Australian Rainfall & Runoff

Revision Projects

PROJECT 6

Loss Models for Catchment Simulation - Rural Catchments

STAGE 2 REPORT

P6/S2/016A

MARCH 2013

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

STAGE 2 REPORT

MARCH, 2013

Project Project 6: Loss Models For Catchment Simulation - Rural Catchments	**AR&R Report Number** P6/S2/016A
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FOREWORD

AR&R Revision Process

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

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

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

However, many of the practices recommended in the 1987 edition of AR&R now are becoming outdated, and no longer represent the accepted views of professionals, both in terms of technique and approach to water management.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

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

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

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

Project 6: Loss Models for Catchment Simulation Rural Catchments
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

AR&R REVISION PROJECTS

The 21 AR&R revision projects are listed below:

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

AR&R Technical Committee:

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Members: Associate Professor James Ball, Editor AR&R, UTS
Professor George Kuczera, University of Newcastle
Professor Martin Lambert, Chair NCWE, University of Adelaide
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BACKGROUND

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

Phase 1 – Pilot Study for Rural Catchments. Involves 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 (outside of current scope). 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 1.

PROJECT TEAM

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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. Involves 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 and is being undertaken by Cardno.

- Phase 4 – Analysis of Data for Catchments across Australia (outside of current scope). 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 covers the work undertaken as part of Phase 1. This pilot study investigates the suitability of the conceptual loss models in both reproducing observed rainfall excess from historic events and for application in design flood estimation. The outcomes from the pilot study will inform the conceptual loss models and approach to be used for analysis of data from a wider data set as part of Phase 4 which will ultimately underpin the new guidance on design losses in ARR.

The following chapters of the report are summarised below:

- Chapter 2 introduces the pilot catchments used for this Phase of the project and the selection criteria on which they were chosen.
- Chapter 3 describes the set up, input data and calibration of flood models for the pilot catchments.
- Chapter 4 introduces and discusses the conceptual loss models considered in this Phase of the project.
- Chapter 5 presents the application of the loss models to the pilot catchments and discussion and some analysis of the loss results, including parametric and non-parametric distributions.
- Chapter 6 discusses analysis of the continuing loss values in terms of their variation with duration
- Chapter 7 introduces SWMOD, discusses its application in this project and presents results of loss values for the pilot catchments, including some analysis.
- Chapter 8 covers the flood frequency analysis done on the pilot catchments.

- Chapter 9 describes the Monte-Carlo approach and inputs used, including rainfall frequency curves, temporal and spatial patterns applied.
- Chapter 10 discusses the comparison of loss values from the models with flood frequency interval results.

2. Pilot catchments

The pilot study will be based on the analysis of ten catchments. The estimation of loss values requires catchments with concurrent records of pluviograph and streamflow records. Sufficient rainfall stations are required to adequately capture the total volume of rainfall and the catchment should be sufficiently small so that the timing of runoff production can be directly determined from the recorded data without having to account for significant routing effects within the catchment.

The majority of other ARR projects have involved the direct analysis of streamflow records and thus have not had the additional requirement of concurrent pluviograph records. Thus the catchments suitable for estimation of losses are likely to be a subset of other data sets (such as those used in projects 5 and 7).

The timing of both the streamflow and pluviograph data is very important for characterising the different components of loss. This is less of an issue for many of the other ARR projects which involve separate analysis of either rainfall or streamflow; however, estimation of loss – particularly its temporal variation – is highly sensitive to the timing of the concurrent rainfall and streamflow time series.

The greatest constraint on the selection of appropriate catchments for inclusion in the pilot 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.

The adopted criteria for selection of the pilot catchments were:

- catchment area between 20 and 60 km^2;
- unregulated (free from transfers, farm dams and lake systems);
- minimum of 25 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;
- preference for an existing calibrated rainfall-runoff model; and,
- mix of catchments covering different broad regions of Australia.

The catchment list was compiled from a number of sources including Hill et al. (1996), Ilahee (2005), ARR Projects 5 and 7, Waugh (1991) and suggestions from local contacts. This combination of criteria has yielded ten eligible catchments. The data available for each catchment is summarised in Table 2-1 and their locations are shown in Figure 2-1. Maps for each catchment are included in Appendix A.

Information about the data available for each catchment was taken in the first instance from the Bureau of Meteorology (BoM) Water Resource Station Catalogue (WRSC). This source includes pluviograph gauges maintained by BoM and those maintained by other agencies. Some additional information about suitability of catchments, including degree of urbanisation and density of farm dams, was compiled from local contacts.

The catchments were 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 m. It has been “hydrologically enforced” to consolidate and incorporate streamline flow paths and other topological features. The DEM was used to produce a flow direction and flow accumulation. These grids show the direction of water flow and the flow paths (the stream networks) of water through the DEM.

The hydrological enforcing used flow direction from the 9 second DEM and the gauge locations to calculate a catchment area. The polygon catchment dataset was then used to derive the catchment centroid. The centroid location was used to obtain the closest pluviograph stations to each catchment based on the WRSC dataset.

Table 2-1 Summary of shortlisted catchments eligible for use in the pilot study

Gauge	Name	Area (km^2)	State	Mean Annual Rainfall (mm)	Flow data start year	Flow data end year	Flow data length of record (yrs)	Adopted pluvio.	Distance pluvio. to catch. centroid (km)	Pluvio. data start year	Pluvio. data end year	Flow & pluvio. overlap (yrs)
614005	Dirk Brook @ Kentish Farm	36	WA	1150	1971	2011	40	509135	1.7	1971	1999	28
								509245	5.1	1974	2001	27
								P9874	1.7	1989	1992	3
125006	Finch Hatton Creek @ Dam Site	36	QLD	1800	1976	2011	36	533010	1.2	1985	2011	27
								533004	6.5	1972	2011	36
410743	Jerrabomberra Creek @ Four Mile Creek	52	ACT	820	1968	1997	30	570973	4	1970	1997	27
G8170075	Manton River u/s Manton Dam	29	NT	1430	1965	2011	46	R8150332	7.5	1963	2011	46
141009	North Maroochy River @ Eumundi	41	QLD	1650	1982	2011	30	P40059	4.7	1971	2011	29
								141009	6	1991	2010	19
A5040523	Sixth Creek @ Castambul	44	SA	1000	1979	2012	33	A5040559	1.3	1983	2011	28
								P23801	4.6	1972	2011	33
422321	Spring Creek @ Killarney	32	QLD	1210	1973	2011	39	P41056	3.9	1972	2011	38
2219	Swan River u/s Hardings Falls	38	TAS	920	1983	2011	28	2219	2.5	1985	2009	24
228217	Toomuc Creek @ Pakenham	42	VIC	1060	1977	2011	34	586201	2.6	1978	2011	33
603190	Yates Flat Creek @ Woonanup	53	WA	800	1963	2011	48	509022	4.1	1972	2011	39

Figure 2-1 Catchment Map

3. Calibration of flood models

3.1. Introduction

There is a dearth of catchments of the required size with calibrated flood event models. Of the ten pilot catchments, none had calibrated flood models available and therefore RORB runoff routing models were created and the routing parameter calibrated for each catchment. The RORB models have been used to derive the loss values for a range of events (Refer Section 5) and in the future stages of the project will be used to derive rainfall-based peak flow estimates to allow comparison with flood frequency quantiles.

The routing in RORB is based on the stream length being representative of both catchment and channel storage, with each storage component conceptually represented as a non-linear reservoir. The RORB model can be calibrated to account for the flood routing characteristics of the catchment of interest by altering two parameters that control routing – the non-linearity exponent, m, and the routing parameter, k_c. Guidance from Australian Rainfall and Runoff (IEAust, 1999) suggests that m should be held constant at 0.8, effectively leaving k_c as the one parameter that defines the catchment routing. The RORB k_c parameter for a catchment is dependent on the average stream length for a catchment (d_{av}) such that to have the same routing characteristics imparted on the model, the ratio of k_c to d_{av}, also known as $C_{0.8}$, must be the same.

The different inputs required to run a RORB model are:

- Catchment file – describes the catchment layout through delineation of the catchment into a number of sub-areas that are linked by nodes and reaches.
- Storm file – describes the rainfall event, including the rainfall spatial and temporal pattern, and in the case of calibration, the recorded surface runoff, which the calculated runoff is compared to assess the fit provided by each set of parameters.

A description of the method used to delineate the catchments for input into the catchment file is provided in Section 3.2 and the method for deriving inputs into the storm file is provided in Section 9.

The largest four to six flow events that had an overlapping period of recorded pluviograph data were extracted to calibrate the models. These are described in Table B-1.

3.2. Model delineation

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, as shown in Figure 3-1. 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 extraction of the RORB catchment files was performed using the MiRORB tool in MapInfo. An example of a catchment delineation is provided in Figure 3-1.

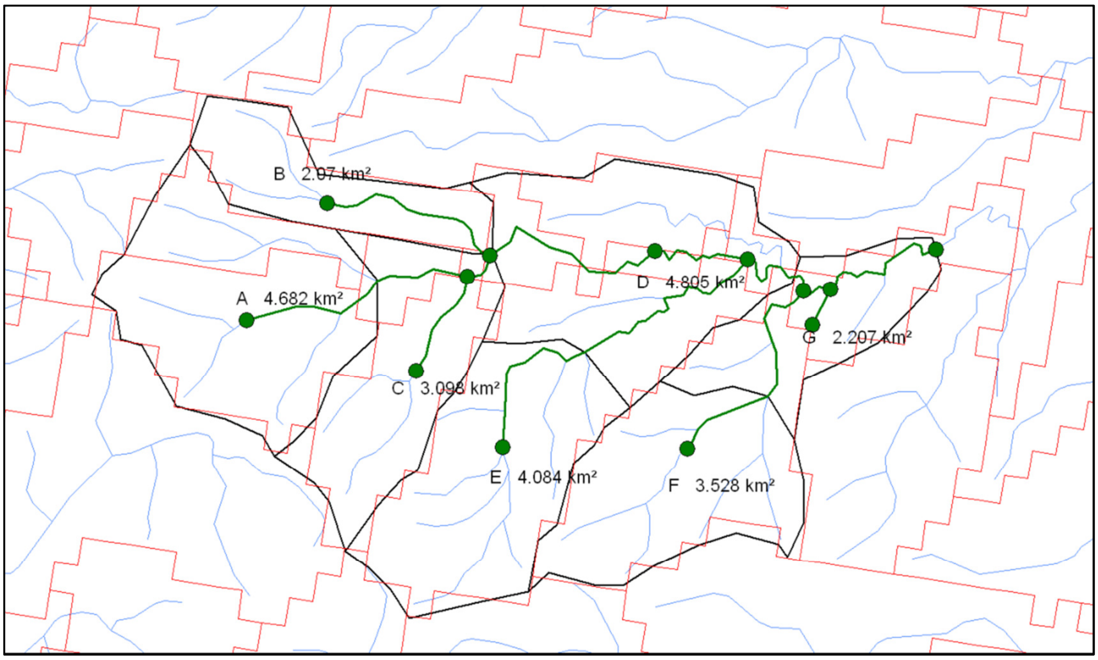


Figure 3-1: Example of catchment delineation using 1:25,000 geofabric spatial information.

The catchment boundaries derived using the geofabric information was compared to those received from the agencies who operate the gauges. In most cases, the catchment areas were found to be within 5% of the reported areas, as shown in Table 3-1.

Table 3-1: Catchments and areas derived from 1:25,000 geofabric spatial information.

Gauge	Name	Location	WRSC Catchment Area (km²)	Geofabric Catchment Area (km²)
614005	Dirk Brook @ Kentish Farm	WA	35	36
125006A	Finch Hatton Creek @ Dam Site	QLD	36	36
410743	Jerrabomberra Creek @ Four Mile Creek	ACT	55	52
G8170075	Manton River u/s Manton Dam	NT	28	29
141009	North Maroochy River @ Eumundi	QLD	40	41
A5040523	Sixth Creek @ Castambul	SA	44	44[1]
422321	Spring Creek @ Killarney	QLD	34	32
2219	Swan River u/s Hardings Falls	TAS	36	38
228217	Toomuc Creek @ Pakenham	VIC	41	42
603190	Yates Flat Creek @ Woonanup	WA	56	53

[1] This catchment area was revised using information obtained from Department for Water (SA).

3.3. Rainfall inputs

The spatial pattern for each event was developed by creating hard copy maps showing the rainfall depth recorded at each rainfall station in relation to the RORB model sub-areas. Isohyets were then manually drawn on those maps to ascertain the spatial distribution of each rainfall event. These maps were then used to interpolate the rainfall depth that fell at the centroid of each sub-area. An example is shown in Figure 3-2. The black dots show daily gauges for which we have data available, however there are some instances where a “#N/A” is shown which indicates that there is missing data over the event of interest.

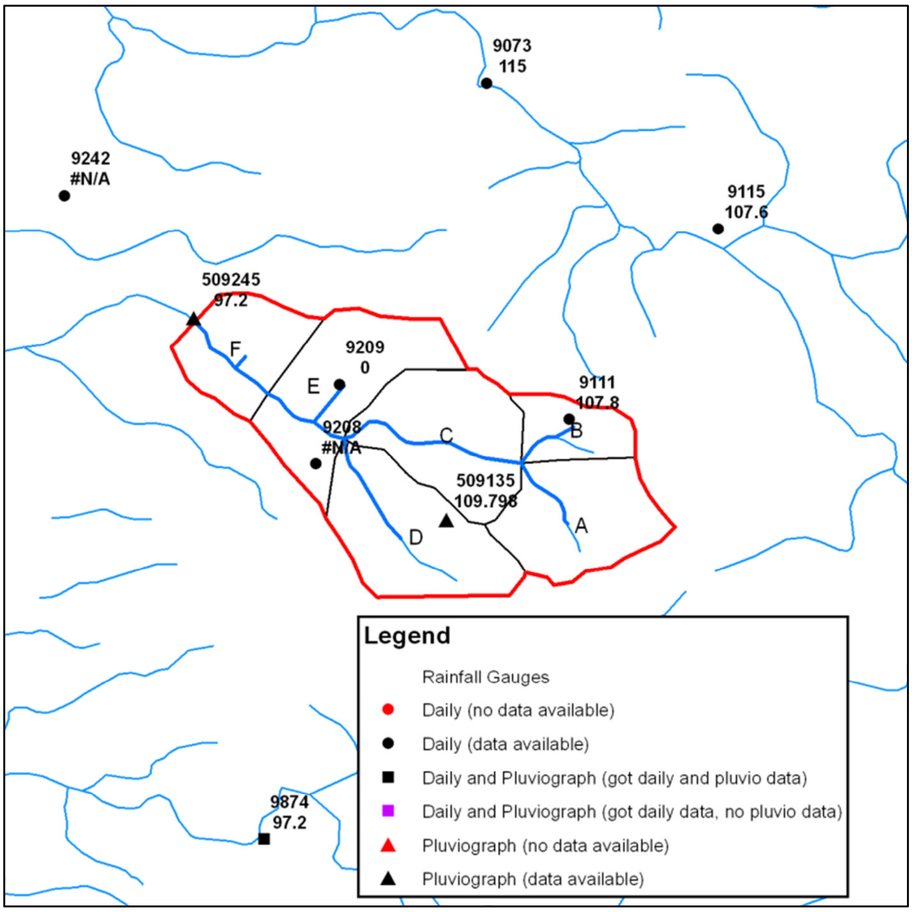


Figure 3-2: Example of rainfall depths available for an event that were used to derive the spatial pattern.

In the cases where there were more than one pluviograph available for an event, the spatial pattern was used to determine which pluviograph should be assigned to each sub-area. In most cases, this was based of the closest pluviograph, but if there was a significant rainfall gradient, this was taken into account to ensure that the temporal representation of the rainfall experienced at each sub-area was best represented.

3.4. Baseflow separation

Recorded streamflow is made up of baseflow, which is sourced from groundwater aquifers, and quickflow, which is sourced from surface runoff. The RORB model only models quickflow, therefore baseflow must be removed from the streamflow time-series before comparing the RORB model results. In order to do this, the shape of the baseflow hydrograph for each event was matched to the description from Nathan and McMahon (1990) and Brodie and Hostetler (2005). The general characteristics are that (see Figure 3-3):

- Low flow conditions prior to the commencement of a flood event consist entirely of baseflow;
- The rapid increase in river level relative to the surrounding groundwater level results in an increase in bank storage. The delayed return of this bank storage to the river causes the baseflow recession to continue after the peak of the total hydrograph;
- Baseflow will peak after the total hydrograph due to the storage-routing effect of the sub-surface stores;
- The baseflow recession will most likely follow an exponential decay function, except in ephemeral streams; and,
- The baseflow hydrograph will rejoin the total hydrograph as direct runoff ceases.

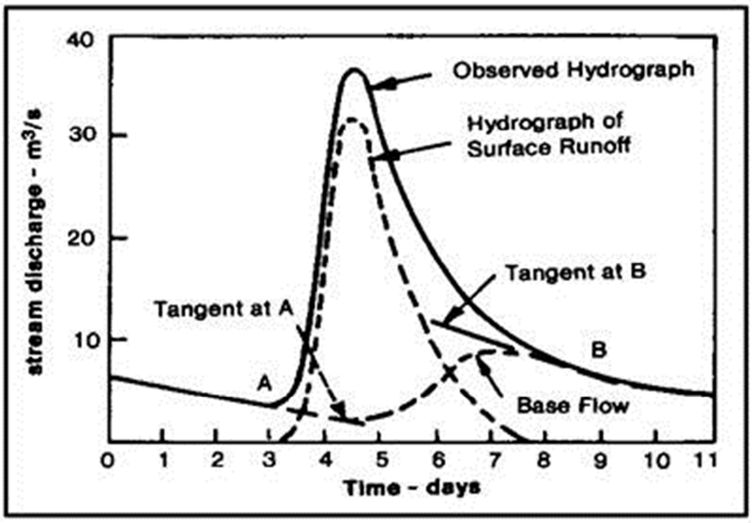


Figure 3-3: Example baseflow separation

3.5. Calibration results

The calibrations were performed using both the initial loss/continuing loss and initial loss/proportional loss models in RORB. Final RORB parameters adopted for each event at each catchment are shown in Table 3-2 and Table 3-3 for the continuing loss model and the proportional loss model, respectively.

Table 3-2: Adopted k_c parameters for initial loss, continuing loss model

Gauge	Catchment	State	d_{av}	Calibration k_c	Adopted k_c	Adopted $C_{0.8}$
614005	Dirk Brook @ Kentish Farm	WA	6.07	7 to 16.5	14	2.3
125006	Finch Hatton Creek @ Dam Site	QLD	5.59	2.5 to 4	4	0.7
410743	Jerrabomberra Creek @ Four Mile Creek	ACT	8.28	2.5 to 8	4	0.5
G8170075	Manton River u/s Manton Dam	NT	7.4	6 to 10.5	8	1.1
141009	North Maroochy River @ Eumundi	QLD	8.01	19 to 25	20	2.5
A5040523	Sixth Creek @ Castambul	SA	8.31	4 to 10	6	0.7
422321	Spring Creek @ Killarney	QLD	5.82	5.5 to 11	6	1.0
2219	Swan River u/s Hardings Falls	TAS	7.09	9 to 10.5[1]	10	1.4
228217	Toomuc Creek @ Pakenham	VIC	8.94	12 to 16	12	1.3
603190	Yates Flat Creek @Woonanup	WA	6.14	10 to 14	10	1.6

[1] Note that Event 3 resulted in a poor fit and so has not been included. This had a k_c of 7.2.

Table 3-3: Adopted k_c parameters for initial loss, proportional loss model

Gauge	Catchment	State	d_{av}	Calibration k_c	Adopted k_c	Adopted $C_{0.8}$
614005	Dirk Brook @ Kentish Farm	WA	6.07	6 to 14	12	2.0
125006	Finch Hatton Creek @ Dam Site	QLD	5.59	2 to 4	4	0.7
410743	Jerrabomberra Creek @ Four Mile Creek	ACT	8.28	2.2 to 10	4	0.5
G8170075	Manton River u/s Manton Dam	NT	7.4	6 to 10	7	0.9
141009	North Maroochy River @ Eumundi	QLD	8.01	18 to 24	20	2.5
A5040523	Sixth Creek @ Castambul	SA	8.31	3.5 to 9	4	0.5
422321	Spring Creek @ Killarney	QLD	5.82	5 to 8	5	0.9
2219	Swan River u/s Hardings Falls	TAS	7.09	9 to 101	10	1.4
228217	Toomuc Creek @ Pakenham	VIC	8.94	10 to 14	11	1.2
603190	Yates Flat Creek @Woonanup	WA	6.14	9 to 112	9	1.5

[1] Note that Event 3 had a k_c of 7.2 but resulted in a poor fit and so has not been included.
[2] Note that Event 4 had a k_c of 12 but resulted in a poor fit and so has not been included.

The Pearse et al. (2002) regional prediction equation for k_c was used to check the adopted routing parameters. That study derived a range of $C_{0.8}$ values (Table 3-4) for three different data sets:

- Victorian – a set of catchments all in Victoria from Hansen et al. (1986) and SMEC Victoria's database of projects;
- Yu – 122 catchments located in NSW, Victoria, Queensland and Western Australia; and,
- CRCCH – 72 catchments located in all states of Australia and the ACT.

Table 3-4: Pearse et al. (2002) regional prediction equations for k_c.

Group	Dataset		
	Victorian	Yu	CRCCH
$C_{0.8}$. expected	1.25	0.96	1.14
$C_{0.8}$, High	20.7	1.94	2.13
$C_{0.8}$, Low	0.75	0.47	0.61

This comparison indicated that the adopted routing parameters were generally within the range indicated by Pearse et al. (2002) with the exception of North Maroochy River and Jerrabomberra Creek.

An analysis of these results found that for many of the events analysed, the adopted k_c was systematically lower for the proportional loss model than the continuing loss model (see Figure 3-4). This indicates that the choice of the loss model affects the routing characteristics, as well as the volume of runoff.

Analysis of the losses for each of the events is provided in Figure 3-5 and Figure 3-6. The initial loss values are fairly consistent between the continuing loss and proportional loss models.

