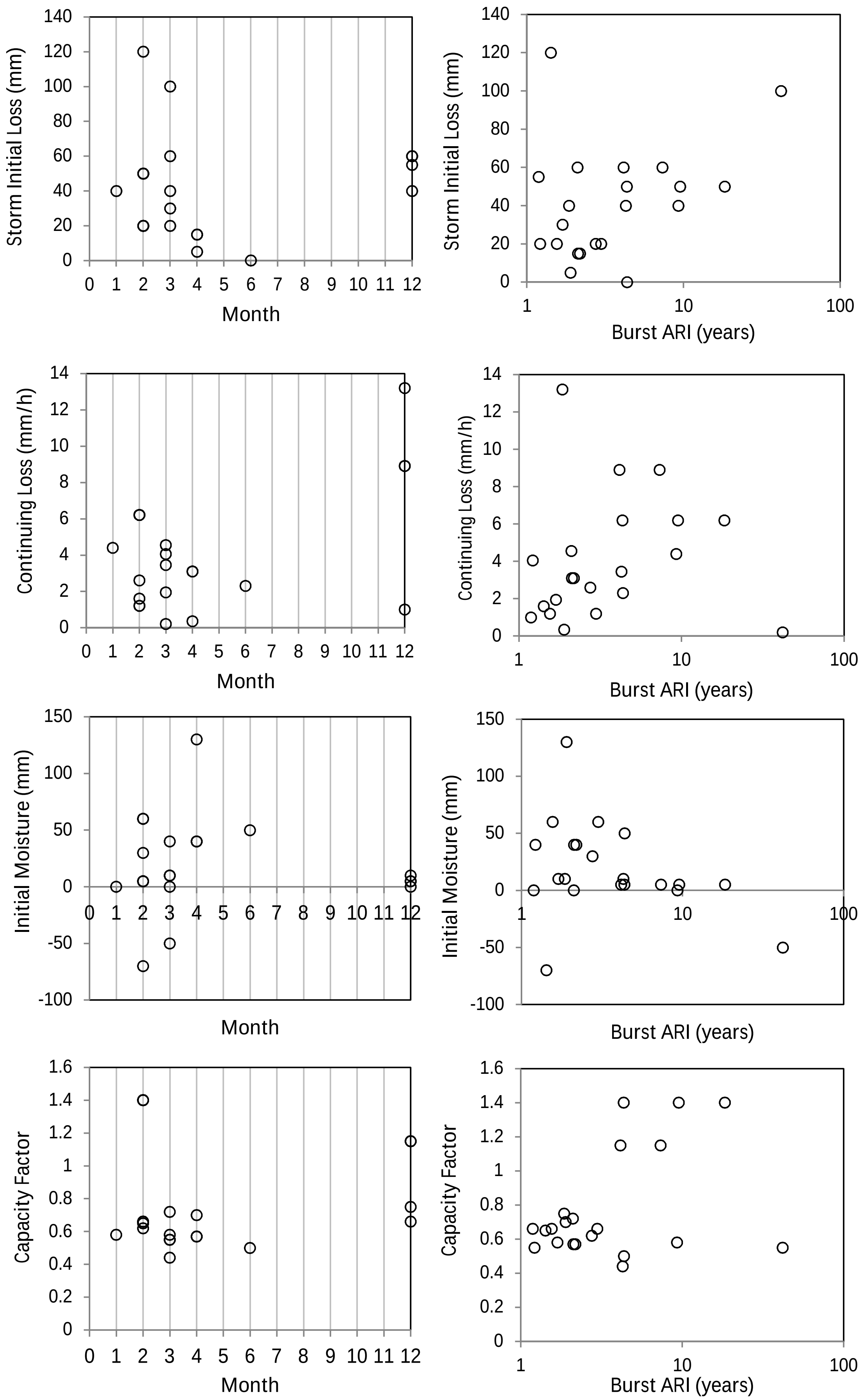




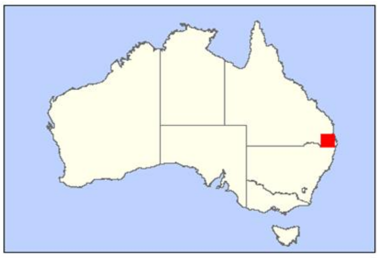


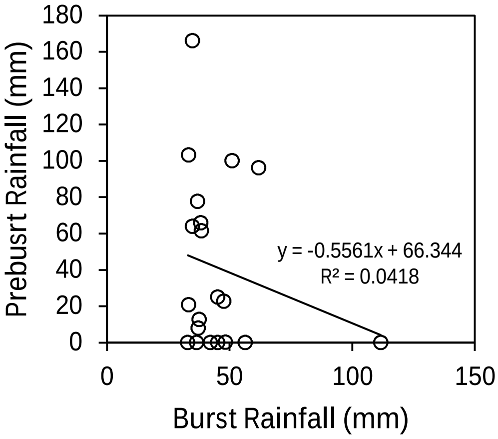


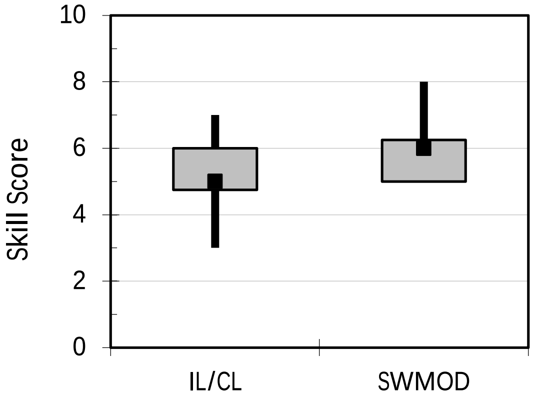
South Maroochy @ Kiamba (QLD) - 3 hour bursts

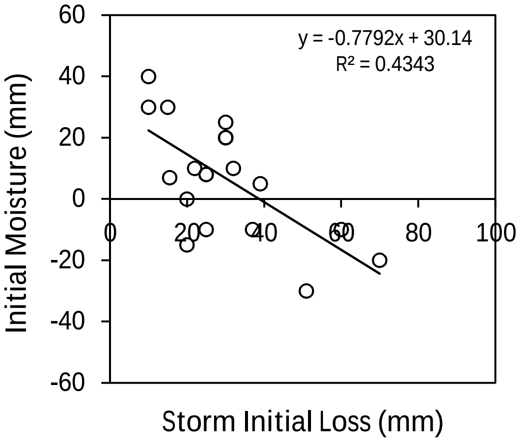


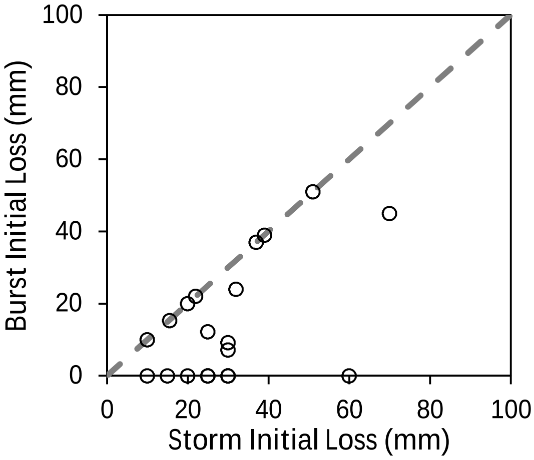
Spring Ck @ Killarney (Qld) - 3 hour bursts

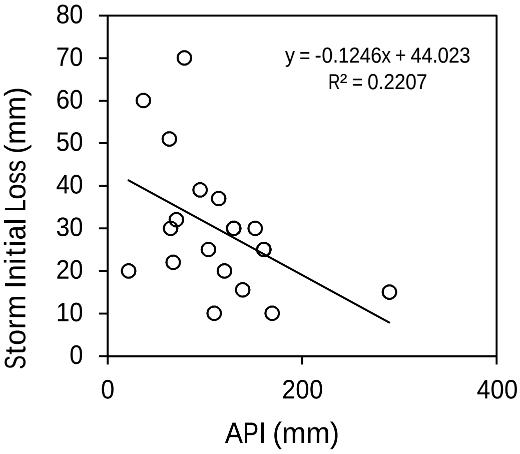


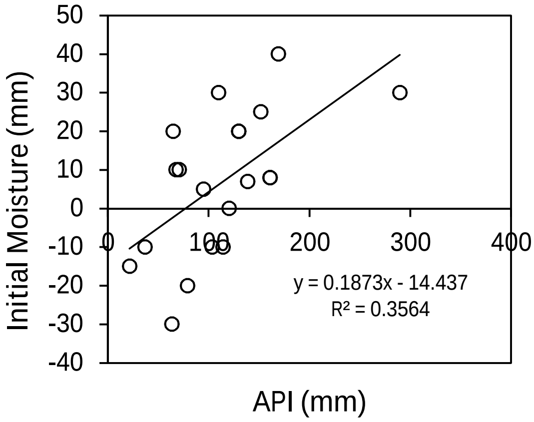




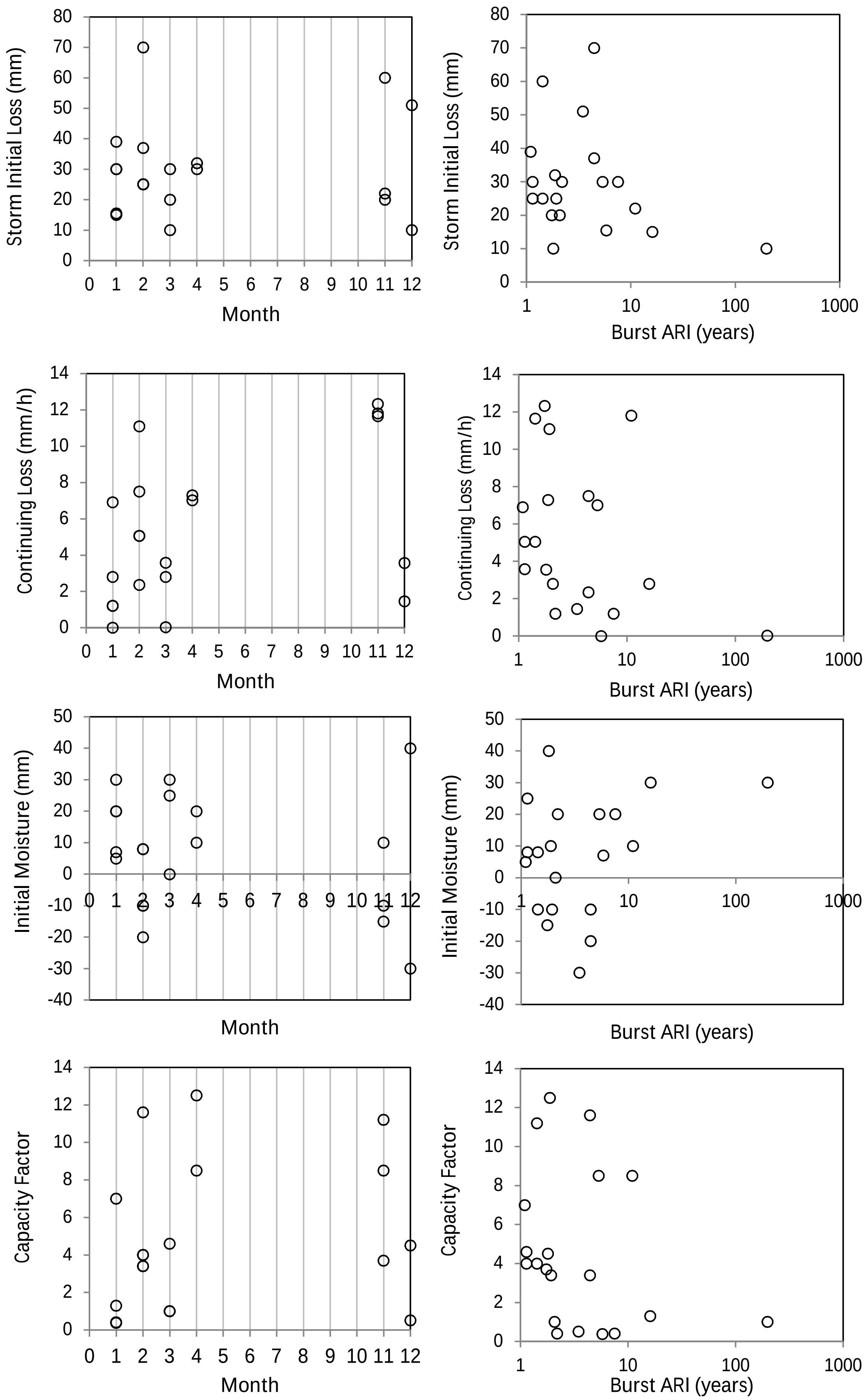




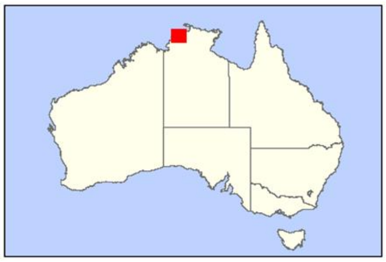


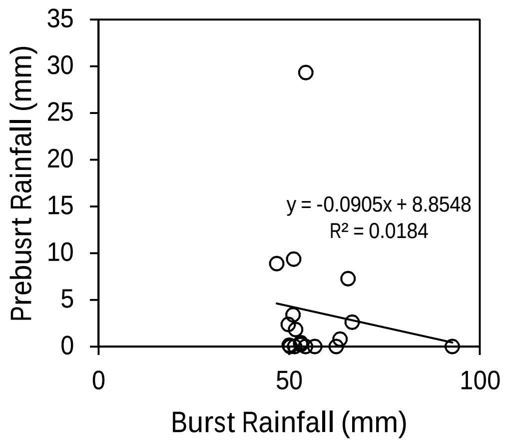


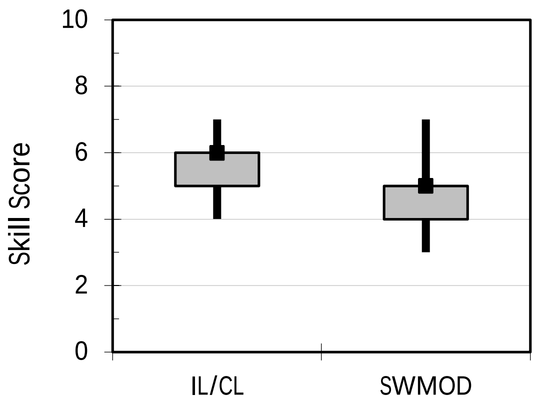
Spring Ck @ Killarney (Qld) - 3 hour bursts

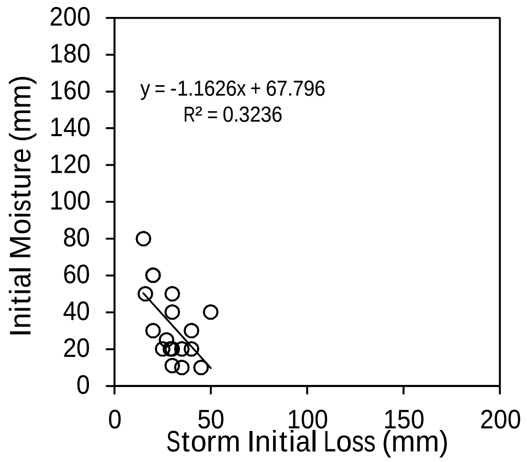


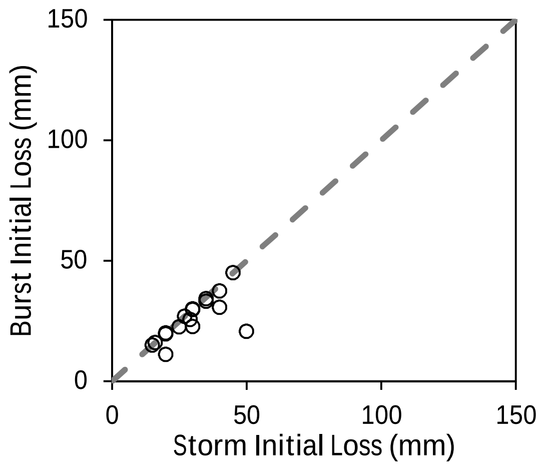
Loss Summary - Fletcher Ck @ Frog Hollow (WA) - 3 hour bursts

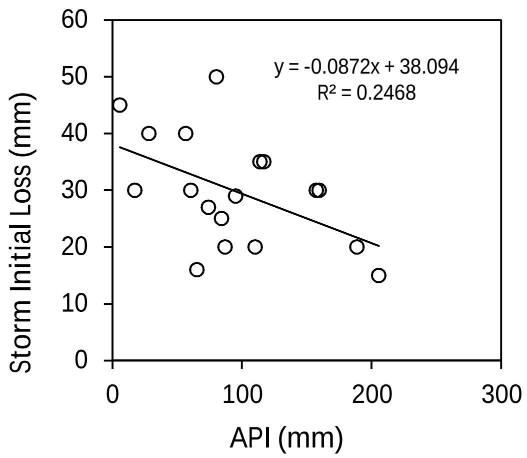


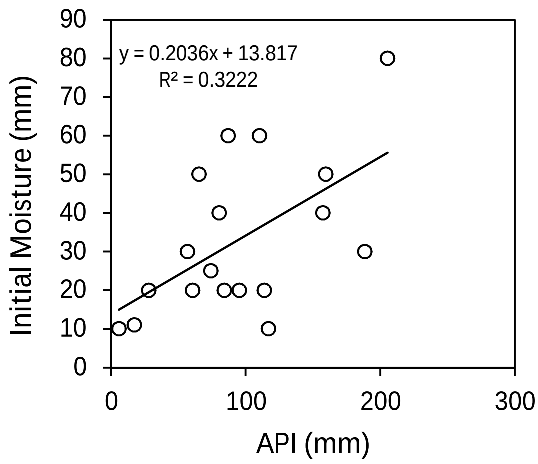




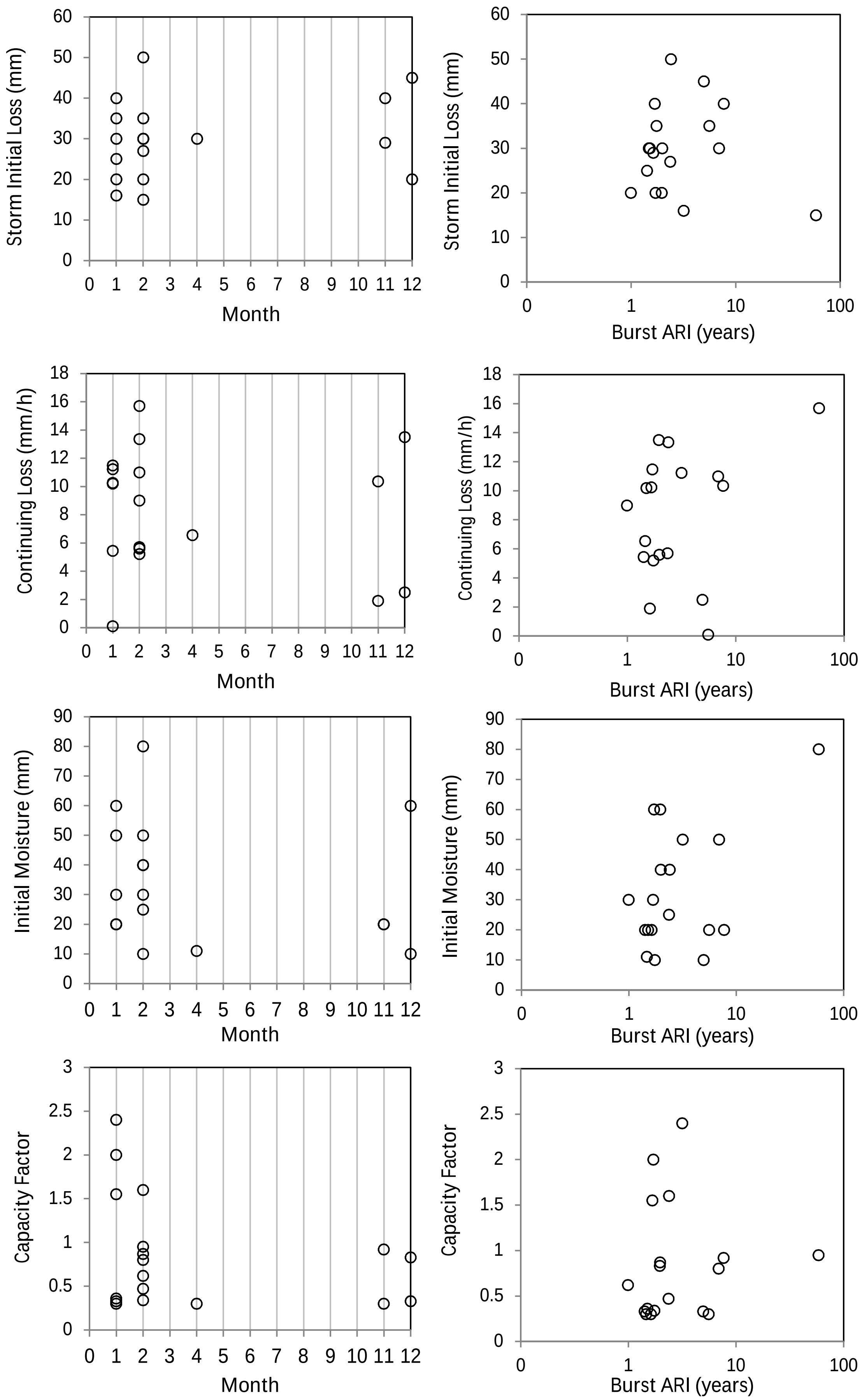




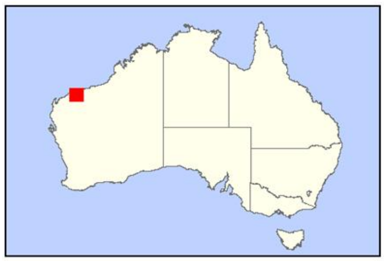


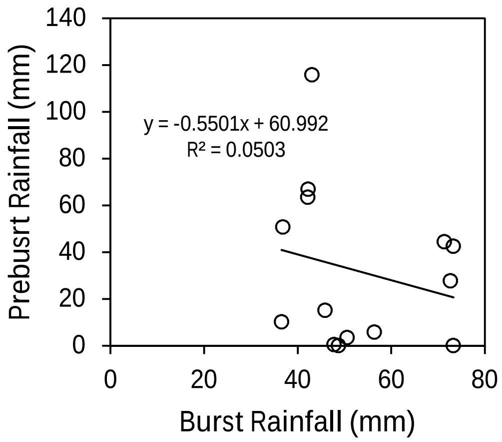


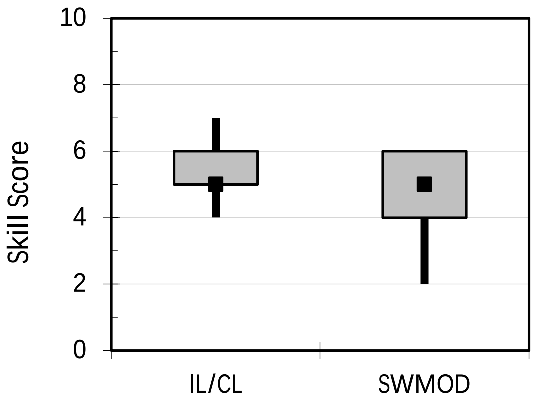
Loss Summary - Fletcher Ck @ Frog Hollow (WA) - 3 hour bursts

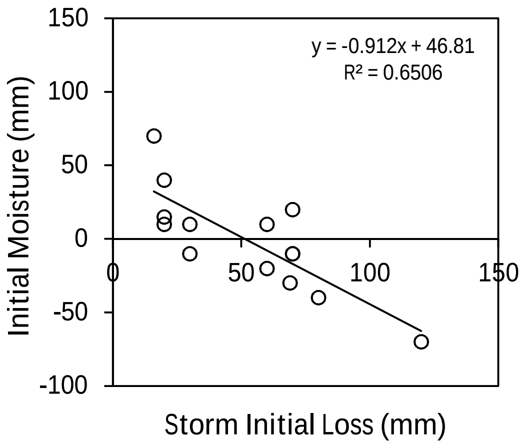


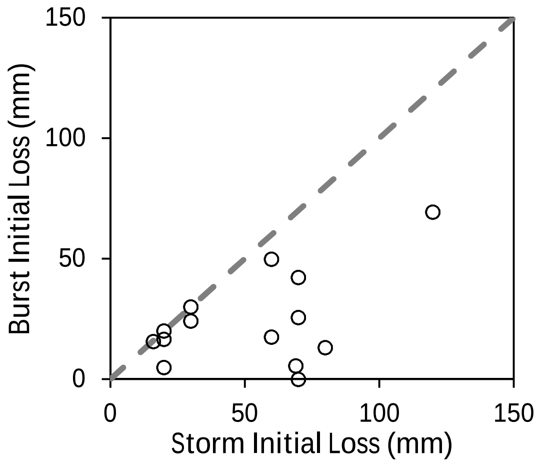
Harding @ Marmurrina Pool U-South (WA) - 3 hour bursts

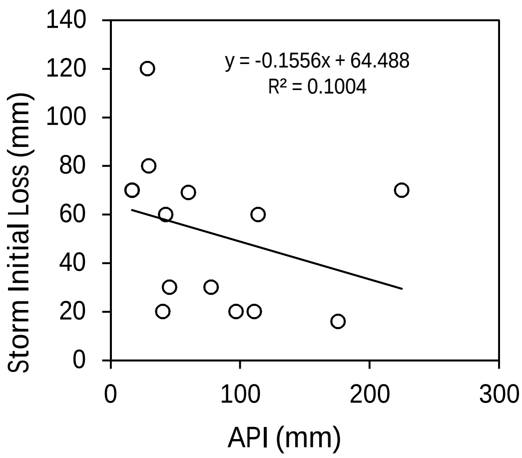


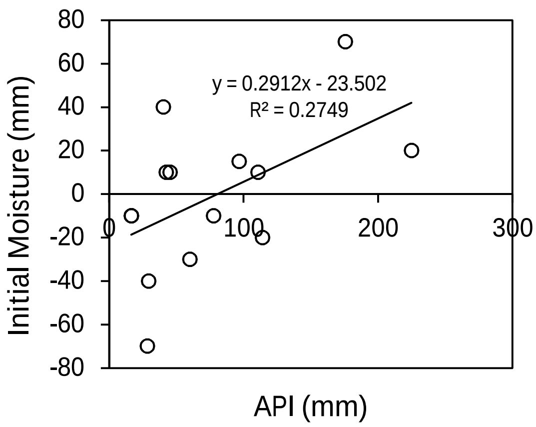




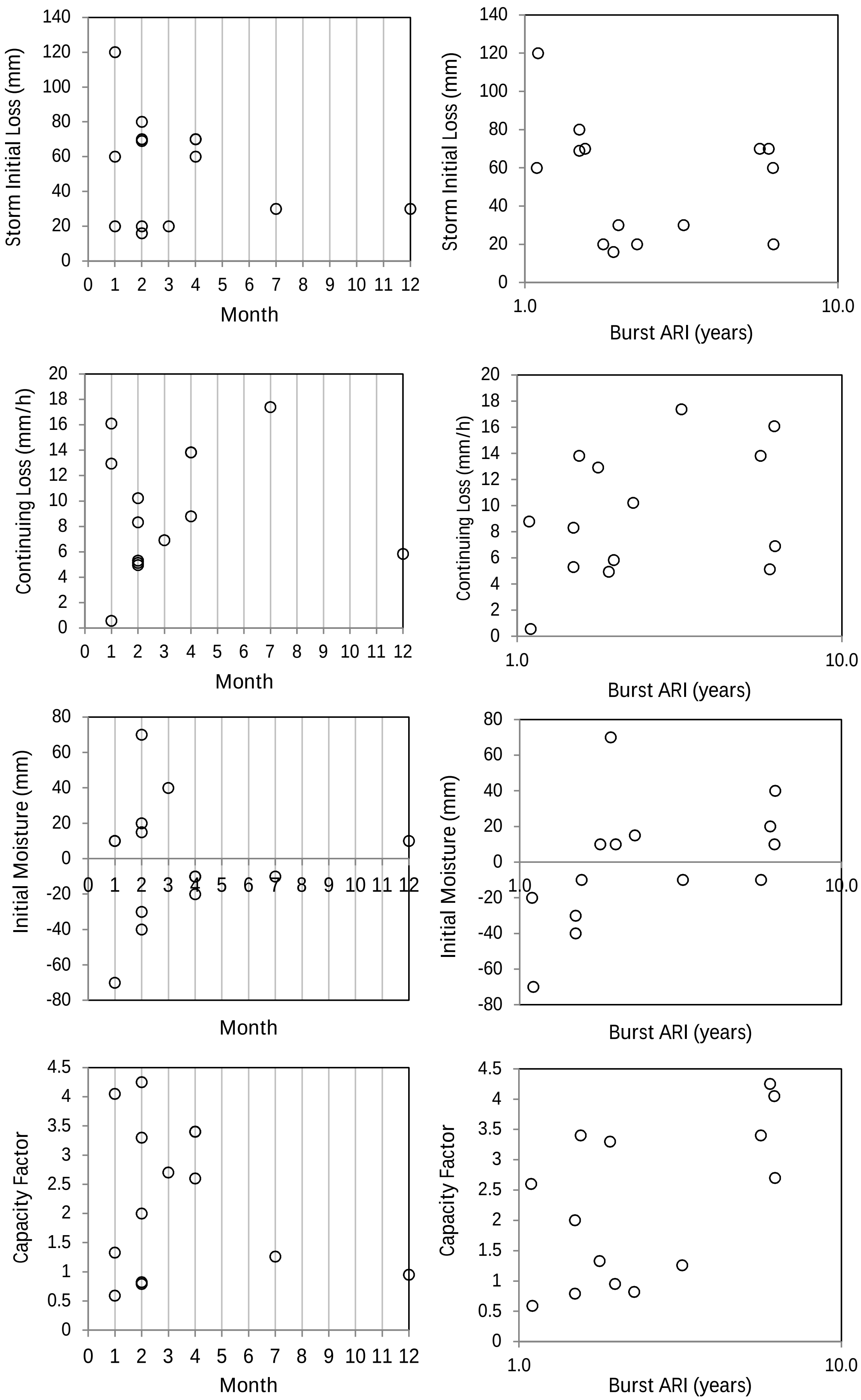




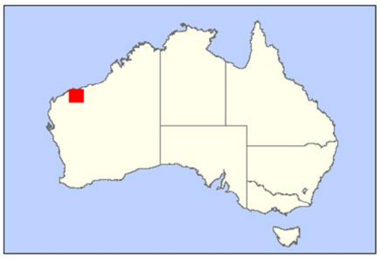


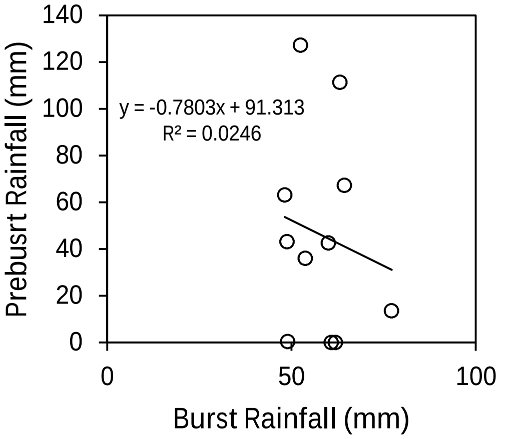


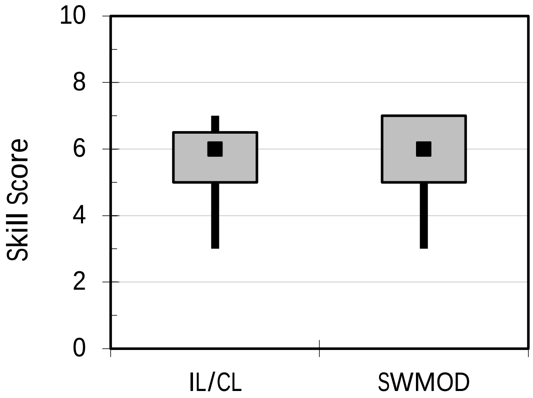
Harding @ Marmurrina Pool U-South (WA) - 3 hour bursts