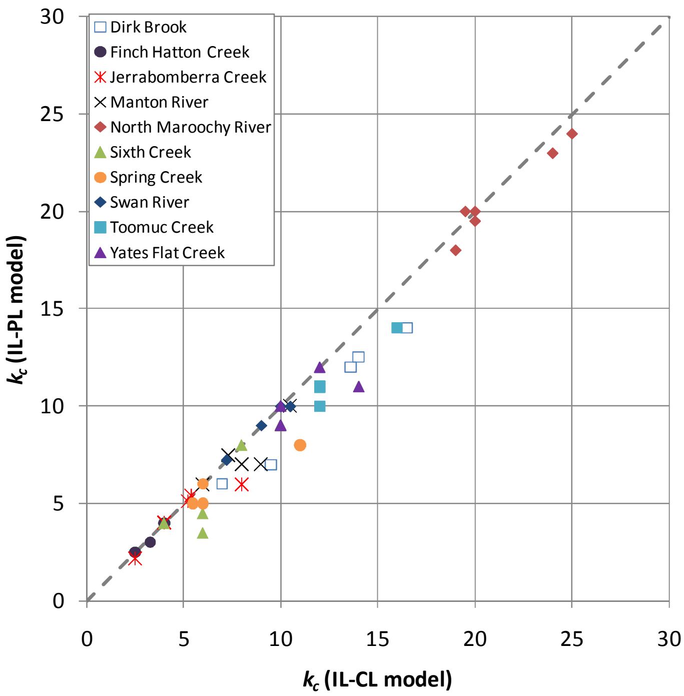


Figure 3-4: Comparison of k_c parameters from calibration events when using the continuing loss model and the proportional loss model

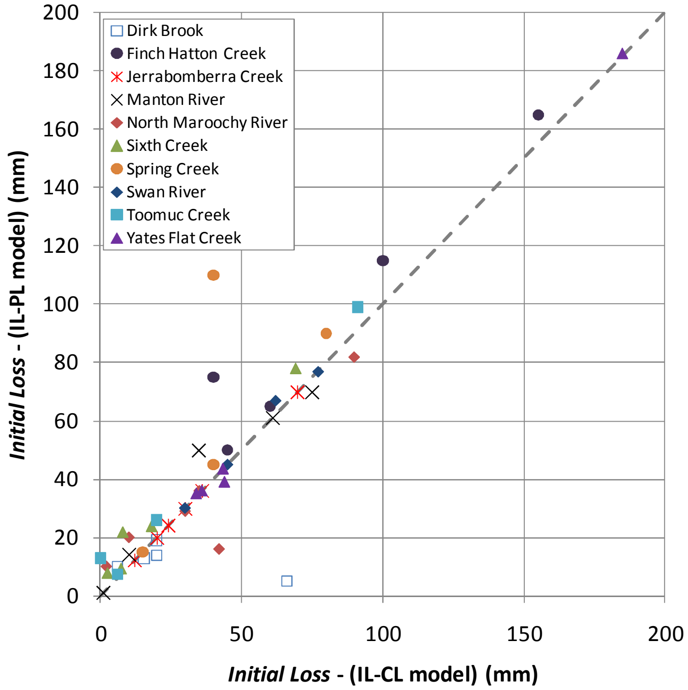


Figure 3-5: Comparison of initial loss from calibration events when using the continuing loss model and the proportional loss model

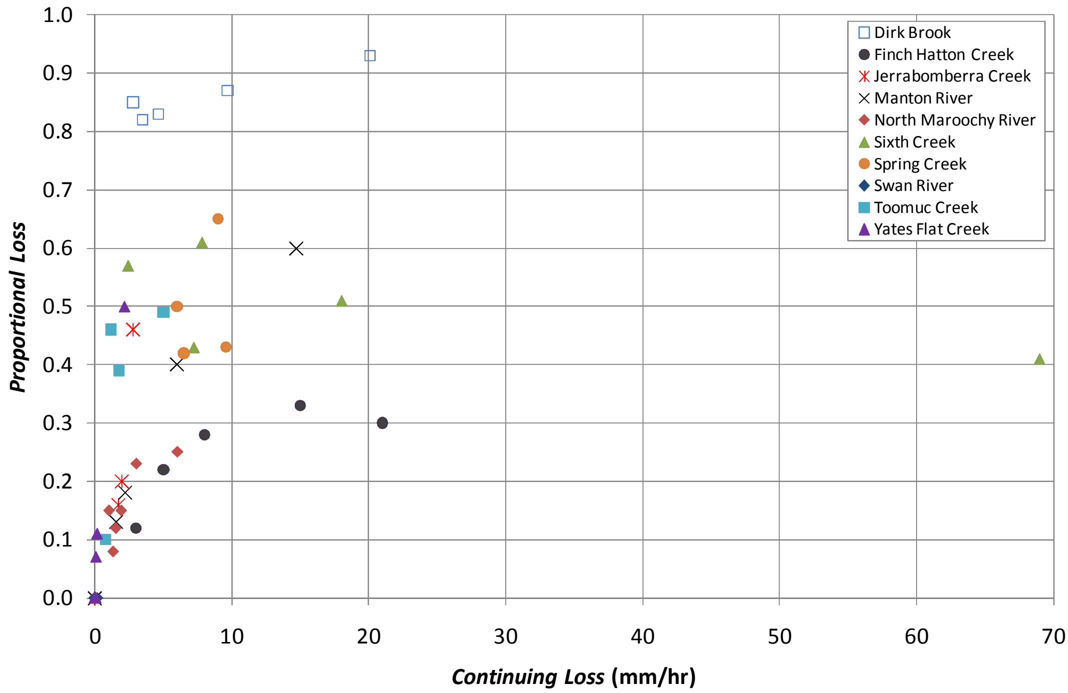


Figure 3-6: Comparison of continuing loss and proportional loss from calibration events.

4. Selection of conceptual loss models

4.1. Introduction

Loss is defined as the precipitation that does not appear as direct runoff, and the loss is typically attributed to the following processes:

- 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 differences in rainfall regime makes it very difficult to link the loss to catchment characteristics.

Mein and Goyen (1988) note that despite the obvious attraction of using infiltration equations; "*the problem is to specify parameters (which relate to soil type) and initial conditions which are satisfactory for design use on a given catchment. In practice, the uncertainties of soil behaviour and the areal variability of soil properties do not justify the use of anything more than the simplest model*".

To overcome this difficulty, lumped conceptual loss models are widely used. 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 floods (Muncaster et al., 1999).

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.

The following criteria were developed to assess candidate loss models:

1) the model produces a temporal distribution of rainfall-excess that is consistent with the effect of the processes contributing to loss
2) suitable for extrapolation beyond calibration and hence applicable to estimate floods over a full range of AEPs

3) inputs are consistent with data readily available across Australia
4) small number of parameters that need to be selected (preferably no more than 2)
5) parameters have been linked to catchment characteristics, or it is considered reasonable that such a link could be established
6) accessibility of documentation and software
7) can be easily incorporated into rainfall-runoff models

These criteria were applied to assess the usefulness of the identified loss models during a workshop held in November, 2011. The four loss models selected for further consideration are:

1) Initial loss – constant continuing loss
2) Initial loss – constant proportional loss
3) Initial loss – variable continuing loss
4) Probability distributed storage capacity loss model

4.2. Initial loss – constant continuing loss

The most commonly-used model in Australia is the initial loss-continuing loss (IL/CL) model (Figure 4-1). The initial loss occurs in the beginning of the storm, prior to the commencement of surface runoff. The continuing loss is the average rate of loss throughout the remainder of the storm. This model is consistent with the concept of runoff being produced by infiltration excess, i.e. runoff occurs when the rainfall intensity exceeds the infiltration capacity of the soil.

Guidance in ARR87 almost exclusively relates to the IL/CL model. One of the reasons that it was originally adopted was because it was easy to adopt in hand calculations. The limitation of this model is that it assumes that runoff is generated by Hortonian overland flow which may not be suitable for some catchments.

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 and therefore this has not been explored further in this pilot study.

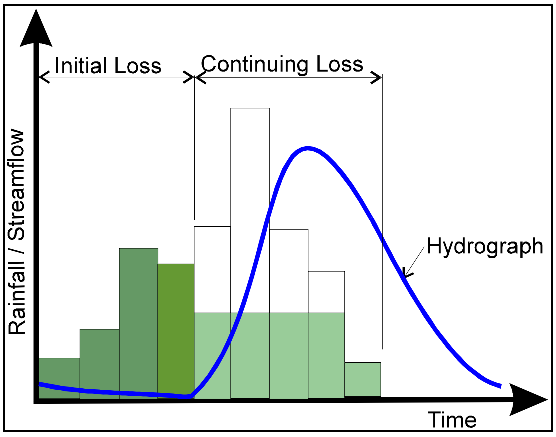


Figure 4-1 Initial loss – continuing loss model

IL/CL values have been derived for a range of events for the pilot catchments and this is discussed in Section 5.

4.3. Initial loss – constant proportional loss

The initial loss-proportional loss (IL/PL) model shown in Figure 4-2 is consistent with this saturated overland flow concept. The proportional loss is a (constant) fraction of the rainfall after surface runoff has commenced, and can be regarded as 100% runoff from the saturated portion of the catchment, and zero runoff from the remainder.

Dyer et al. (1994) compared the performance of the IL/CL and IL/PL models for 24 catchments and found the IL/PL model resulted in generally improved calibrations using RORB. This finding was supported by Hill et al. (1996) which calibrated RORB models for 11 Victorian catchments.

Although the IL/PL model is arguably a theoretically superior loss model in catchments where runoff is predominantly generated by saturated overland (or partial area) flood response, there is virtually no guidance in ARR87, and little research, as to suitable values of proportional losses for design. This is particularly an issue when design estimates are required beyond the range of events found in the historical record.

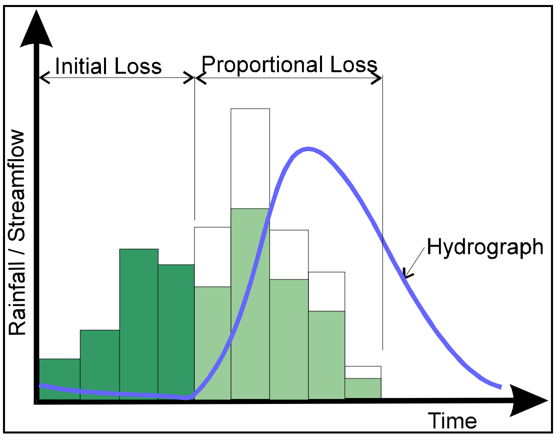


Figure 4-2 Initial loss - proportional loss model

IL/PL values have been derived for a range of events for the pilot catchments and this is discussed in Section 5.

4.4. Initial loss – variable continuing loss

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 variation of continuing loss is further investigated in Section 6.

4.5. Distributed storage capacity models

Most conceptual loss models are lumped in that a similar parameter value is assumed over a catchment or subcatchment. 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 exist in:

- 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 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 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 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 assumes a distribution of soil moisture in the catchment as shown in Figure 4-3. This form of PDM has been updated applied in the Revitalised Flood Hydrograph (ReFH) model in the UK.

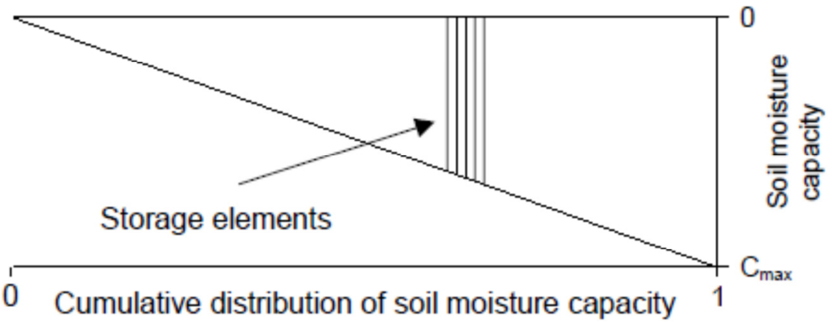


Figure 4-3 PDM distribution of catchment storage elements of different depths (Kjeldsen et.al., 2005)

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.

One such model is SWMOD which was developed for use in the south west of Western Australia. SWMOD is based on saturation excess overland flow as the dominant runoff mechanism for storm events and 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 have saturation-excess overland flow for any additional rainfall. Infiltration capacity is assumed to vary within an area due only to soil depth.

The infiltration capacity over a sub-catchment is defined below and shown in Figure 4-4:

$C_f = C_{\max} - (C_{max} - C_{min}) \times (1 - F)^{1/B}$ (equation 4.1)

Where C_f is the infiltration capacity at fraction F of the sub-catchment
F is the saturation fraction of the sub-catchment
B is the shape parameter
C_{max} is the maximum infiltration capacity
C_{min} is the minimum infiltration capacity

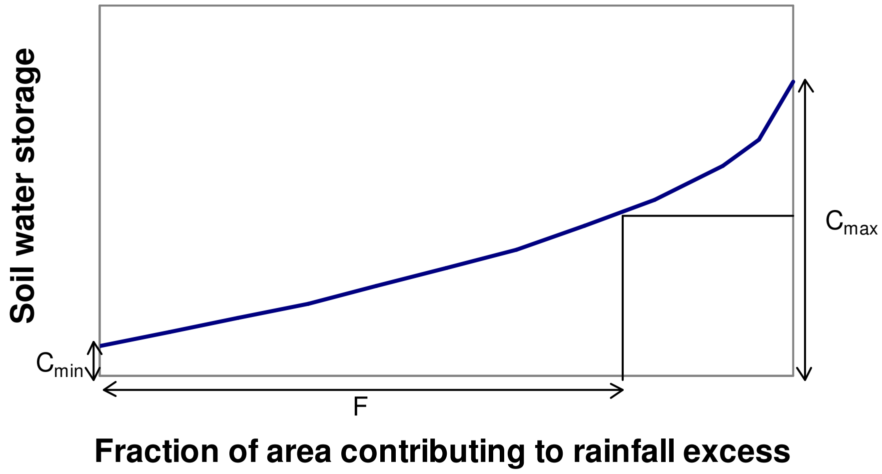


Figure 4-4 Soil water storage relationship (Water and Rivers Commission, 2003)

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).

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 estimation of profile water holding capacity is discussed in Section 7.

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.

The application of SWMOD to a catchment is discussed in Section 7.

5. Estimation of IL/CL and IL/PL values

5.1. Selection of events

ARR identifies that the selection criteria used to select the events for deriving loss values can bias the results; particularly the selection of the largest floods can bias the sample towards wet antecedent conditions and hence underestimate the values suitable for design. For this reason, events were selected on the basis of rainfall.

Events were initially selected on the basis of intense bursts of rainfalls. A 12 hour duration was adopted as being representative of the critical durations for the catchments being analysed and was therefore adopted for the selection of bursts. A partial series of events was adopted to identify the events for analysis and the threshold set so that the number of events was equal to the years of concurrent streamflow and pluviograph data for the catchment. The number of years of concurrent data is summarised below in Table 5-1).

Table 5-1 Period of concurrent streamflow and pluviograph data for pilot catchments

Gauge	Catchment	Start	End	Years
614005	Dirk Brook @ Kentish Farm	1971	2011	28
125006	Finch Hatton Creek @ Dam Site	1976	2011	36
410743	Jerrabomberra Creek @ Four Mile Creek	1968	1997	27
G8170075	Manton River u/s Manton Dam	1965	2011	46
141009	North Maroochy River @ Eumundi	1982	2011	29
A5040523	Sixth Creek @ Castambul	1979	2012	33
422321	Spring Creek @ Killarney	1973	2011	38
2219	Swan River u/s Hardings Falls	1983	2011	24
228217	Toomuc Creek @ Pakenham	1977	2011	33
603190	Yates Flat Creek @ Woonanup	1963	2011	39

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 timeseries of catchment average rainfall and surface runoff. The adopted criteria were:

- Start time was set to capture the beginning of the storm (indicated by a period of approximately 12 hours of no rain);
- End time 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 9:00am 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 competing objectives.

Where a complete storm contained more than one of the identified bursts, the complete storm was attributed to the most intense burst so that the storm was note analysed twice.

The definition of complete storms is illustrated in Figure 5-1 for 2 events from the Finch Hatton catchment.

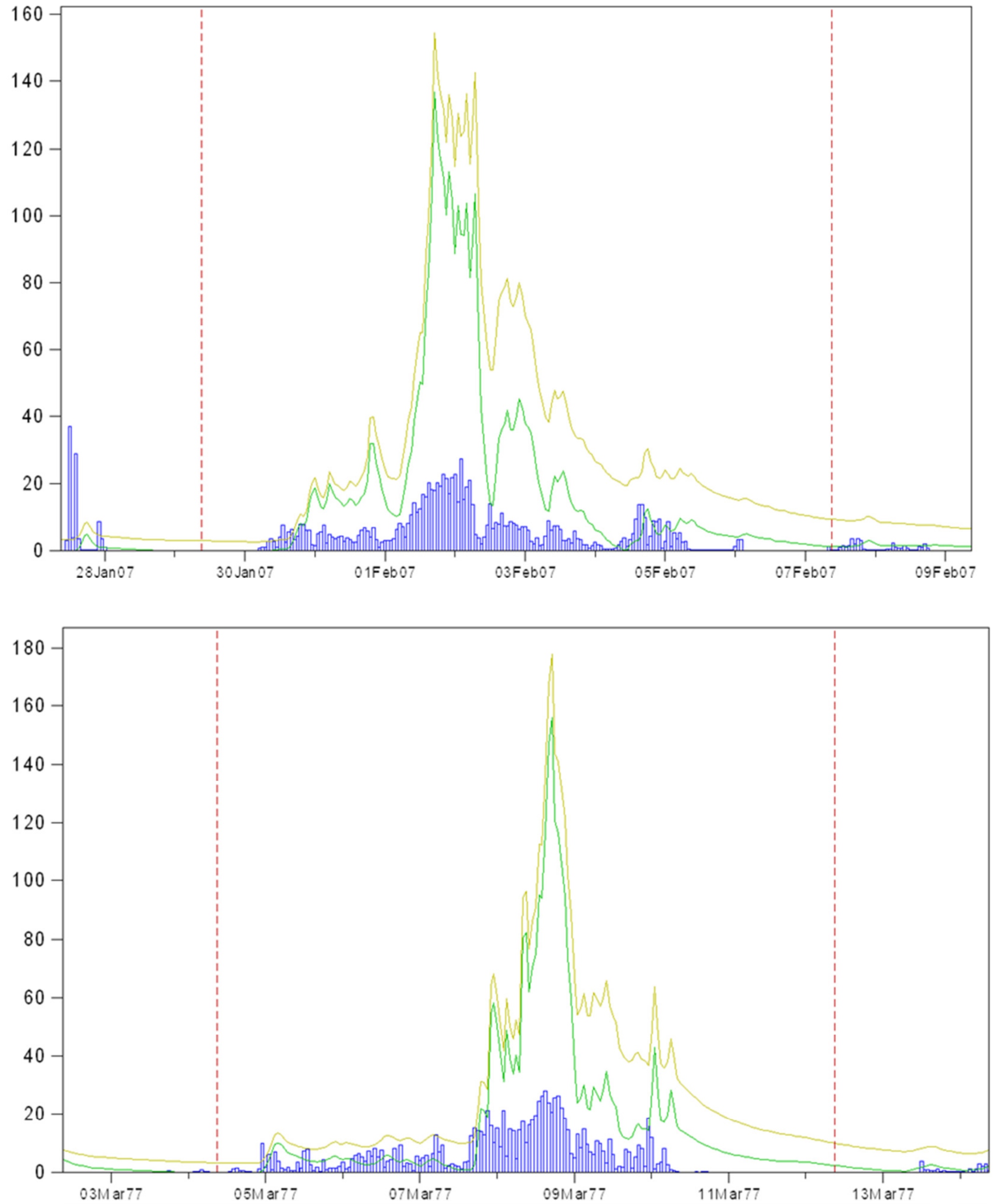


Figure 5-1 Example of complete storm definition for 2 events for Finch Hatton [total flow (m³/s) in yellow, estimated surface runoff (m³/s) in green, hourly rainfall data (mm) in blue and storm start and end indicated by dotted red lines]

The range of event durations for each catchment is shown in Appendix D. This demonstrates that the duration of the complete storms analysed is typically a few days and hence considerably longer than the 12 hour bursts used in their identification.

5.2. Baseflow separation

Recorded streamflow is made up of baseflow, which is sourced from groundwater aquifers, and quickflow, which is sourced from surface runoff. RORB models quickflow, therefore baseflow must be removed from the streamflow time-series before comparing the RORB model results. 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) (see Section 3.4 for more information on this process).

Manual baseflow extraction for a large number of events for each of the 10 pilot catchments would be time consuming, and so this process was automated by using a recursive digital filter. The filter factor and number of passes for each site was chosen to best match the manual baseflow separation performed for the four to six calibration events used to derive a design kc. A summary of the adopted baseflow parameters is shown in Table 5-2, along with the resulting baseflow index for each site.

Table 5-2: Adopted recursive digital filter parameters for baseflow extraction

Gauge	Catchment	Location	Factor	No. Passes	BFI
614005	Dirk Brook @ Kentish Farm	WA	0.925	9	0.69
125006	Finch Hatton Creek @ Dam Site	QLD	0.925	5	0.66
410743	Jerrabomberra Creek @ Four Mile Creek	ACT	0.925	3	0.40
G8170075	Manton River u/s Manton Dam	NT	0.925	5	0.48
141009	North Maroochy River @ Eumundi	QLD	0.925	9	0.22
A5040523	Sixth Creek @ Castambul	SA	0.925	5	0.63
422321	Spring Creek @ Killarney	QLD	0.925	5	0.72
2219	Swan River u/s Hardings Falls	TAS	0.925	5	0.42
228217	Toomuc Creek @ Pakenham	VIC	0.925	5	0.51
603190	Yates Flat Creek @ Woonanup	WA	0.925	7	0.43

5.3. Methodology

Preliminary analysis attempted to apply the lag relationships developed in Appendix C with 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, this investigation demonstrated the difficulty in defining a single threshold that reproduces the loss values obtained from calibration of the 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 the RORB model developed in Section 3. 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 – the routing parameter k_c was kept fixed to the value in Table 3-2 and Table 3-3 for every event on a catchment.

- Timing – the temporal distribution of rainfall and streamflow was adopted without adjustment (the manual calibration described in Section 3 did include lagging the rainfall for a small number of events)
- Baseflow separation – the contribution of baseflow to each event was estimated using the recursive digital filter and the parameters summarised in Table 5-2 rather than manually estimate the baseflow.

Based upon the above simplifications, RORB was used to estimate the values of IL/CL and IL/PL for each of the events identified in Section 5.1 for the pilot catchments. Values for the SWMOD model were also derived for the Toomuc catchment and these results are described in Section 7.

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. The fitting considered the following attributes:

- Timing
- Overall shape
- Volume
- 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.

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 initial loss value was reported as the commencement of some runoff indicated that initial loss had been satisfied but the value of CL or PL was discarded as they were subject to considerable uncertainty. Thus, for some catchments there were less values of CL and PL available than for IL.

For each catchment there was between 3 and 5 events for which the values derived from the above approach could be compared to the manual approach described in Chapter 3. The results are shown in the following 3 figures. These figures demonstrate that for some events the loss values from the 2 approaches are significantly different. These differences are likely to be due to be a combination of the simplifying assumptions listed above. In addition there are possible differences in the adopted start times and hence estimates of IL.

Importantly however, there did not appear to be any bias introduced by the simplified approach and hence this was adopted for the analysis of the large number of events.