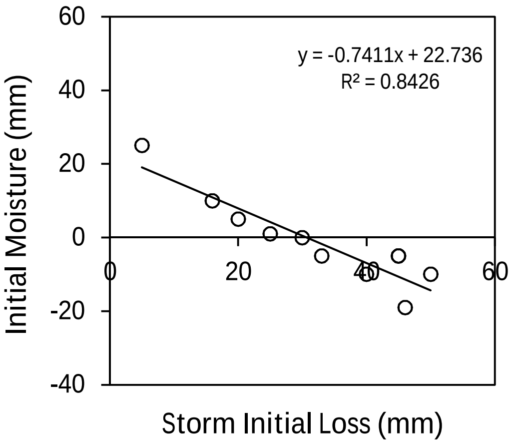


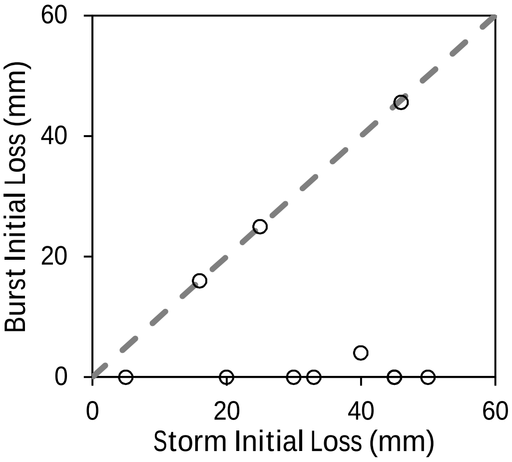
Kanjenjie Ck Trib. @ Fish Pool (WA) - 3 hour bursts

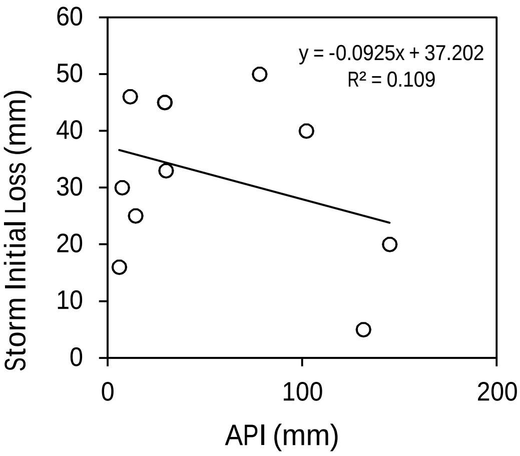


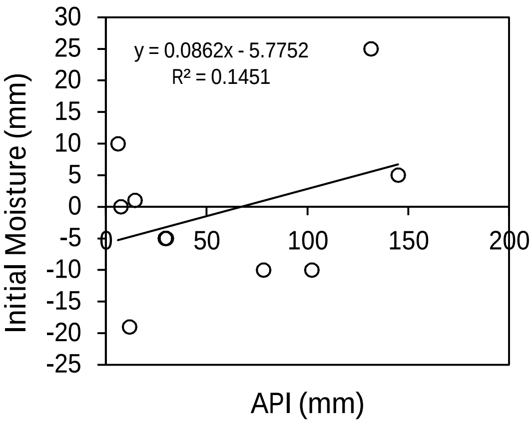




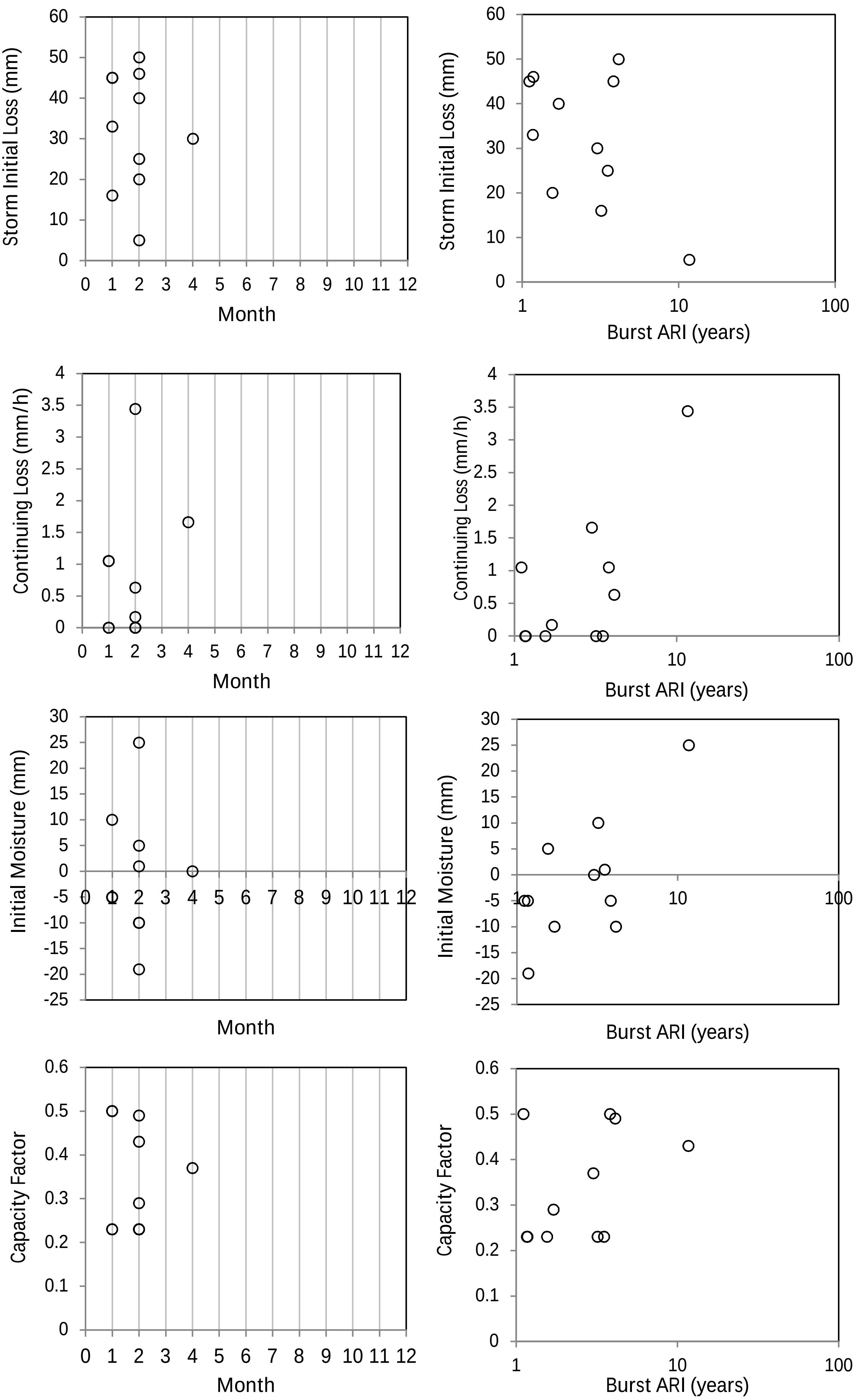




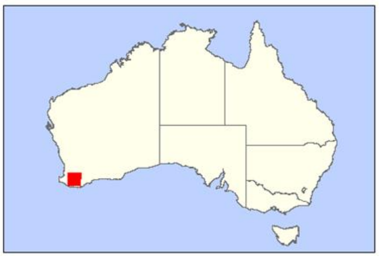


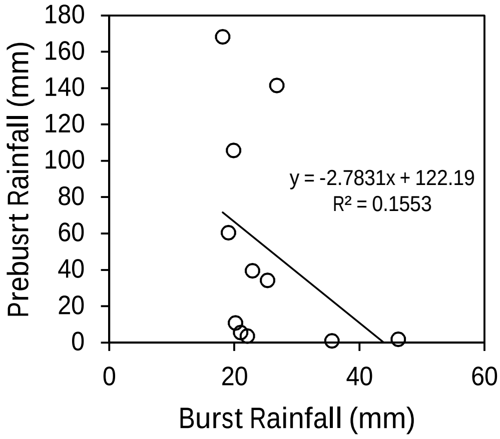


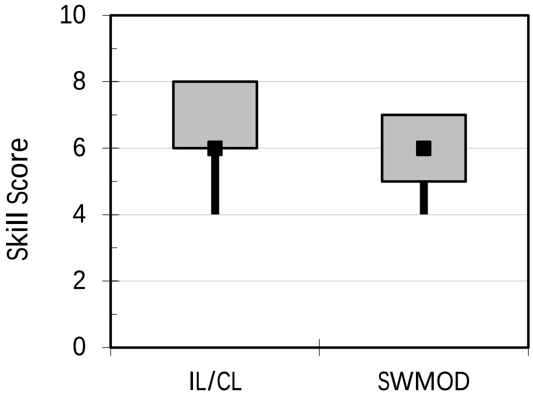
Kanjenjie Ck Trib. @ Fish Pool (WA) - 3 hour bursts

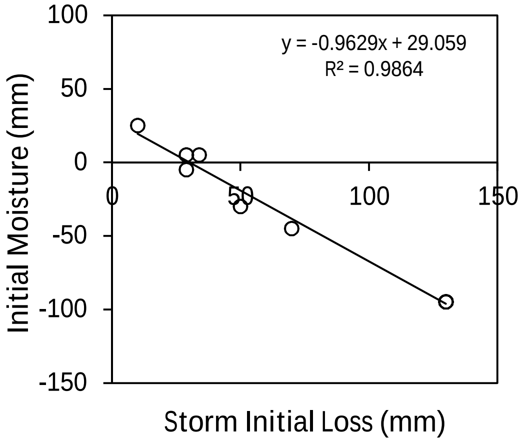


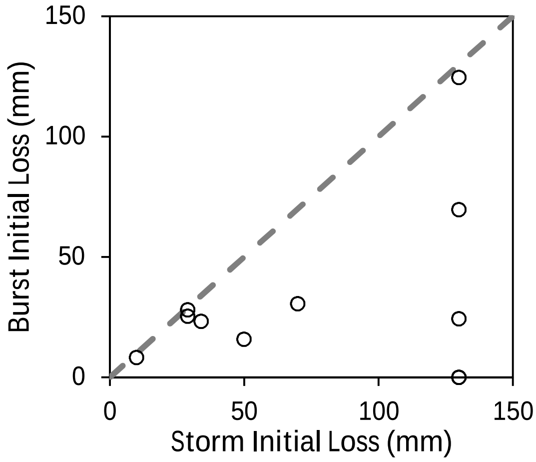
Balgarup @ Mandelup Pool (WA) - 3 hour bursts

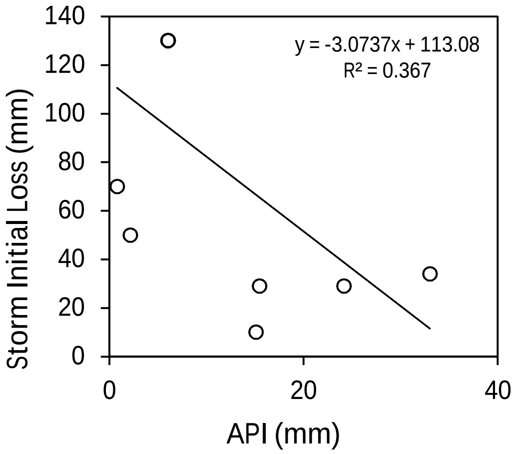


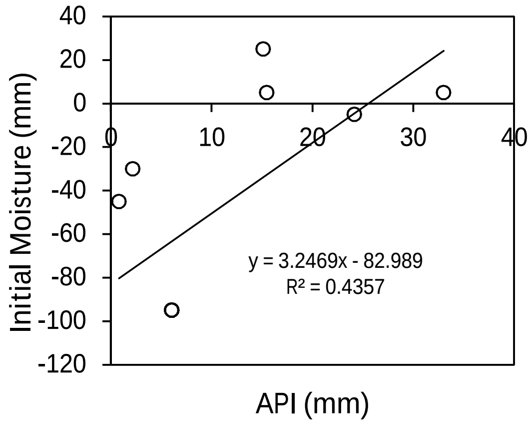




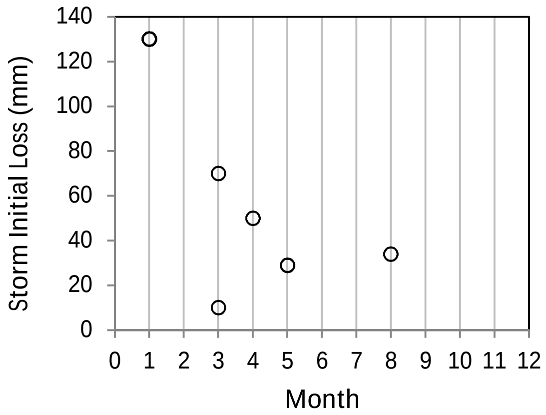


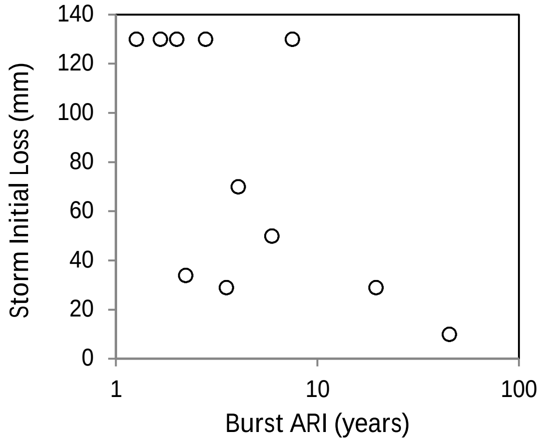


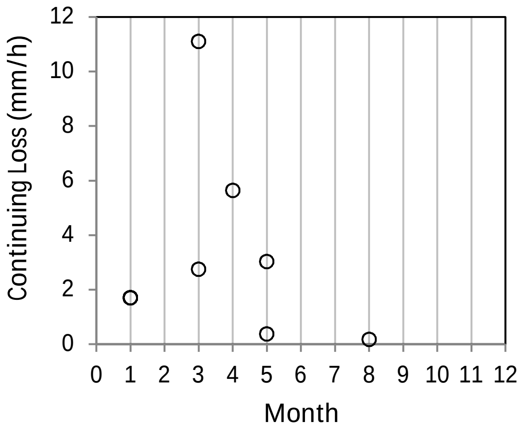


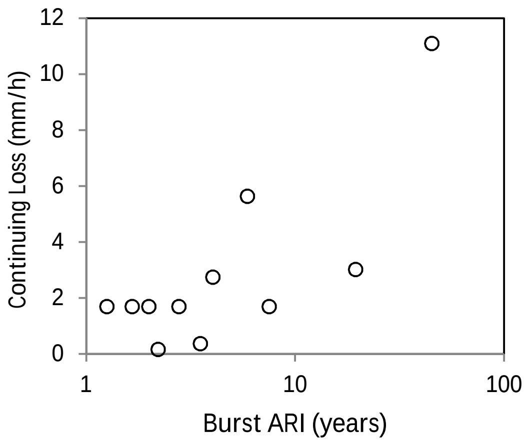


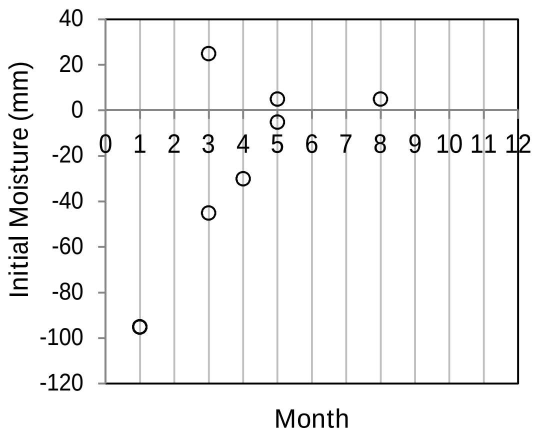
Balgarup @ Mandelup Pool (WA) - 3 hour bursts