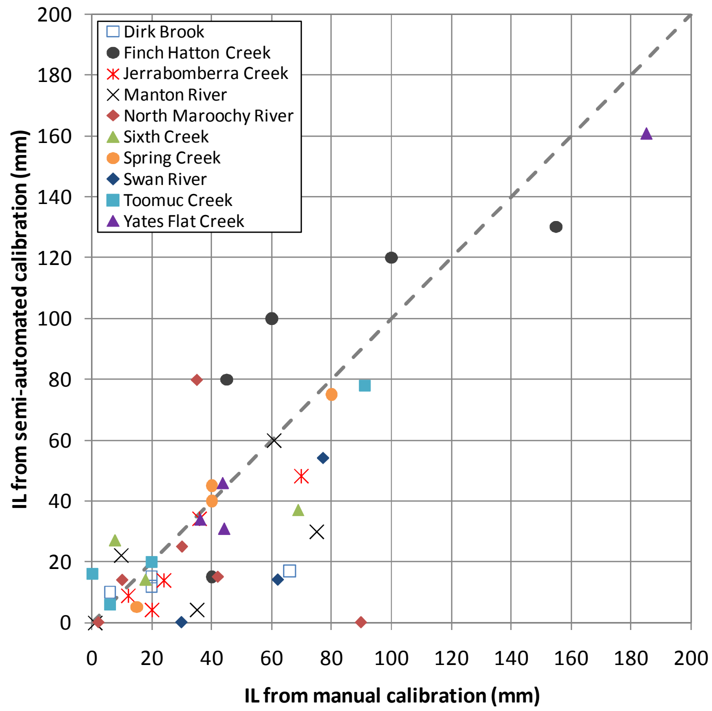


Figure 5-2 Comparison of IL from manual calibration with simplified approach

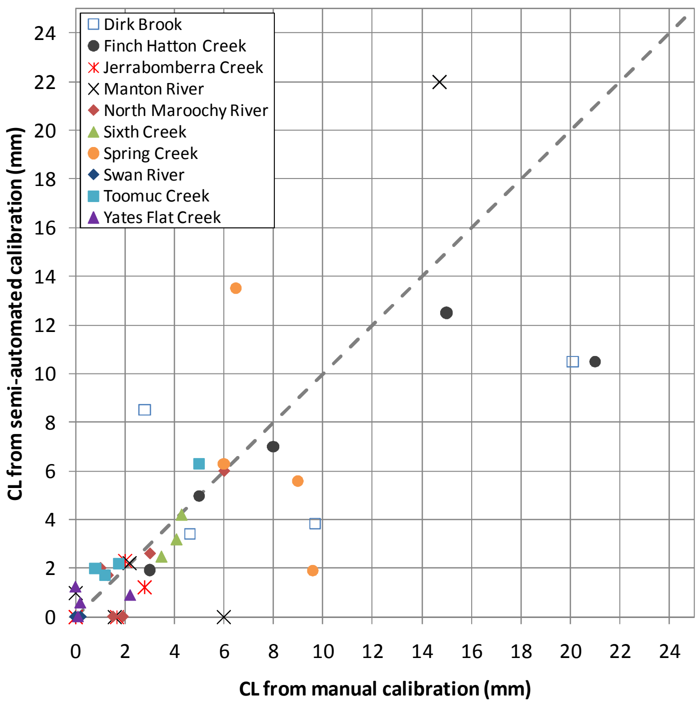


Figure 5-3 Comparison of CL from manual calibration with simplified approach

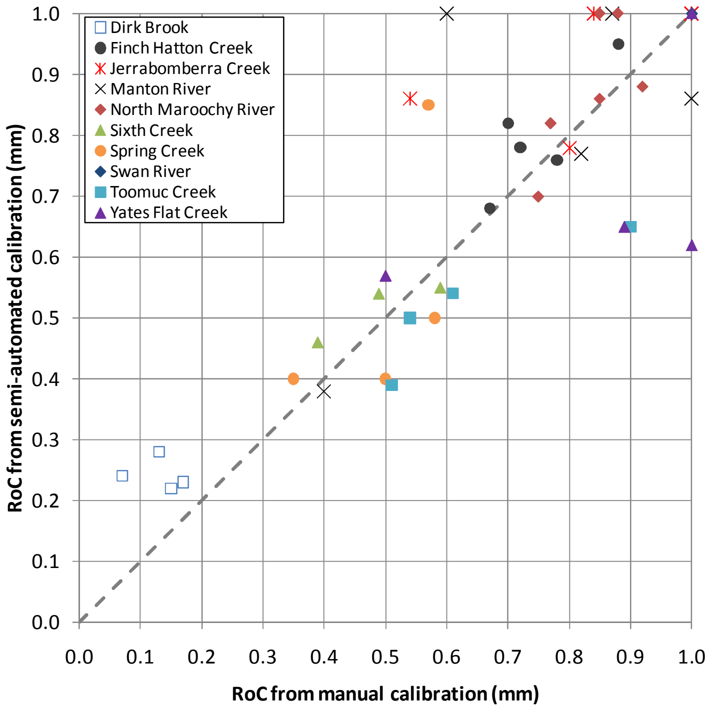


Figure 5-4 Comparison of RoC from manual calibration with simplified approach

5.4. Results

The approach described in the preceding sections was applied to estimate loss values for each of the 10 catchments. The results for all catchments are presented in Appendix E. The median values are summarised in Table 5-3 and the range of values shown in the following figures.

Table 5-3 Median loss values for pilot catchments

Gauge	Catchment	Events	IL (mm)	CL (mm/h)	IL (mm)	RoC
614005	Dirk Brook @ Kentish Farm	20	17	8.8	15	0.12
125006	Finch Hatton Creek @ Dam Site	27	60	7.0	60	0.57
410743	Jerrabomberra Creek @ Four Mile Creek	20	19	2.3	20	0.59
G8170075	Manton River u/s Manton Dam	35	36	2.4	34	0.67
141009	North Maroochy River @ Eumundi	27	25	2.0	22	0.84
A5040523	Sixth Creek @ Castambul	19	37	2.5	37	0.39
422321	Spring Creek @ Killarney	29	45	5.0	44	0.35
2219	Swan River u/s Hardings Falls	21	30	1.2	29	0.71
228217	Toomuc Creek @ Pakenham	21	31	2.1	28	0.44
603190	Yates Flat Creek @ Woonanup	12	36	0.3	25	0.86

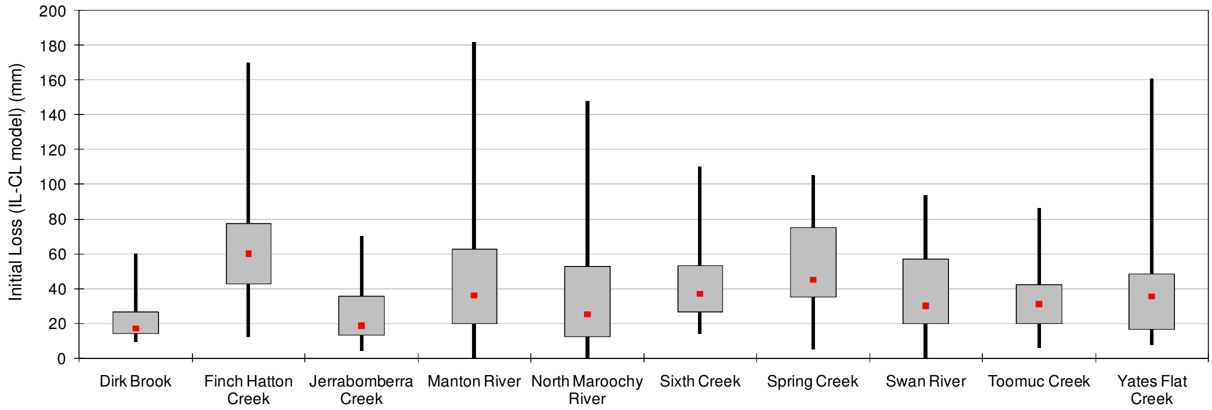


Figure 5-5 Range of Initial Loss values (box indicates quartiles and line shows max and min values)

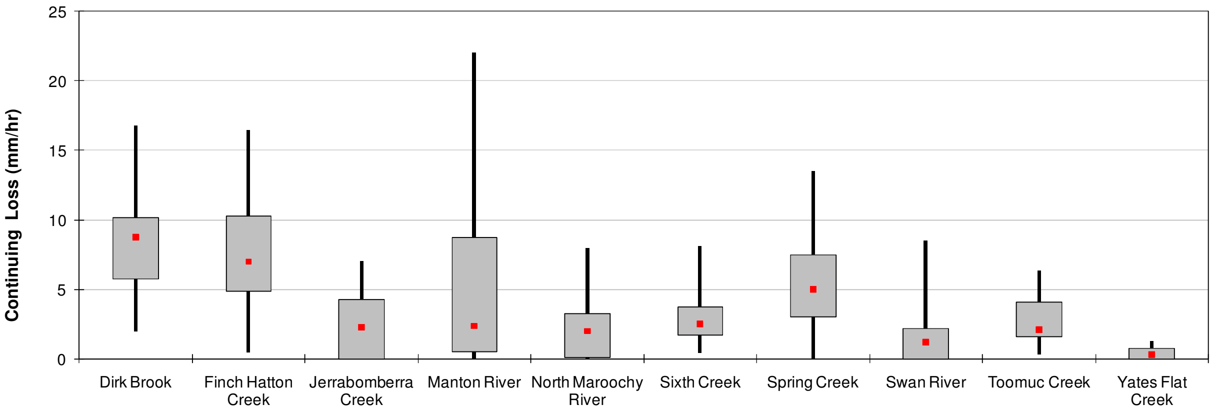


Figure 5-6 Range of Continuing Loss values (box indicates quartiles and line shows max and min values)

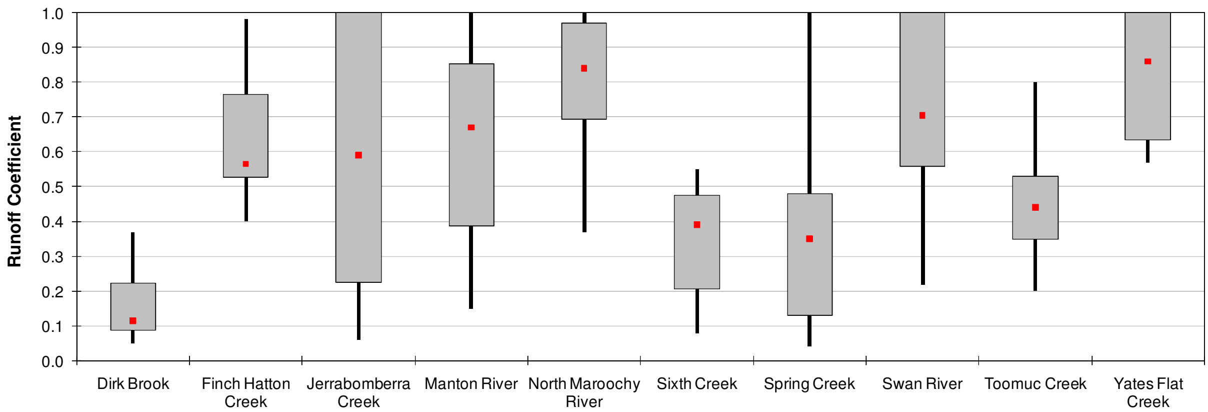


Figure 5-7 Range of Runoff Coefficient values (box indicates quartiles and line shows max and min values)

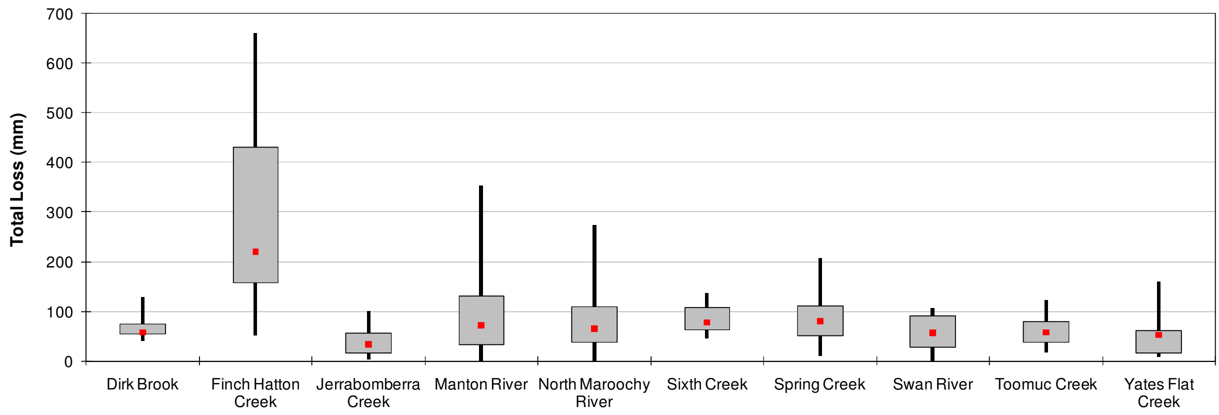


Figure 5-8 Range of total loss values for IL/CL model (box indicates quartiles and line shows max and min values)

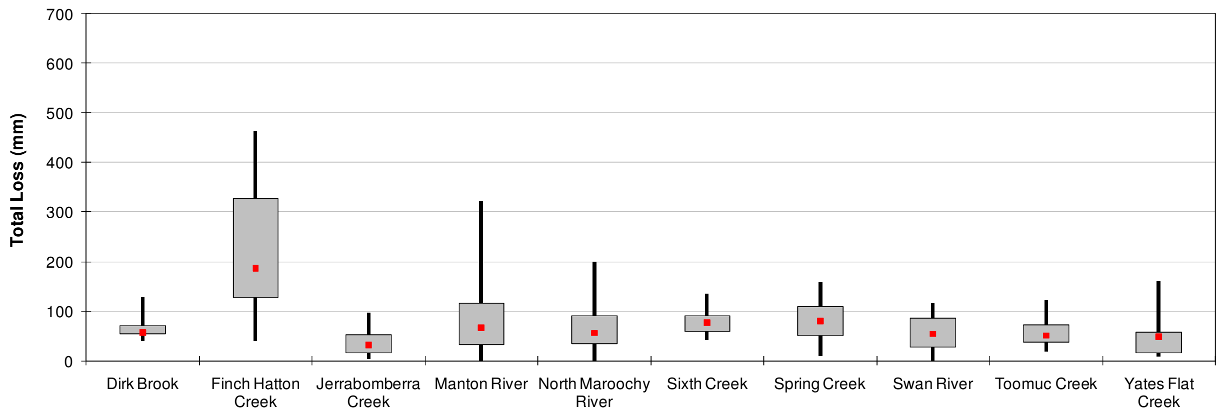


Figure 5-9 Range of total loss values for IL/PL model (box indicates quartiles and line shows max and min values)

5.4.1. Relative performance of loss models

For each event, a subjective assessment was made of which of the two loss models provided the better fit to the estimated surface runoff. The results are shown in Figure 5-10. For example, for Manton River for 66% of the event it was assessed that the IL/PL model outperformed the IL/CL model, for 17% of events the IL/CL model was preferred and for a further 17% the models produced a similar quality of fit.

It is evident from Figure 5-10 that the IL/PL outperformed the IL/CL for the majority of events for 9 out of the 10 catchments. This is consistent with the findings from a number of other studies as described in Section 4.3. However, the key requirements for design losses is not to reproduce recorded hydrographs but rather, when combined with other design inputs, produce unbiased estimates of design floods. The application of the conceptual loss models to estimate design floods is discussed in Section 10.

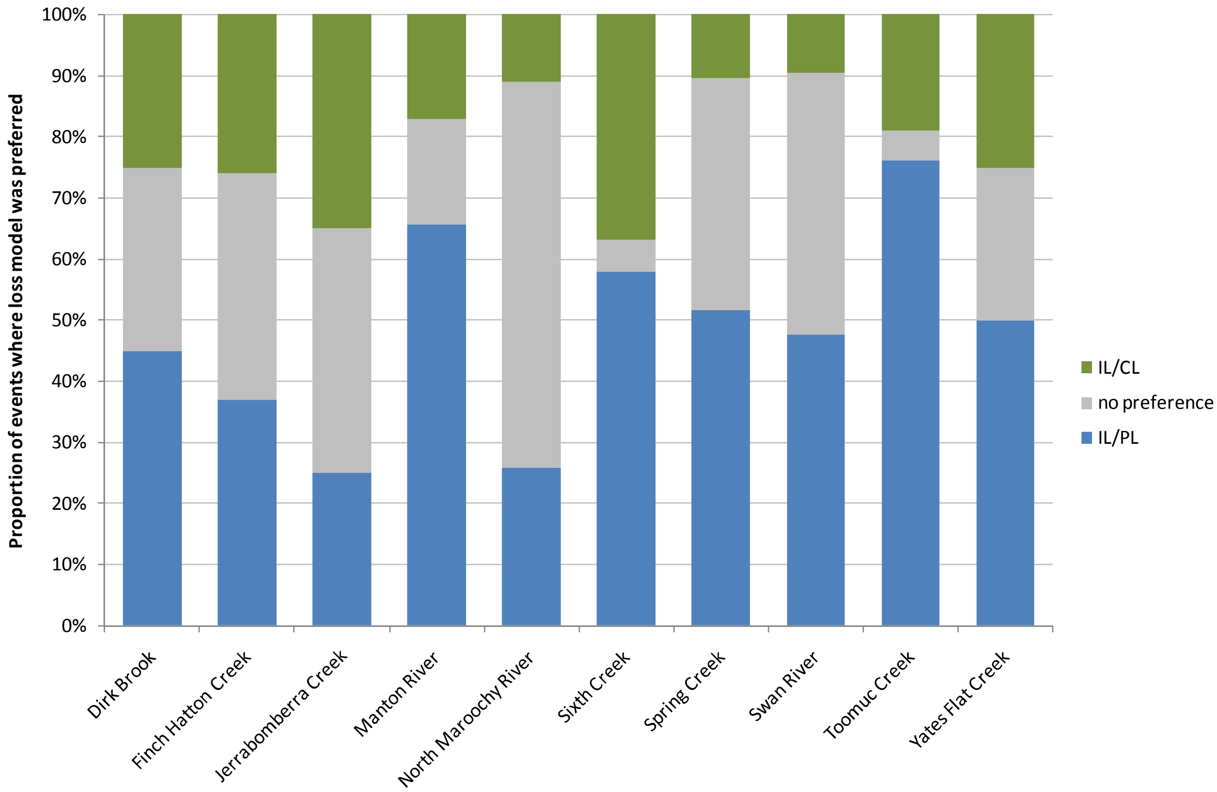


Figure 5-10 Relative performance of IL/CL and IL/PL models

5.4.2. Comparison of values based on calibration events

The loss values derived from the analysis of the large number of events were compared to those from the small number of events used to calibrate the RORB routing parameter as described in Section 3. Given the small number of calibration events, the comparison was based upon the mean rather than the median. The results for IL, CL and RoC are shown in the following figures and demonstrate a scatter around the 1-to-1 line which can be attributable to sampling variability and it is difficult to draw conclusions regarding the potential bias introduced by the selection criteria.

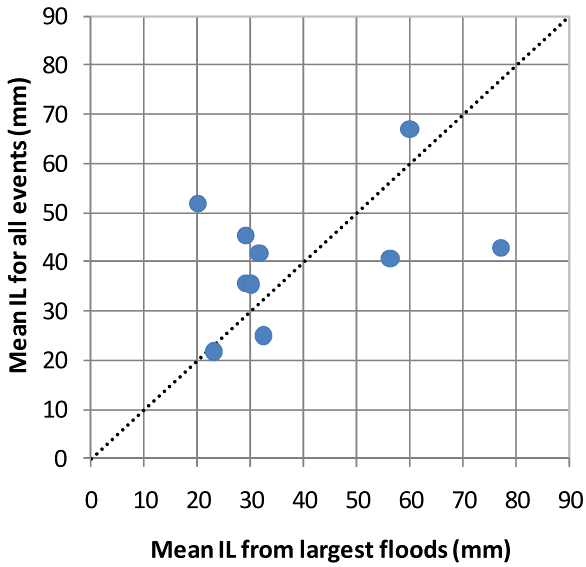


Figure 5-11 Comparison of Mean Initial Loss values from calibration of models to small number of largest flood events and 1xN events selected by rainfall

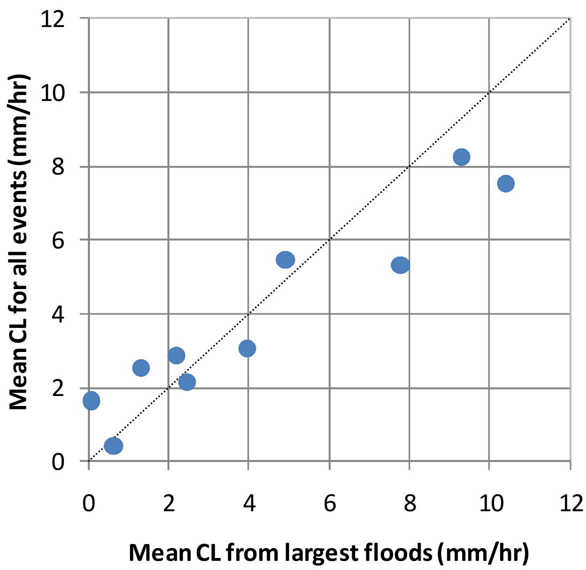


Figure 5-12 Comparison of Mean Continuing Loss values from calibration of RORB models to small number of largest flood events and 1xN events selected by rainfall

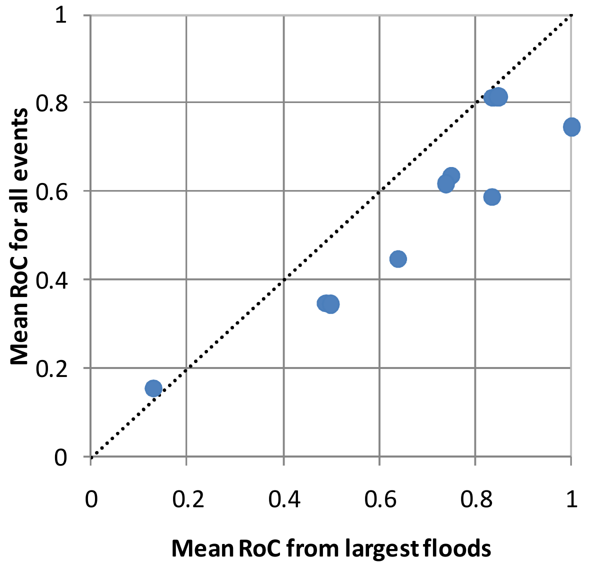


Figure 5-13 Comparison of Mean Runoff Coefficient values from calibration of RORB models to small number of largest flood events and 1xN events selected by rainfall

5.4.3. Seasonality

The month of each event was recorded which allowed the variation of the loss values with season to be explored. The seasonal distribution of loss values for each catchment are summarised in Appendix D and they reflect the expected variation with season based upon typical antecedent conditions.

5.4.4. Variation with storm severity

Appendix D also includes 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.