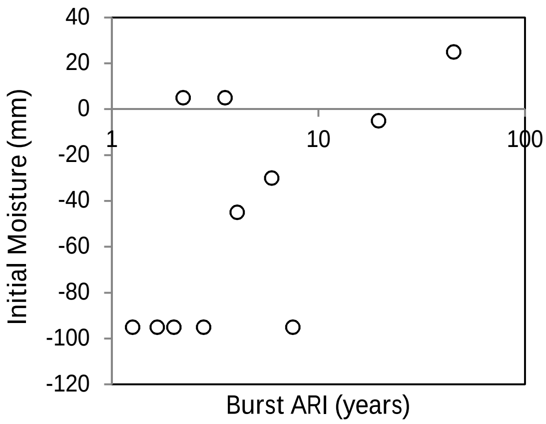


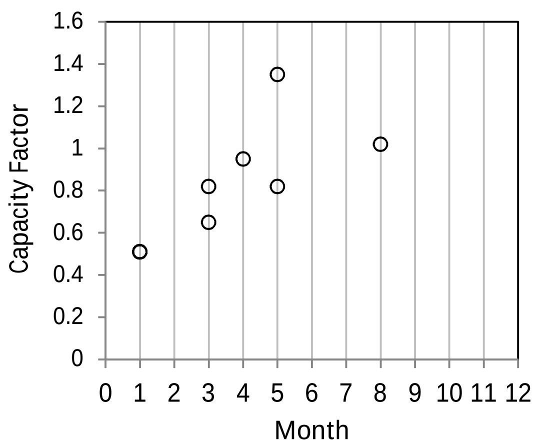


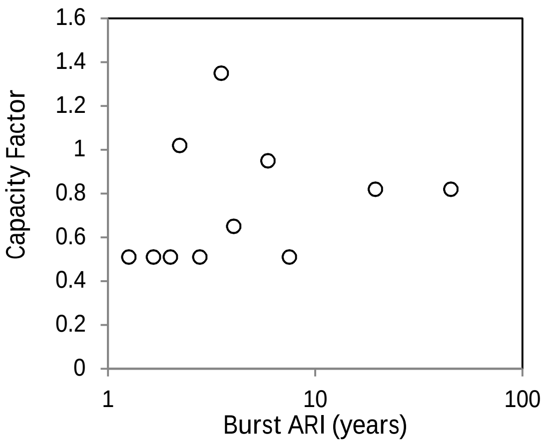




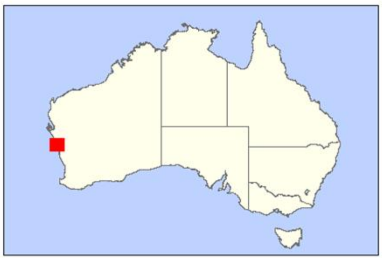


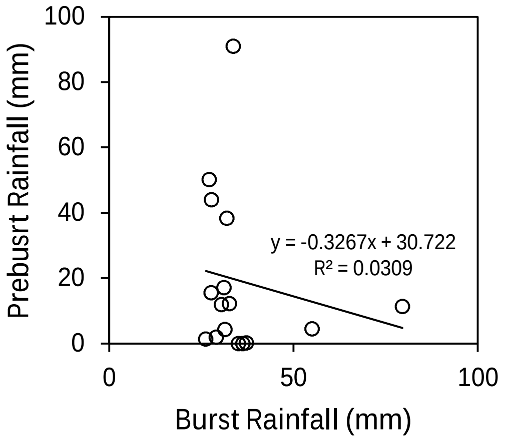


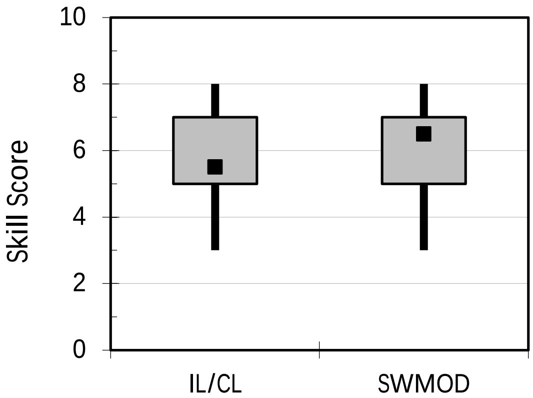


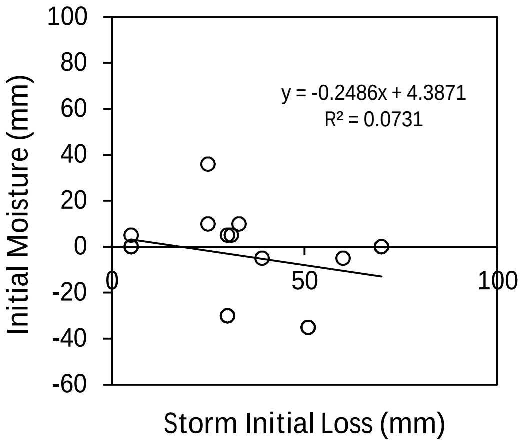


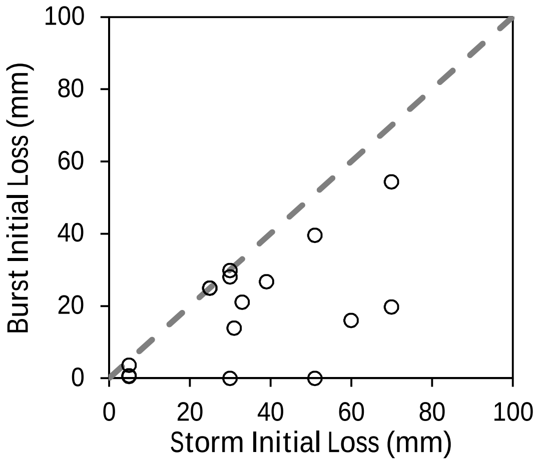
Buller @ Buller (WA) - 3 hour bursts

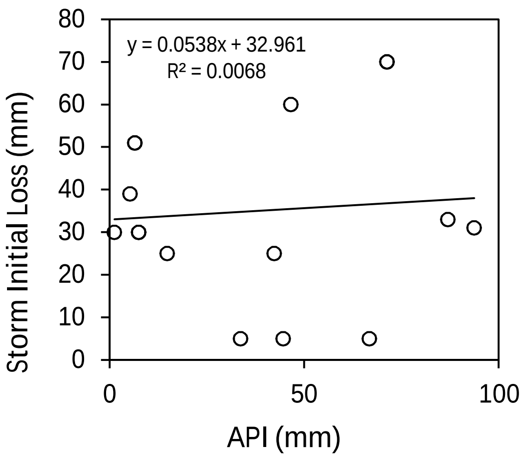


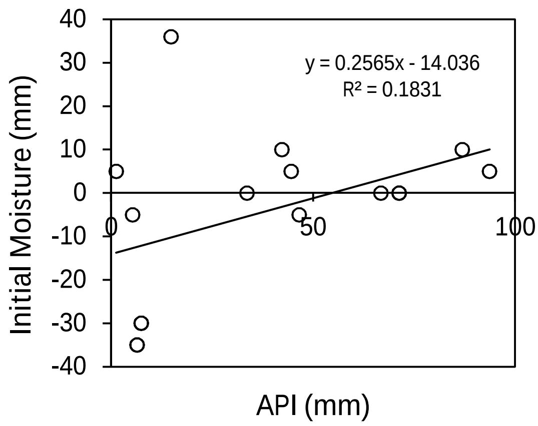




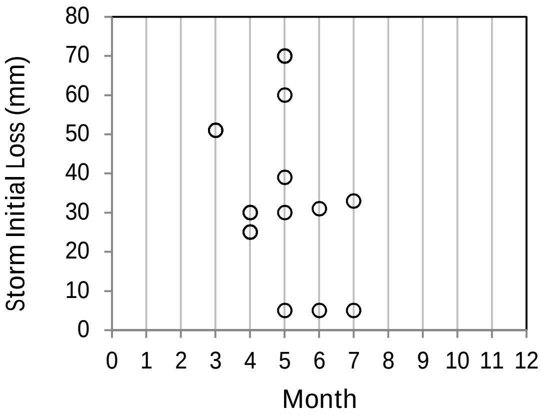


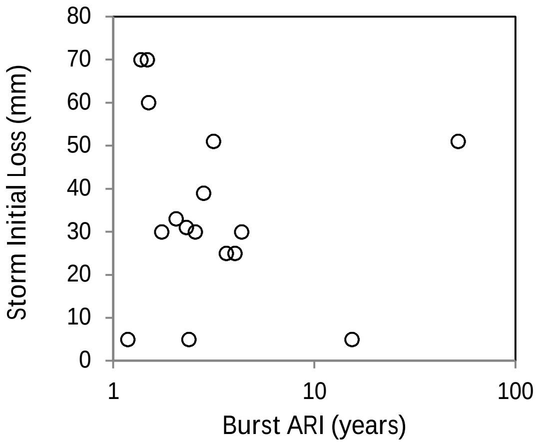


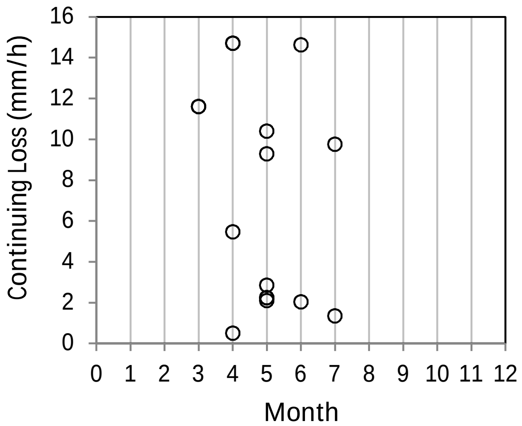


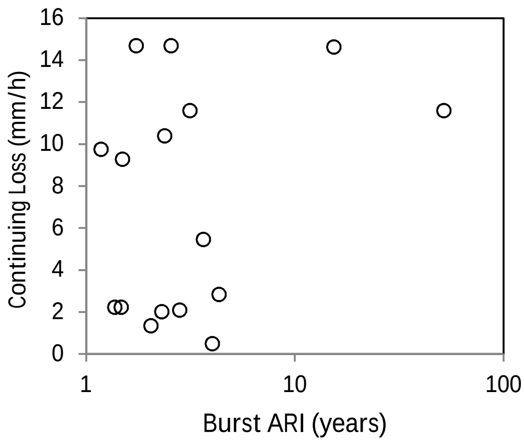


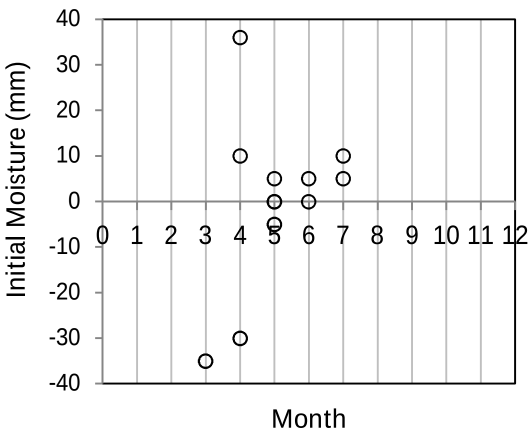
Buller @ Buller (WA) - 3 hour bursts

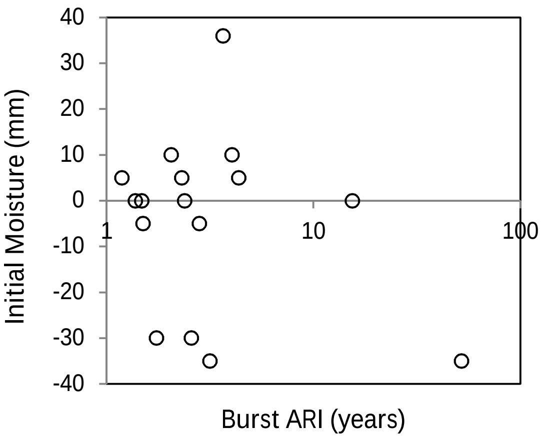


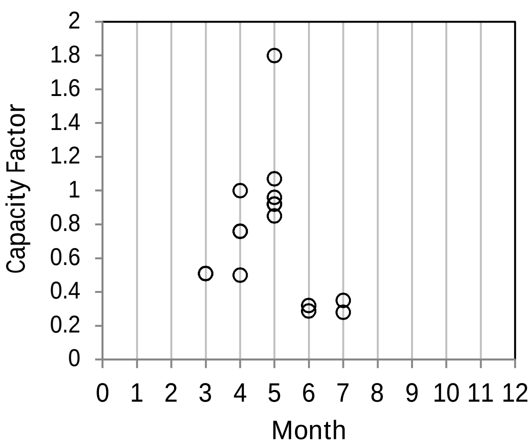


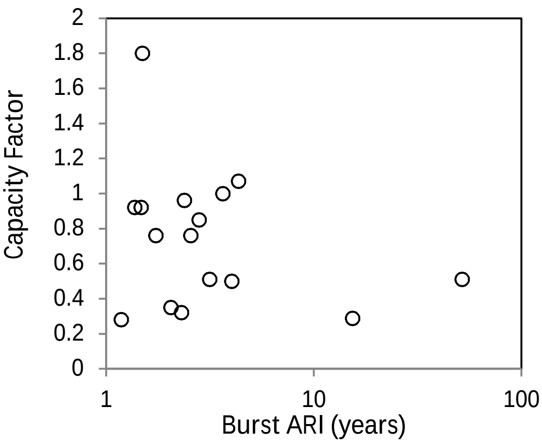




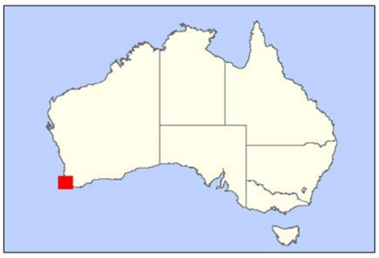


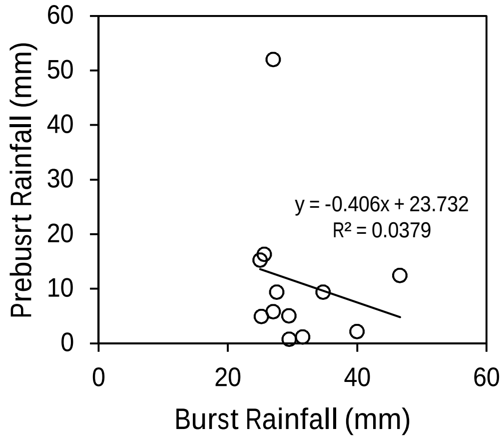


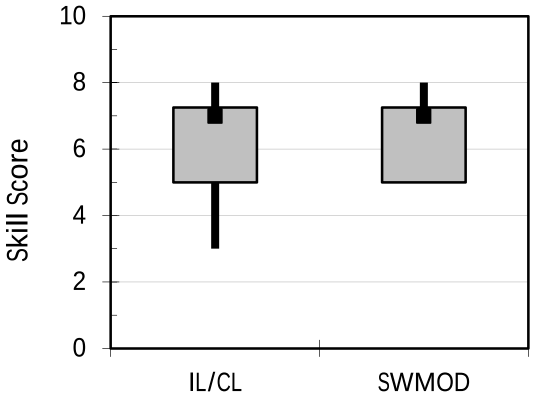


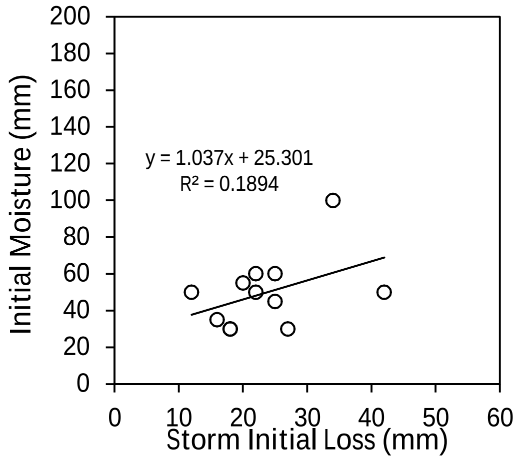


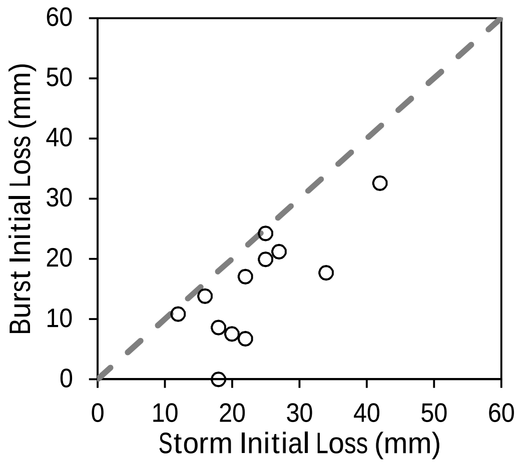
Carey Brook @ Staircase Rd (WA) - 3 hour bursts

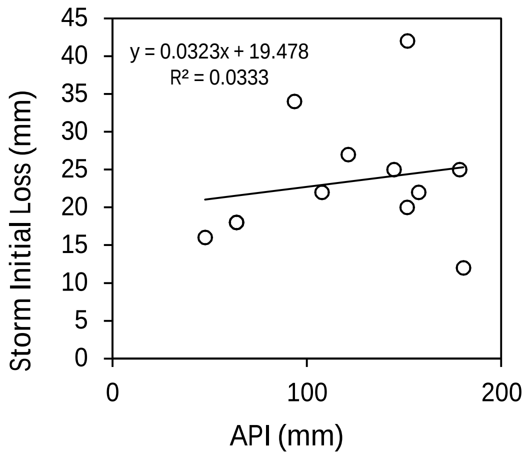


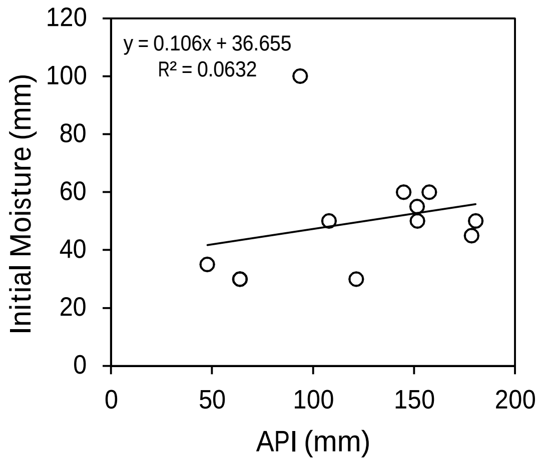




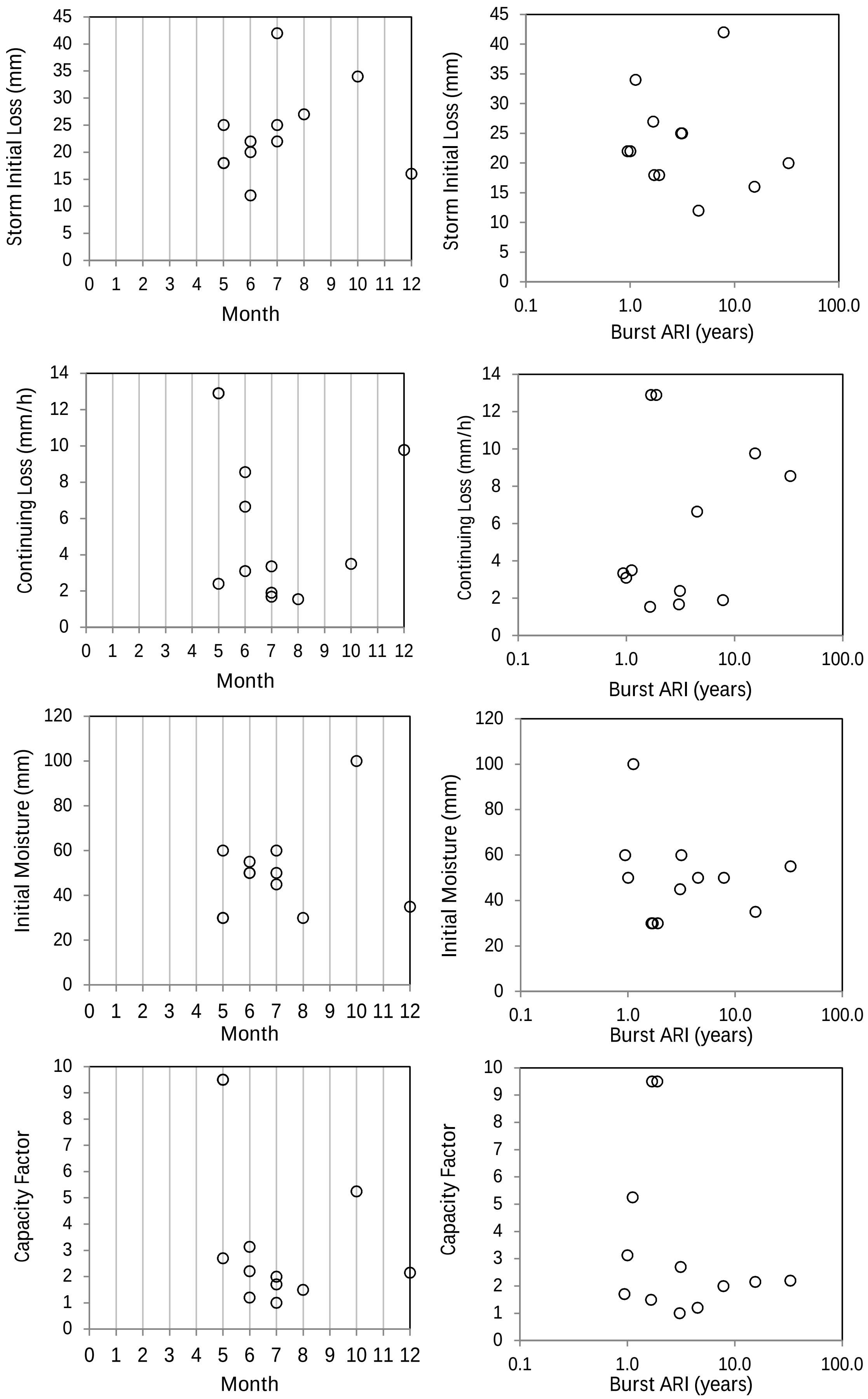




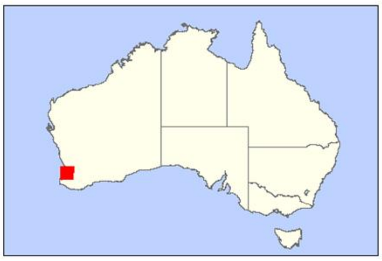


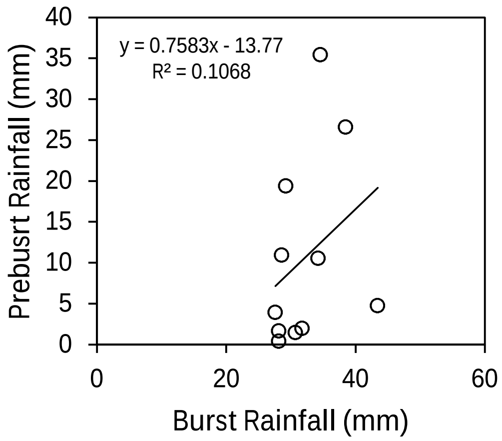


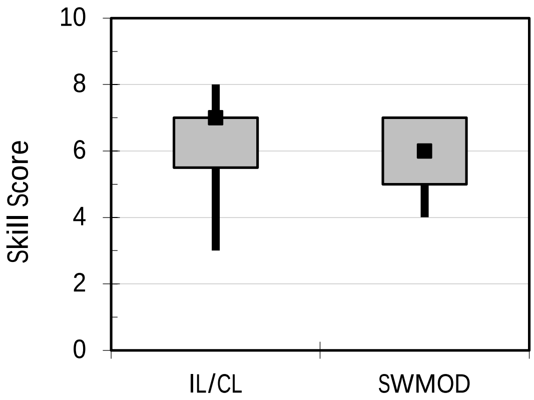
Carey Brook @ Staircase Rd (WA) - 3 hour bursts

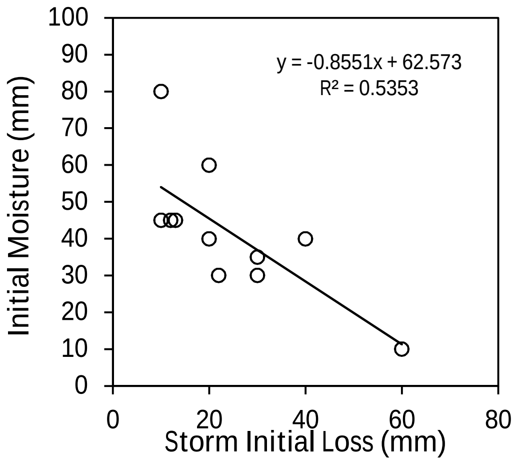


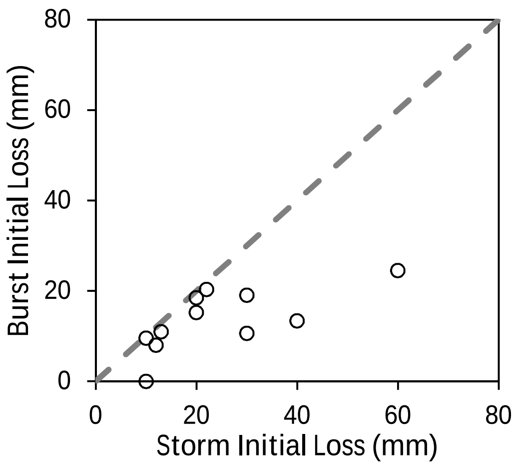
Davis Brook @ Murray Valley Plntn (WA) - 3 hour bursts

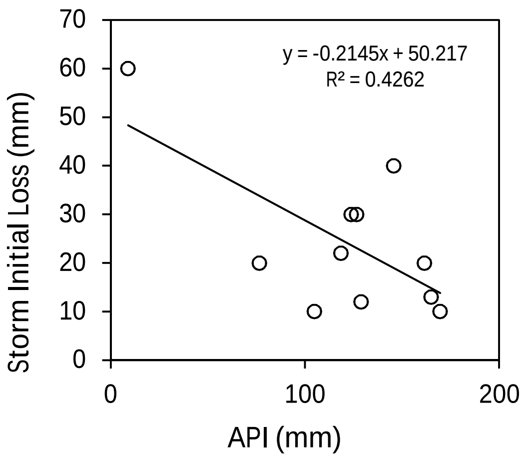


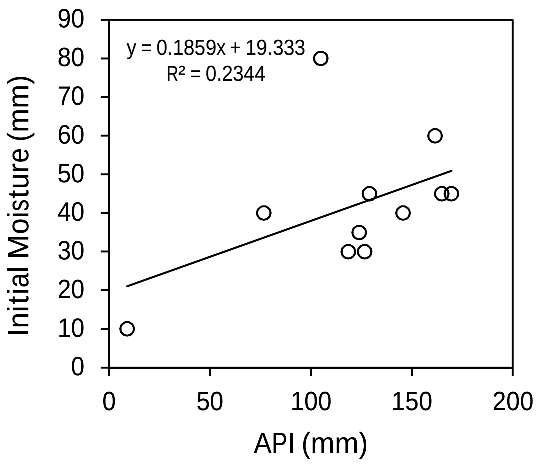




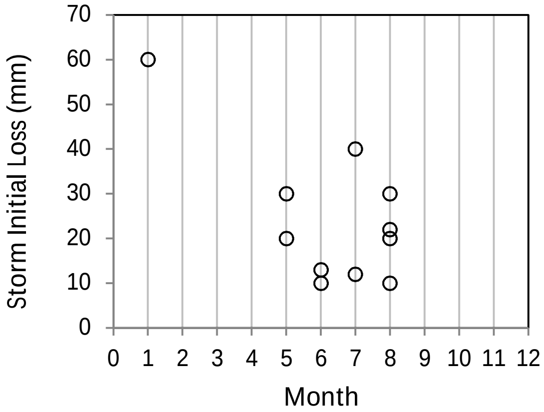


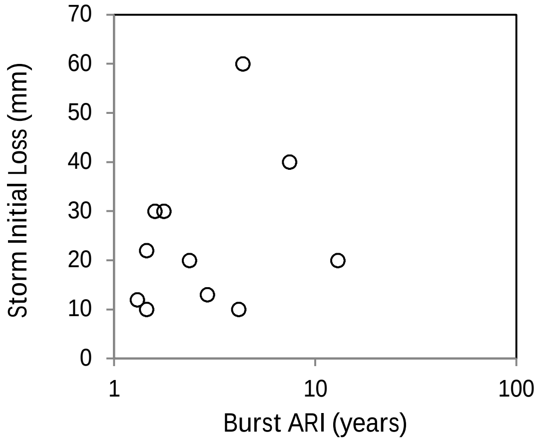


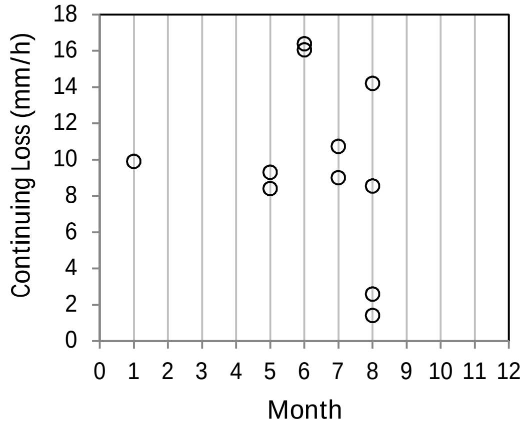


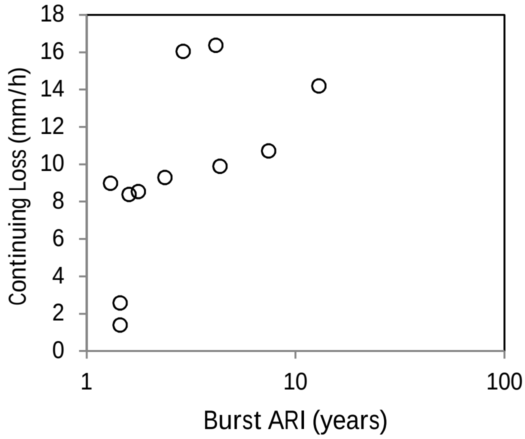


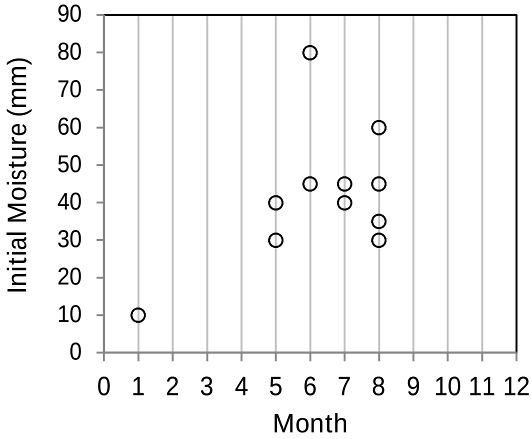
Davis Brook @ Murray Valley Plntn (WA) - 3 hour bursts

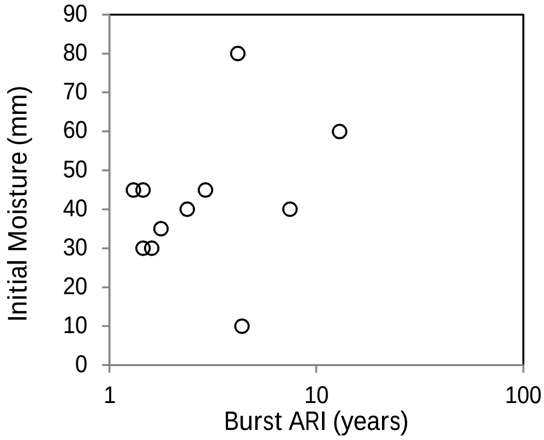


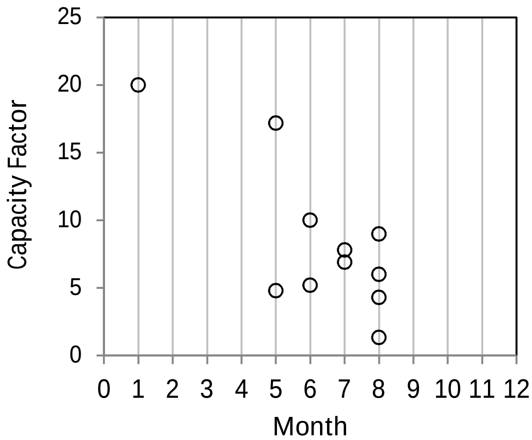


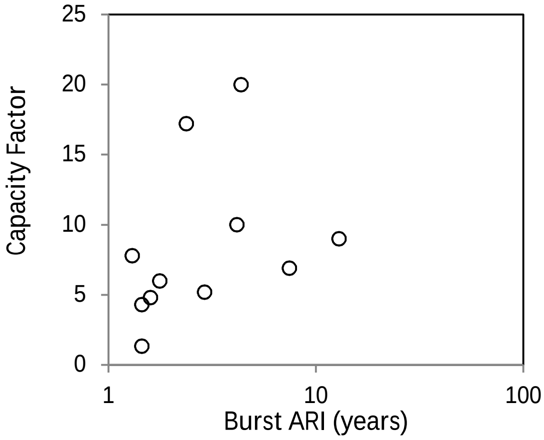




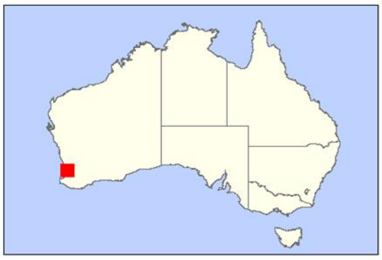


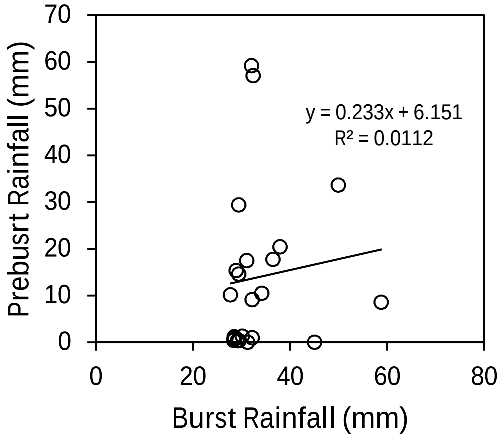


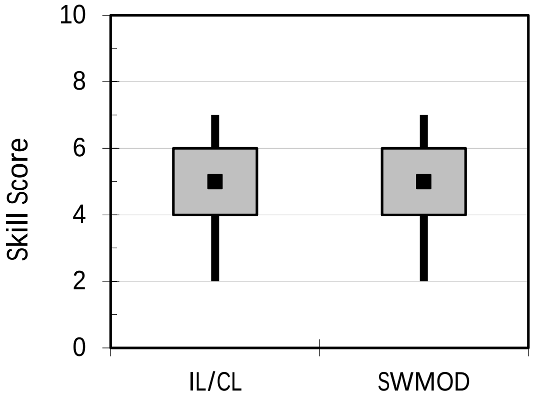


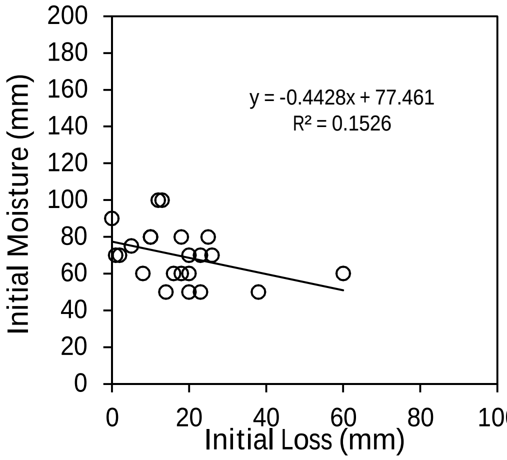


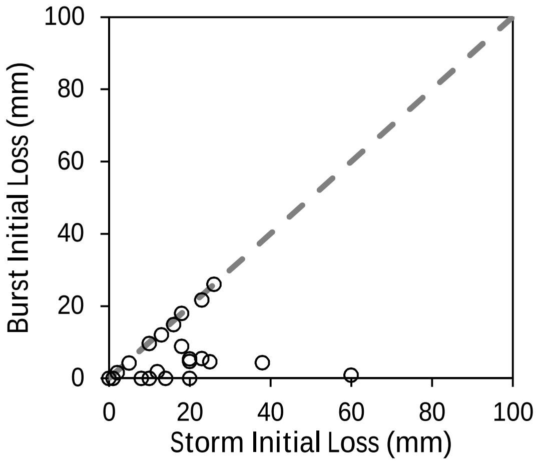
Dirk Brook @ Kentish Farm (WA) - 3 hour bursts

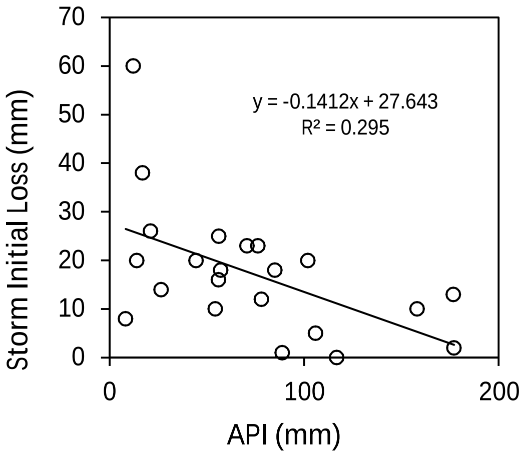


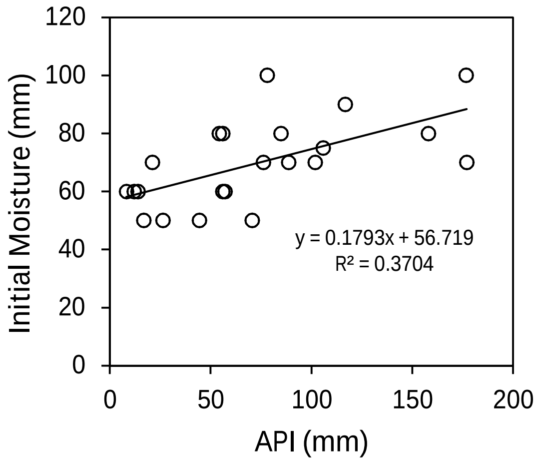




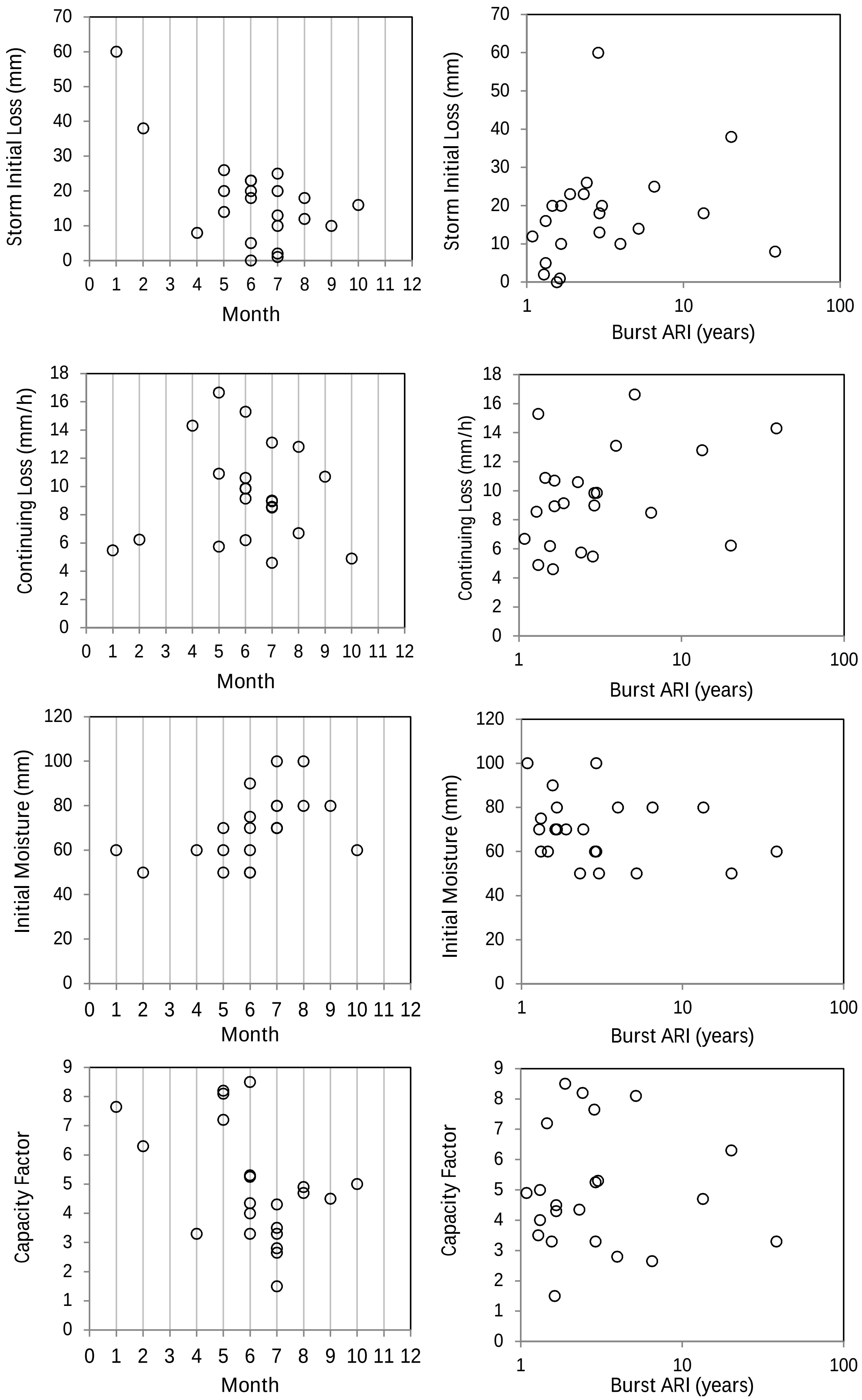




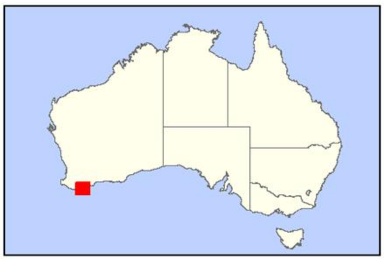


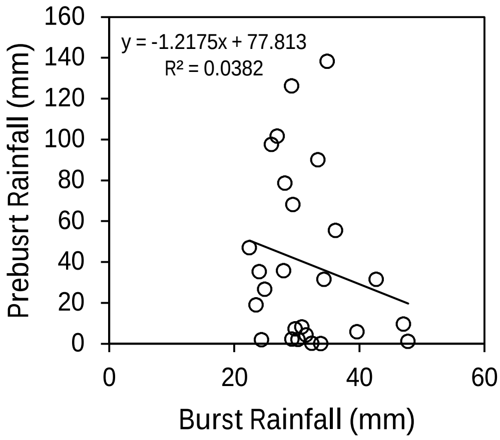


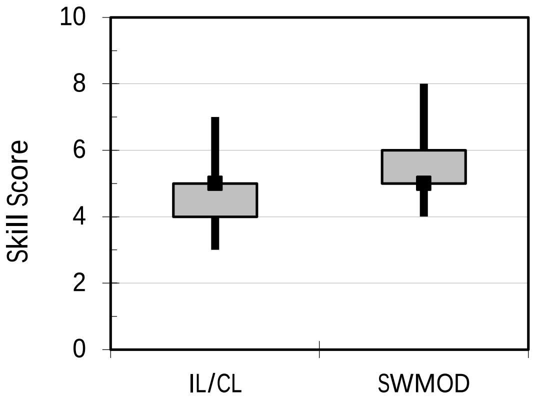
Dirk Brook @ Kentish Farm (WA) - 3 hour bursts

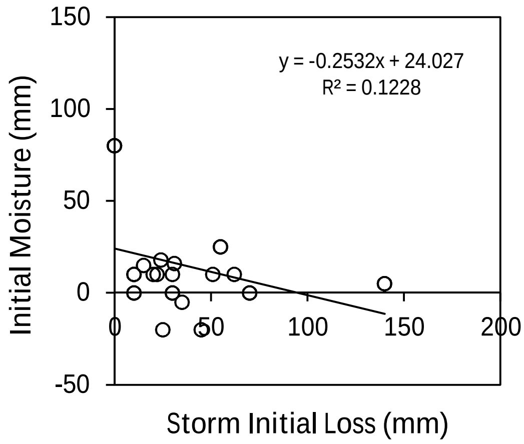


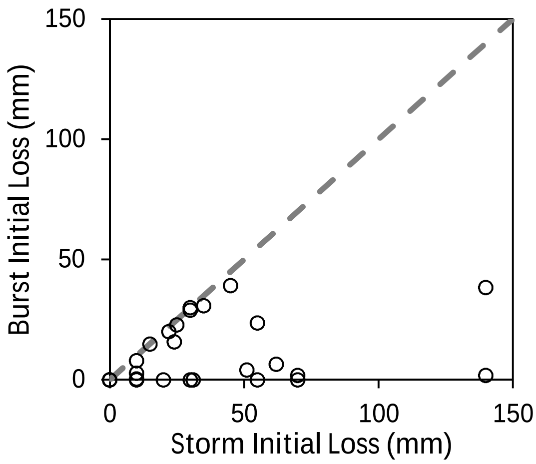
Goodga @ Black Cat (WA) - 3 hour bursts

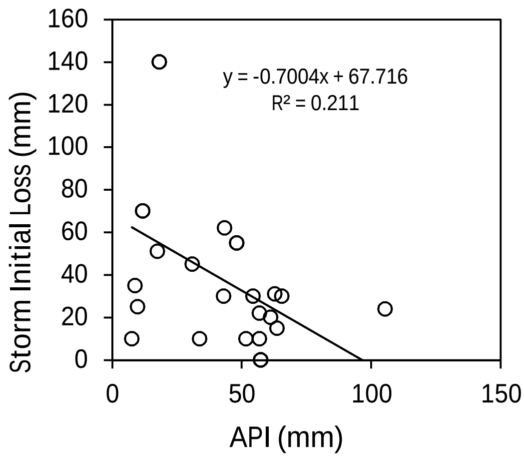


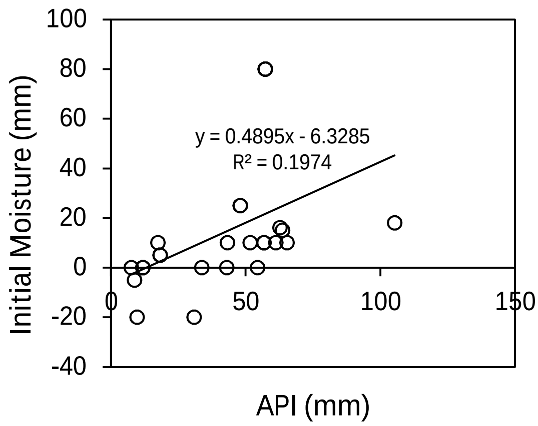




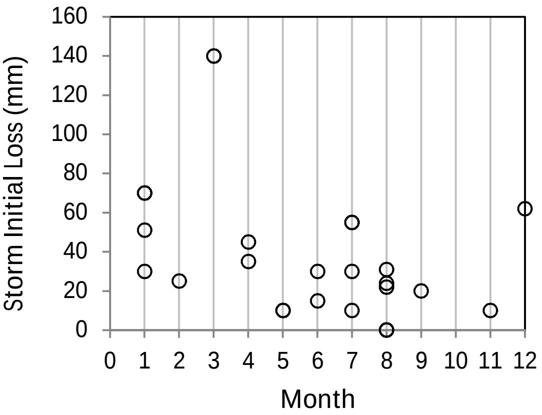


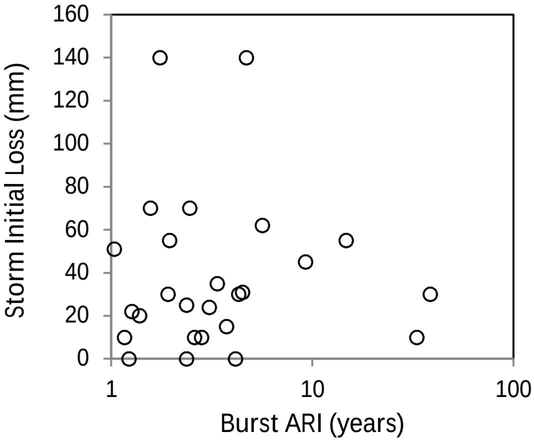


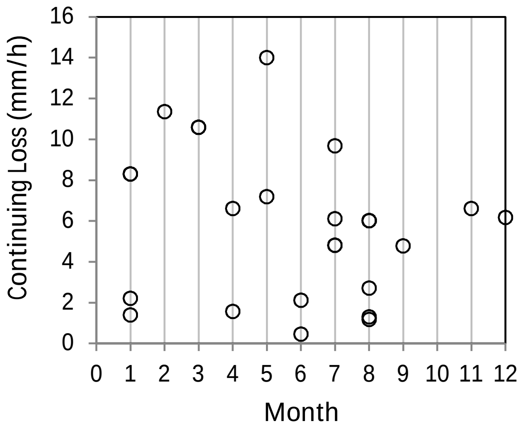


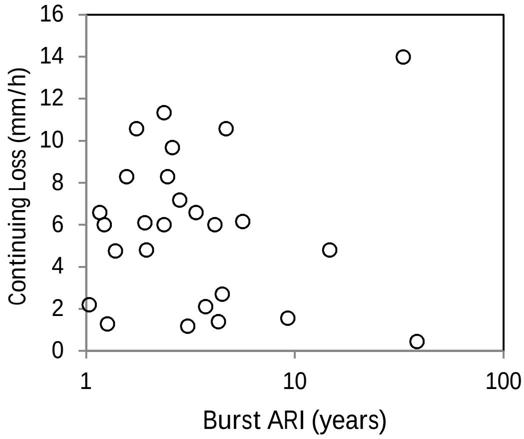


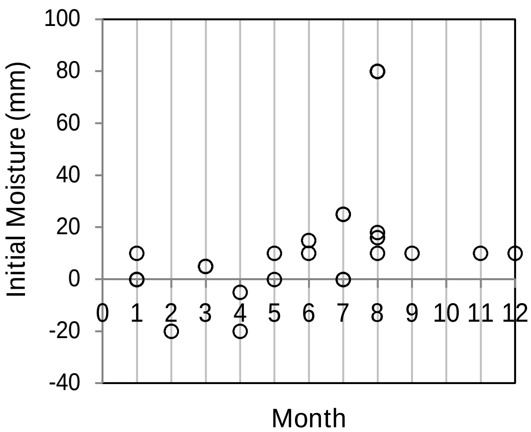
Goodga @ Black Cat (WA) - 3 hour bursts

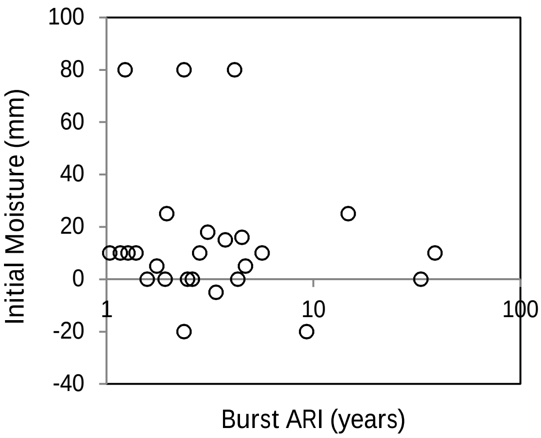


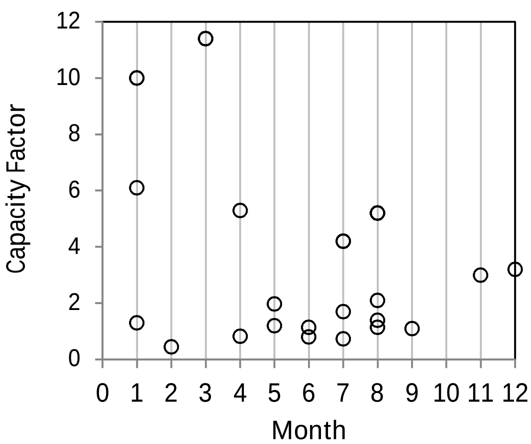


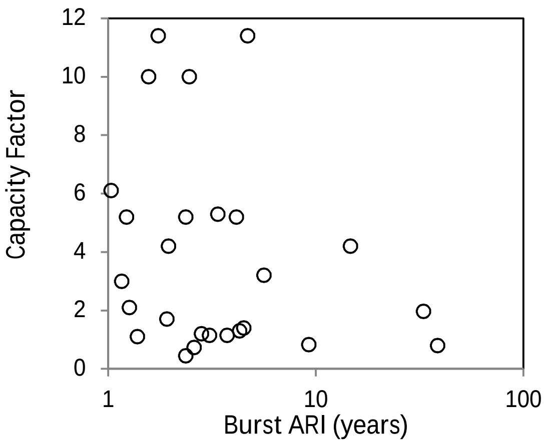




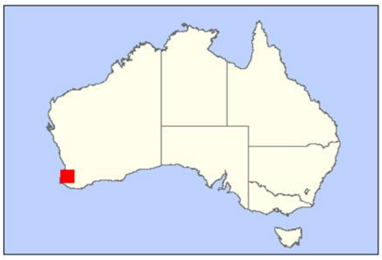


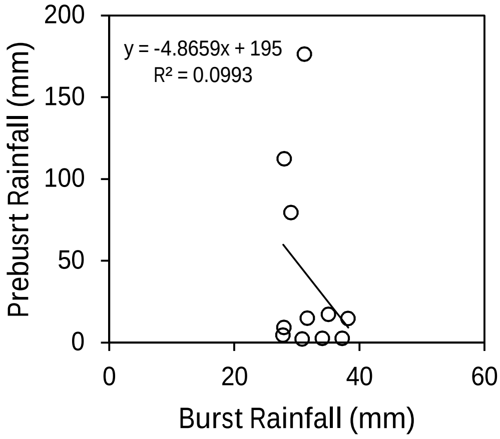


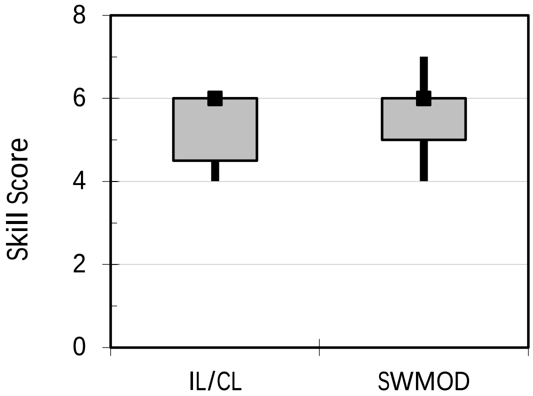


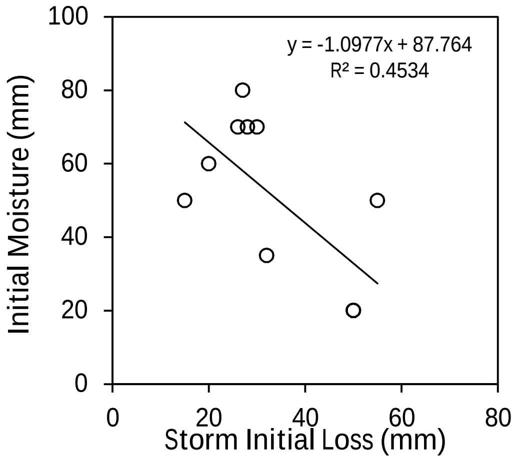


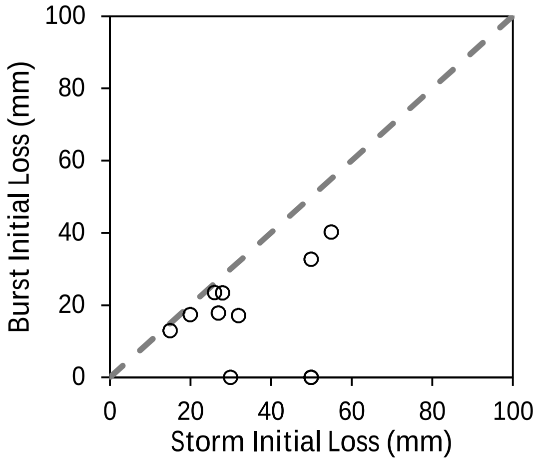
Hamilton @ Worsley (WA) - 3 hour bursts

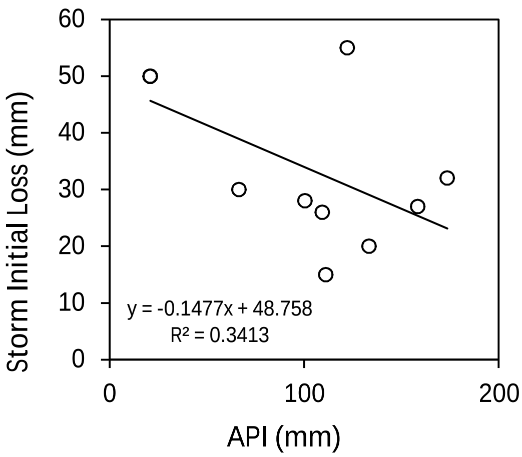


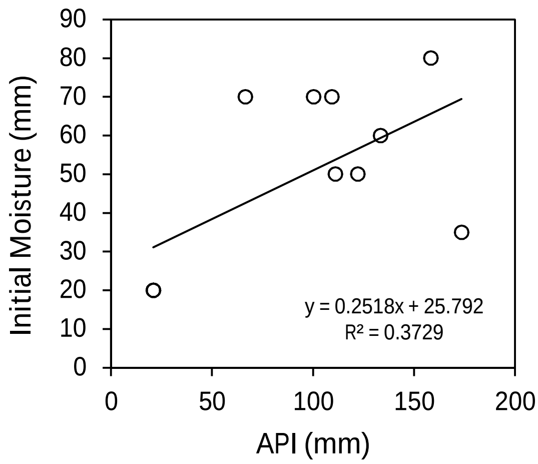




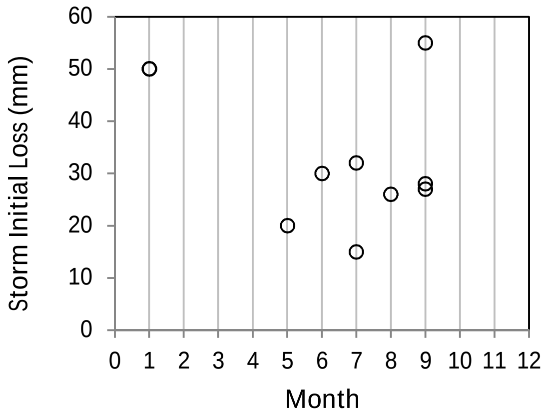


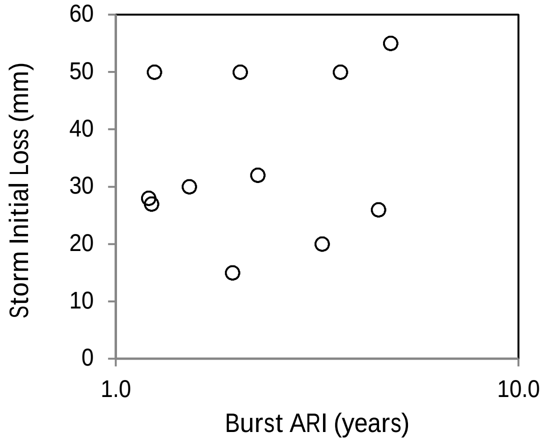


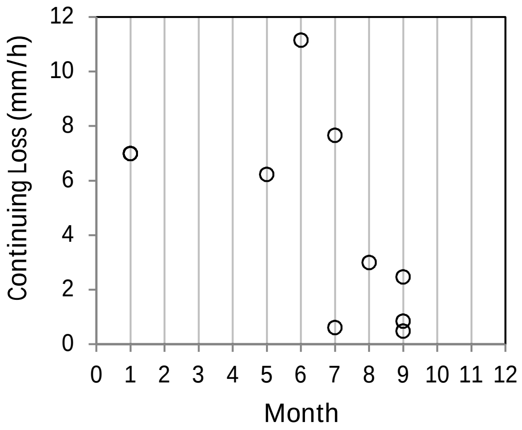


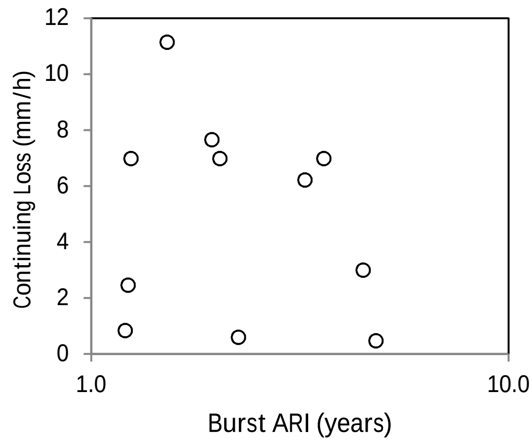


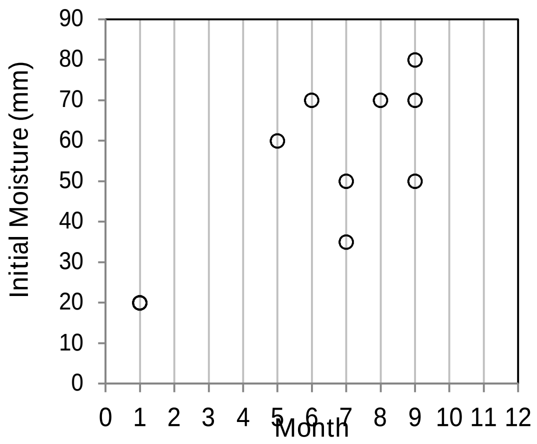
Hamilton @ Worsley (WA) - 3 hour bursts

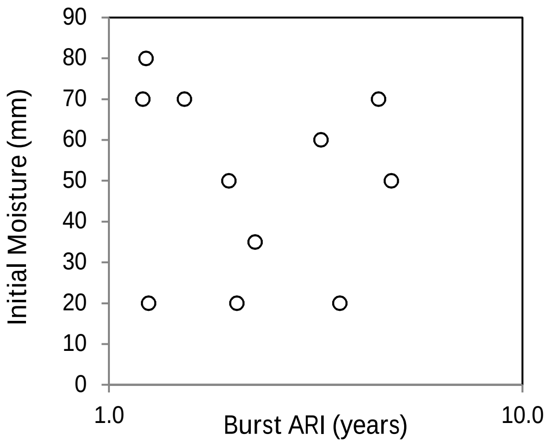


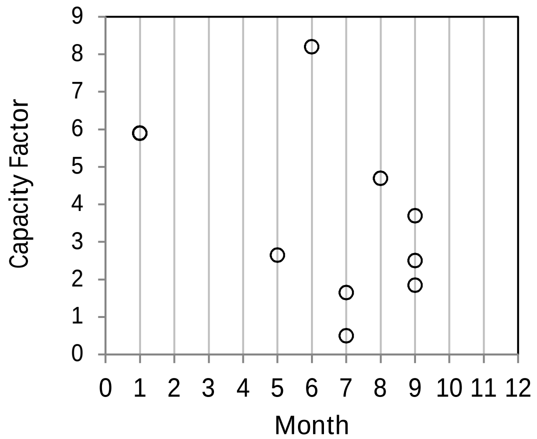


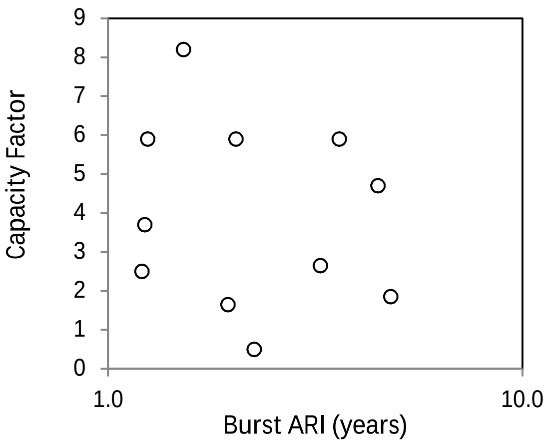




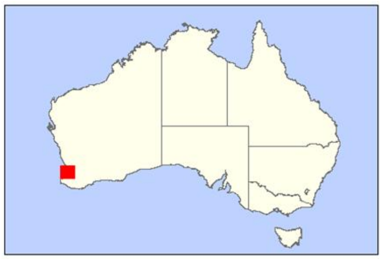


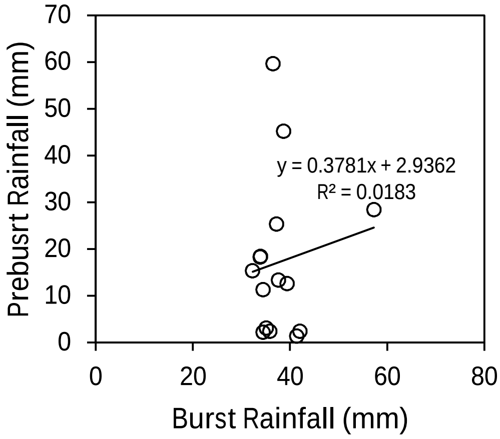


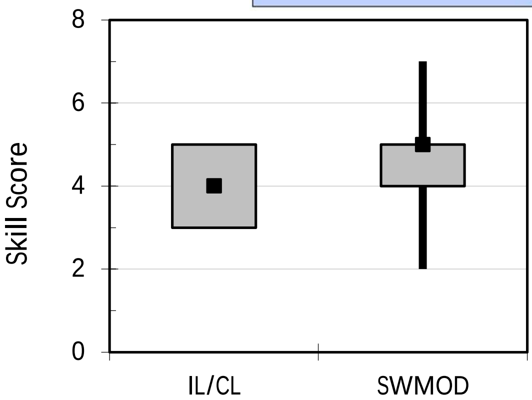


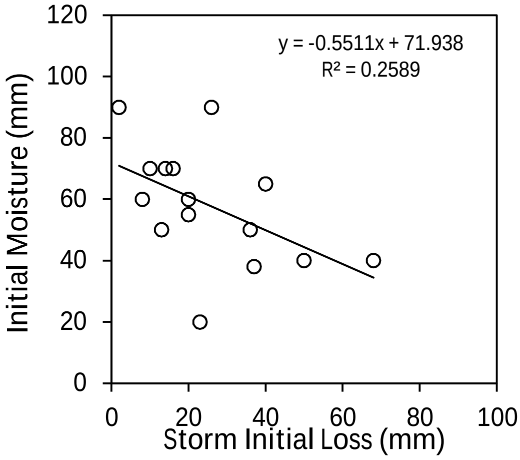


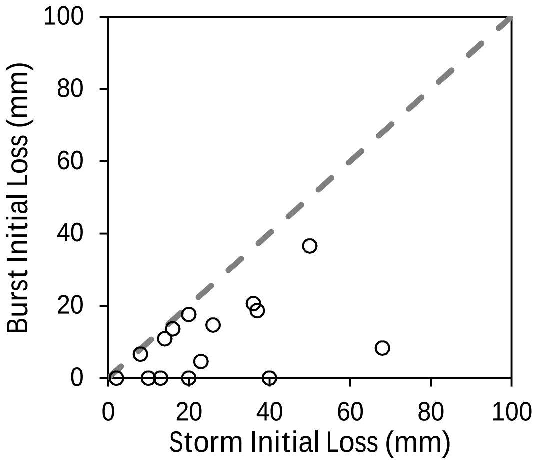
Marrinup Bk @ Brookdale Siding (WA) - 3 hour bursts