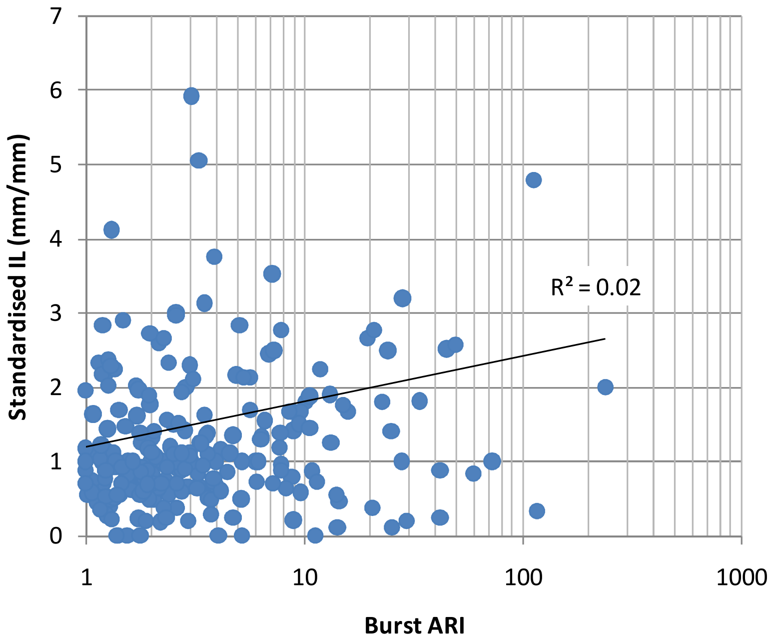


Figure 5-14 Variation of standardised storm Initial Loss with ARI of the Burst Rainfall

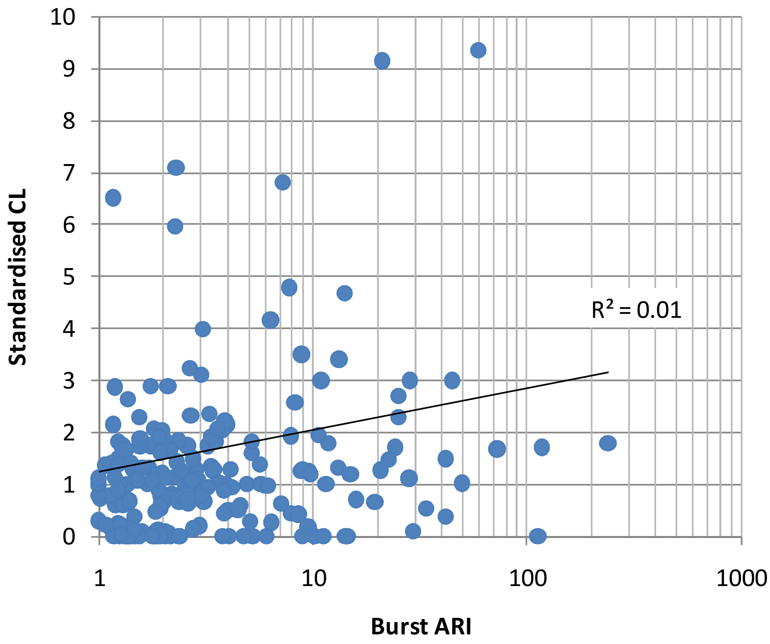


Figure 5-15 Variation of standardised storm Continuing Loss with ARI of the Burst Rainfall

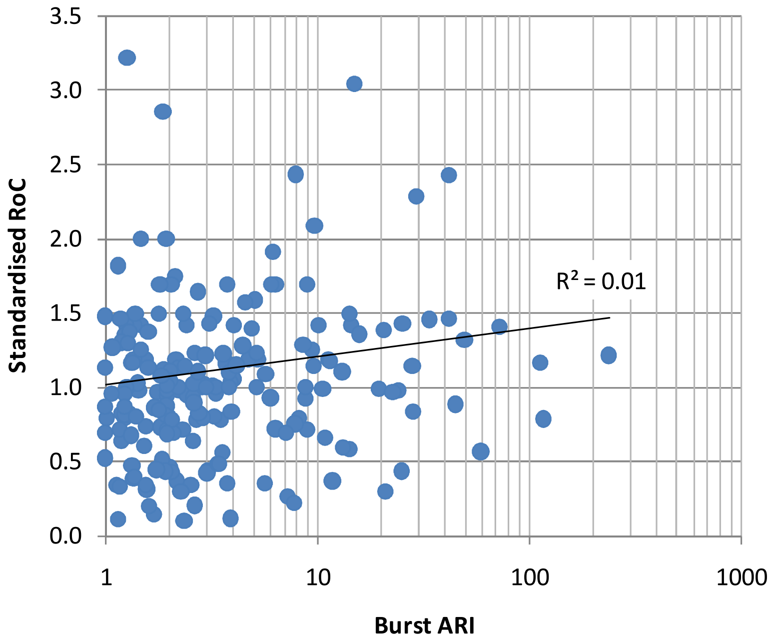


Figure 5-16 Variation of standardised Runoff Coefficient with ARI of the Burst Rainfall

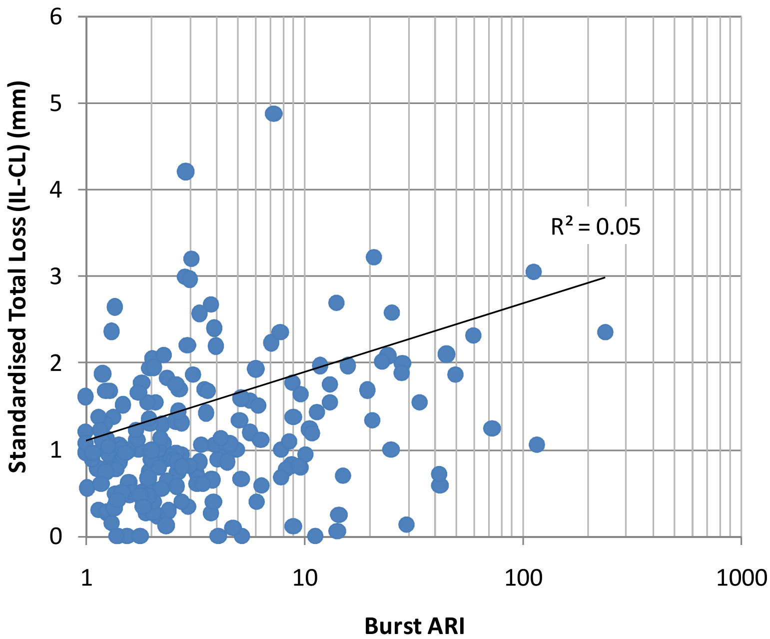


Figure 5-17 Variation of standardised Total Loss with ARI of the Burst Rainfall for the IL/PL model

5.4.5. Relationship with catchment characteristics

The relationship between the loss values and catchment characteristics will be explored as part of Phase 4 using a larger data set, however some preliminary work was undertaken using the results from the pilot catchments. The median values from the pilot catchments were plotted against soil profile water holding capacity (refer next Section) and BFI to see if there was any relationship (refer to the following figures). This preliminary analysis results look promising and suggests that it may be possible to relate the loss values to catchment characteristics. It is likely that multi-parameter relationships will be necessary to account for factors that have a compensating effect.

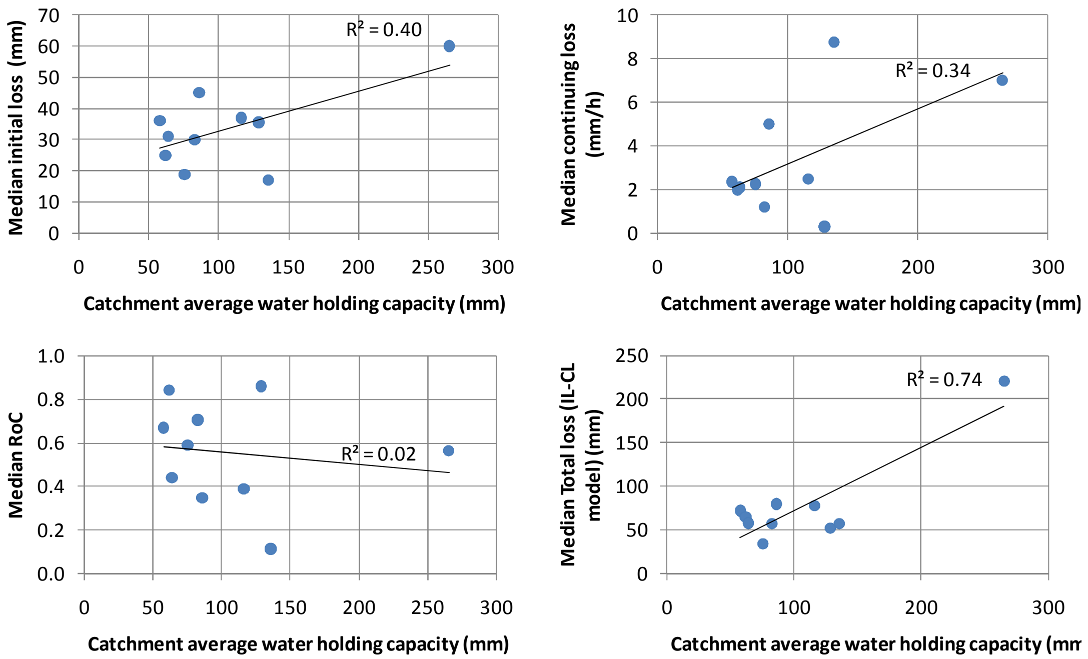


Figure 5-18 Median loss values against catchment average water holding capacity

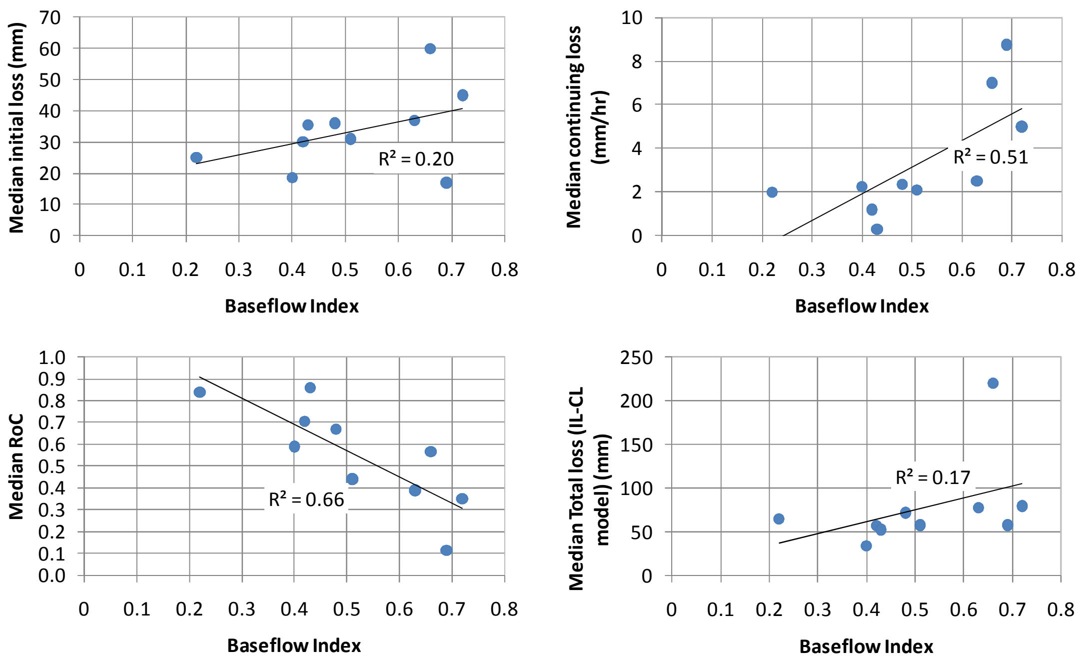


Figure 5-19 Median loss values against catchment baseflow index

5.5. Non-parametric distribution

The losses obtained from the analysis of single events on the 10 pilot catchments (described in Section 5) have been further analysed to develop loss distributions for sampling in the joint probability framework.

The exceedance percentiles for each of the loss parameters for each catchment were extracted, and then standardised by the median value for each catchment (see Figure 5-20). These were then averaged across all catchments to obtain a single curve. The initial loss distributions and the continuing loss distribution 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 5-21 and Figure 5-22.

The initial loss distributions from the continuing loss and proportional loss models are very similar, and these are also in agreement with the previous studies. The initial loss distribution from the continuing loss model was therefore sampled for both the initial loss/continuing loss model runs and the initial loss/proportional loss model runs.

The continuing loss distribution from this study is also similar to those from the previous studies (Figure 5-22). Conceptually, the continuing loss and proportional loss represent the losses due to soil characteristics, and therefore are not expected to vary significantly between events, however the distributions shown indicate that it can be up to 4 times the median value. For the verification model runs, the continuing loss and proportional loss have been held constant, rather than sampled from a distribution.

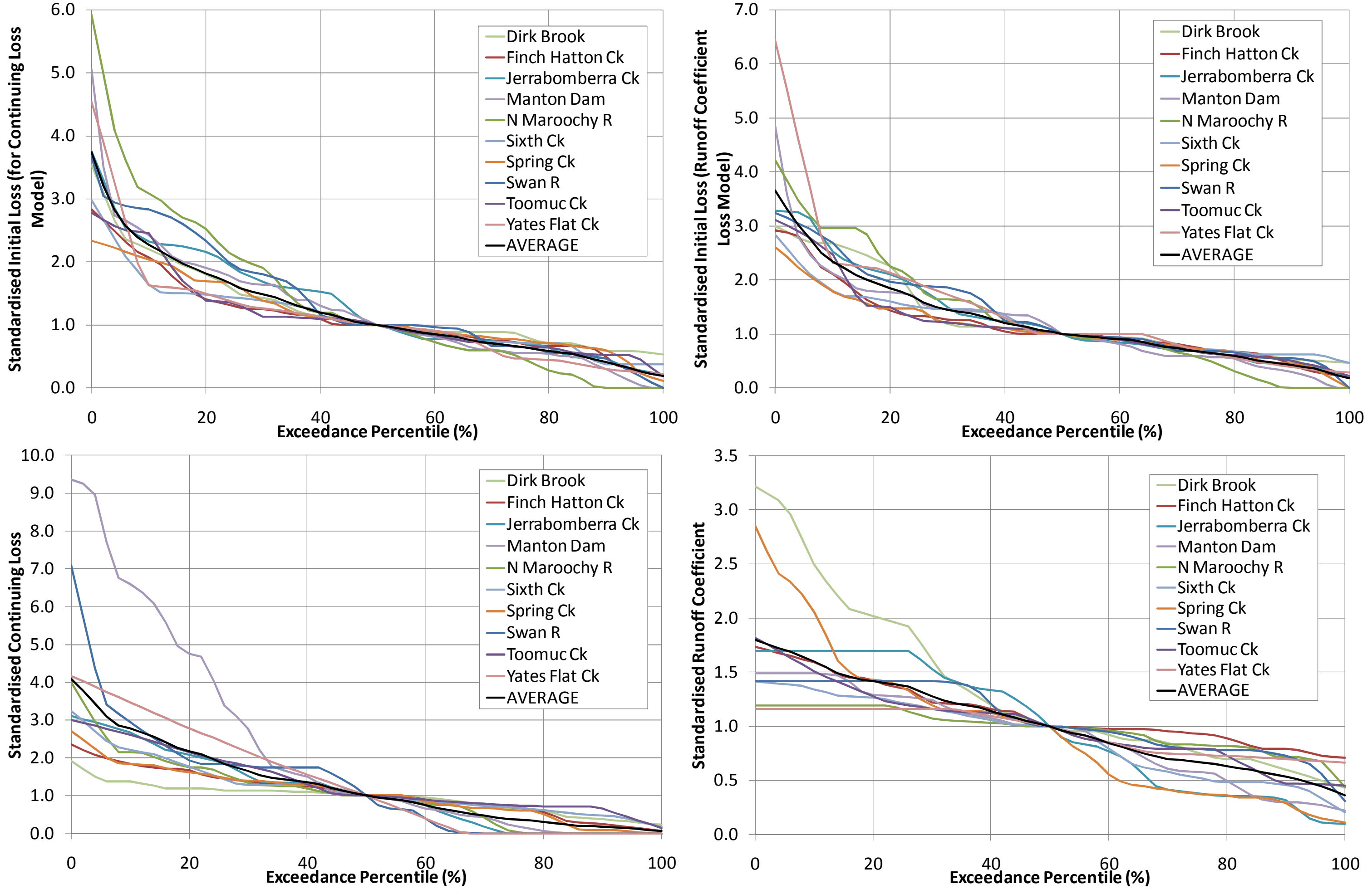


Figure 5-20: Standardised loss distributions for each catchment for the continuing loss and proportional loss models

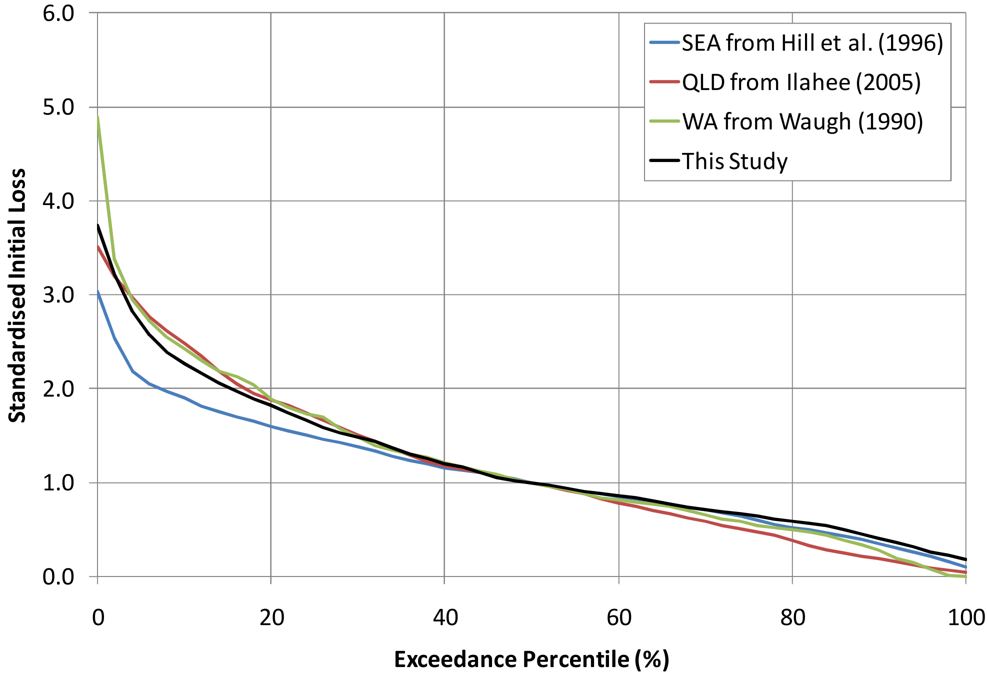


Figure 5-21: Comparison of standardised initial loss distributions

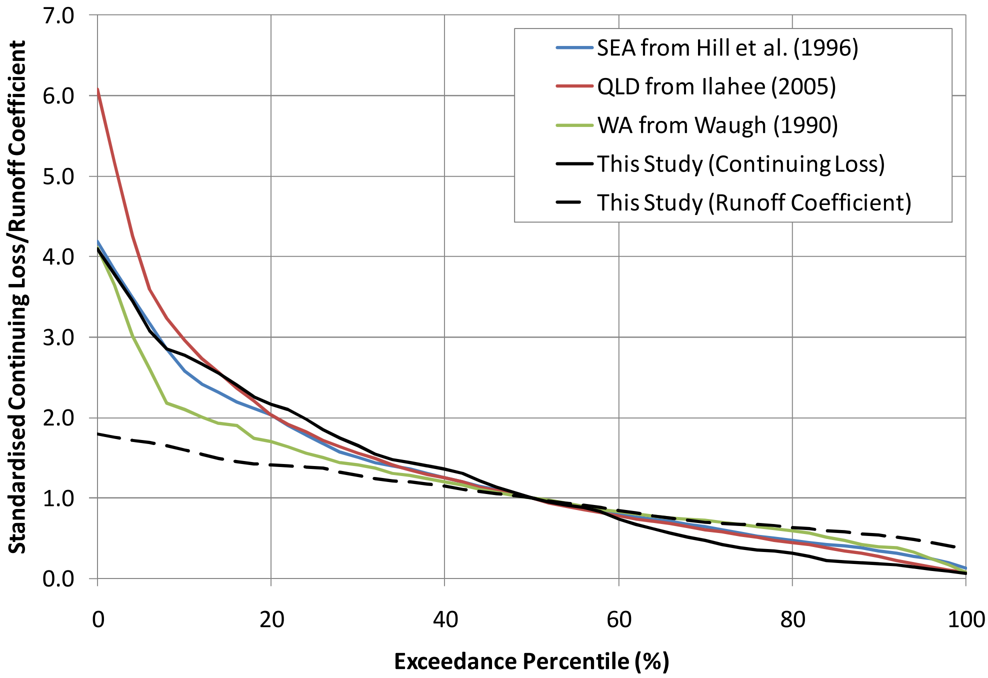


Figure 5-22: Comparison of standardised continuing loss and runoff coefficient distributions

5.6. Parametric distributions

In addition to the non-parametric distributions discussed in the previous section, typical parametric distributions were also fitted to the sample of loss values derived for each pilot catchment. Parametric distributions provide an efficient means of describing the distribution and help facilitate characterising uncertainty.

Each distribution was fitted using the Maximum Likelihood Estimates (MLE) method. An iterative parameter estimation algorithm was adopted. A total of 14 parametric distributions were tested, as listed in Table 5-4.

Table 5-4 Probability distributions fitted to loss values

Bounded Distribution	Unbounded Distribution	Non-negative Distribution	Advanced Distribution
Beta	Gumbel Max Normal	Chi-squared (1 and 2 parameter) Exponential (1 and 2 parameter) Gamma (2 and 3 parameter) Generalised Gamma (3 and 4 parameter) Lognormal (2 and 3 parameter) Pareto Rayleigh (1 and 2 parameter) Weibull (2 and 3 parameter)	Generalised Extreme Value Generalised Pareto Log-Pearson 3

Up to five distributions of reasonable fit per catchment per loss model were selected to generate random values. Goodness of fit tests and graphs were considered when determining which distributions were of a reasonable fit. The goodness of fit tests applied were the Kolmogorov-Smirnov, Anderson-Darling and Chi-Squared tests.

The graphs used to determine the goodness of fit were:

- Probability Density Function (PDF) was used to match the shape of the empirical and theoretical PDFs. For this graph, the number of intervals/bins depends on the sample size. The Empirical PDF (from the sample data) was displayed as a histogram of equal width bins, which represent the number of points in a bin divided by the sample size. The Theoretical PDF (from the generated data) was displayed as continuous curve, which was scaled by multiplying the PDF values by the interval/bin width.
- probability-probability (P-P) plot was expected to be approximately linear if the specified theoretical distribution is the correct model.
- quantile-quantile (Q-Q) plot was expected to be approximately linear if the specified theoretical distribution is the correct model.

The process of determining goodness of fit was subjective and the best combination of GOF tests, shape of the PDF, linear P-P plot and linear Q-Q plot was sought.

A total of 10,000 random values was generated from the selected distributions. The statistics (mean, median, minimum, maximum, skew, variance and standard deviation) were calculated on these and compared to the sample data set. A summary of the selected distribution is in Figure 5-6. Fitted distribution parameters and error statistics are in Appendix J.

Table 5-5 Summary of selected parametric distribution for each model and catchment

Gauge	Catchment	Selected distribution		
		IL (IL/CL model)	**CL (IL/CL model)**	**RoC (IL/PL model)**
614005	Dirk Brook @ Kentish Farm	Gamma	Log-Pearson 3 Gamma (second best)	Beta*
125006	Finch Hatton Creek @ Dam Site	Gamma	Gamma	Beta#
410743	Jerrabomberra Creek @ Four Mile Creek	Generalised Pareto LP3 (second best) Gamma (third best)	Generalised Pareto LP3 (second best) Gamma (third best)	Beta
G8170075	Manton River u/s Manton Dam	Gamma	Gamma	Beta
141009	North Maroochy River @ Eumundi	Gamma	Gamma	Beta
A5040523	Sixth Creek @ Castambul	Gamma	Generalised Pareto Gamma (second best)	Beta
422321	Spring Creek @ Killarney	Gamma	Generalised Extreme Value Generalised Pareto (second best) Gamma (third best)	Beta*
2219	Swan River u/s Hardings Falls	Gamma	Generalised Pareto Generalised Extreme Value (second best) Gamma (third best)	Beta*
228217	Toomuc Creek @ Pakenham	Gamma	Gamma	Beta#
603190	Yates Flat Creek @ Woonanup	Gamma	Gamma	Beta

*Poor goodness of fit result
#PDF does not match

For the standardised IL values, the Generalised Gamma (three parameter) is the best fitting distribution. For the raw IL values, the Gamma (two parameter) is the best for 9 out of 10 catchments. For Jerrabomberra Creek Gamma is the third best, after the Generalised Pareto and LP3.

For the standardised CL values, the Gamma (two parameter) distribution is best. For the raw CL values, the Gamma (two parameter) is best for five of the catchments. Gamma is the second best distribution for two other catchments and the third best for the remaining three catchments.

The Generalised Gamma distribution (three parameter) is the best for the standardised RoC values. For the raw RoC values, Beta is the best distribution for all the pilot catchments.

6. Variation of continuing loss

6.1. Review of previous studies

Ilahee and Imtaez (2009) investigated the relationship between continuing loss and storm duration in 48 catchments in Queensland. They observed that the continuing loss decreases with duration, rather than the constant continuing loss recommended in ARR.

Continuing and proportional losses were calculated on nine catchments in south-eastern Australia by Hill et al. (1996). This data was used to perform a similar analysis of the loss-duration relationship for south-eastern Australia.

Figure 6-1and Figure 6-2 show the combined results for continuing and proportional loss of the events for the nine catchments with more than 15 events each. The relationship between continuing loss and duration is stronger than that between proportional loss and duration, which was not examined by Ilahee and Imtaez (2009). A relationship was fitted to each catchment individually. The fitted relationship showed R^2 values of between 0.7 and 0.03 for continuing loss with duration and between 0 and 0.5 for proportional loss with duration. Individual catchment graphs are shown in Appendix G.

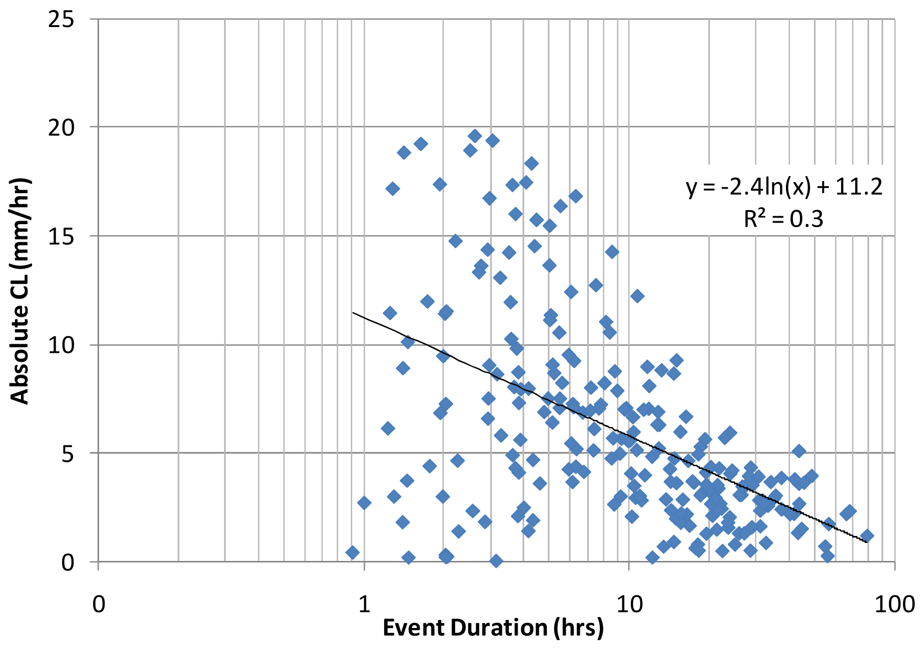


Figure 6-1 Absolute continuing loss and duration for south-eastern Australian catchments with more than 15 events (Hill et al, 1996)

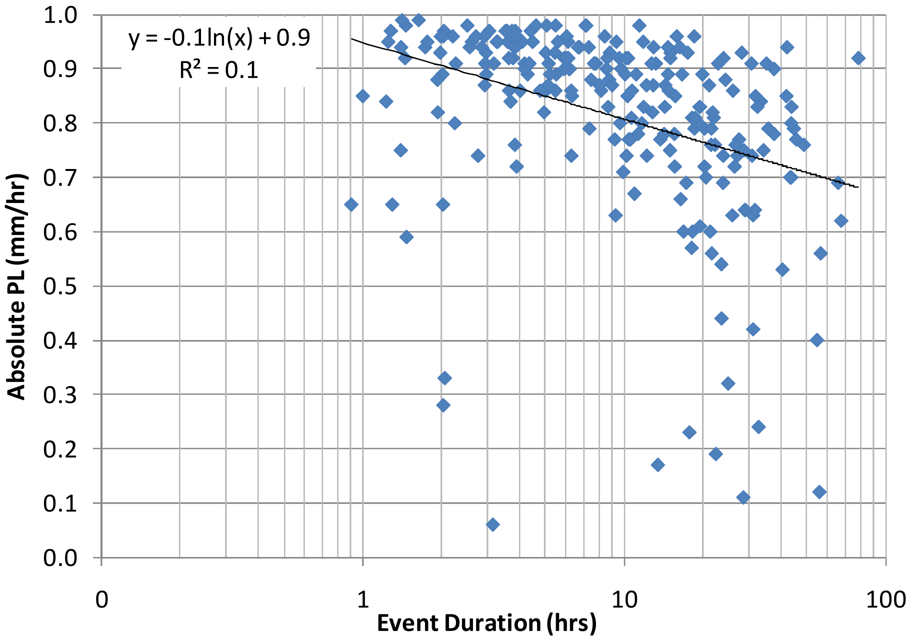


Figure 6-2 Absolute proportional loss and duration for south-eastern Australian catchments with more than 15 events (Hill et al, 1996)

Figure 6-3 shows the relationship between continuing loss and storm duration determined for south eastern Australia along with the relationships reported for Queensland catchments reported by Ilahee and Imtaez (2009). The south eastern catchments show a similar relationship to those determined for Queensland, with significant scatter. Similarly, Ilahee and Imtaez (2009) also reported significant scatter around the Queensland relationships.

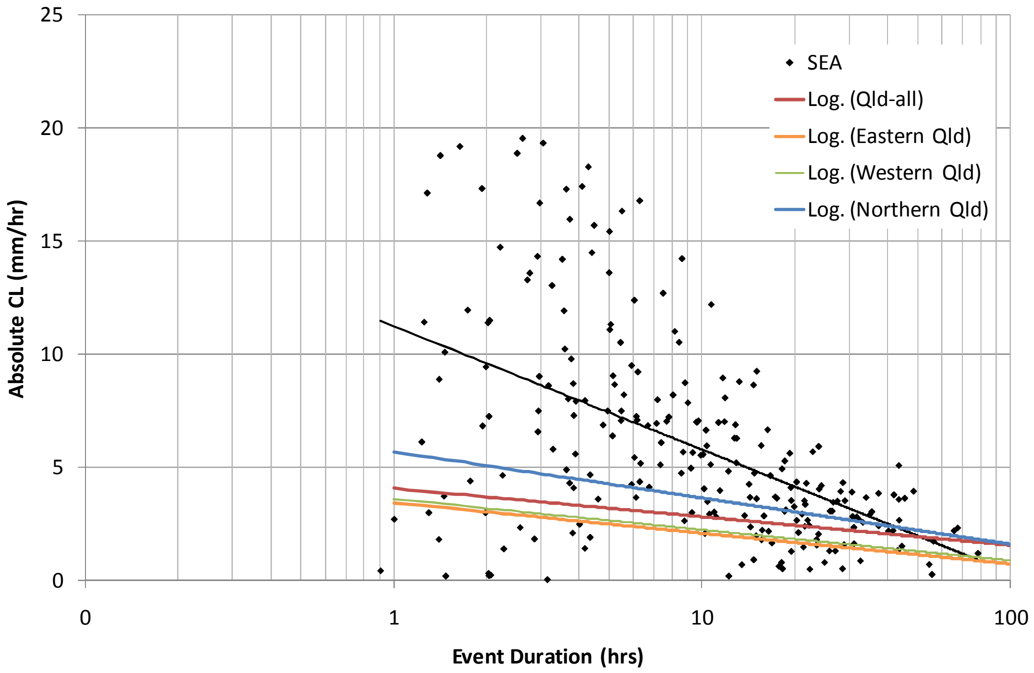


Figure 6-3 Relationship between continuing loss and duration calculated for south eastern Australian catchments and the relationships determined for Queensland catchments (Ilahee and Imtaez, 2009)

6.2. Results from pilot catchments

Figure 6-4 shows the relationship between continuing loss and event duration for the pilot catchment events that were analysed. Figure 6-5 and Figure 6-6 show the relationships between total loss after initial loss and the continuing loss and runoff coefficient determined from the IL/CL and IL/PL models respectively. These figures show that there is no clear trend to suggest a relationship between losses and event duration or between the event total loss and that attributed to the continuing or proportional loss.

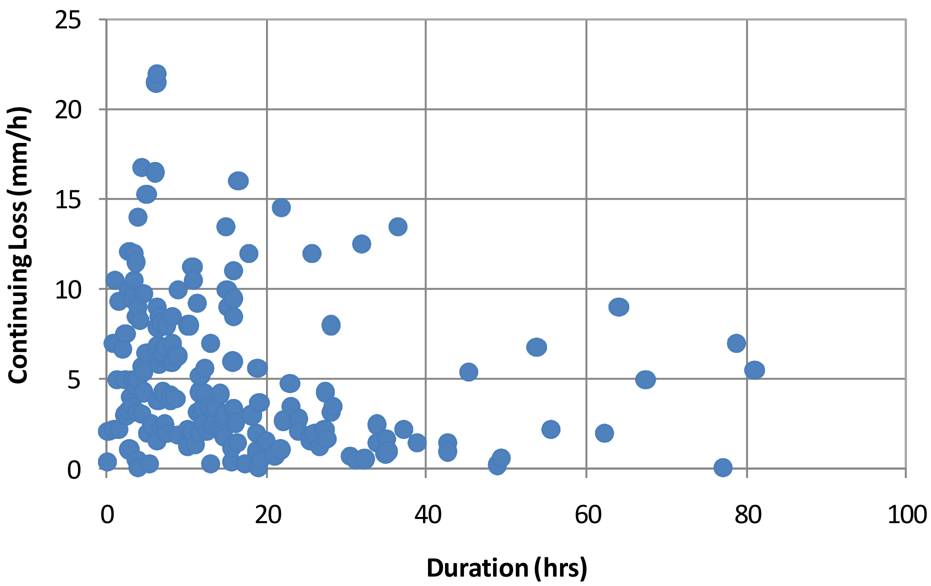


Figure 6-4 Relationship between continuing loss and event duration for all pilot catchment events

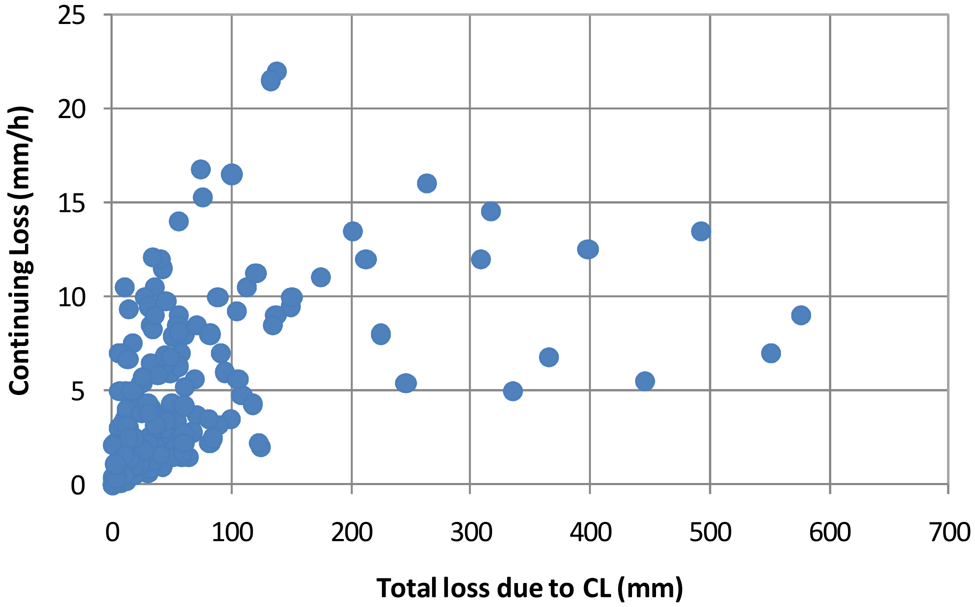


Figure 6-5 Relationship between total loss from continuing losses and continuing loss rate

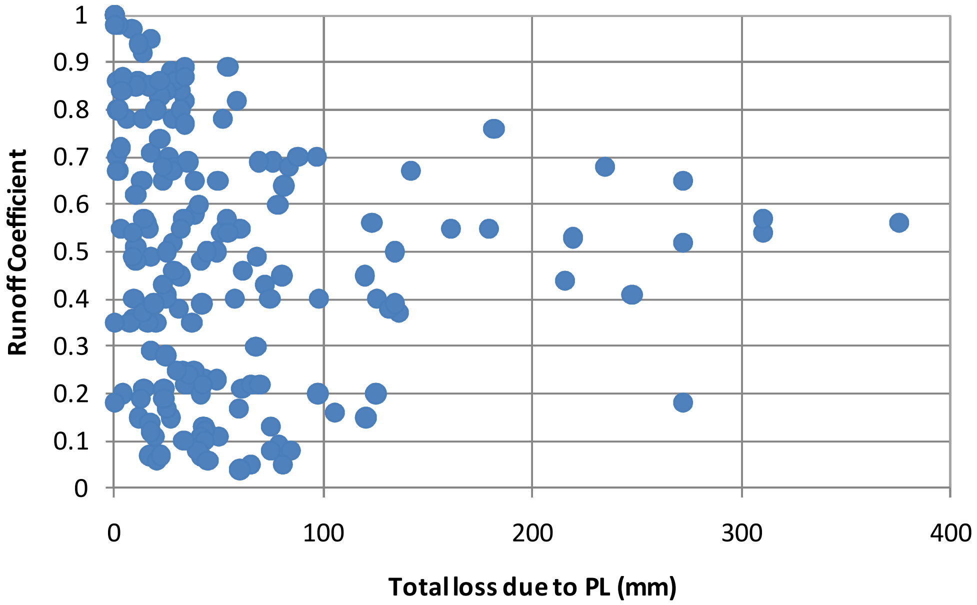


Figure 6-6 Relationship between total loss from proportional losses and the runoff coefficient

7. SWMOD

7.1. Estimation of profile water holding capacity

Previous applications of variable infiltration capacity models have been hindered by lack of information on soil water holding capacity. 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 in each of the pilot catchments examined in the current study. 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.

McKenzie et al. (2000) use a pedotransfer function to predict the soil water retention curve from more readily available data. This method is less reliable for soils with high clay content. The available water holding capacity determined for the layers is also constrained by limitations associated with the estimate of horizon thickness. The authors note that there are other physical and practical reasons why the estimates of water holding capacity are an approximate and possibly erroneous estimate of available water capacity (Hillel, 1980). It is important to note that there are significant limitations of this data. A large proportion of soil variation within a region occurs over short distances and cannot be covered in significant detail in large scale databases (McKenzie et al, 2000).

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 4 catchments (Leanne Pearce, Water Corporation., pers. Comm.) and Table 7-1 shows a comparison of the water holding capacity determined from the method described above and that calculated by the DoW.

Table 7-1 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	0.29
Samson Brook Dam	141	525	0.26
South Dandalup Dam	127	467	0.27
Wellington Dam	285	521	0.54

Table 7-1 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.

7.2. SWMOD conceptualisation

SWMOD was incorporated into RORB. All of the water capacities parameters were taken directly from the Atlas of Australian soils and hence the loss model only has 1 parameter; the initial moisture content. Initial application of the 1 parameter model demonstrated that this did not provide sufficient flexibility to calibrate the model and therefore a global scaling parameter was incorporated which scaled the maximum soil profile water holding capacities for all soil types in a catchment by the same amount. This resulted in a 2 parameter loss model:

- Initial moisture content which was assumed to be the same for all soil types across the catchment (ie the moisture is evenly redistributed between events)
- Capacity factor which scales the maximum profile water holding capacities in a catchment

7.3. SWMOD results

SWMOD was applied to the pilot catchments in the same way and using the same events as the IL/CL and IL/PL, using the program incorporated into RORB and described in Section 7.2.

Table 7-2 shows the parameter values determined for the pilot catchments.

Table 7-2 Median SWMOD initial moisture (IM) and capacity factor (CF) values for pilot catchments

Gauge	Catchment	Events	IM (mm)	CF
614005	Dirk Brook @ Kentish Farm	20	190	2.05
125006	Finch Hatton Creek @ Dam Site	27	80	0.59
410743	Jerrabomberra Creek @ Four Mile Creek	20	10	0.33
G8170075	Manton River u/s Manton Dam	35	25	1.30
141009	North Maroochy River @ Eumundi	27	25	0.68
A5040523	Sixth Creek @ Castambul	19	45	0.95
422321	Spring Creek @ Killarney	29	-10	2.00
2219	Swan River u/s Hardings Falls	21	-10	0.36
228217	Toomuc Creek @ Pakenham	21	11	0.89
603190	Yates Flat Creek @Woonanup	12	25	0.32

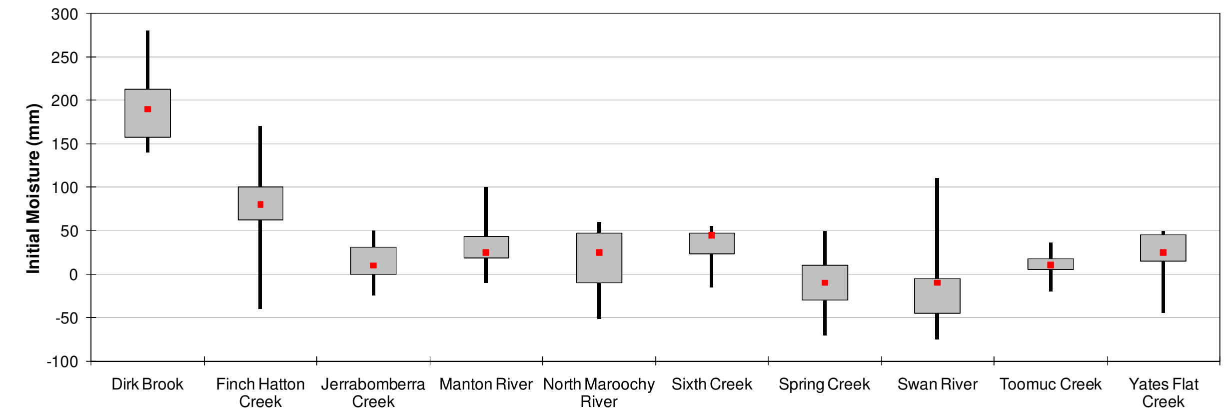


Figure 7-1 Range of initial moisture values for SWMOD model (box indicates quartiles and line shows max and min values)

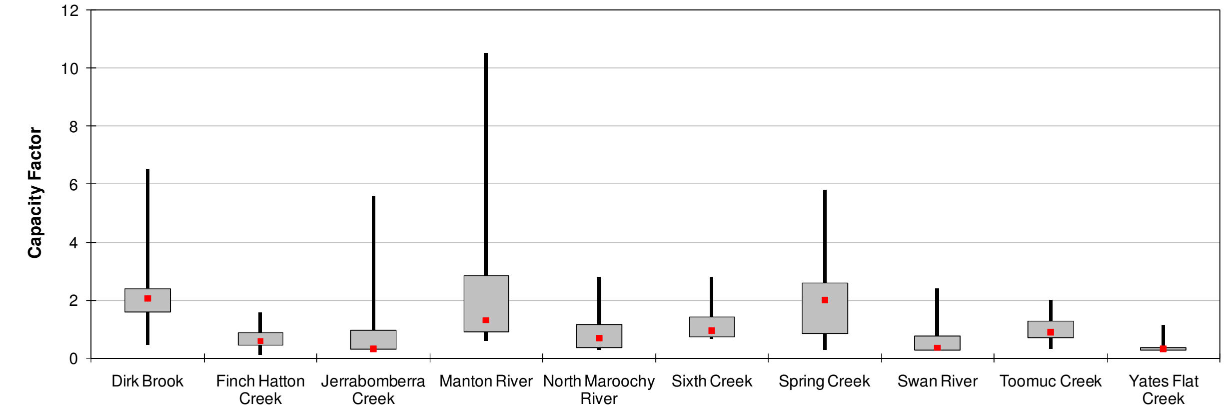


Figure 7-2 Range of capacity factor values for SWMOD model (box indicates quartiles and line shows max and min values)

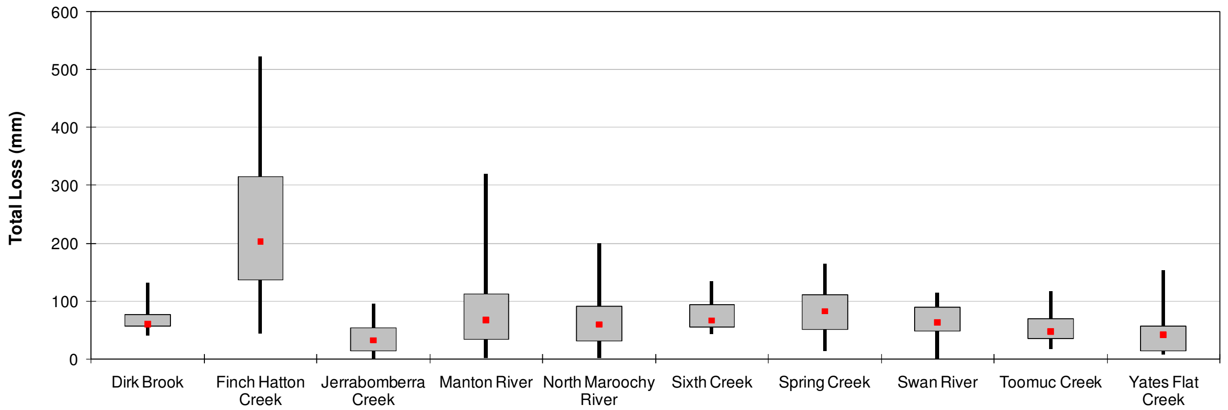


Figure 7-3 Range of total loss values for SWMOD model (box indicates quartiles and line shows max and min values)

7.3.1. Seasonality

The variation of SWMOD loss values with season distribution for each catchment is shown in Appendix D.

7.3.2. Variation with storm severity

Plots of SWMOD loss values versus storm severity are shown in Appendix D. The storm severity is characterised by the average recurrence (ARI) of the rainfall burst, as for IL/CL and IL/PL results. The events for all catchments were pooled by standardising against the catchment median values. Similar to the results for the IL, CL and PL values, there was no relationship between the loss values and the ARI of the rainfall burst.