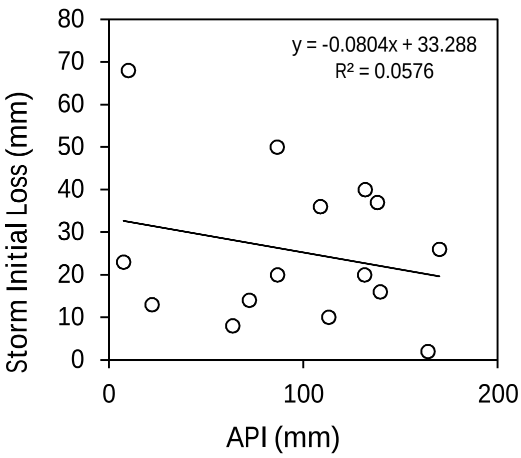


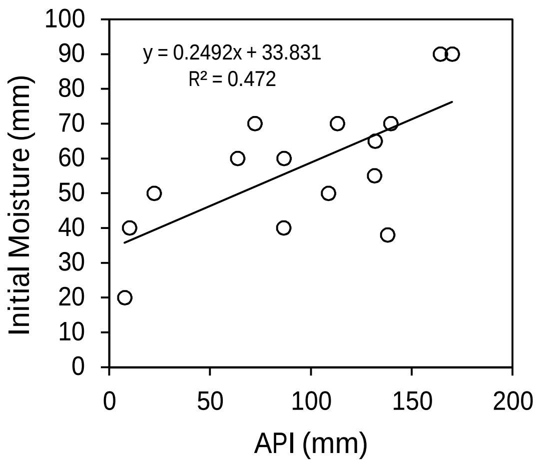




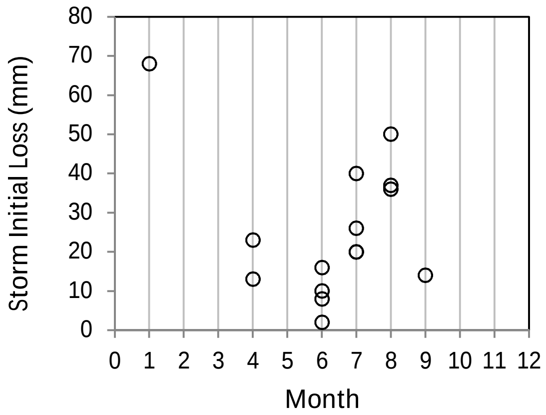


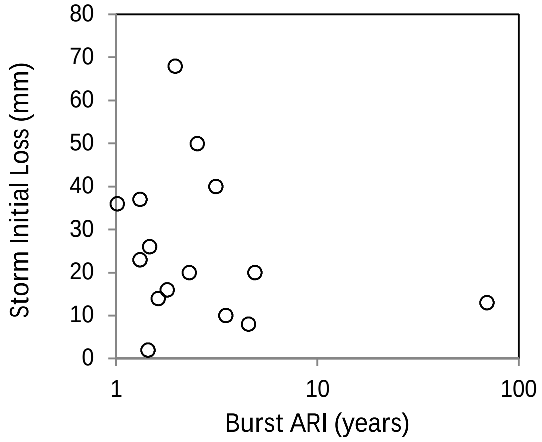


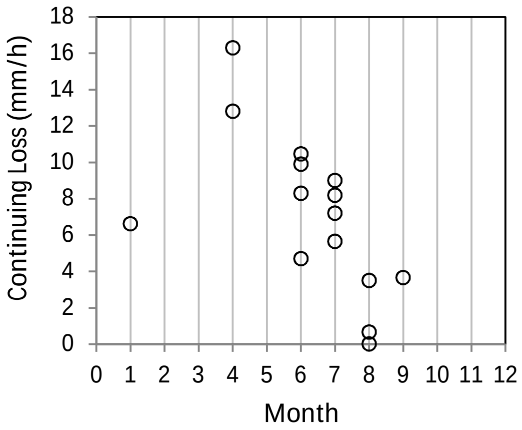


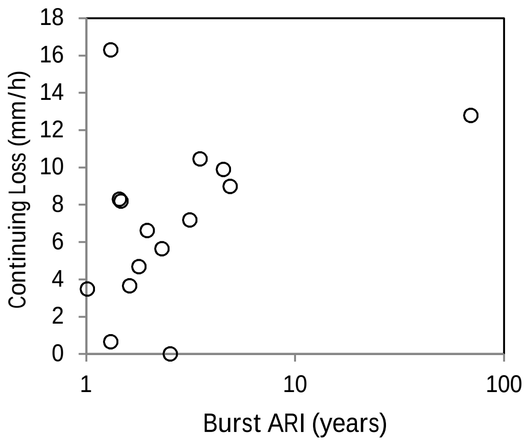


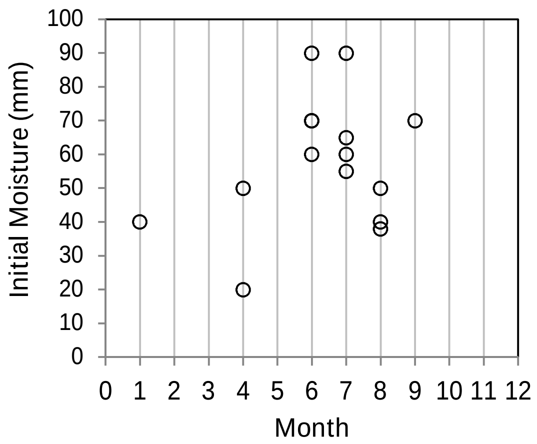
Marrinup Bk @ Brookdale Siding (WA) - 3 hour bursts

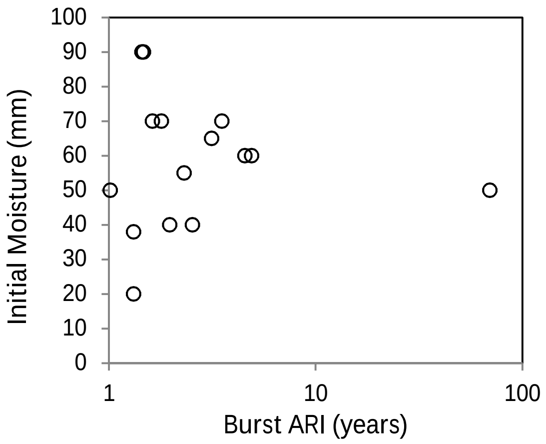


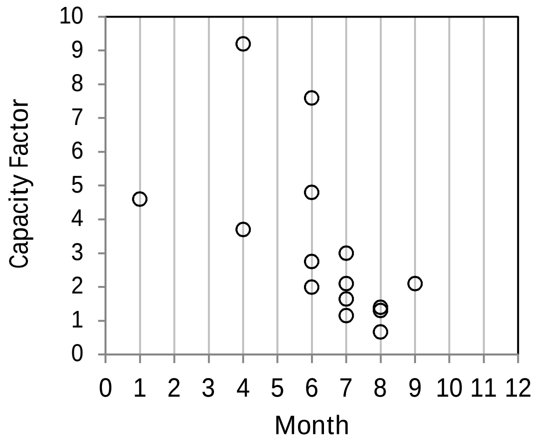


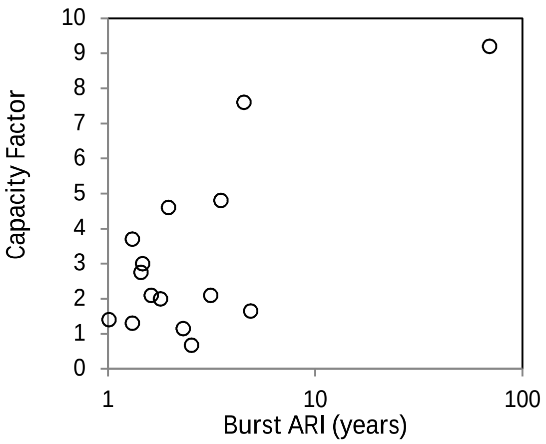




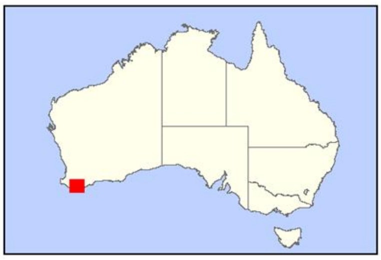


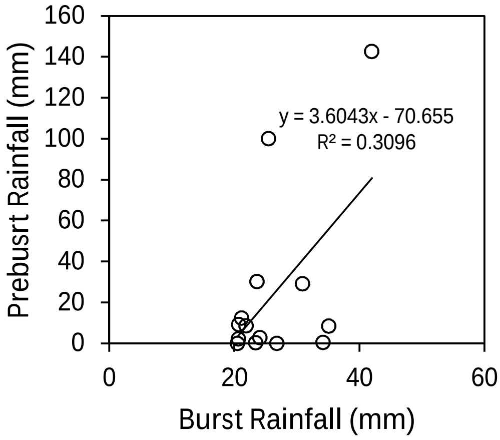


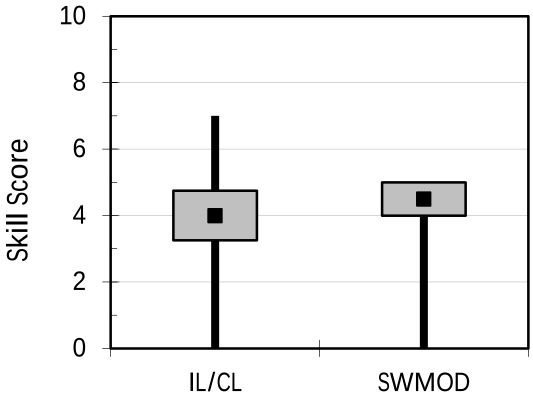


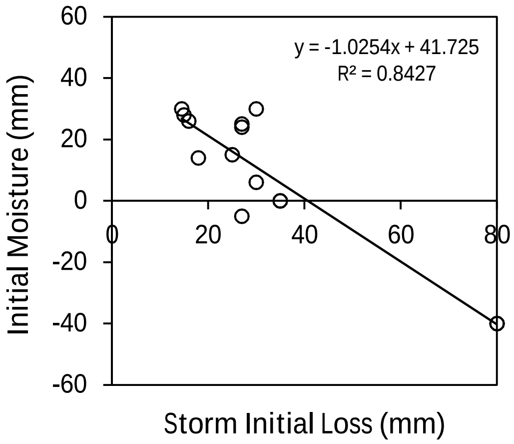


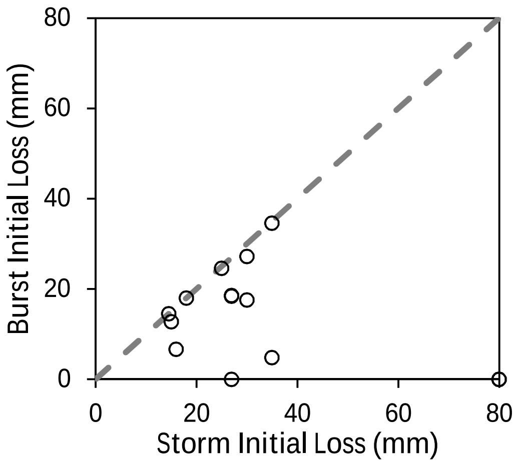
Yates Flat Ck @ Woonanup (WA) - 3 hour bursts

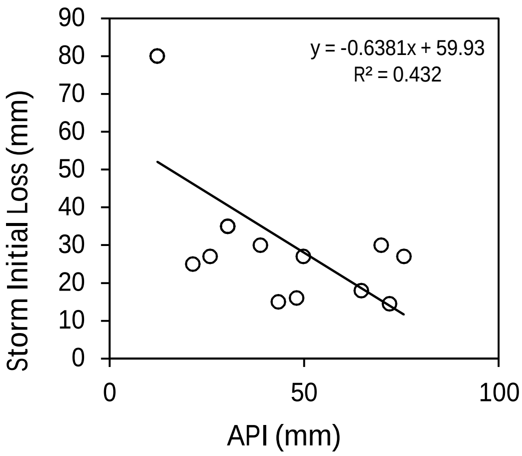


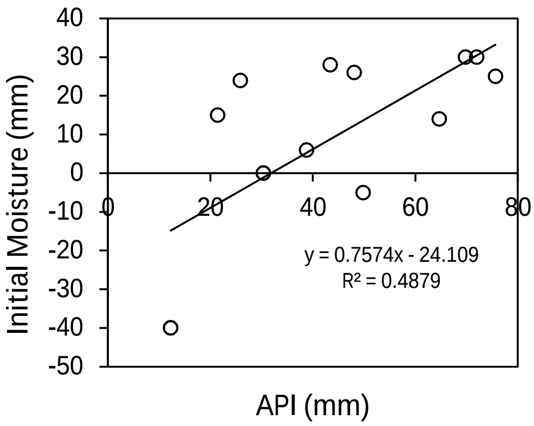




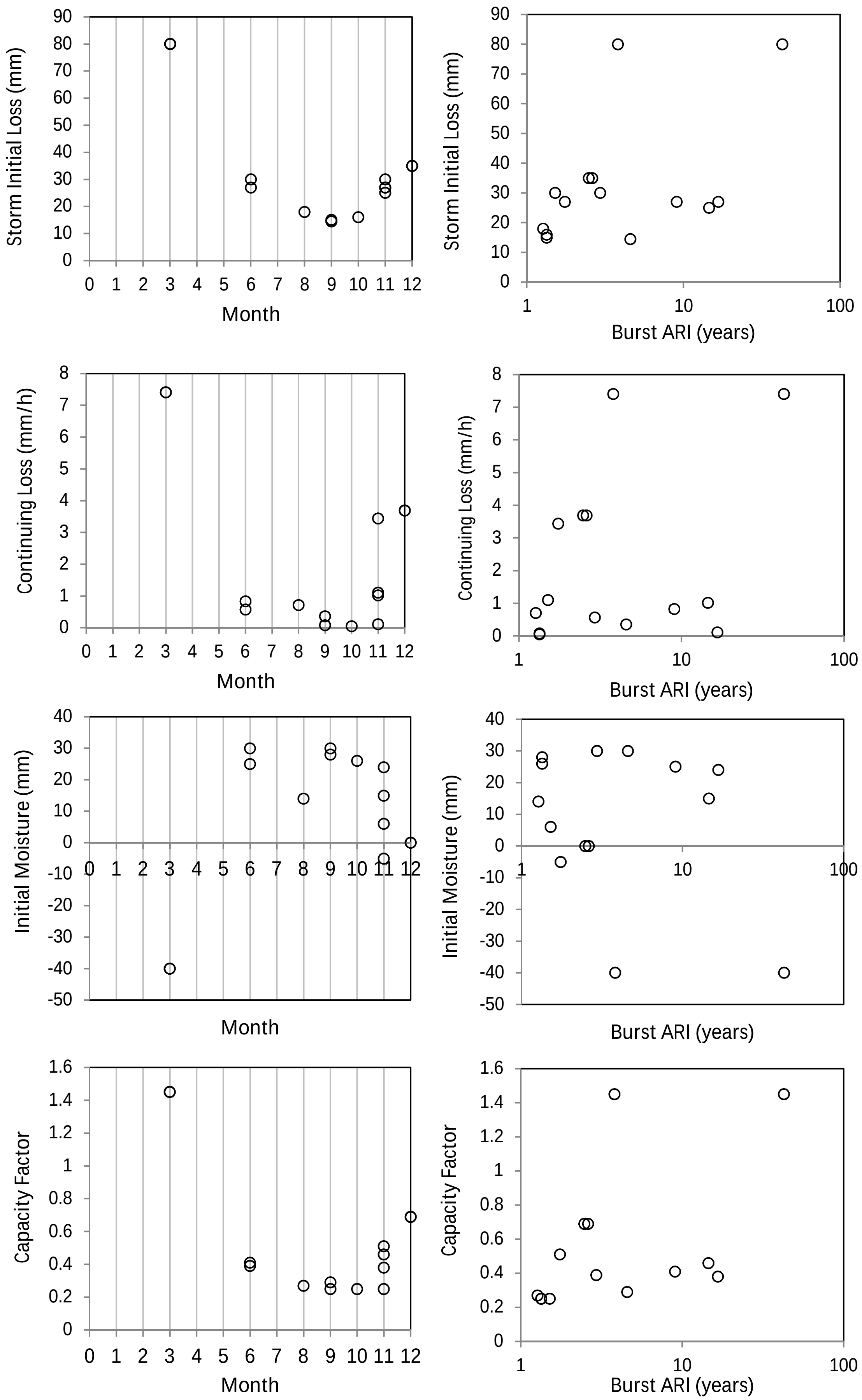






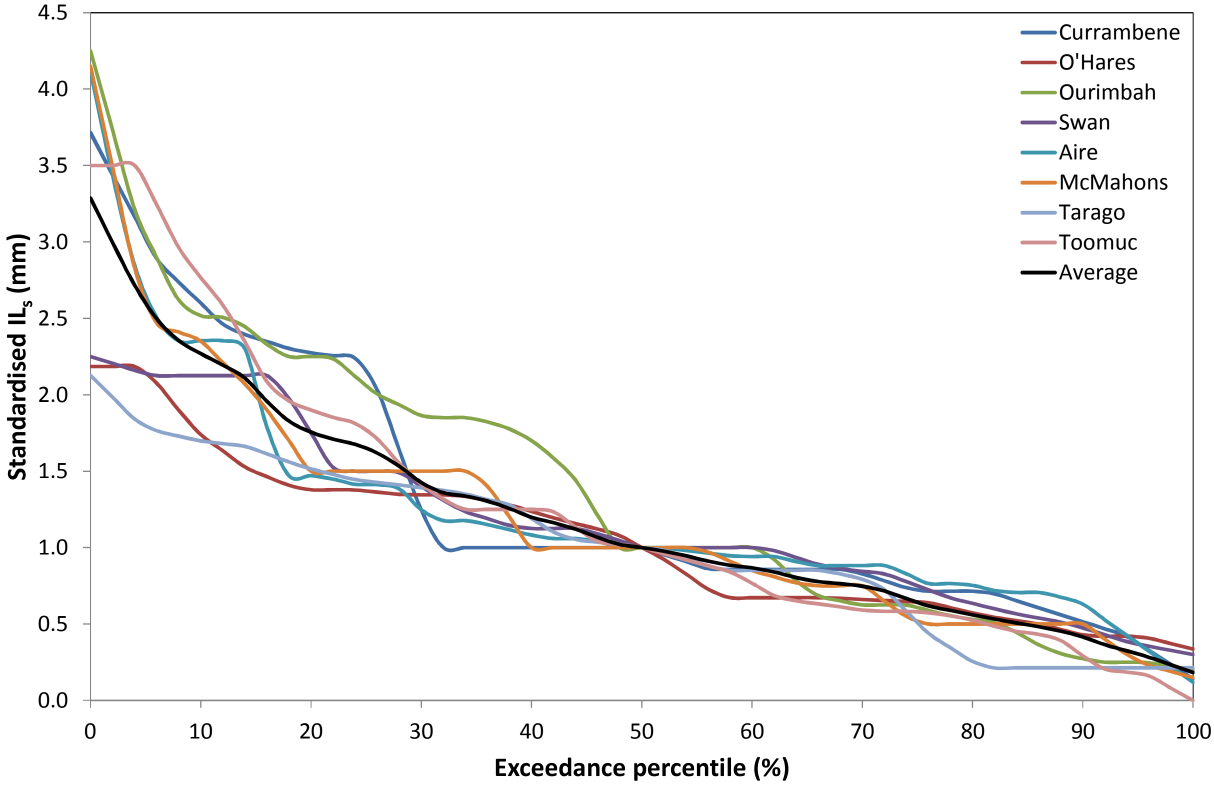


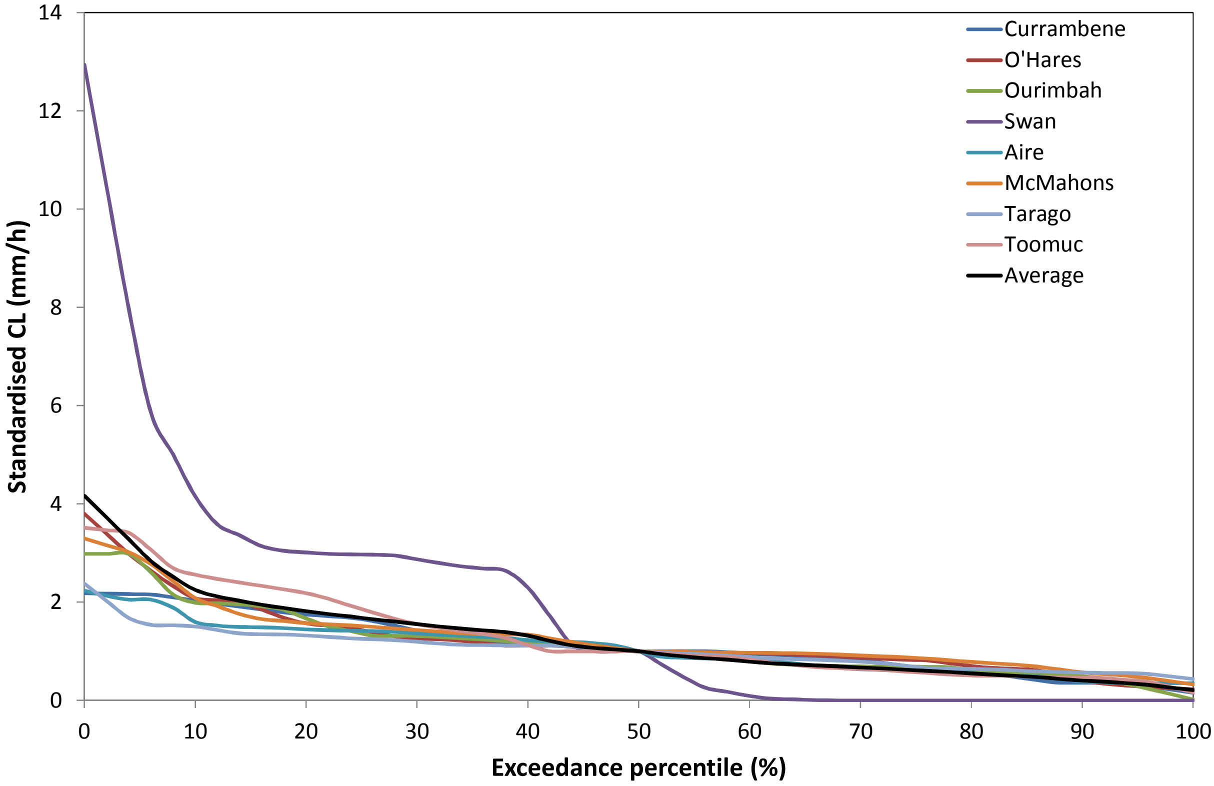
Yates Flat Ck @ Woonanup (WA) - 3 hour bursts



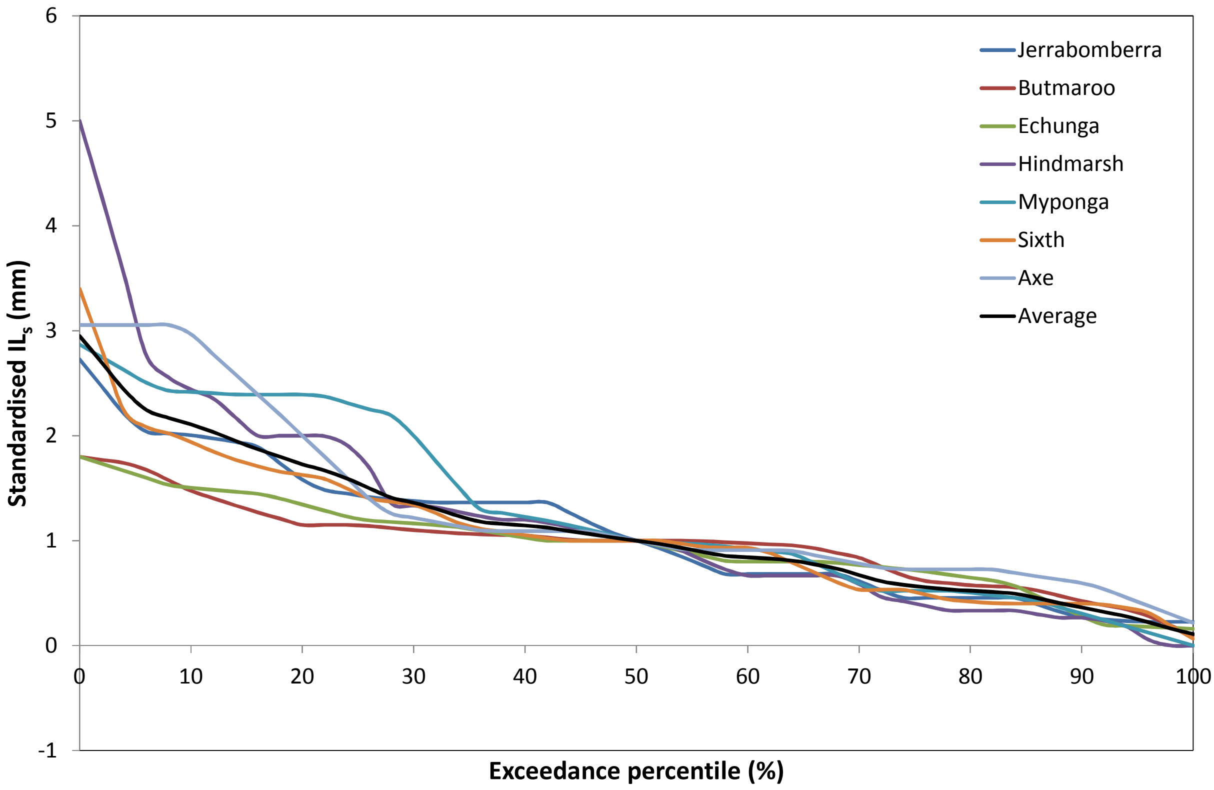
Appendix K Non-parametric loss distributions

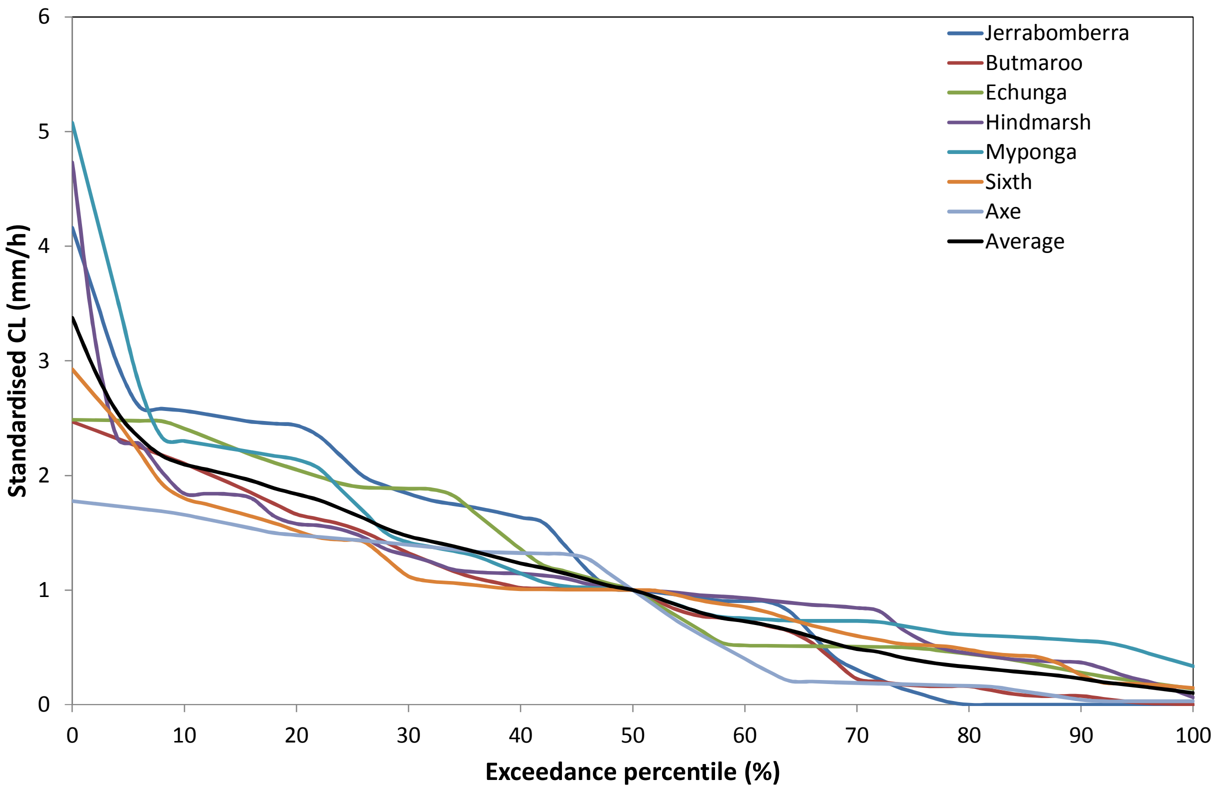
GSAM Coastal



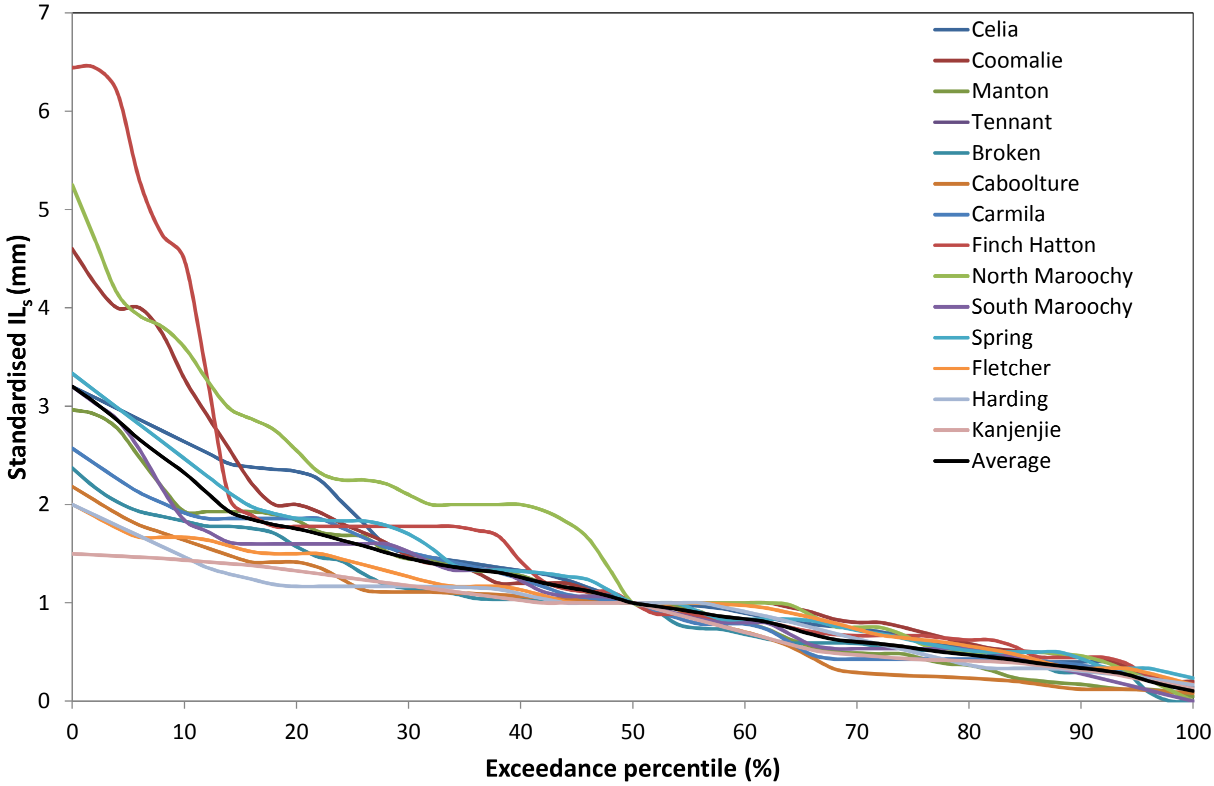


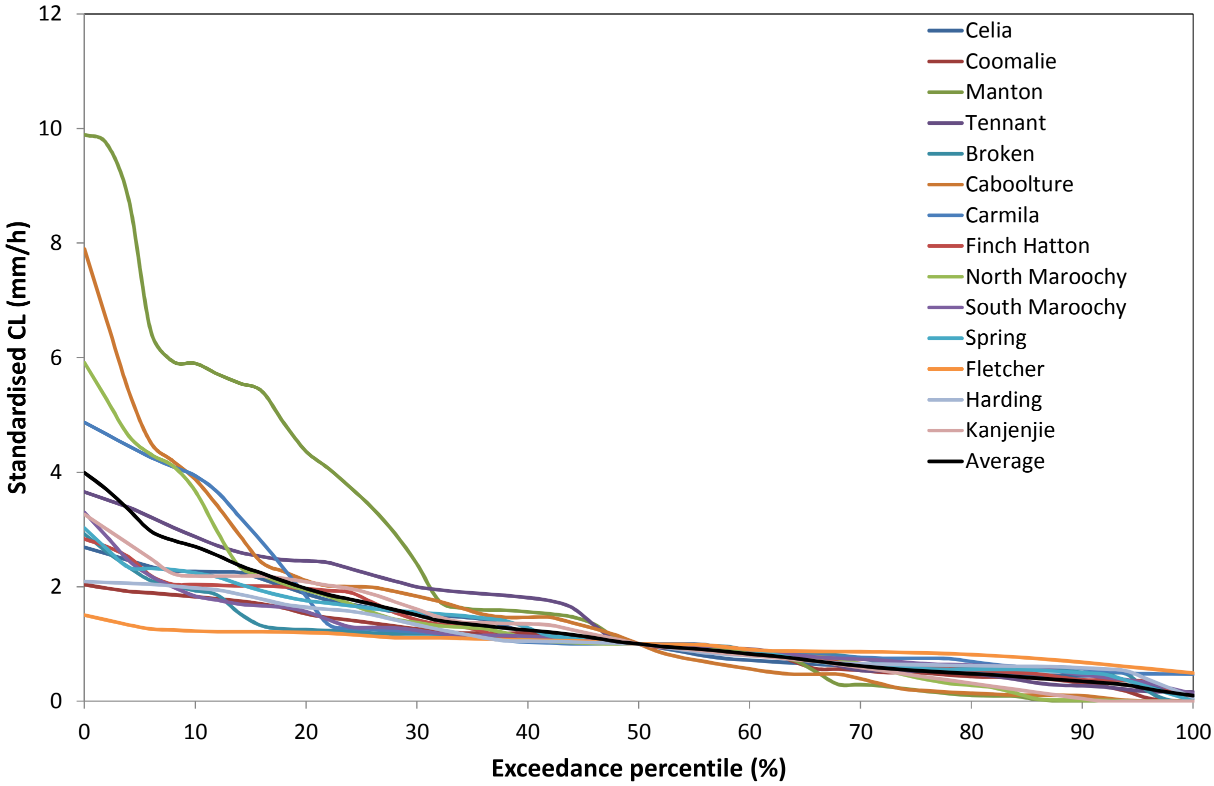
GSAM Inland


Standardised IL$_s$ (mm)
Exceedance percentile (%)
Jerrabomberra
Butmaroo
Echunga
Hindmarsh
Myponga
Sixth
Axe
Average