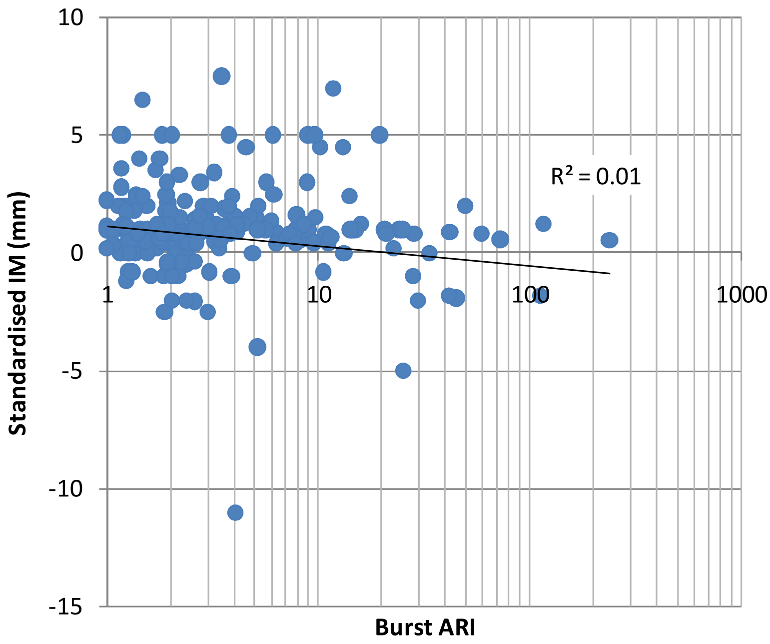


Figure 7-4 Variation of standardised initial moisture with ARI of the burst rainfall

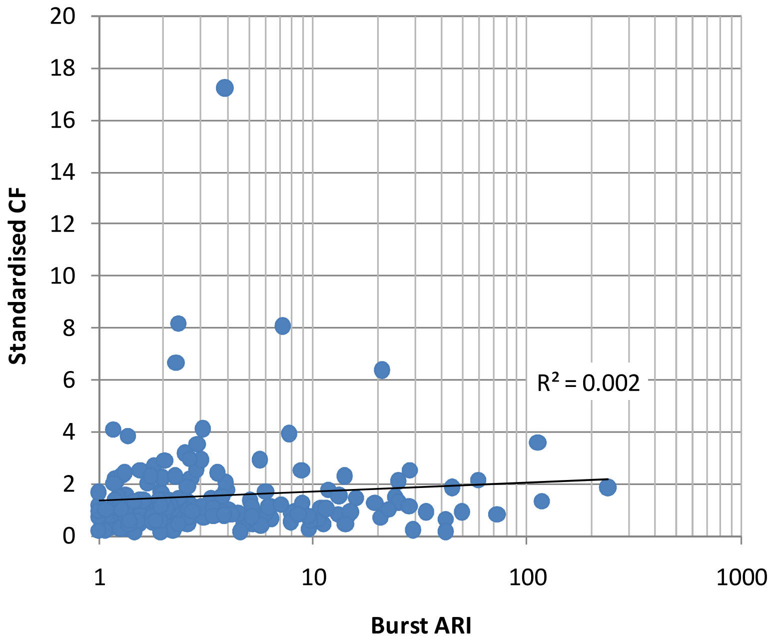


Figure 7-5 Variation of standardised capacity factor values with ARI of the burst rainfall

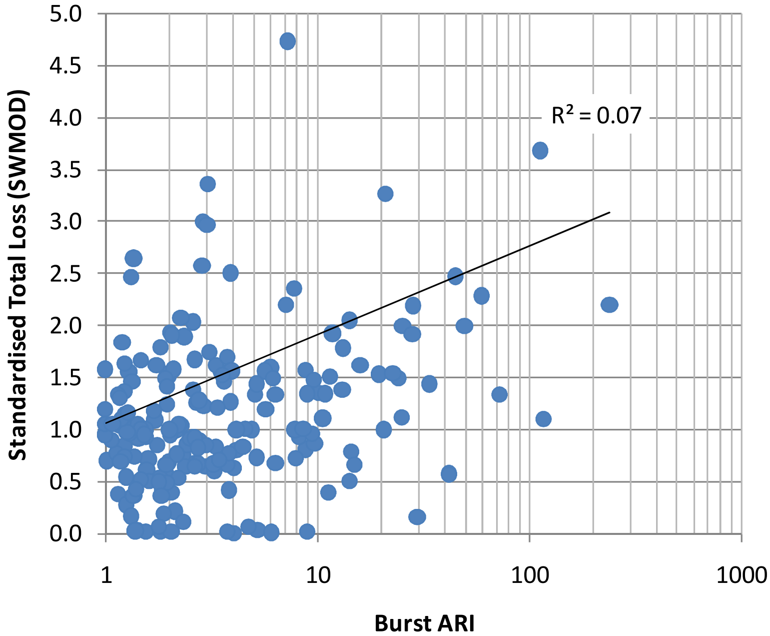


Figure 7-6 Variation of standardised total losses with ARI of the burst rainfall

7.3.3. Relationship with catchment characteristics

A preliminary analysis was undertaken on the relationship between the SWMOD parameters and some catchment characteristics. The loss values determined for each of the catchments were examined with the water holding capacity and baseflow index.

Baseflow index correlates relatively well with both parameters of SWMOD for the pilot catchments, particularly the capacity factor, as shown in Figure 7-8. Figure 7-7 shows that there is some correlation with catchment average water holding capacity and the median initial moisture, but none with the capacity factor. This preliminary analysis results look promising and suggests that it may be possible to relate the SWMOD parameters values to catchment characteristics as part of Phase 4.

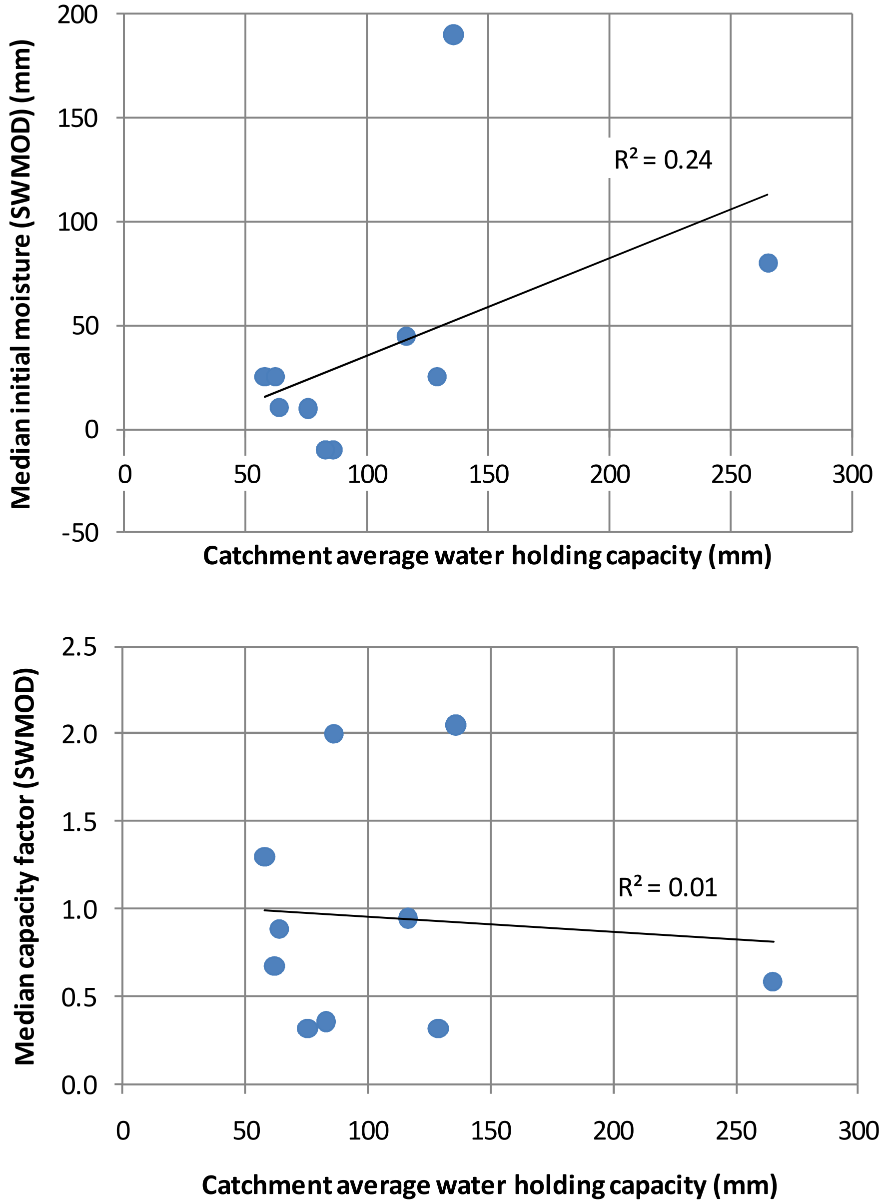
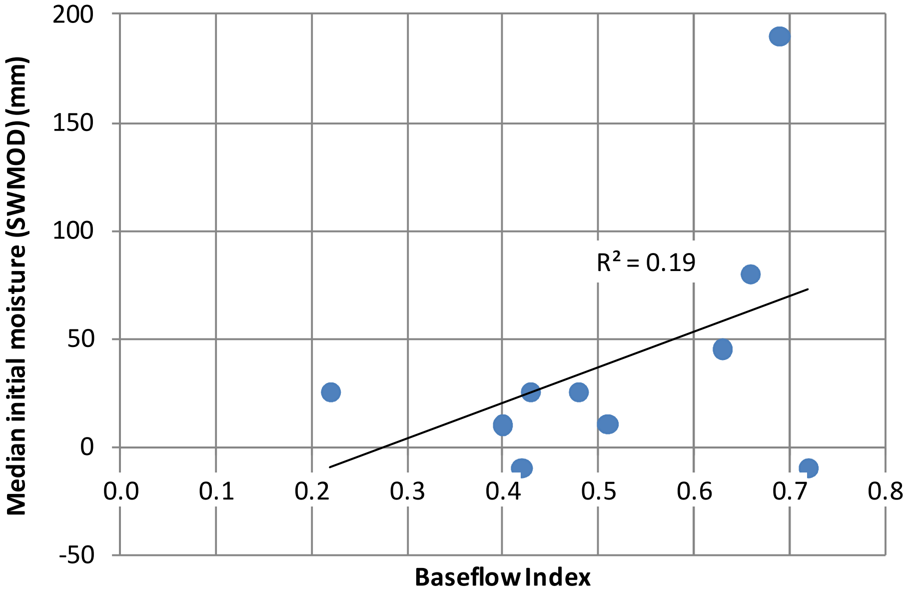


Figure 7-7 Median initial moisture values and median capacity factor values against catchment average water holding capacity



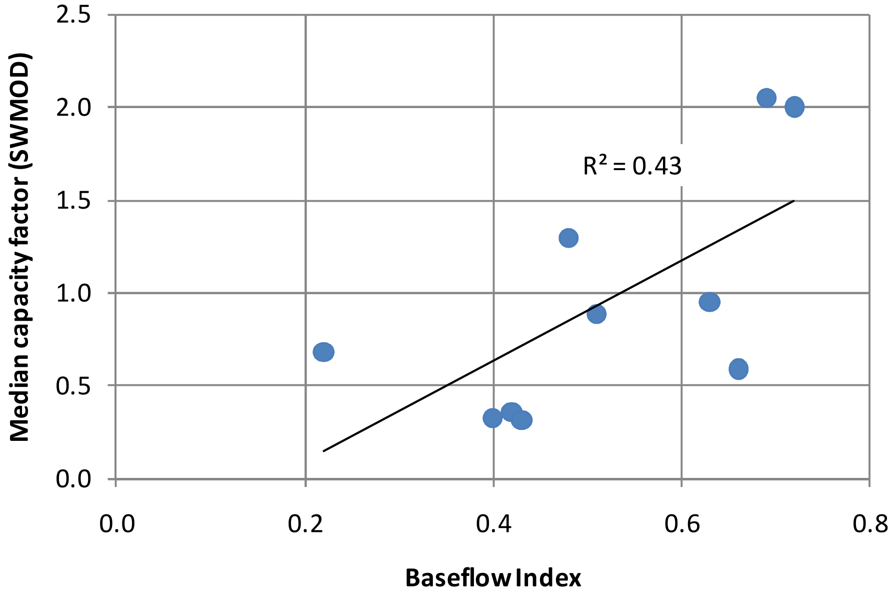


Figure 7-8 Median initial moisture values and median capacity factor values against catchment baseflow index

7.4. Non-parametric distribution

The losses obtained from the analysis of single events on the 10 pilot catchments (described in Section 5) have been further analysed to develop a distribution of initial moisture content for sampling in the joint probability framework.

The exceedance percentiles for each catchment were extracted, and then standardised by the median value for each catchment (see Figure 7-9). These were then averaged across all catchments to obtain a single curve. From Figure 7-9, it can be seen that some of the initial moisture contents are negative, which indicates that the moisture capacity obtained from soil characteristics may underestimating the actual moisture capacity. The average initial moisture content distribution has been sampled in the joint probability framework in the verification.

The other loss parameter required for SWMOD, soil moisture capacity factor, was held at the median value obtained from the analysis performed for each catchment in Section 5.

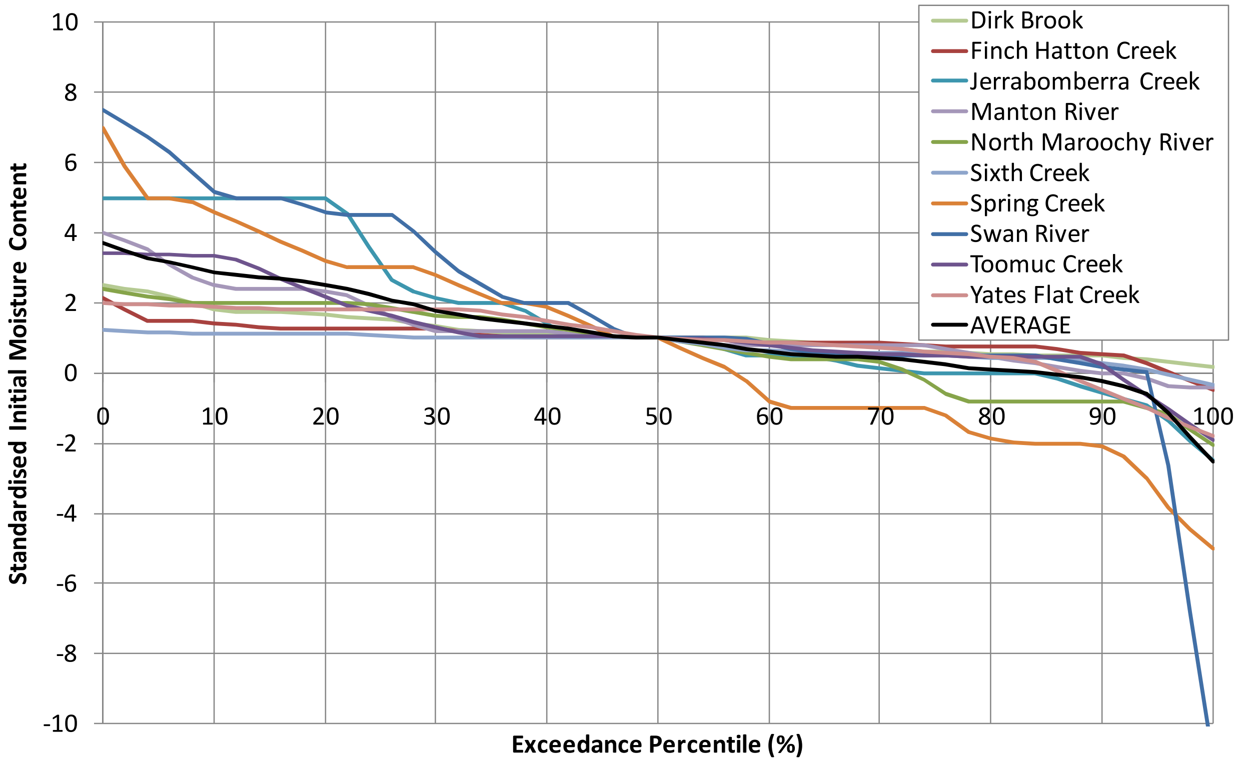


Figure 7-9: Standardised SWMOD distributions.

7.5. Parametric distributions

Parametric distributions were fitted to the SWMOD loss results as described in Section 5.5. The selected distributions are listed in Table 7-3 and this demonstrates that there is no preferable distribution.

Table 7-3 Summary of selected distribution for SWMOD initial moisture content values

Gauge	Catchment	Selected distribution
614005	Dirk Brook @ Kentish Farm	Generalised Extreme Value
125006	Finch Hatton Creek @ Dam Site	Weibull 3P
410743	Jerrabomberra Creek @ Four Mile Creek	Gumbel Max
G8170075	Manton River u/s Manton Dam	Weibull 3P
141009	North Maroochy River @ Eumundi	Generalised Pareto
A5040523	Sixth Creek @ Castambul	Generalised Pareto
422321	Spring Creek @ Killarney	Beta
2219	Swan River u/s Hardings Falls	Log Normal 3P
228217	Toomuc Creek @ Pakenham	Log Normal 3P
603190	Yates Flat Creek @ Woonanup	Generalised Pareto*

*Small sample size. P-P plot and Q-Q plot not linear

8. Flood frequency analysis

8.1. Introduction

Flood frequency analysis involves estimation of flood quantiles which is generally done by fitting a probability distribution to the observed annual maximum flood data. This section of the report presents estimation of flood quantiles for the 10 pilot catchments. At the beginning, preparation of streamflow data is presented, which is followed by the selection of the best-fit probability distribution. Estimation of flood quantiles are then presented. Appendix F contains the extracted annual maximum flood series data, additional results and plots.

8.2. Streamflow data preparation

Streamflow data were obtained from state water agencies. The primary data consisted of monthly maximum flow, maximum and mean daily flow. The annual maximum flood series were constructed from these primary data series.

In preparing the streamflow data the procedures described in Haddad et al. (2010) were followed. There were only three gaps that needed in-filling which were done by method of regression. The outlier was detected by Bulletin 17B Method. From the 10 stations, seven low outliers were found as shown in Table 8-1.

Table 8-1 Summary of streamflow data preparation

Site ID	Site name	Area (km^2)	Start year	End year	Record length (years)	Trend	Outlier (Year)
614005	Dirk Brook @ Kentish Farm	35.1	1971	2001	31	No	Low (2001)
125006A	Finch Hatton Creek @ Dam Site	36	1976	2011	36	No	Low (1992)
410743	Jerrabomberra Creek @ Four Mile Creek	55.3	1968	1997	30	No	Low (1979)
G8170075	Manton River u/s Manton Dam	28	1965	2011	47	Downward	Low (1990)
141009A	North Maroochy River @ Eumundi	40	1982	2011	30	No	No
A5040523	Sixth Creek @ Castambul	44	1973	2011	39	No	No
422321B	Spring Creek @ Killarney	34	1973	2011	39	No	No
2219	Swan River u/s Hardings Falls	36.4	1983	2011	29	No	No
228217C	Toomuc Creek @ Pakenham	41	1978	2011	34	No	Low (2002)
603190	Yates Flat Creek @ Woonanup	56.3	1963	2010	48	Downward	Low (2006, 2010)

The detected low outliers were excluded in flood frequency analysis. Trend analysis was done using Mann-Kendall test (Mann, 1945; Kendall, 1975). For two stations downward trend was detected (see Table 8-1). However, these two stations were not excluded from the data series as it was not possible to confirm whether this detected trend was due to climate change or due to normal climate variability. The finally selected annual maximum flood series data of the 10 pilot catchments are provided in Appendix F.

The annual maximum flood series record lengths range 29 to 48 years (average: 36 years), which represents a reasonable long record lengths to carry out flood frequency analysis. The histogram of record lengths is presented in Figure 8-1.

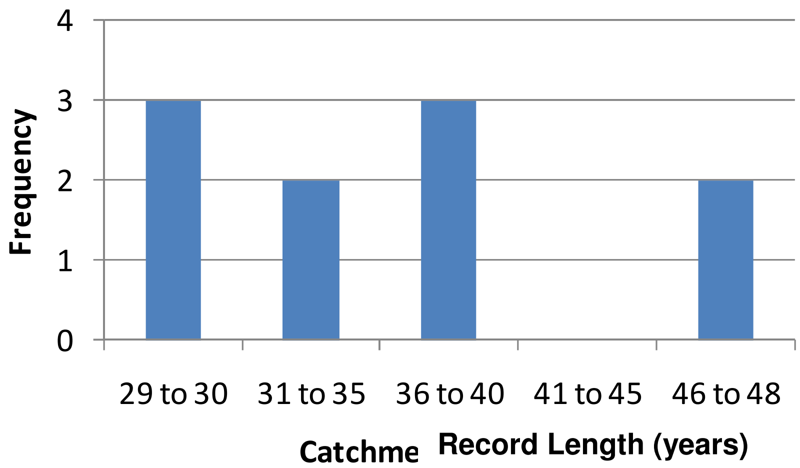


Figure 8-1 Histogram of annual maximum flood series record lengths

8.3. Fitting and comparison of probability distributions

Four different probability distributions were fitted using FLIKE (Kuczera, 1999) to the annual maximum flood series data of each of the 10 selected catchments. These are Log Pearson Type 3, Generalised Pareto (GP), Generalised Extreme Value (GEV) and Log Normal (LN). For estimating the parameters of the distribution, Bayesian fitting procedure was adopted.

The goodness-of-fit of these distributions were assessed by visual examination and numerical procedure (i.e. Bayesian Information Criteria and Akaike Information Criteria). The results of this comparison are shown in Table 8-2. Example plots are shown in Figure 8-2 and Figure 8-3 (all the plots are provided in Appendix F). It was found that out of the 10 stations, LP3 was the best-fit distribution for 5 stations out of 10 (i.e. 50% cases), followed by the GEV distribution which showed the best-fit for 4 stations (i.e. 40% cases). The LN was the poorest performer. Based on the 1st and 2nd positions (see Table 8-2), the LP3 was the best-fit distribution for 10 cases (i.e. 100%), followed by the GEV (8 cases i.e. 80%). It seems that LP3 and GEV distributions have performed similarly, however, LP3 was slightly better and hence it was selected as the best-fit distribution and flood quantiles were estimated from the LP3 distribution.