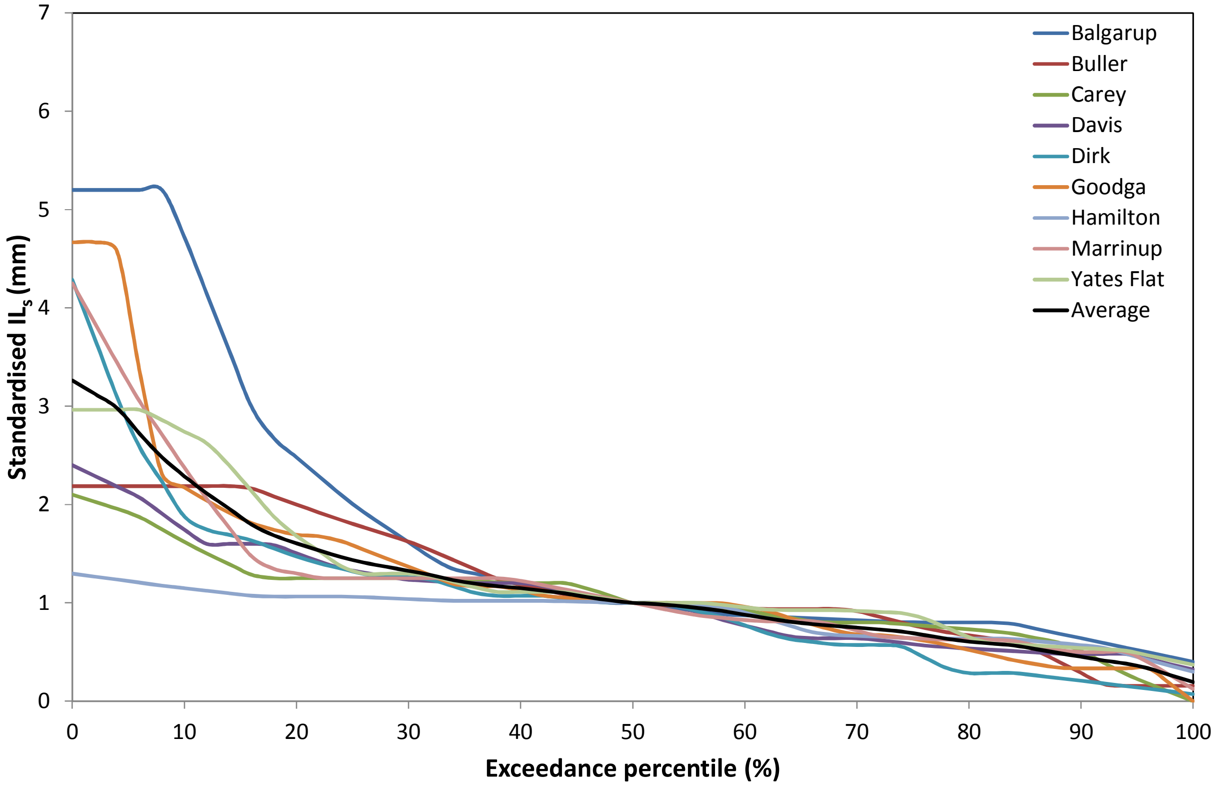

Standardised CL (mm/h)
Exceedance percentile (%)
Jerrabomberra
Butmaroo
Echunga
Hindmarsh
Myponga
Sixth
Axe
Average

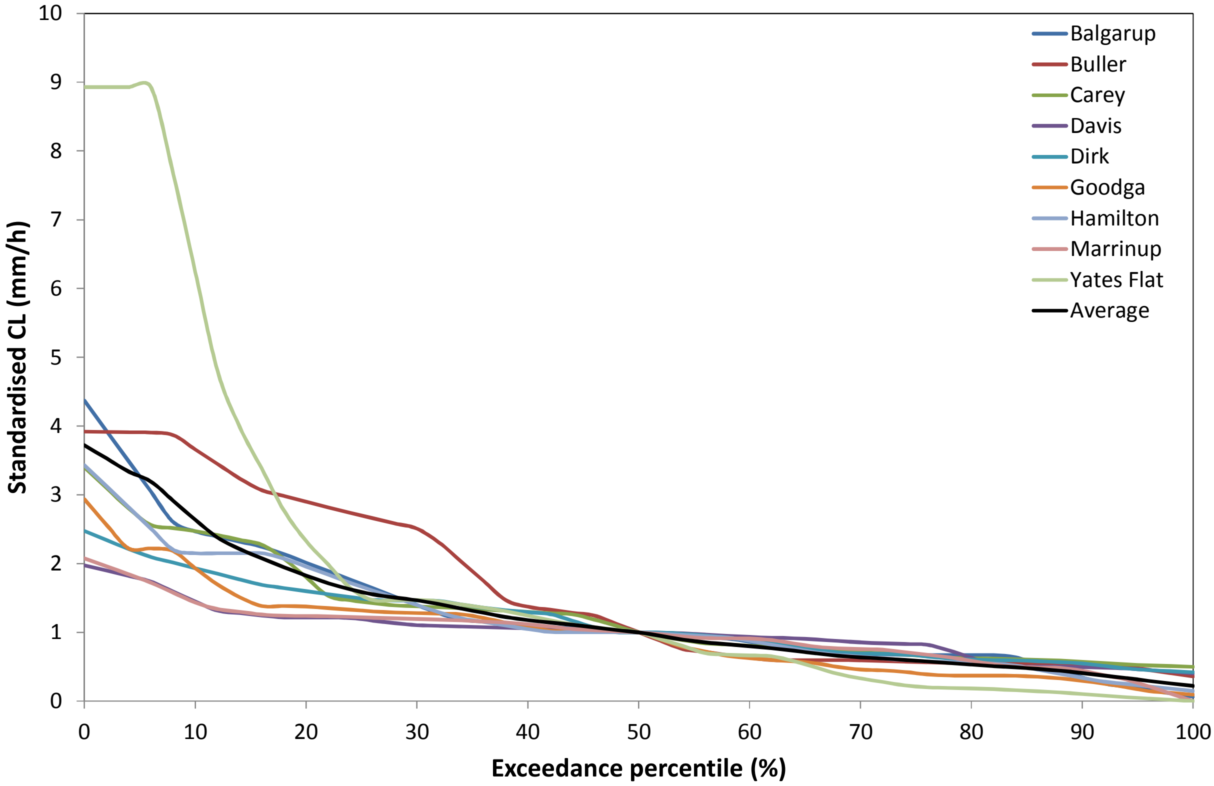
GTSMR Coastal





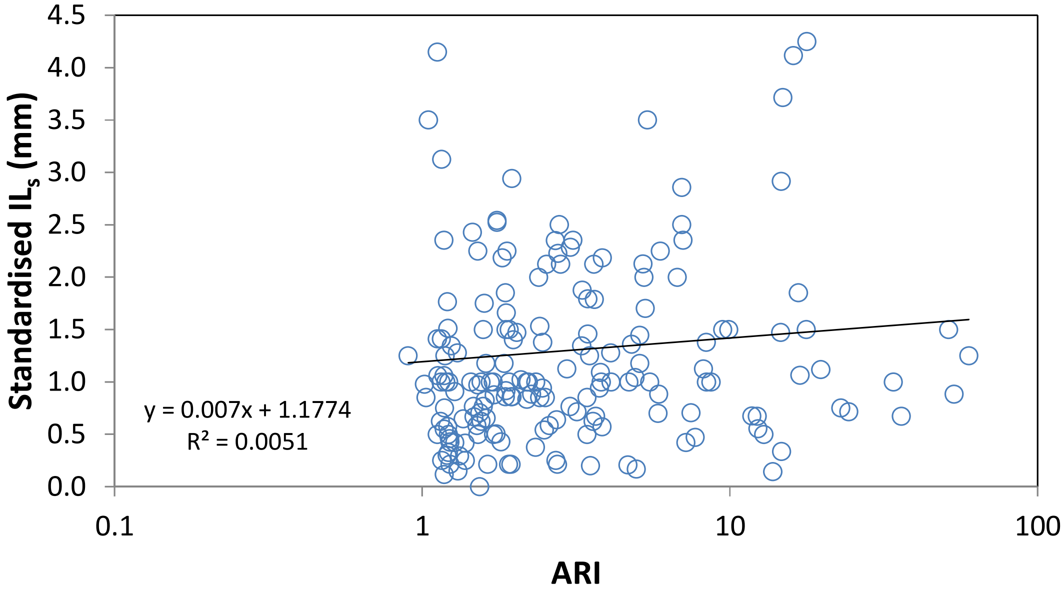
GTSMR SW WA

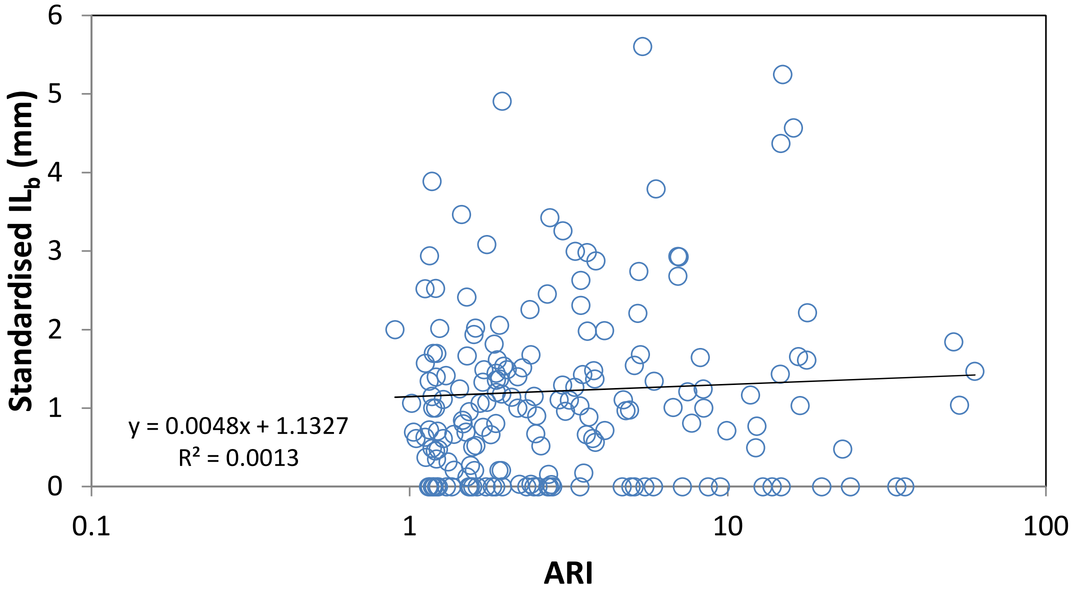

Standardised IL_s (mm)
Exceedance percentile (%)
Balgarup
Buller
Carey
Davis
Dirk
Goodga
Hamilton
Marrinup
Yates Flat
Average

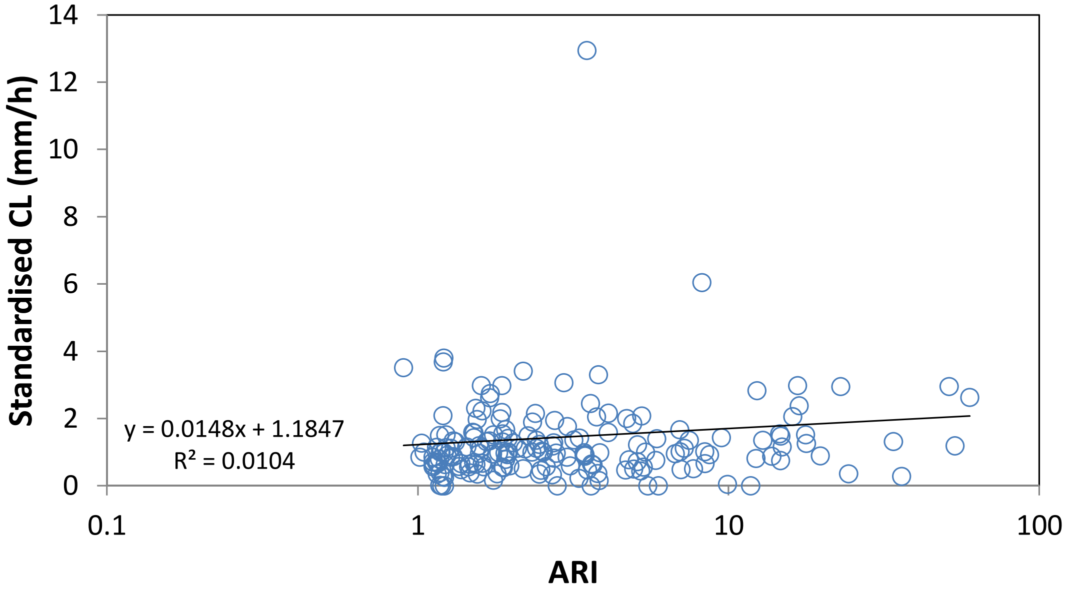

Standardised CL (mm/h)
Exceedance percentile (%)
Balgarup
Buller
Carey
Davis
Dirk
Goodga
Hamilton
Marrinup
Yates Flat
Average

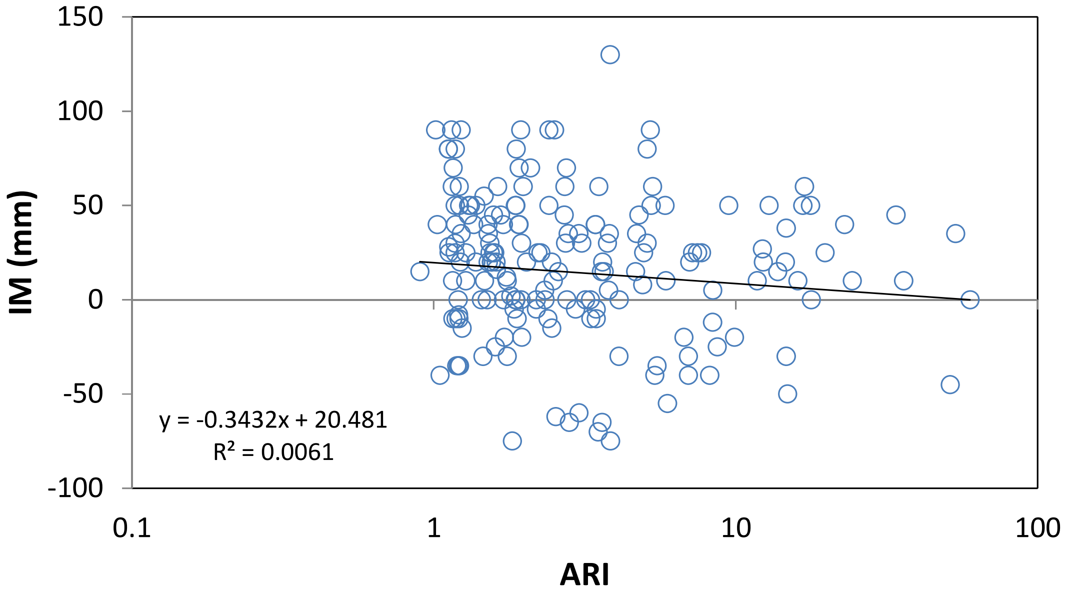
Appendix L Variation of loss values with ARI

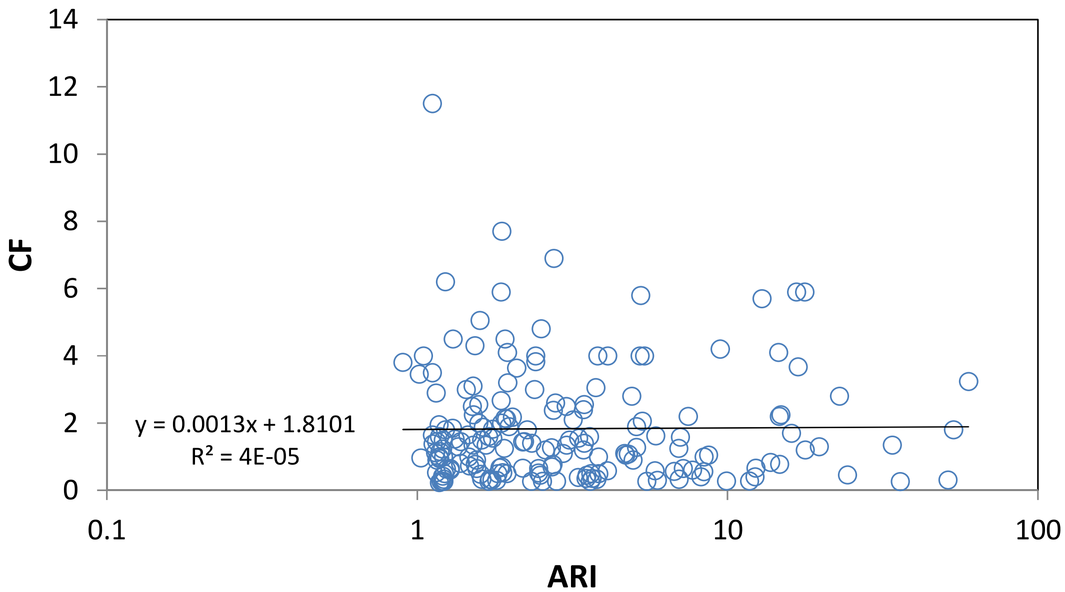
GSAM Coastal



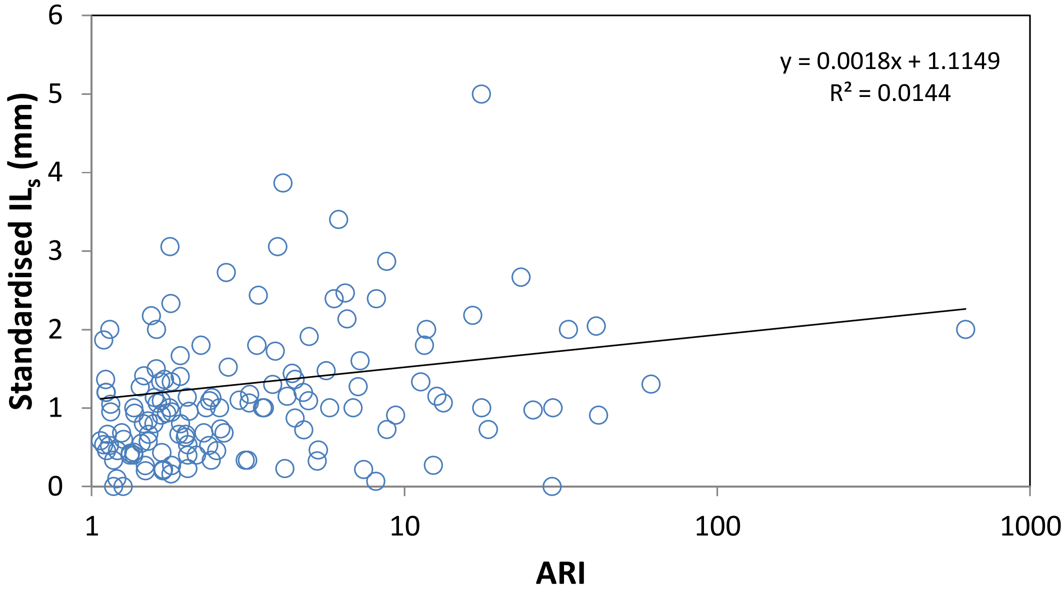



Standardised CL (mm/h)
14
12
10
8
6
4
2
0
0.1
1
10
100
ARI
y = 0.0148x + 1.1847
R² = 0.0104


IM (mm)
150
100
50
0
-50
-100
0.1
1
10
100
ARI
y = -0.3432x + 20.481
R² = 0.0061

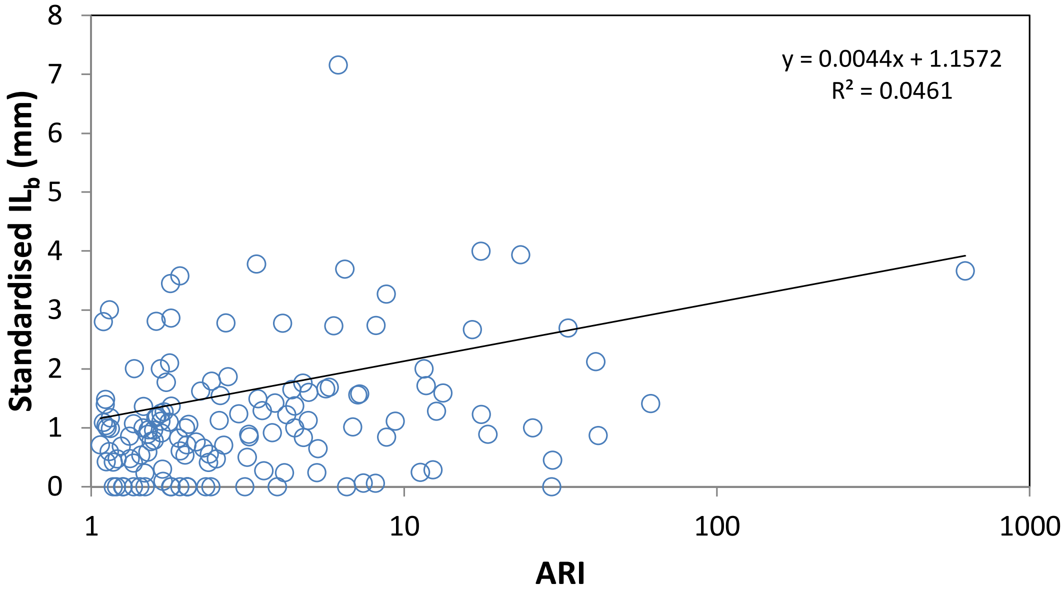

CF
14
12
10
8
6
4
2
0
0.1
1
10
100
ARI
y = 0.0013x + 1.8101
R² = 4E-05

GSAM Inland

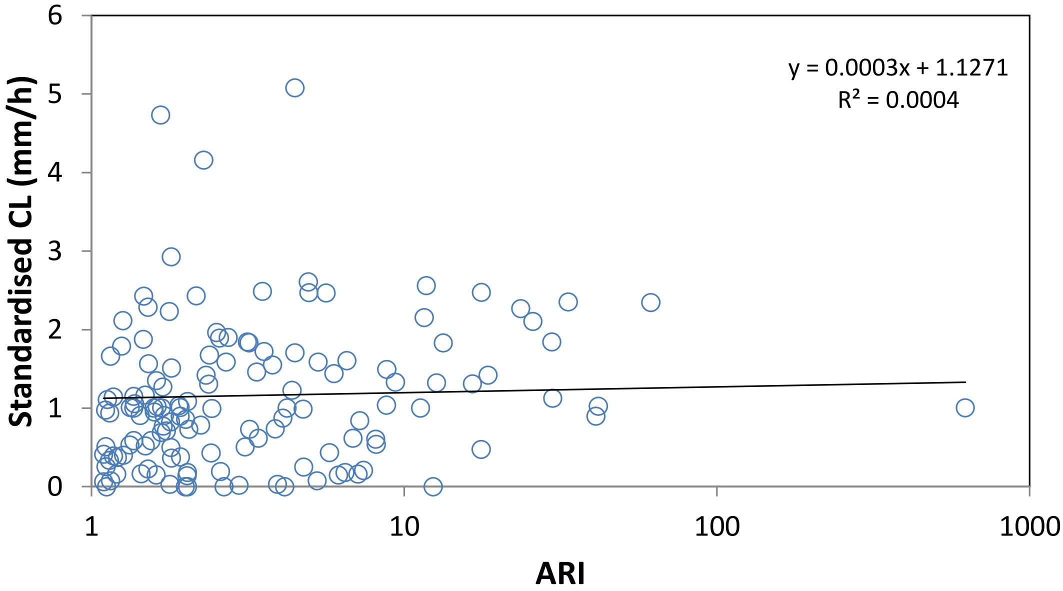


6
5
4
3
2
1
0
Standardised IL_s (mm)
y = 0.0018x + 1.1149
R^2 = 0.0144
1
10
100
1000
ARI

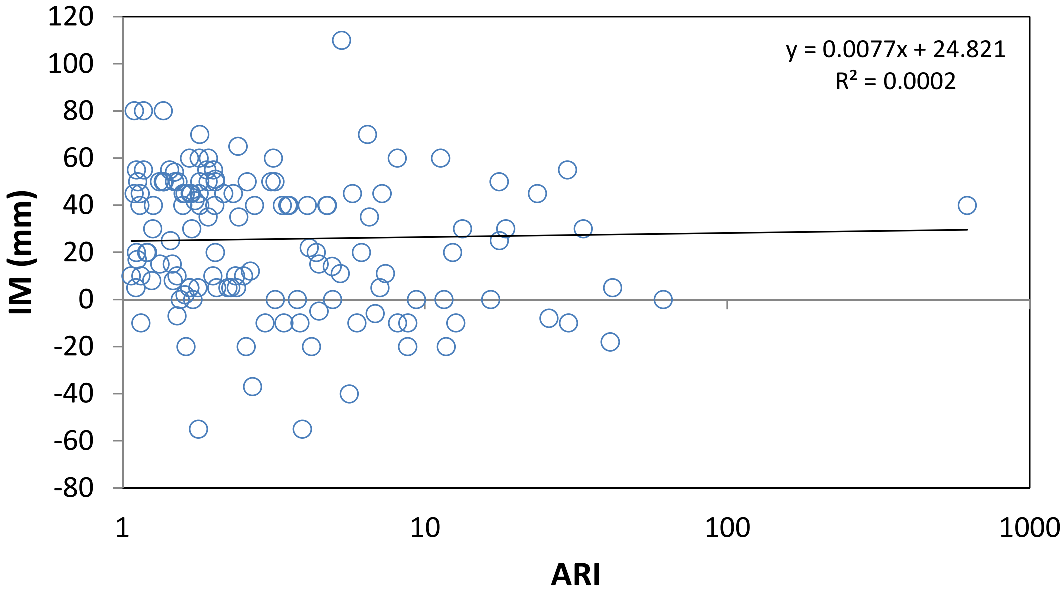
.



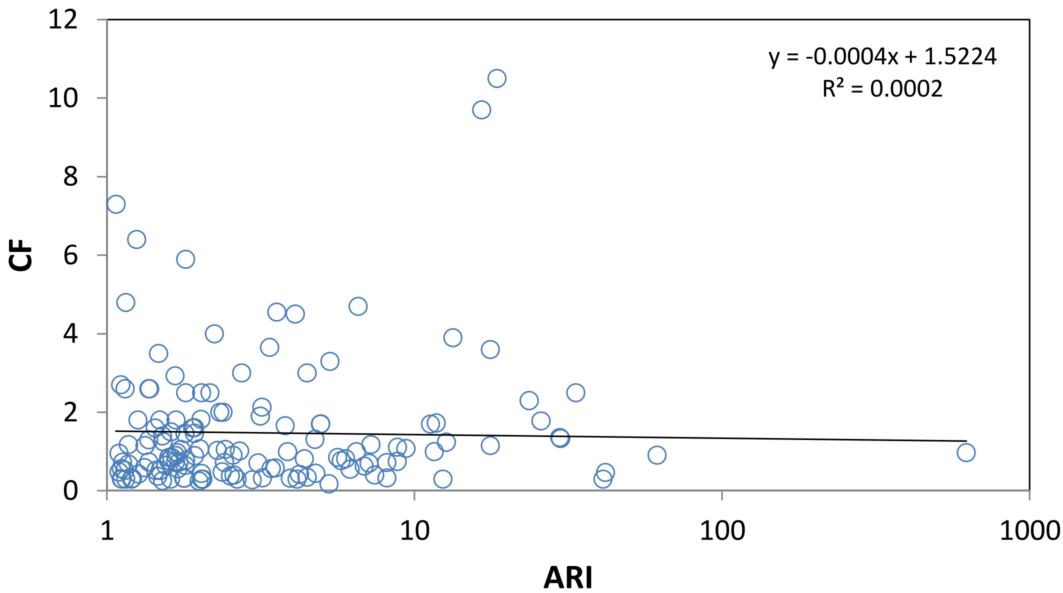
8
7
6
5
4
3
2
1
0
Standardised IL_b (mm)
y = 0.0044x + 1.1572
R^2 = 0.0461
1
10
100
1000
ARI



y = 0.0003x + 1.1271
R² = 0.0004
Standardised CL (mm/h)
ARI
0
1
2
3
4
5
6
1
10
100
1000

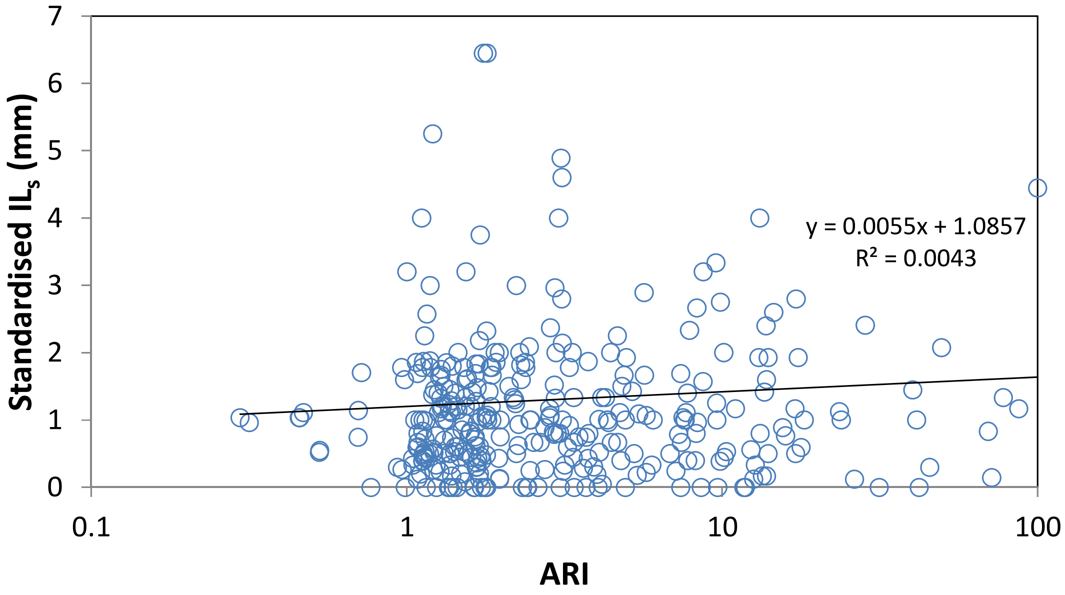


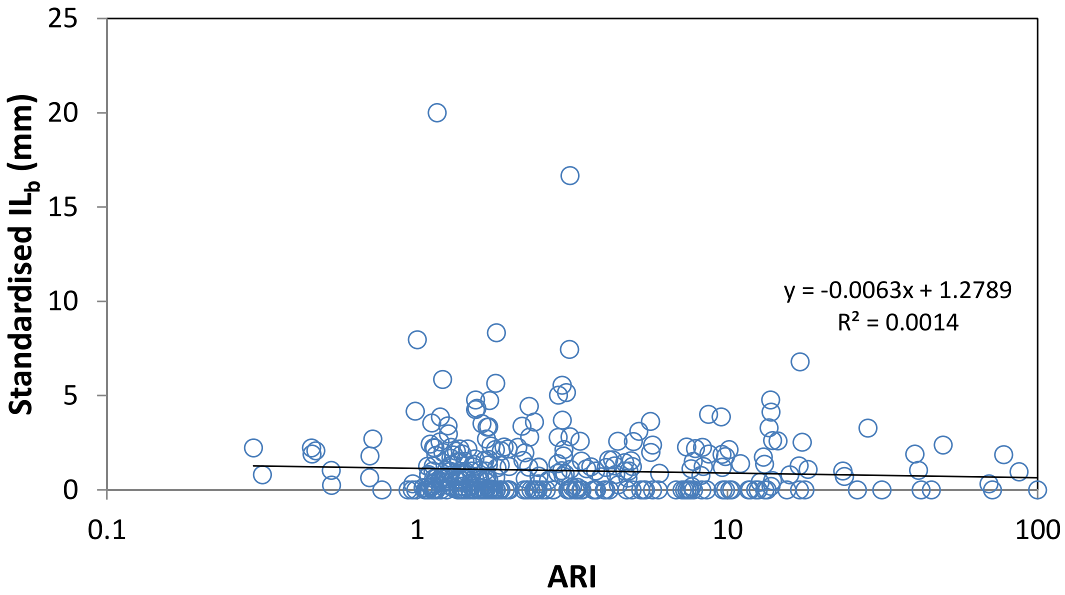
y = 0.0077x + 24.821
R² = 0.0002
IM (mm)
ARI
-80
-60
-40
-20
0
20
40
60
80
100
120
1
10
100
1000

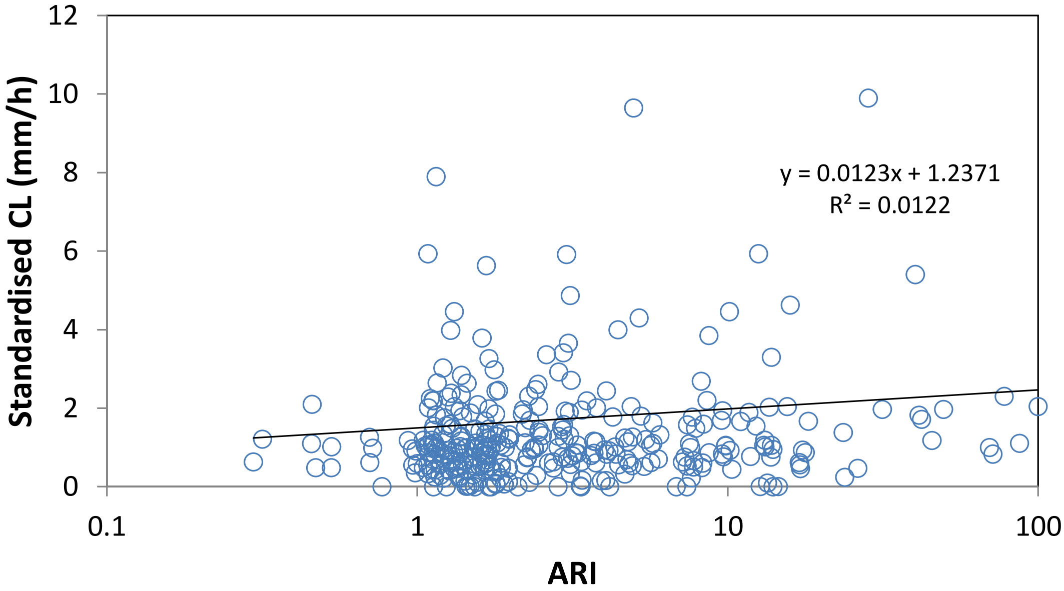


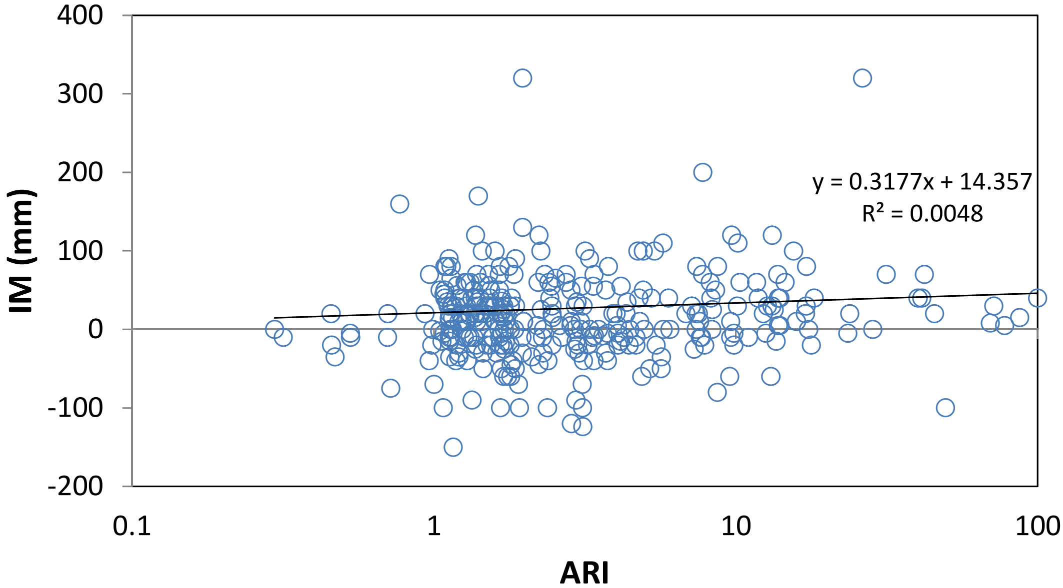
y = -0.0004x + 1.5224
R² = 0.0002
CF
ARI
0
2
4
6
8
10
12
1
10
100
1000

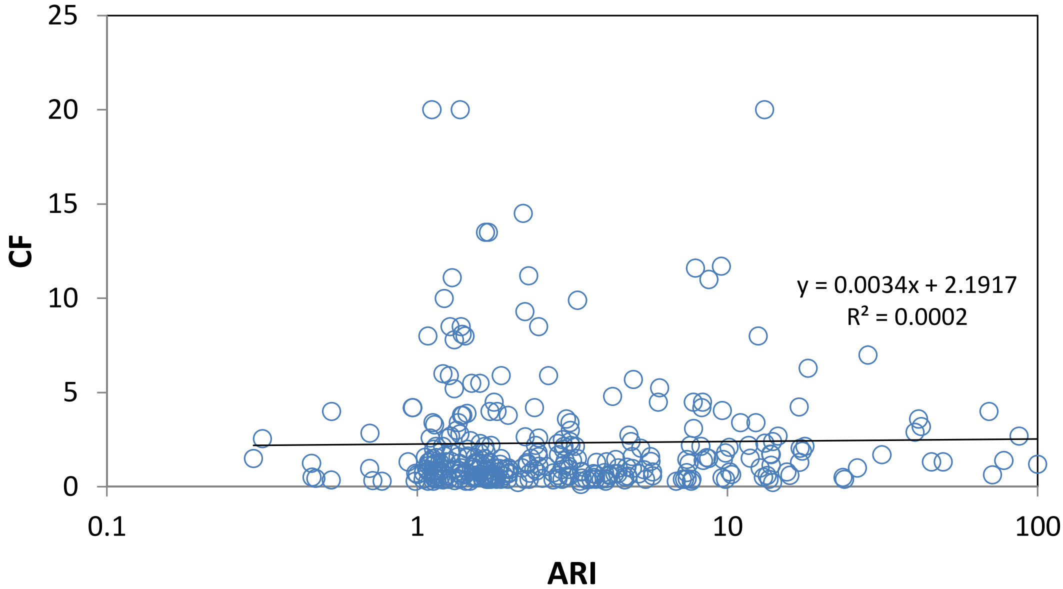
GTSMR Coastal



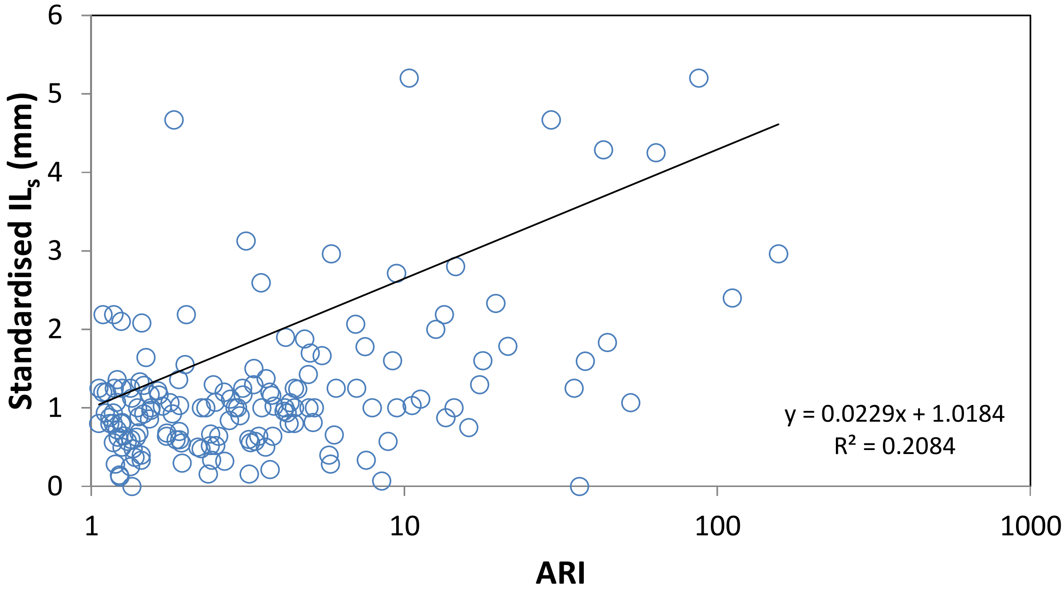


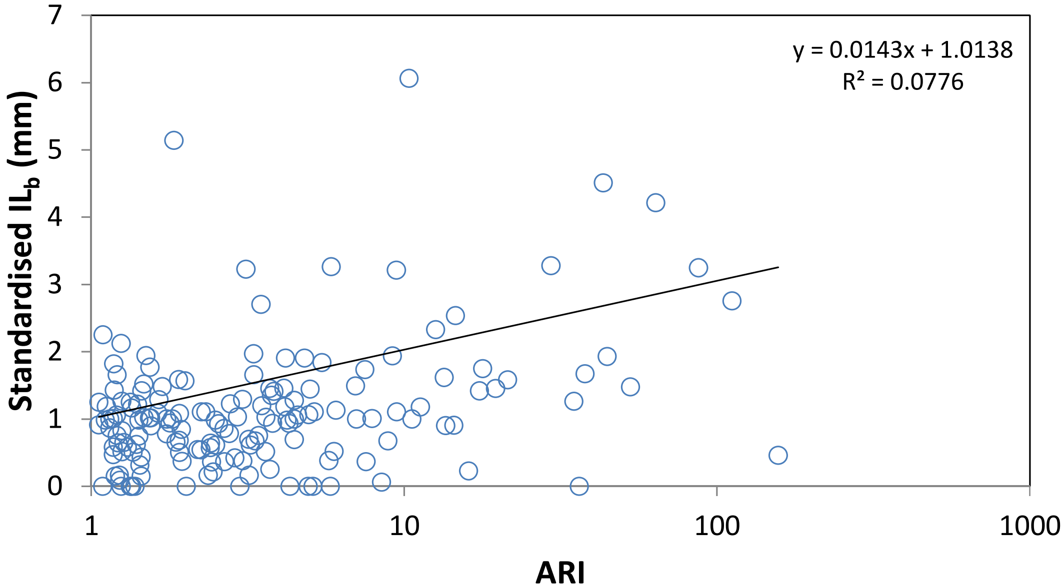

Standardised CL (mm/h)
ARI
y = 0.0123x + 1.2371
R² = 0.0122

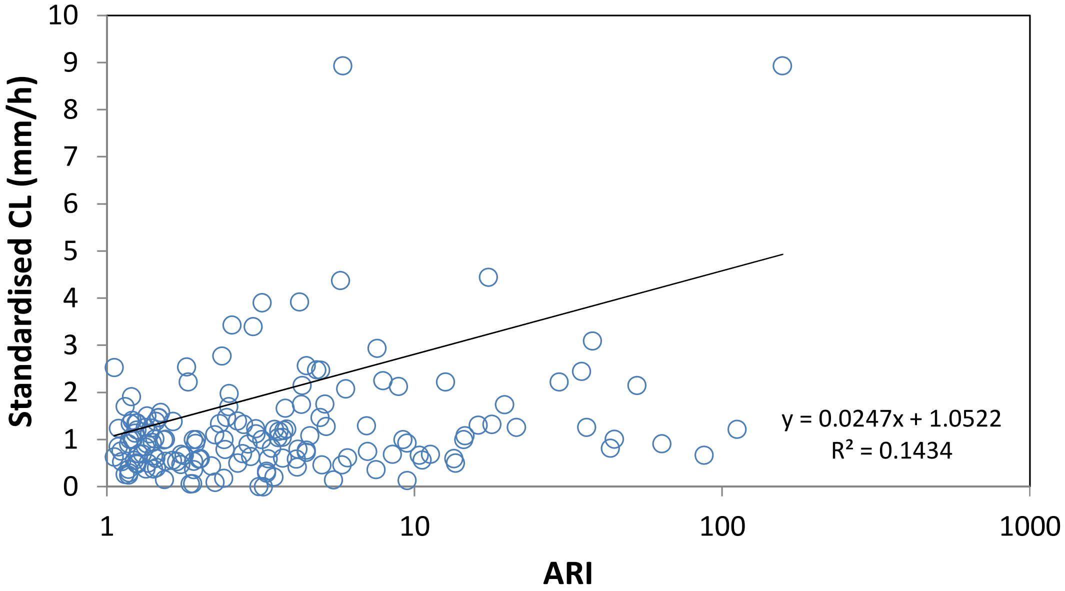

IM (mm)
ARI
y = 0.3177x + 14.357
R² = 0.0048

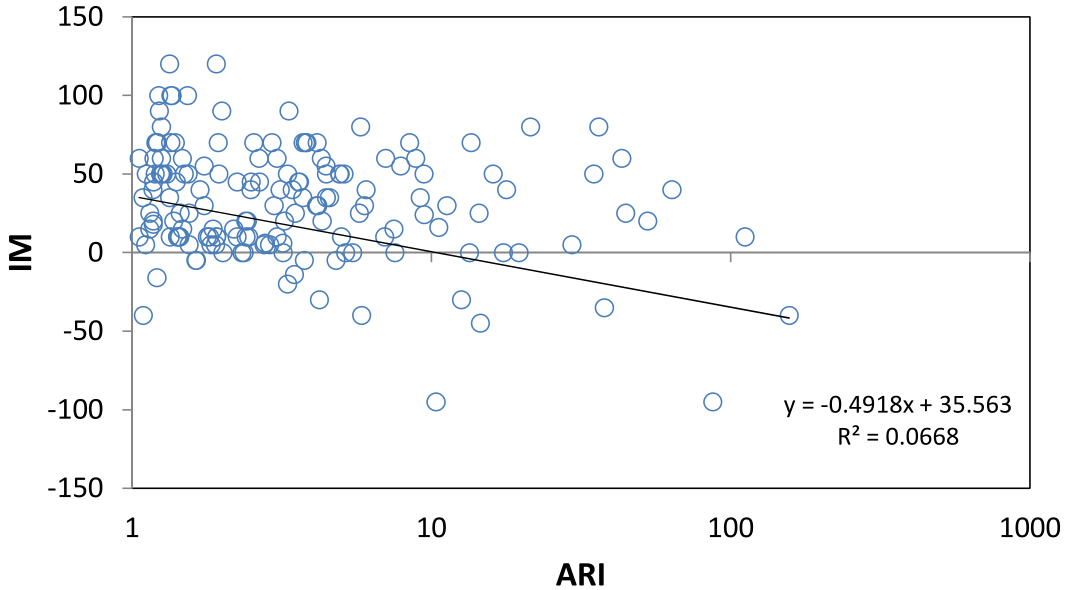

CF
ARI
y = 0.0034x + 2.1917
R² = 0.0002

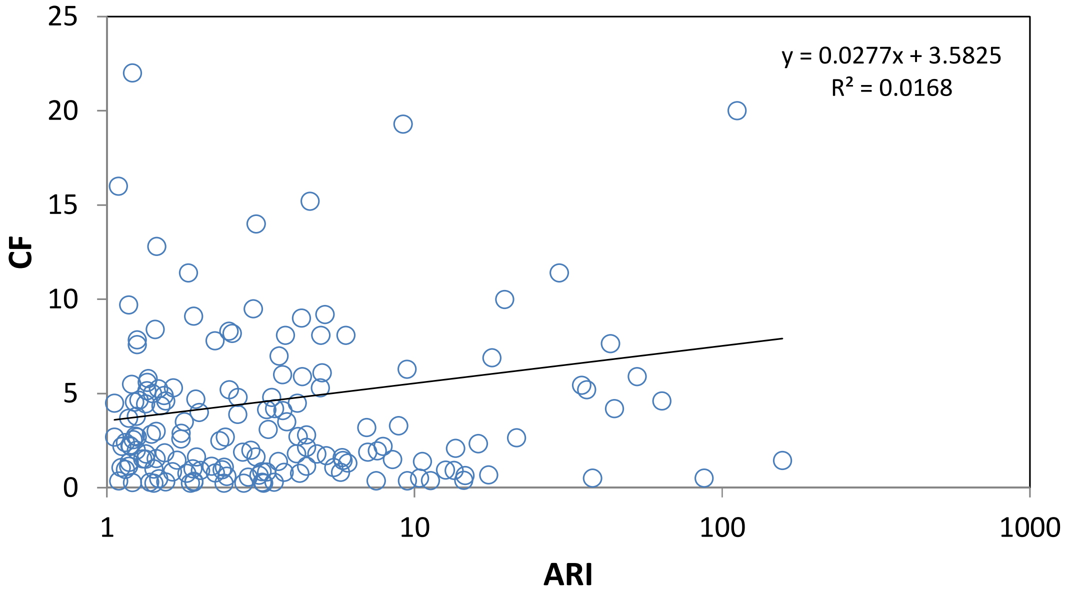
GTSMR SW WA


Standardised ILs (mm)
ARI
y = 0.0229x + 1.0184
R² = 0.2084
0
1
2
3
4
5
6
1
10
100
1000


Standardised ILb (mm)
ARI
y = 0.0143x + 1.0138
R² = 0.0776
0
1
2
3
4
5
6
7
1
10
100
1000


Standardised CL (mm/h)
ARI
y = 0.0247x + 1.0522
R² = 0.1434


IM
ARI
y = -0.4918x + 35.563
R² = 0.0668


CF
ARI
y = 0.0277x + 3.5825
R² = 0.0168

Appendix M Prediction equation diagnostics

GSAM Coastal and Inland

Dependent Variable	IL_S
N	15
Multiple R	0.886
Squared Multiple R	0.784
Adjusted Squared Multiple R	0.749
Standard Error of Estimate	6.179

Regression Coefficients B = $(X'X)^{-1}X'Y$

Effect	Coefficient	Standard Error	Std. Coefficient	Tolerance	t	p-Value
CONSTANT	16.730	5.608	0.000	.	2.984	0.011
MED_API	-0.291	0.108	-0.377	0.917	-2.692	0.020
DES_RAIN_24HR	0.141	0.021	0.917	0.917	6.555	0.000

Analysis of Variance

Source	SS	df	Mean Squares	F-Ratio	p-Value
Regression	1,667.563	2	833.781	21.838	0.000
Residual	458.170	12	38.181		

WARNING

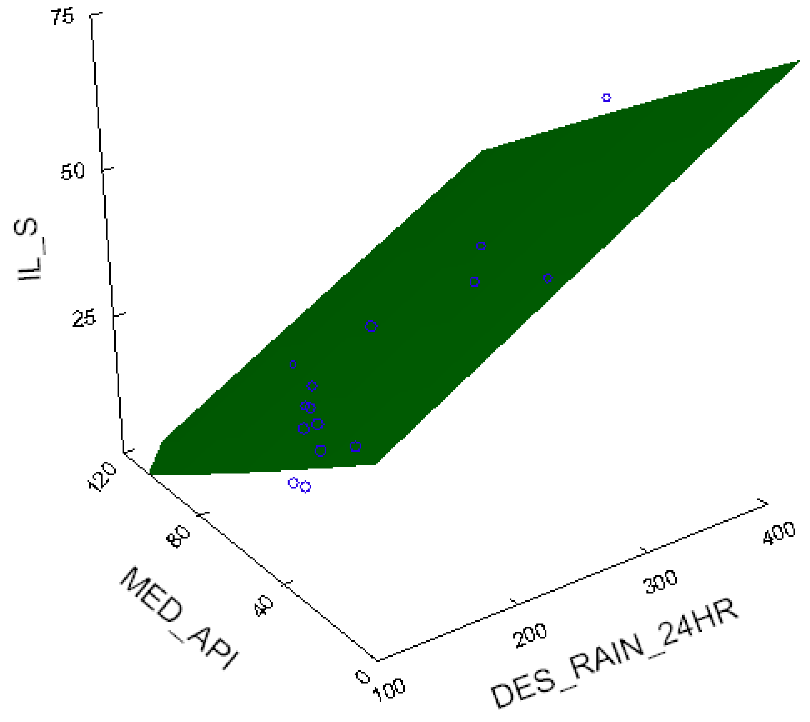
Case 1 is an Outlier (Studentized Residual : -2.902)
Case 5 has large Leverage (Leverage : 0.656)

Durbin-Watson D-Statistic	2.265
First Order Autocorrelation	-0.309

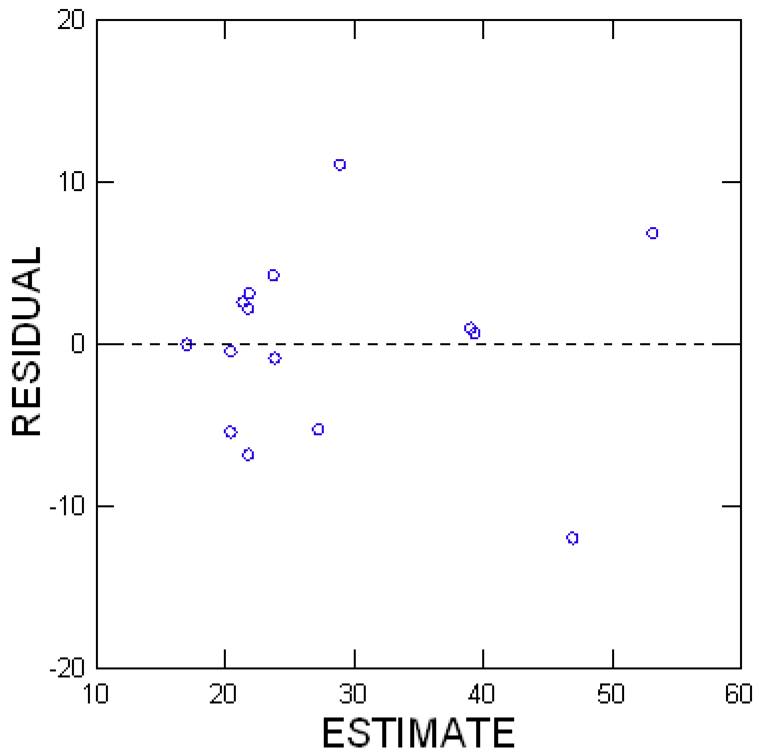
Information Criteria

AIC	101.856
AIC (Corrected)	105.856
Schwarz's BIC	104.688

Fitted Model Plot



Plot of Residuals vs. Predicted Values



Dependent Variable	IM
N	15
Multiple R	0.656
Squared Multiple R	0.430
Adjusted Squared Multiple R	0.387
Standard Error of Estimate	21.413

Regression Coefficients $B = (X'X)^{-1}X'Y$

Effect	Coefficient	Standard Error	Std. Coefficient	Tolerance	t	p-Value
CONSTANT	-4.502	9.522	0.000	.	-0.473	0.644
A_KSAT	0.229	0.073	0.656	1.000	3.135	0.008

Analysis of Variance

Source	SS	df	Mean Squares	F-Ratio	p-Value
Regression	4,505.934	1	4,505.934	9.827	0.008
Residual	5,960.966	13	458.536		