Table 8-2 Comparison of fitting probability distributions to the annual maximum flood series data of 10 pilot study catchments

Gauge	Catchment	Best fit distribution		
		1st	2nd	3rd
614005	Dirk Brook @ Kentish Farm	GEV	LP3	GP
125006A	Finch Hatton Creek @ Dam Site	GP	LP3	GEV
410743	Jerrabomberra Creek @ Four Mile Creek	GEV	LP3	LN
G8170075	Manton River u/s Manton Dam	GEV	LP3	LN
141009A	North Maroochy River @ Eumundi	LP3	GEV	LN
A5040523	Sixth Creek @ Castambul	GEV	LP3	LN
422321B	Spring Creek @ Killarney	LP3	GEV	LN
2219	Swan River u/s Hardings Falls	LP3	GEV	LN/GP
228217C	Toomuc Creek @ Pakenham	LP3	GEV	GP
603190	Yates Flat Creek @ Woonanup	LP3	GP	GEV

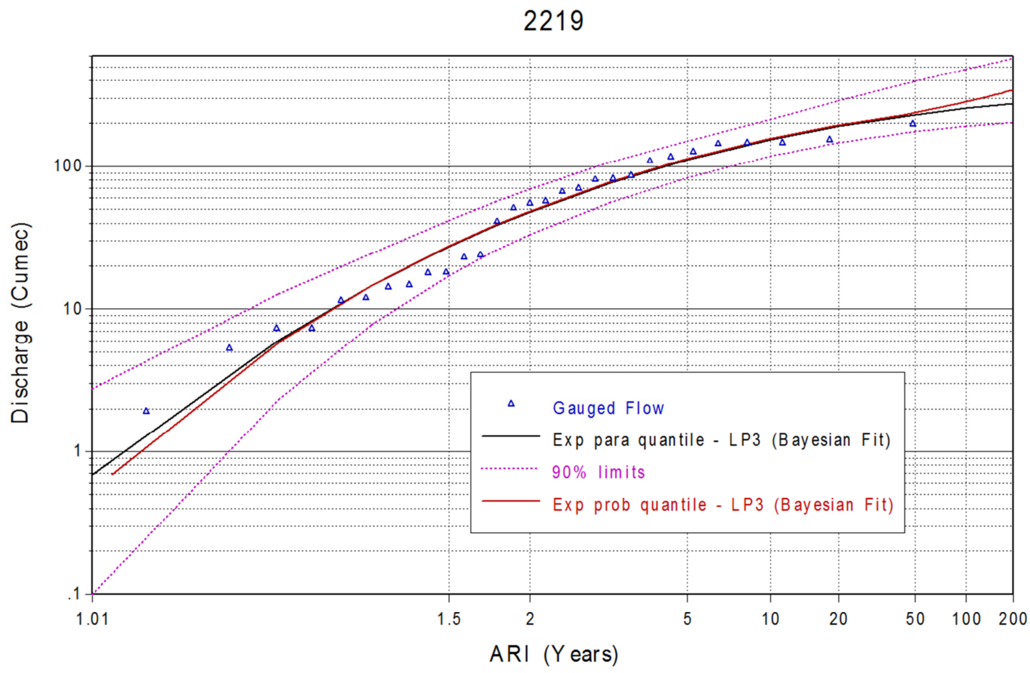


Figure 8-2 Flood frequency analysis plot for Swan River (LP3 distribution)

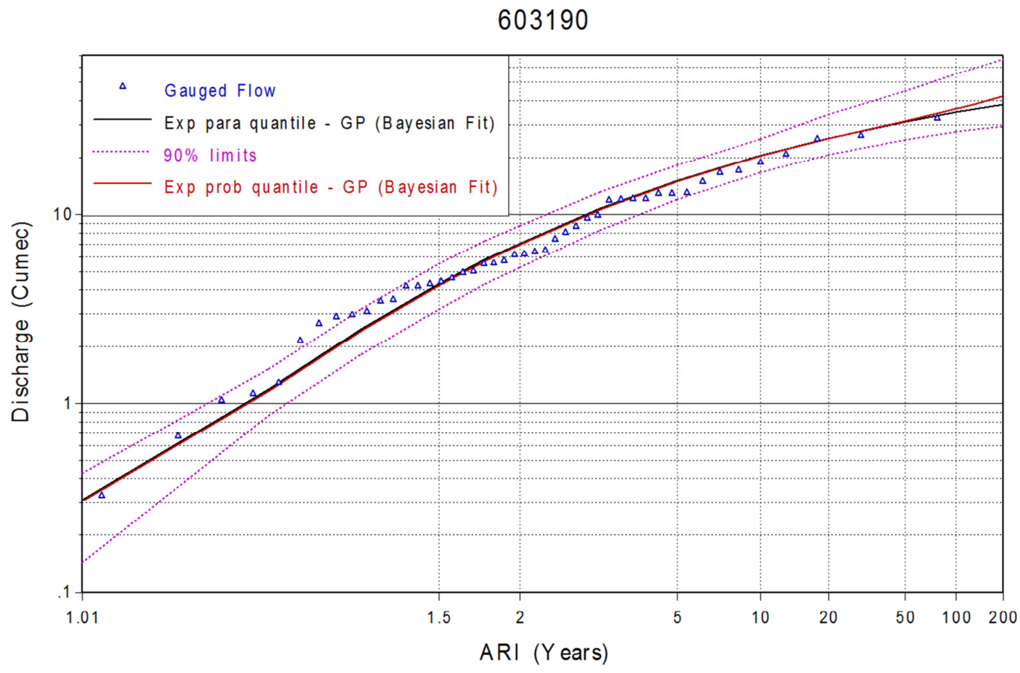


Figure 8-3 Flood frequency analysis plot for Yates Flat (LP3 distribution)

8.4. Estimated flood quantiles

The flood quantiles estimated from the fitted LP3 distribution were extracted from the FLIKE output and are presented in Table 8-3. Figure 8-4 shows the quantiles graphically and this highlights that, despite the similar catchment areas, the values vary over approximately two orders of magnitude. The difference in design rainfall depths only accounts for some of this variation and hence the large range reflects the different losses for the catchments.

Table 8-3 Flood quantiles from at-site flood frequency analysis

Gauge	Catchment	Flood quantiles (m^3/s) for ARI (years)					
		2	5	10	20	50	100
614005	Dirk Brook @ Kentish Farm	3.7	5.6	6.9	8.3	10.1	11.6
125006A	Finch Hatton Creek @ Dam Site	126	258	354	446	562	644
410743	Jerrabomberra Creek @ Four Mile Creek	28.0	84.3	134	187	258	310
G8170075	Manton River u/s Manton Dam	34.4	66.2	90.0	114	146	171
141009A	North Maroochy River @ Eumundi	60.3	115	153	189	233	265
A5040523	Sixth Creek @ Castambul	13.0	29.4	45.2	64.5	96.3	125.9
422321B	Spring Creek @ Killarney	12.6	40.2	70.0	108	171	229
2219	Swan River u/s Hardings Falls	47.3	111	155	193	236	263
228217C	Toomuc Creek @ Pakenham	11.2	22.2	28.7	33.7	38.8	41.7
603190	Yates Flat Creek @ Woonanup	6.7	14.0	20.0	24.9	31.7	36.7

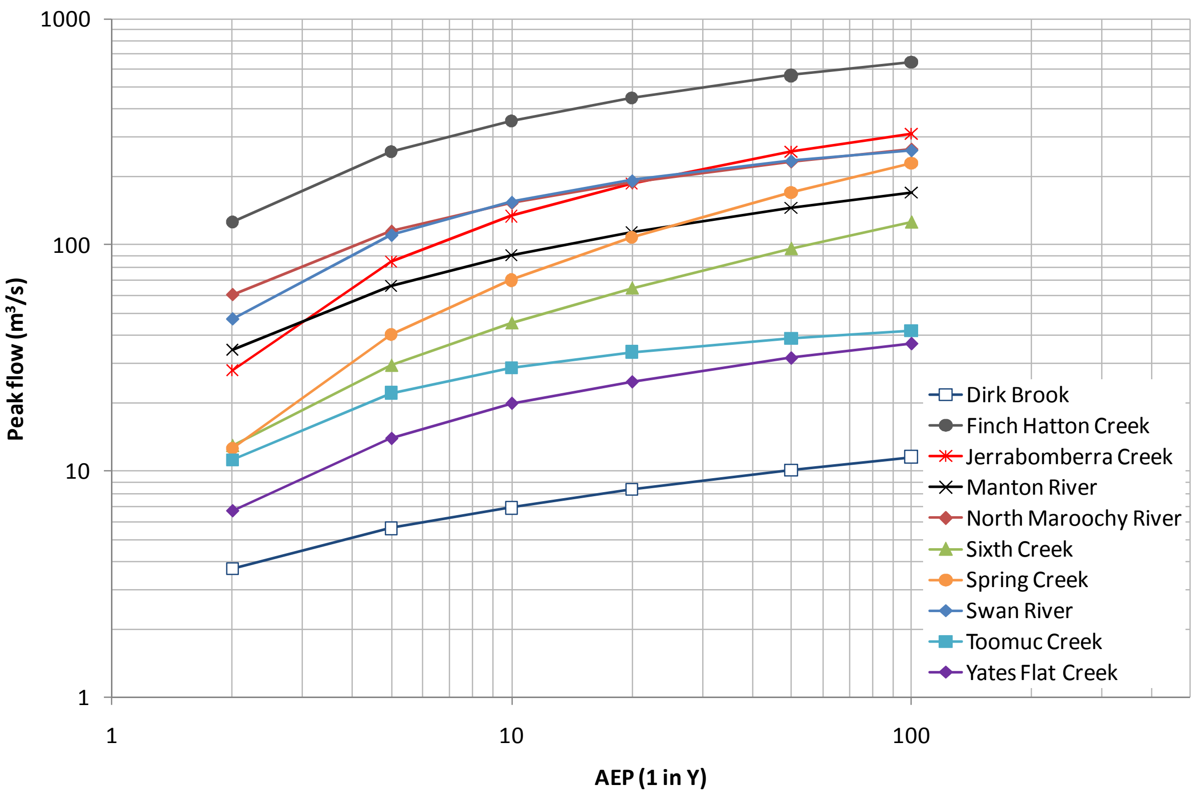


Figure 8-4 Plot of flood quantiles from at-site flood frequency analysis

9. Monte-Carlo approach and inputs

A joint probability (Monte-Carlo) Monte-Carlo approach was applied to estimate peak flows for a range of AEPs for each catchment. This section describes the adopted framework and the characterisation of the various inputs. Section 10 then outlines the comparison of the rainfall-based estimates to those from the frequency analysis of recorded flows.

9.1. Joint probability approach to design flood estimation

Joint probability techniques offer an alternative to the traditional design event method. These techniques recognise that any design flood characteristics (e.g. peakflow) could result from a variety of combinations of flood producing factors, rather than from a single combination.

An overview of the adopted joint probability framework adopted is illustrated in Figure 9-1. In essence the approach involves the undertaking of numerous model simulations where the model inputs are sampled from non-parametric distributions that are either based on readily available design information or else on the results of recent research. It builds upon some of the concepts presented by Rahman et al. (2001) and Rahman et al. (2002), and is similar in concept to approaches developed for the U.S. Bureau of Reclamation by Schaefer (2001). Further details are provided in Nathan et al. (2003) and Nathan and Weinmann (2004).

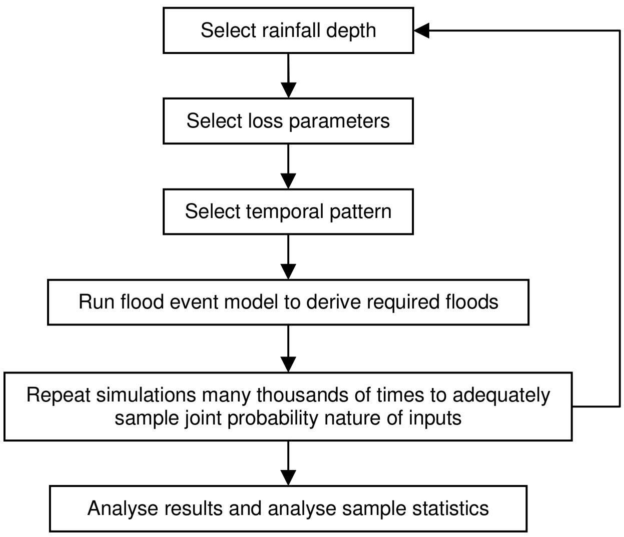


Figure 9-1: Overview of adopted joint probability framework.

In developing the joint probability framework particular attention was given to ensuring that the nature of the inputs and the manner in which they are incorporated are consistent with the philosophy detailed in the current “Australian Rainfall and Runoff” Book VI (Nathan and Weinmann, 1999) guidelines. The following briefly describes the main elements of the approach, and the manner in which they relate to established design information.

Select rainfall depth. Rainfall depths are stochastically sampled from the cumulative distribution of rainfall depths. Further information describing the source of the rainfall frequency curve adopted is provided in Section 9.2.1.

Select losses: Initial losses (for the continuing and proportional loss models) and initial moisture content (for SWMOD loss model) are stochastically sampled from non-parametric distributions determined from the analysis of the catchments in Section 5. See Sections 5.5 and 7.4 for more information on these distributions. Continuing and proportional losses (runoff coefficient) are kept at constant values. The initial loss values were adjusted to accounted for the embedded nature of bursts (refer Section 9.3).

Select Temporal Pattern. Temporal patterns are randomly selected from a sample of temporal patterns relevant to the catchment area and duration of the storm. The temporal patterns are derived from large historic storms that have been observed in each catchment. See Section 9.2.2 for more information on the method used to extract the temporal patterns.

Monte Carlo simulation. Simulations are undertaken using a stratified sampling approach in which the sampling procedure focuses selectively on the probabilistic range of interest. Thus, rather than undertake many millions of simulations in order to estimate an event with, say, a 1 in 10^6 probability of exceedance, a reduced number of simulations are undertaken over a specified number of probability intervals. The rainfall frequency curve was divided into 50 intervals uniformly spaced over the standardised normal probability domain, and 200 simulations were taken within each division. Thus, a total of 10,000 simulations were undertaken to derive the frequency curve corresponding to each storm duration considered.

9.2. Rainfall inputs

9.2.1. Rainfall frequency curve

New IFD estimates are being developed by the Bureau of Meteorology (BoM) as part of ARR Project 1. These estimates will be available in late 2012 and unfortunately were not available for this pilot project. Thus, the following IFD information was available:

- ARR87 – The design rainfalls from the 1987 edition of ARR (IEAust, 1987).
- TESTIFD – A preliminary gridded design rainfall data set developed by the BoM for the whole of Australia using only BoM rainfall gauge data which was made available to other ARR projects as interim values, pending the completion of ARR Project 1.

For each catchment, both IFD estimates were compared to the frequency analysis of the recorded pluviograph data for durations of 6 hour, 12 hour and 24 hour durations as these are expected to span the critical duration for the catchments of interest. An example of this comparison for Spring Creek at Killarney (Qld) is shown in Figure 9-2. For this catchment, the results of the analysis of the at-site data for 12 hours are consistently below the ARR87 and TestIFD values (by about 10 to 20%). Comparison for all sites are contained Appendix H.

The approach adopted to derive IFD estimates for each catchment was to factor the ARR87 values to better match the results of the at-site frequency analysis. This was performed by determining the ratio of the at-site estimates to the ARR87 estimates for each quantile (2, 5, 10, 20, 50 years ARI) for each comparison duration (6, 12, 24 hrs). These adjustment ratios were then averaged such that a single adjustment ratio was developed for each ARI and applied to all durations (3, 6, 12, 24, 48 hrs). An example of these adjustments for the Spring Creek (Qld) site is shown in Table 9-1 and the resulting adjustment to the 12 hour rainfall frequency curve is shown in Figure 9-2. The adjustments for all sites are shown in Appendix H for each site, and a summary of the adjustments applied for each site are provided in Table 9-2 which shows that the estimates were generally within 20%.

Table 9-1: Example of adjustment ratios applied to Spring Creek at Killarney (Qld) ARR87 design point rainfall estimates to better match the at-site rainfall estimates

ARI (yrs)	6 hr Adjustment Ratio	12 hr Adjustment Ratio	24 hr Adjustment Ratio	Average Adjustment Ratio for each ARI
2	0.76	0.73	0.70	**0.73**
5	0.72	0.68	0.70	**0.70**
10	0.73	0.71	0.74	**0.73**
20	0.72	0.73	0.75	**0.74**
50	0.73	0.80	0.79	**0.77**

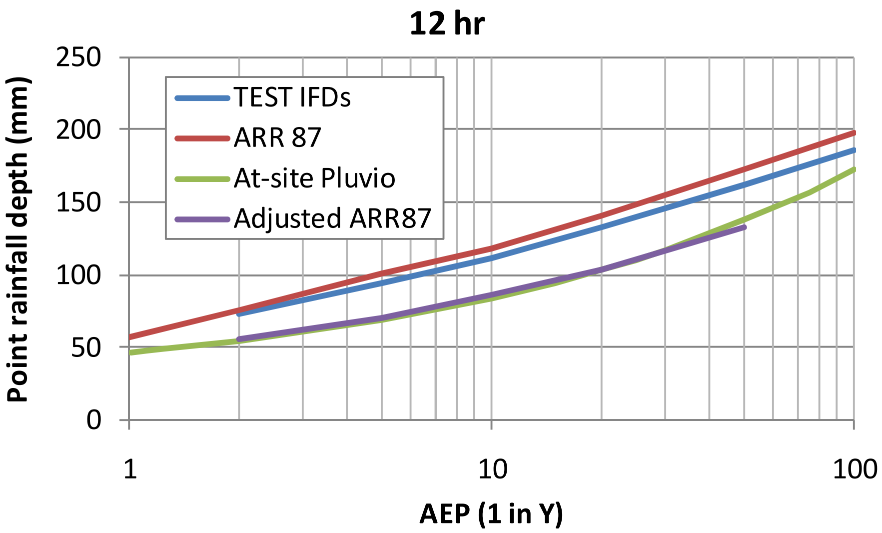


Figure 9-2: Example of adjustment made to ARR87 12 hour point design rainfall depths for Spring Creek at Killarney (Qld) to better match the at-site pluviograph rainfall estimates

Table 9-2: Adopted adjustment factors applied to ARR87 design point rainfalls to obtain rainfall frequency curves more similar to the at-site analysis.

Gauge	Catchment	ARI (years)				
		2	5	10	20	50
614005	Dirk Brook @ Kentish Farm	0.96	0.94	0.95	0.92	0.88
125006	Finch Hatton Creek @ Dam Site	1.06	1.10	1.15	1.14	1.12
410743	Jerrabomberra Creek @ Four Mile Creek	1.01	1.01	1.05	1.05	1.07
G8170075	Manton River u/s Manton Dam	0.91	0.95	1.01	1.02	1.03
141009	North Maroochy River @ Eumundi	1.11	1.07	1.07	1.02	0.95
A5040523	Sixth Creek @ Castambul	0.85	0.79	0.77	0.72	0.67
422321	Spring Creek @ Killarney	0.73	0.70	0.73	0.74	0.77
2219	Swan River u/s Hardings Falls	1.16	1.17	1.19	1.15	1.11
228217	Toomuc Creek @ Pakenham	0.79	0.78	0.82	0.86	0.95
603190	Yates Flat Creek @ Woonanup	0.94	0.97	1.00	0.98	0.96

Design rainfall estimates were required for AEPs rarer than 1 in 100 and therefore the rainfall frequency curves were extended to 1 in 2000 AEP using the growth factors from Jordan et al. (2005). These are strictly only appropriate for application to short duration rainfall frequency curves, but as the curves are only being extended to allow sampling of rainfall events rarer than 1 in 100 AEP this is likely to have negligible impact on the resulting peak flow estimates.

To convert these point rainfall estimates to catchment average estimates, areal reduction factors (ARFs) were applied from the CRC-FORGE projects that have been completed for each region in Australia (Weinmann et al., 1999; Hargreaves et al., 1999; Gamble & McConachy, 1999; Hill et al., 2000; Durrant et al., 2006; Jordan et al., 2011). No short duration ARFs were available for Western Australia from the CRC-FORGE project for that state and therefor short duration ARFs were derived in a manner consistent with the other states and this is described in Appendix I.

9.2.2. Temporal patterns

The full period of record for each pluviograph within each catchment was analysed to extract a sample of 10 temporal patterns for each duration for each catchment. These temporal patterns were extracted using the temporal pattern extractor in RORBWin.

The extracted temporal patterns were filtered to remove embedded bursts which were more extreme than the overall pattern. These embedded bursts of rainfall result in sub-periods of rainfall that are rarer (i.e. lower AEP) than the design event of interest. Filtering involves distributing some of the rainfall from embedded bursts across other time periods proportionally to the depth of rainfall in each time increment.

The filtered temporal patterns obtained from this process were sampled in the joint probability framework. Temporal patterns for each catchment are shown in Appendix K.

9.2.3. Spatial pattern

As the catchments being analysed are small, the spatial distribution of rainfall across the catchment is expected to be a minor factor influencing the magnitude of the resultant peak floods. For this reason, a uniform spatial pattern has been adopted for all catchments.

9.3. Burst losses

The median initial loss values derived in Section 5.4 were derived from analysis of complete storms whereas the IFD information in ARR and the temporal patterns described above relate to discrete bursts of rainfalls. This requires the initial loss values to be reduced to account for the embedded nature of design rainfalls.

It was then necessary to consider the estimation of losses for bursts of rainfall embedded within longer duration storms. The difference between the initial loss for a burst and for a complete storm is illustrated in Figure 9-3.

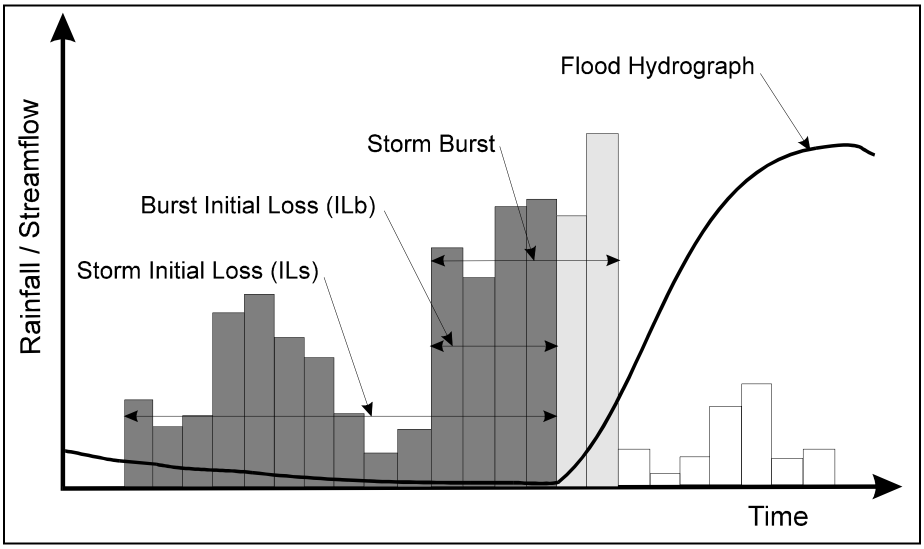


Figure 9-3 Initial Loss for an Embedded Rainfall Burst

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.

This pilot study only considered complete storms and therefore the relationship developed by Hill et al. (1997) was used to convert the Storm Initial Loss (IL_s) to equivalent Burst Initial Loss (IL_b) values:

$$IL_b = IL_s \left\{ 1 - \frac{1}{1 + 142 \frac{\sqrt{(duration)}}{MAR}} \right\} \qquad r^2=0.43,\ SE=0.18 \qquad \text{(equation 9.1)}$$

While the relatively low value of r^2 indicates considerable scatter about the fitted line, even after allowing for the effect of mean annual rainfall, Hill et al. (1997) concluded that the relationship should provide a satisfactory basis for probability-based design.

Equation 9.1 indicates that the relationship between IL_b and IL_s varies with the duration and hence a different IL_b is applicable for each duration. The Monte-Carlo framework applied in this pilot study is based upon an initial loss that is invariant with duration and hence IL_b was calculated from IL_s using a duration of 18 hours which is representative of the critical duration for the pilot catchments over the AEPs of interest in this study. The adopted IL_b values are summarised in Table 9-3.

Table 9-3 Adopted Burst Initial Losses

Gauge	Catchment	Mean Annual Rainfall (mm)	IL/CL model		IL/PL model	
			IL_s (mm)	IL_b (mm)	IL_s (mm)	IL_b (mm)
614005	Dirk Brook @ Kentish Farm	1150	17	6	15	5
125006	Finch Hatton Creek @ Dam Site	1800	60	15	60	15
410743	Jerrabomberra Creek @ Four Mile Creek	820	19	8	20	8
G8170075	Manton River u/s Manton Dam	1430	36	11	34	10
141009	North Maroochy River @ Eumundi	1650	25	7	22	6
A5040523	Sixth Creek @ Castambul	1000	37	14	37	14
422321	Spring Creek @ Killarney	1210	45	15	44	15
2219	Swan River u/s Hardings Falls	920	30	12	29	11
228217	Toomuc Creek @ Pakenham	1060	31	11	28	10
603190	Yates Flat Creek @ Woonanup	800	36	15	25	11

The median value of burst loss was applied to the non-parametric distributions derived in Section 5.5.