WARNING

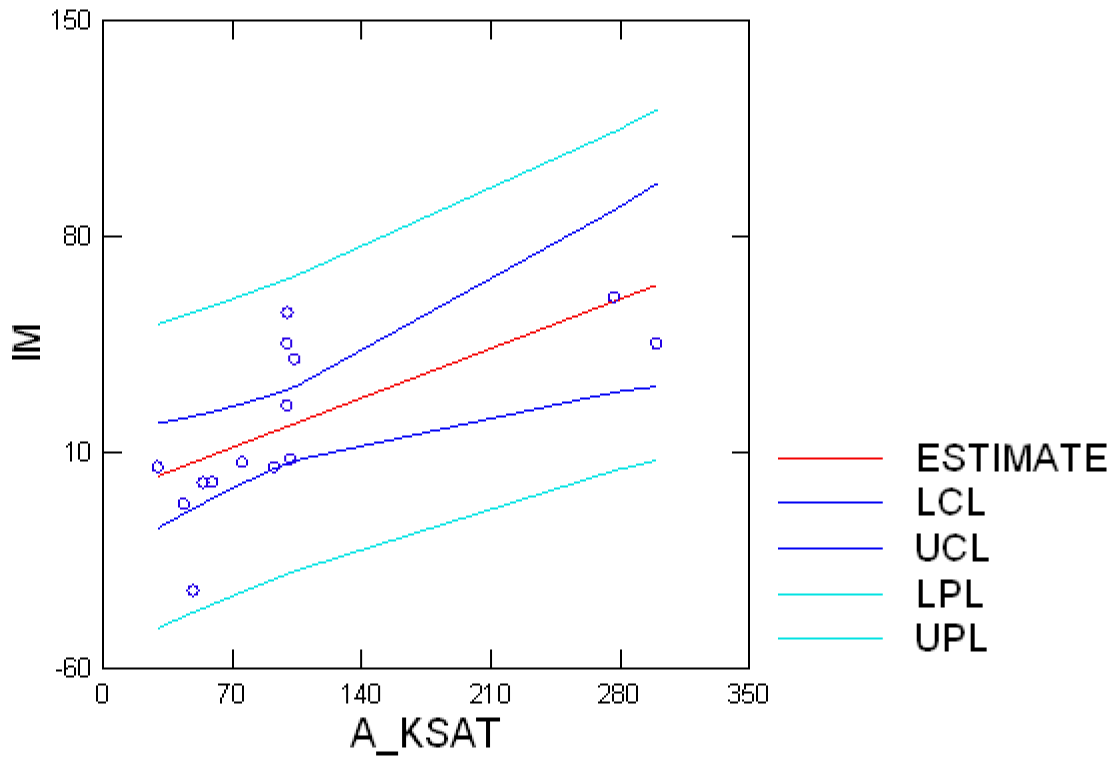
Case 6 has large Leverage (Leverage : 0.506)

Durbin-Watson D-Statistic	2.584
First Order Autocorrelation	-0.300

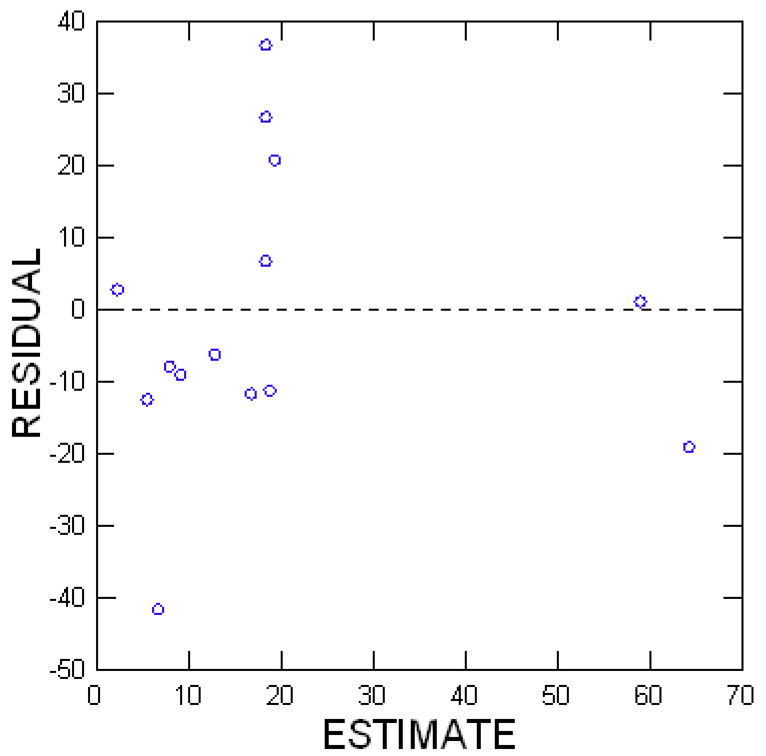
Information Criteria

AIC	138.342
AIC (Corrected)	140.524
Schwarz's BIC	140.466

Confidence Interval and Prediction Interval



Plot of Residuals vs. Predicted Values



Dependent Variable	CF
N	15
Multiple R	0.760
Squared Multiple R	0.577
Adjusted Squared Multiple R	0.544
Standard Error of Estimate	0.446

Regression Coefficients $B = (X'X)^{-1}X'Y$

Effect	Coefficient	Standard Error	Std. Coefficient	Tolerance	t	p-Value
CONSTANT	0.514	0.198	0.000	.	2.591	0.022
A_KSAT	0.006	0.002	0.760	1.000	4.210	0.001

Analysis of Variance

Source	SS	df	Mean Squares	F-Ratio	p-Value
Regression	3.524	1	3.524	17.721	0.001
Residual	2.585	13	0.199		

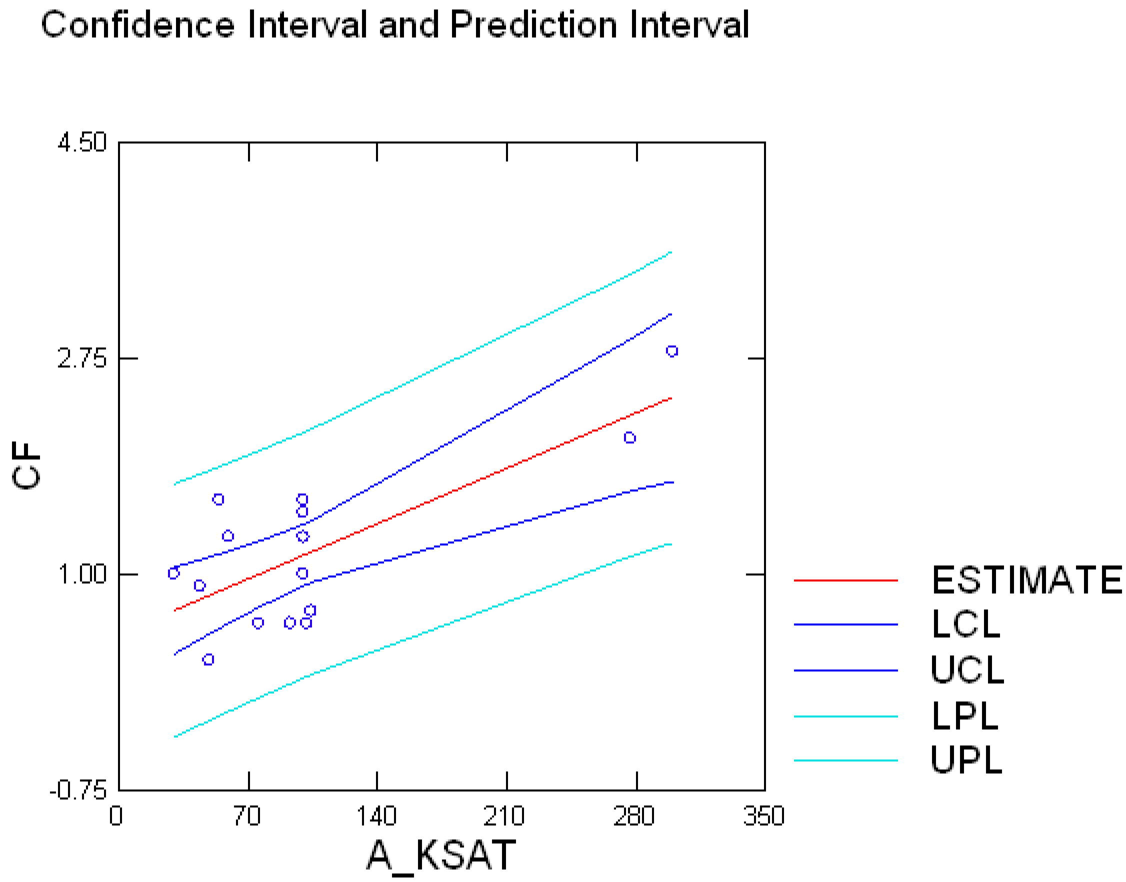
WARNING

Case 6 has large Leverage (Leverage : 0.506)

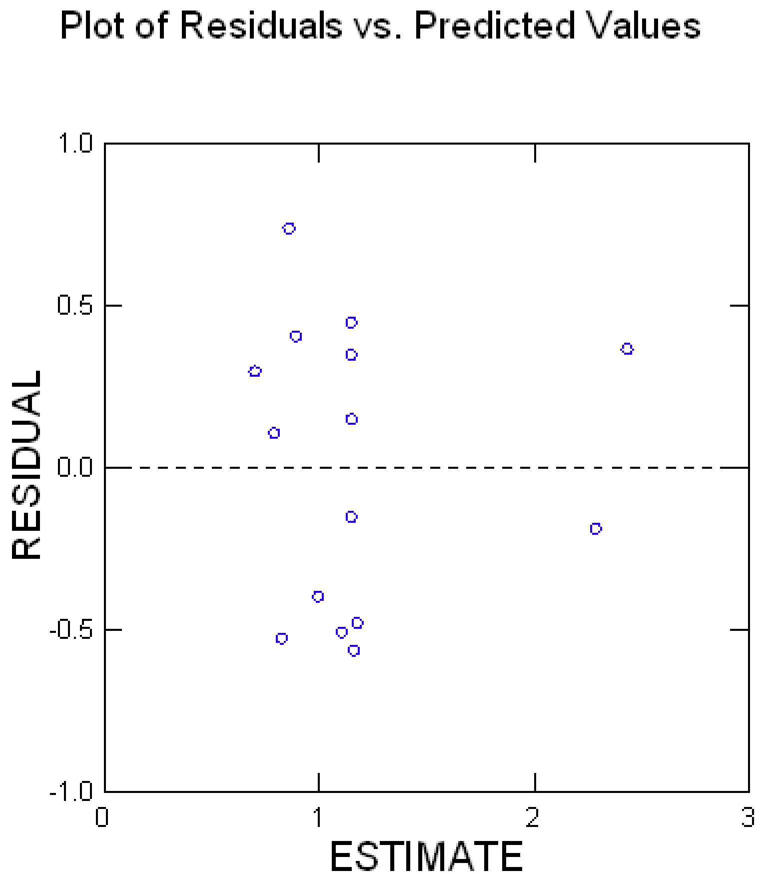
Durbin-Watson D-Statistic	2.755
First Order Autocorrelation	-0.426

Information Criteria

AIC	22.195
AIC (Corrected)	24.376
Schwarz's BIC	24.319



Confidence Interval and Prediction Interval
4.50
2.75
1.00
-0.75
CF
0
70
140
210
280
350
A_KSAT
ESTIMATE
LCL
UCL
LPL
UPL



Plot of Residuals vs. Predicted Values
1.0
0.5
0.0
-0.5
-1.0
RESIDUAL
0
1
2
3
ESTIMATE

GTSMR Coastal

Dependent Variable	IM
N	14
Multiple R	0.812
Squared Multiple R	0.659
Adjusted Squared Multiple R	0.598
Standard Error of Estimate	17.924

Regression Coefficients B = $(X'X)^{-1}X'Y$

Effect	Coefficient	Standard Error	Std. Coefficient	Tolerance	t	p-Value
CONSTANT	108.404	24.871	0.000	.	4.359	0.001
ELEVRANGE_SQRTCA	622.208	146.744	1.061	0.495	4.240	0.001
A_FCP	-393.526	91.601	-1.075	0.495	-4.296	0.001

Analysis of Variance

Source	SS	df	Mean Squares	F-Ratio	p-Value
Regression	6,843.297	2	3,421.649	10.650	0.003
Residual	3,533.935	11	321.267		

WARNING

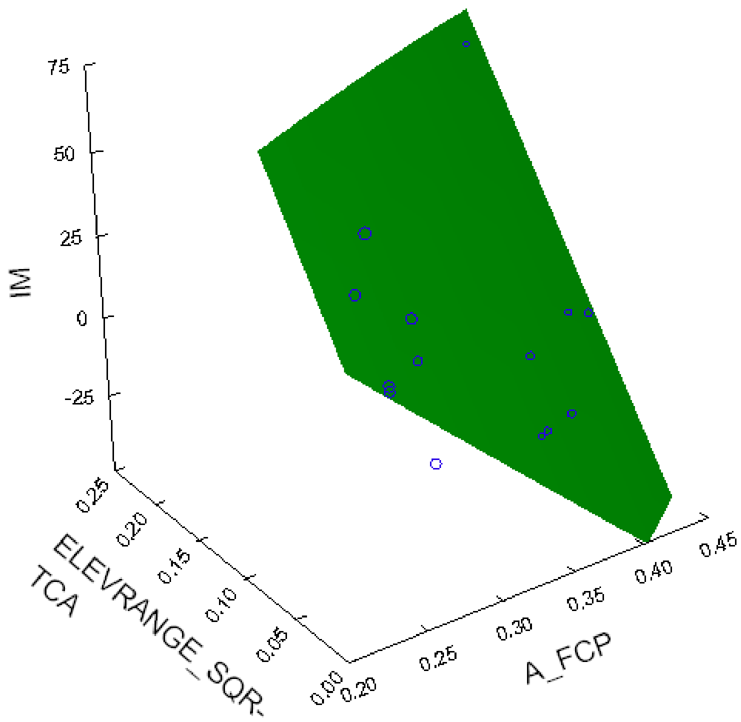
Case 8 has large Leverage (Leverage : 0.834)

Durbin-Watson D-Statistic	2.138
First Order Autocorrelation	-0.228

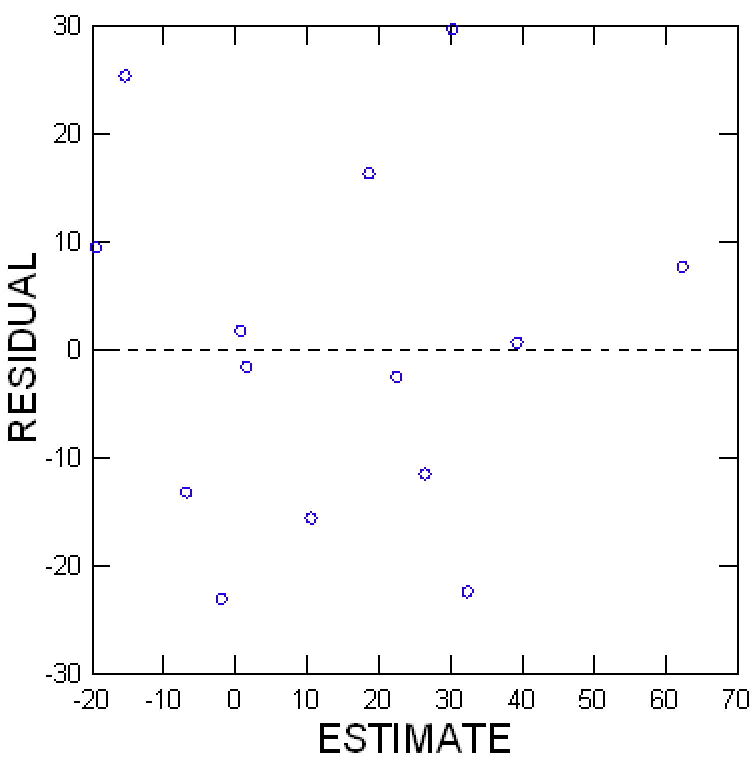
Information Criteria

AIC	125.166
AIC (Corrected)	129.610
Schwarz's BIC	127.722

Fitted Model Plot



Plot of Residuals vs. Predicted Values



GTSMR SW WA

Dependent Variable	CL
N	9
Multiple R	0.738
Squared Multiple R	0.544
Adjusted Squared Multiple R	0.479
Standard Error of Estimate	1.727

Regression Coefficients B = (X'X)$^{-1}$X'Y

Effect	Coefficient	Standard Error	Std. Coefficient	Tolerance	t	p-Value
CONSTANT	-10.695	5.314	0.000	.	-2.013	0.084
DES_RAIN_12HR	0.159	0.055	0.738	1.000	2.889	0.023

Analysis of Variance

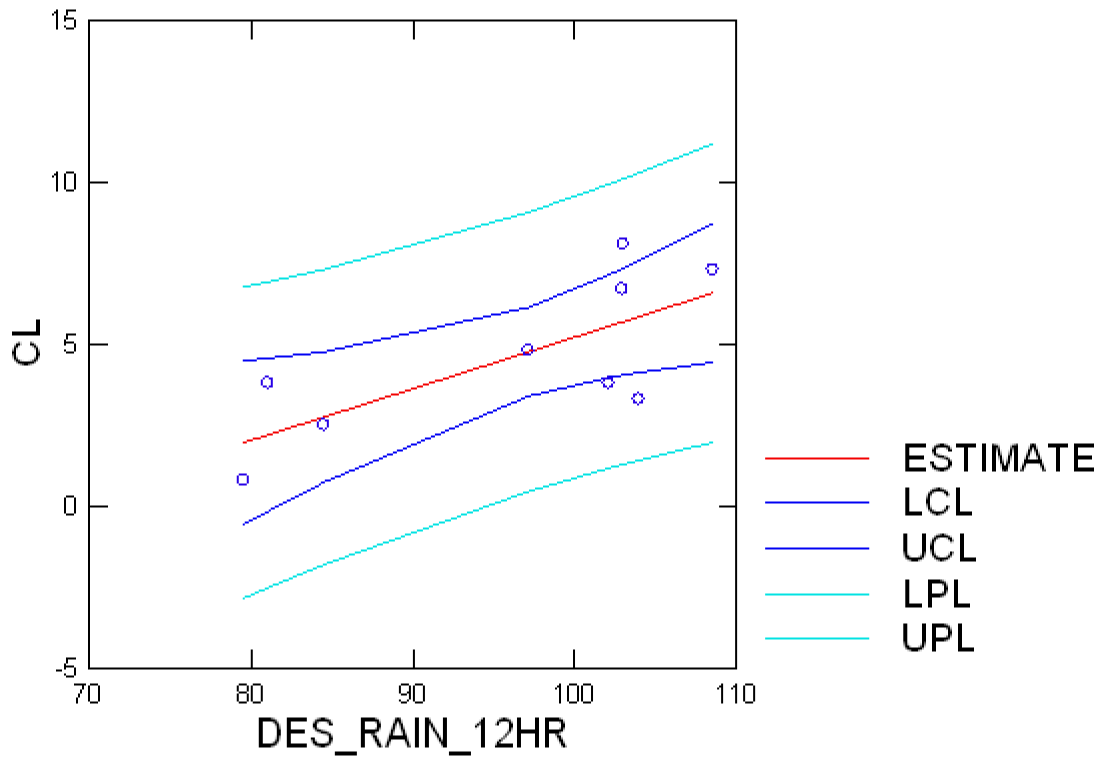
Source	SS	df	Mean Squares	F-Ratio	p-Value
Regression	24.912	1	24.912	8.348	0.023
Residual	20.888	7	2.984		

Durbin-Watson D-Statistic	1.819
First Order Autocorrelation	0.056

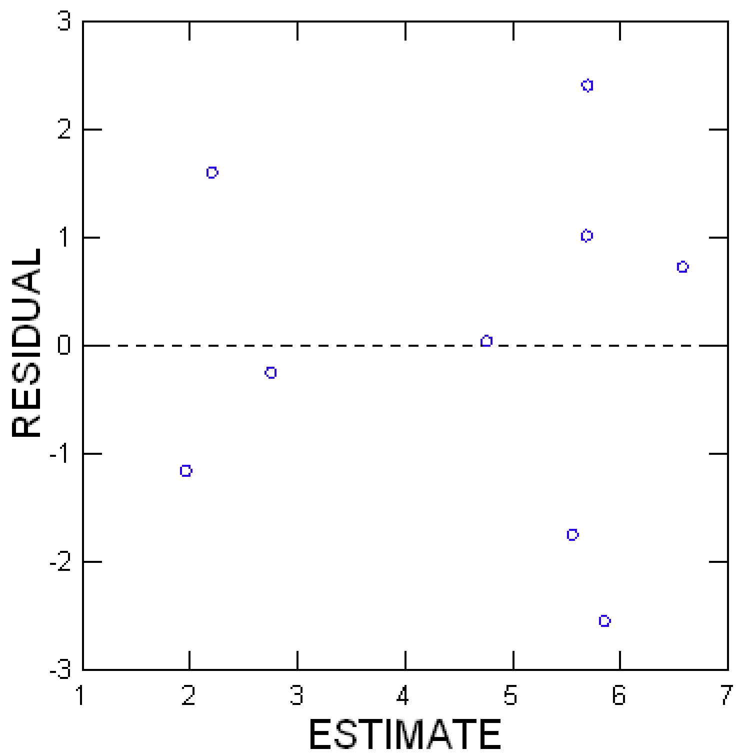
Information Criteria

AIC	39.119
AIC (Corrected)	43.919
Schwarz's BIC	39.710

Confidence Interval and Prediction Interval



Plot of Residuals vs. Predicted Values



Dependent Variable	IM
N	9
Multiple R	0.946
Squared Multiple R	0.894
Adjusted Squared Multiple R	0.879
Standard Error of Estimate	8.527

Regression Coefficients $B = (X'X)^{-1}X'Y$

Effect	Coefficient	Standard Error	Std. Coefficient	Tolerance	t	p-Value
CONSTANT	-36.122	9.334	0.000	.	-3.870	0.006
TOP_2PC_API	0.472	0.061	0.946	1.000	7.688	0.000

Analysis of Variance

Source	SS	df	Mean Squares	F-Ratio	p-Value
Regression	4,296.629	1	4,296.629	59.098	0.000
Residual	508.927	7	72.704		

WARNING

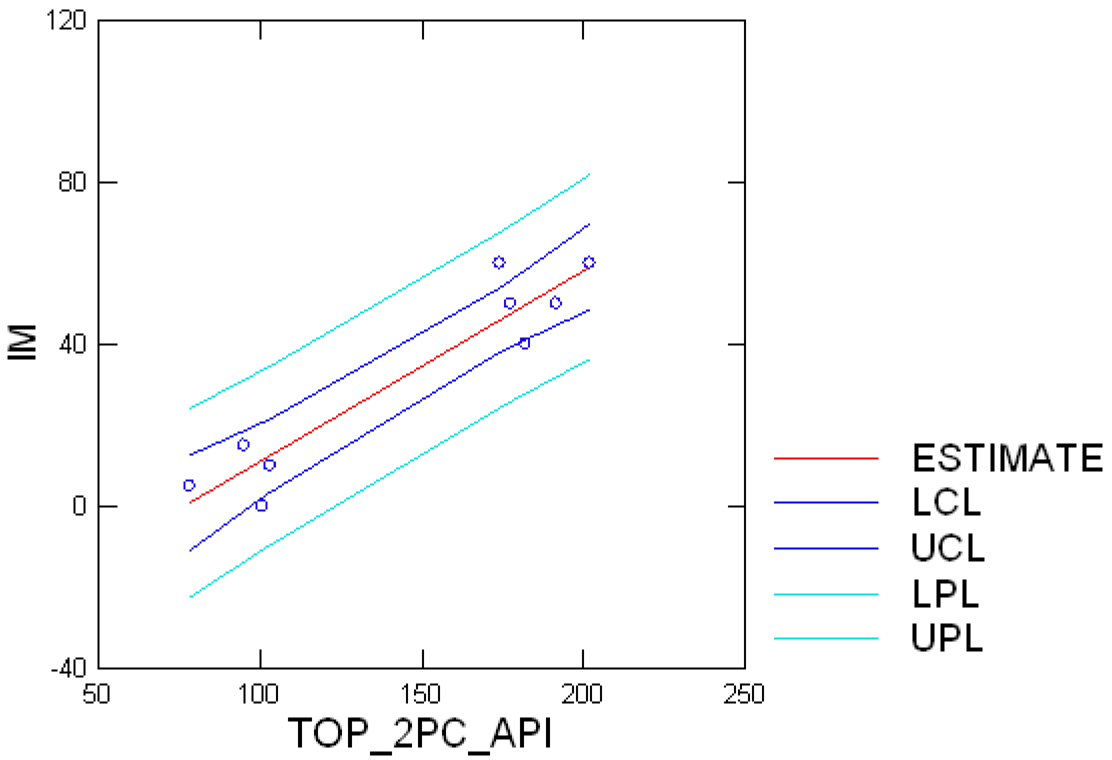
Case 5 is an Outlier (Studentized Residual : 2.254)

Durbin-Watson D-Statistic	2.397
First Order Autocorrelation	-0.254

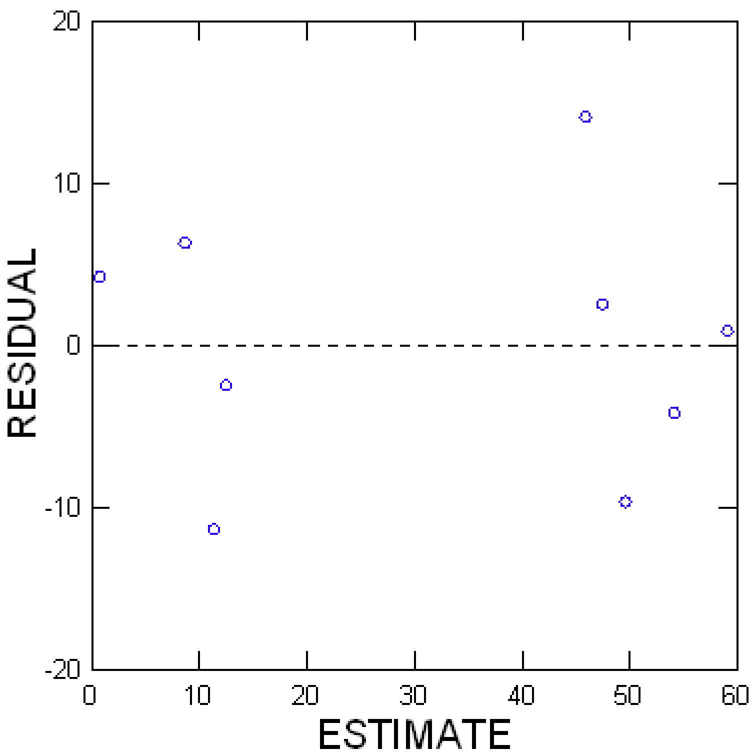
Information Criteria

AIC	67.857
AIC (Corrected)	72.657
Schwarz's BIC	68.448

Confidence Interval and Prediction Interval



Plot of Residuals vs. Predicted Values



Dependent Variable	CF
N	9
Multiple R	0.703
Squared Multiple R	0.494
Adjusted Squared Multiple R	0.421
Standard Error of Estimate	1.705

Regression Coefficients $B = (X'X)^{-1}X'Y$

Effect	Coefficient	Standard Error	Std. Coefficient	Tolerance	t	p-Value
CONSTANT	0.881	0.960	0.000	.	0.918	0.389
B_KSAT	0.012	0.005	0.703	1.000	2.612	0.035

Analysis of Variance

Source	SS	df	Mean Squares	F-Ratio	p-Value
Regression	19.821	1	19.821	6.822	0.035
Residual	20.339	7	2.906		

WARNING

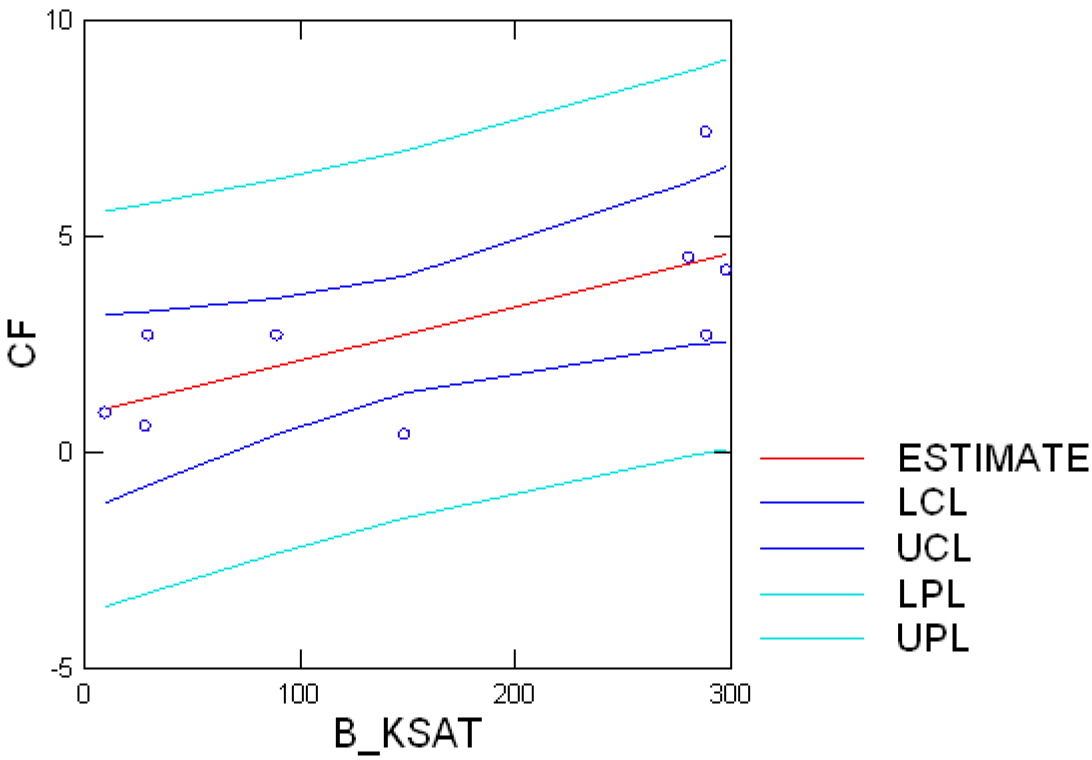
Case 4 is an Outlier (Studentized Residual : 2.726)

Durbin-Watson D-Statistic	0.907
First Order Autocorrelation	0.413

Information Criteria

AIC	38.879
AIC (Corrected)	43.679
Schwarz's BIC	39.470

Confidence Interval and Prediction Interval



Plot of Residuals vs. Predicted Values