9.4. Baseflow

The at-site frequency analysis values that this verification is aiming to match (see Section 8) has been derived using the total recorded flow at the gauge site. As discussed in Section 3.4 and Section 5.2, RORB models the conversion of rainfall to surface runoff, but does not account for the baseflow component of the total recorded flow. Therefore, in order to compare the rainfall-based estimates to those from the at-site frequency analysis, it is necessary to add on a baseflow component.

An analysis of the baseflow manually extracted from the calibration events (see Section 3.4) was performed, with the baseflow under the peak of the hydrographs extracted. These were reviewed for a trend with event magnitude, but none was found, with an example for the Swan River (Tasmania) site shown in Figure 9-4. Therefore the proportion of baseflow estimated to be included in the total recorded flow was determined for each event, and the average value was then adopted as the baseflow that was added back to the flood peaks obtained from RORB for all AEPs (Figure 9-4).

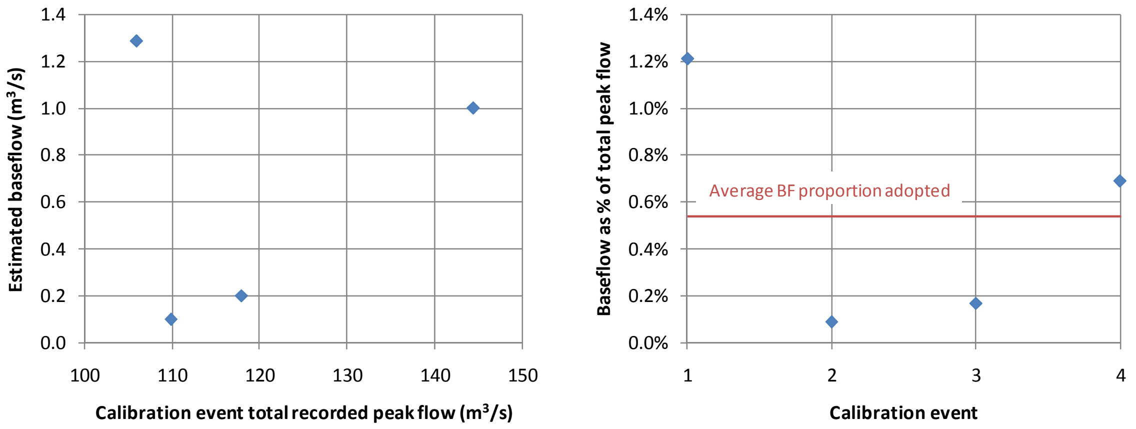


Figure 9-4: Summary of baseflow contribution for calibration events for Swan River

Table 9-4 shows the range of baseflow (as a proportion of the peak) estimated for the calibration events and the value adopted for design flood estimation.

Table 9-4 Baseflow contribution to calibration events

Gauge	Catchment	Range	Adopted
614005	Dirk Brook @ Kentish Farm	0%-18.1%	5.9%
125006	Finch Hatton Creek @ Dam Site	0.1%-1.9%	0.9%
410743	Jerrabomberra Creek @ Four Mile Creek	0%-1.8%	0.4%
G8170075	Manton River upstream Manton Dam	0.2%-2.0%	0.8%
141009	North Maroochy River @ Eumundi	0.01%-4.1%	1.5%
A5040523	Sixth Creek @ Castambul	0.3%-14.2%	4.3%
422321	Spring Creek @ Killarney	0.8%-7.5%	3.4%
2219	Swan River upstream Hardings Falls	0.1%-1.2%	0.5%
228217	Toomuc Creek @ Pakenham	0.3%-1.2%	0.6%
603190	Yates Flat Creek @ Woonanup	0.5%-2.0%	1.2%

Note: Values represent the ratio of the baseflow coinciding with the peak to the peak flow

10. Independent comparison with flood frequency quantiles

The loss values derived from the analysis of data were combined with other design inputs to derive design peak flows which were then compared with flood frequency quantiles. The Monte-Carlo approach and inputs described in the previous section was adopted. The following key design inputs were treated stochastically and sampled in the analysis:

- Rainfall depth – as described in Section 9.2.1
- Temporal patterns – as described in Section 9.2.2
- Initial Loss – The IL was sampled from a non-parametric distribution of the values derived in this study as described in Section 5.5.

Other design inputs such as the routing parameters, rainfall spatial pattern, continuing loss and contribution of baseflow were kept as fixed inputs.

The rainfall-based design flood peaks for an AEP of 1 in 10 are compared to the flood frequency quantiles for the 3 different loss models in Figure 10-1. The 90% confidence limits on the flood frequency estimates are shown as horizontal lines.

For the IL/CL and SWMOD models the values are remarkably consistent with the flood frequency quantiles and generally distributed about the 1:1 line. However, the IL/PL tends to underestimate the peak flows. This low bias for the IL/PL model is more pronounced for an AEP of 1 in 50 (refer Figure 10-2).

In percentage terms the estimates derived using the IL/CL and SWMOD model were within approximately 30% for 8 of the 10 catchments (the exceptions were Spring Creek and Yates Flat) and the median difference across the 10 catchments was less than 5%. For the IL/PL model the results were generally lower and within approximately 50% for 8 of the 10 catchments. The median difference for the IL/PL model was -25%. This demonstrates the difficulties in applying the IL/PL for design flood estimation.

The discrepancies between the rainfall-based estimates and the flood frequency quantiles is a function of any biases and uncertainties introduced at every step in the design process; from uncertainties in the measured data (such as rating curves, catchment average rainfall), conceptualisation and calibration of flood models (e.g. routing parameters) through to each of the design inputs (e.g. design rainfall depth, sample of temporal pattern, baseflow contribution and losses). It is clear that any misclosure cannot be attributed solely to the adopted loss values.

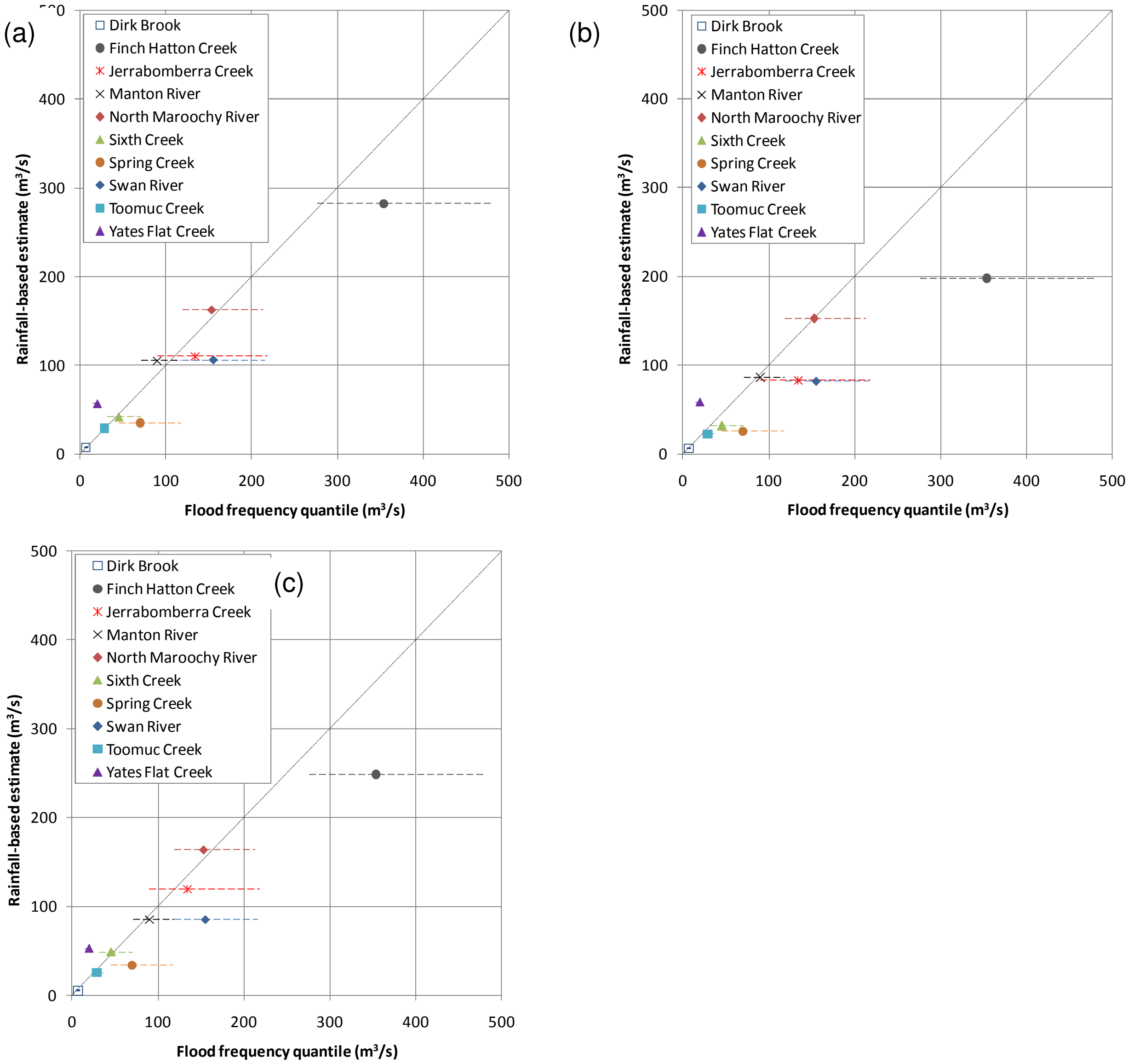


Figure 10-1 Comparison of rainfall-based and flood frequency quantiles for 1 in 10 AEP for (a) IL/CL model, (b) IL/PL model and (c) SWMOD model. Horizontal lines represent 90% confidence limits.

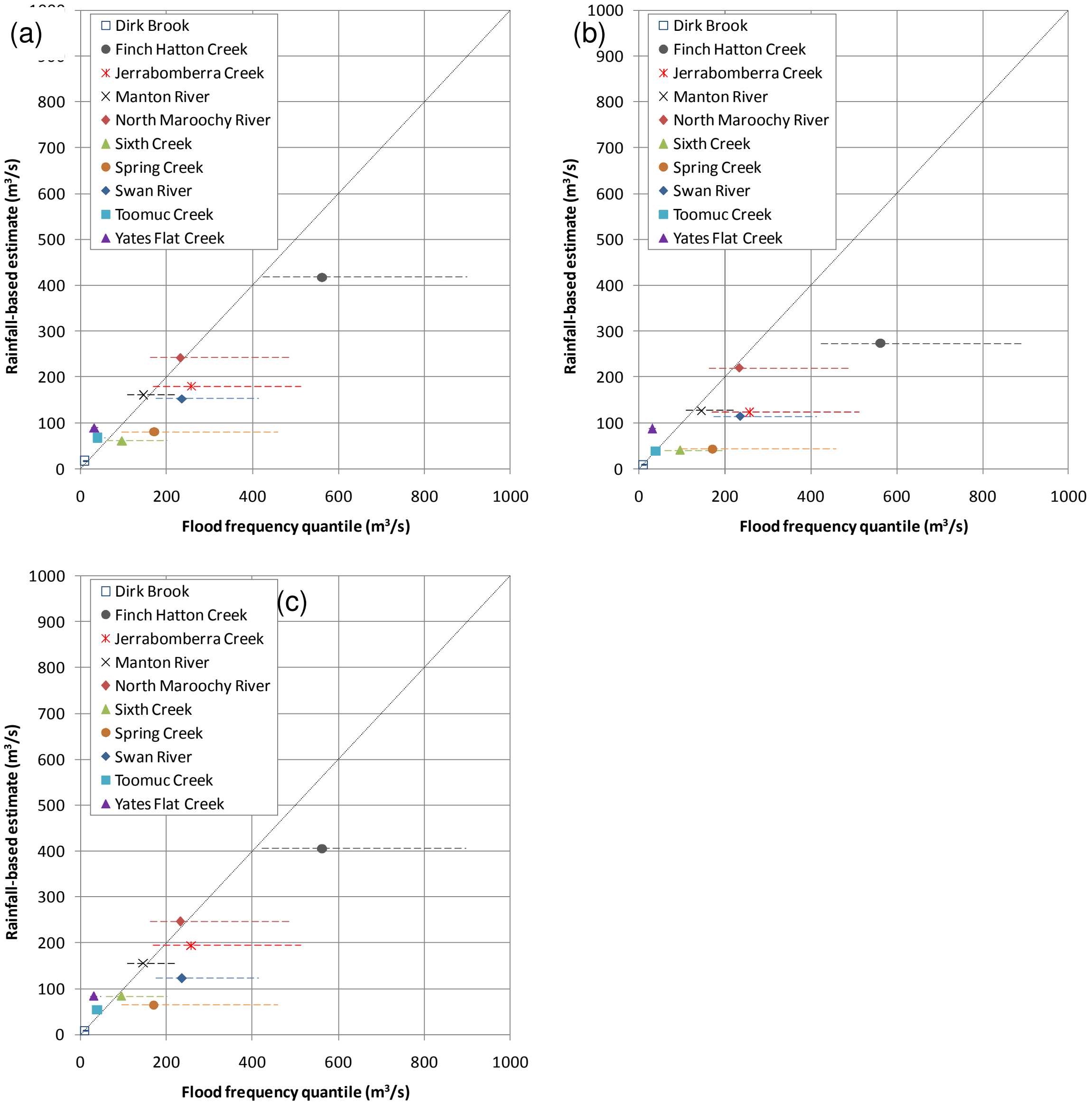
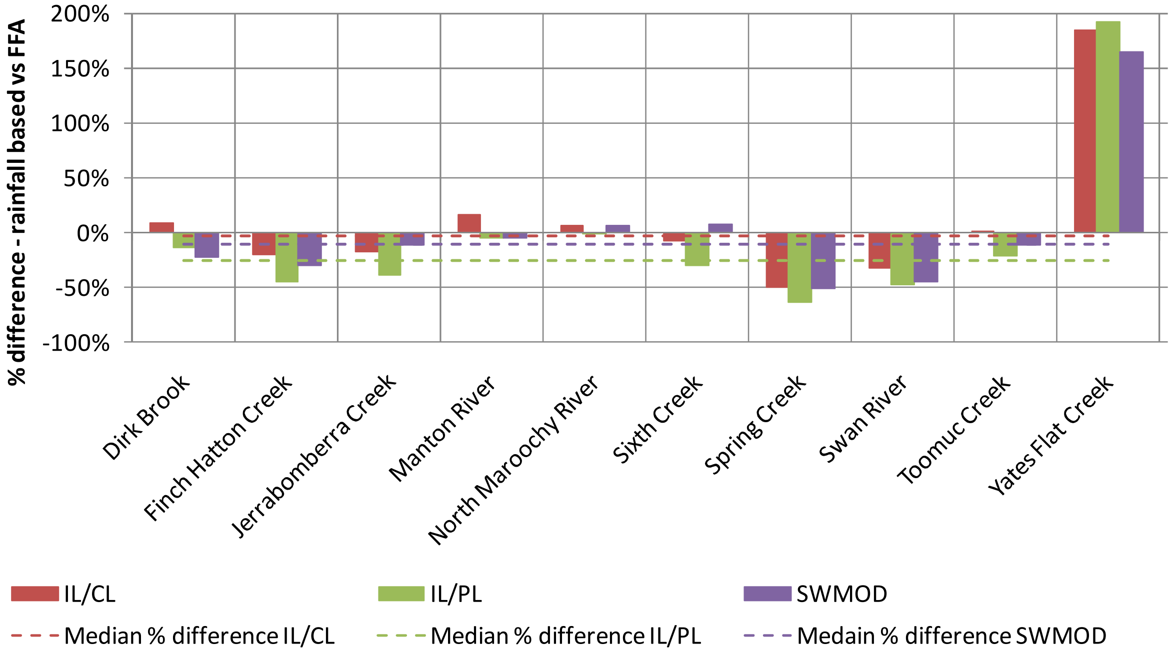


Figure 10-2 Comparison of rainfall-based and flood frequency quantiles for 1 in 50 AEP for (a) IL/CL model, (b) IL/PL model and (c) SWMOD. Horizontal lines represent 90% confidence limits.

The peak flows for all AEPs and loss model considered in the study are summarised in Appendix L. For those cases where the rainfall-based estimates were under the results from the flood frequency analysis, the model were also run with zero initial loss to see if this could produce a better match to the flood frequency quantiles. The results of these runs are also included in Appendix L.

(a)



(b)

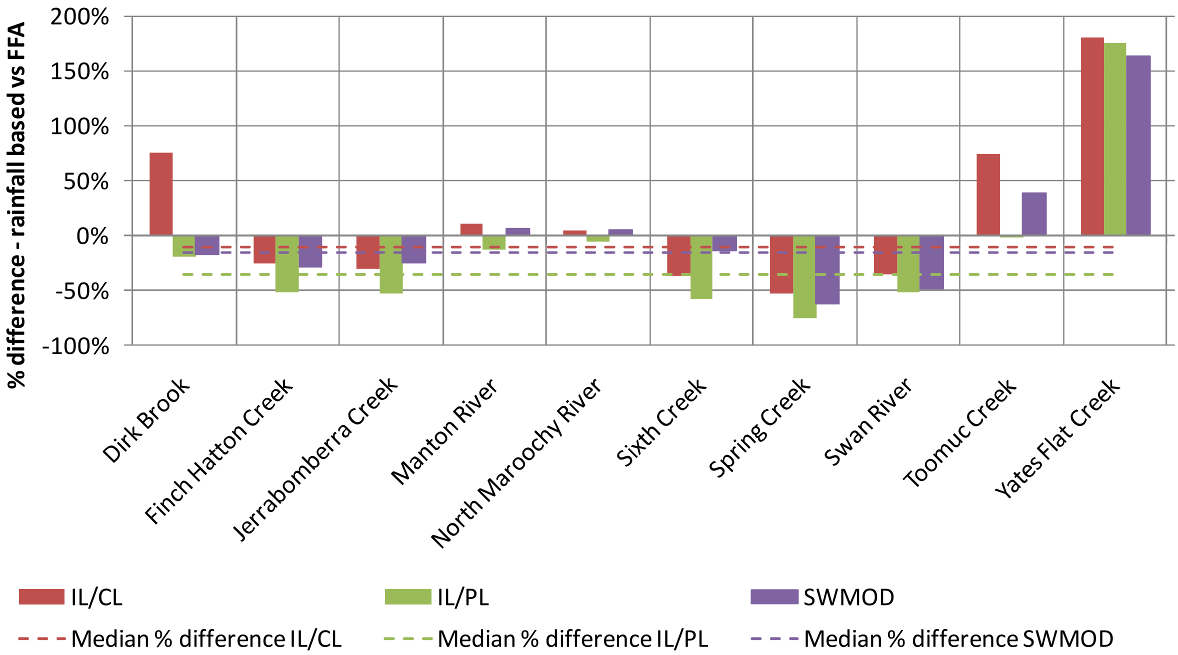


Figure 10-3 Rainfall based vs flood frequency analysis for pilot catchments at (a) an AEP of 1 in 10 and (b) an AEP of 1 in 50

11. Conclusions

Lumped conceptual loss models are well suited to design flood estimation as their complexity is commensurate with the other design inputs and their simplicity allows extrapolation to rarer events. 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 floods.

A range of conceptual loss models were considered for application to rural catchments and the following 4 models are considered most suited for further development for design flood estimation in Australia:

1) Initial loss – constant continuing loss
2) Initial loss – constant proportional loss
3) Initial loss – variable continuing loss
4) Probability distributed storage capacity loss model

Loss values were then estimated for each of the models for the 10 pilot catchments. Some previous investigations have estimated the loss values directly from the analysis of rainfall and streamflow. This involves defining a threshold flow above which IL was deemed to be satisfied and then calculating the CL or PL from a volume balance. However, this pilot study has demonstrated the difficulty in defining a single threshold that reproduces the loss values from the manual estimation using a flood model which explicitly account for the catchment routing. Therefore loss values were estimated using a calibrated flood model.

Lag relationships should be investigated to see if the lag behaviour can be generalized to obviate the need for calibrating a rainfall-runoff model. If this is not possible, then it may be necessary to continue to estimate loss values using a flood model that explicitly incorporates routing of the rainfall excess.

The IL/PL model outperformed the IL/CL model for calibration to historical events for the majority of events for 9 out of the 10 catchments. This is consistent with a number of other studies such as Dyer et al. (1994) and Hill et al. (1996) which also found the IL/PL model resulted in generally improved calibrations using flood models.

The limited sample made it difficult to investigate the variation of loss values with storm severity. Even when the data was pooled by standardising individual values by the median for the catchment, the values appeared to be independent of the ARI.

From infiltration theory it would be expected that the CL rate would reduce with the infiltrated volume. However, the values derived as part of this pilot study did not demonstrate a reduction in the CL with either the infiltrated volume or the duration over which the CL applied. It is recommended that these relationships are investigated with a larger data set as part of Phase 4.

Although the identification of events for analysis was on the basis of bursts of rainfall, the subsequent estimation of loss parameters was based upon complete storms. The IL_b was estimated from the IL_s using a relationship developed by Hill et al. (1997) based upon analysis of data from SE Australia. However this required application to a much broader geographic region (including tropical catchments) for which its applicability has not been tested. It is recommended that further analysis be undertaken on the embedded nature of rainfall bursts to develop relationships that are applicable to the whole of Australia.

The derived loss values were combined with other design inputs to estimate peak design flows for AEPs from 1 in 10 to 1 in 100. The rainfall based estimates were closer to the flood frequency quantiles for the IL/CL and SWMOD models than the IL/PL model which tended to underestimate the 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.

The discrepancies between the rainfall-based estimates and the flood frequency quantiles is a function of any biases and uncertainties introduced at every step in the design process; from uncertainties in the measured data (such as rating curves, catchment average rainfall), conceptualisation and calibration of flood models (e.g. routing parameters) through to each of the design inputs (e.g. design rainfall depth, sample of temporal pattern, baseflow contribution and losses). It is clear that any misclosure cannot be attributed solely to the adopted loss values.

The structure of a distributed storage loss model such as SWMOD addresses the limitations of the IL/PL model for design flood estimation as the updating of the soil moisture content during the event results in a reducing PL (increasing RoC) as the event progresses. From the limited benchmarking undertaken in this project, application of SWMOD appears to reduce the bias observed in the application of the IL/PL model.

The application of variable infiltration capacity models such as SWMOD has in the past been constrained by the lack of information on soil water holding capacity. This study estimated the water holding capacity from the data set developed by McKenzie et al (2000). However a comparison with estimates for 4 catchments in south-west WA indicated that the values are likely to underestimate the capacities and this is consistent with the conclusions by Ladson et al. (2006). Further work is required to derive estimates of soil water capacity across Australia to assist the application of variable infiltration capacity models and link loss values to catchment characteristics.

It is recommended that this pilot study be extended in Phase 4 to a wider set of catchments covering a broader range of catchment areas and catchment characteristics. The careful extension of the study to a larger number of catchments should provide the best opportunity to link the derived loss values to catchment characteristics; a link that has in the past proven elusive.

Future benchmarking of losses should be extended to also consider improved design inputs from other ARR projects (including IFD, temporal patterns and pre-burst patterns).

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Appendix A Catchment maps

Appendix B Runoff routing model calibration

Table B-1: Events used to calibrate RORB routing parameters

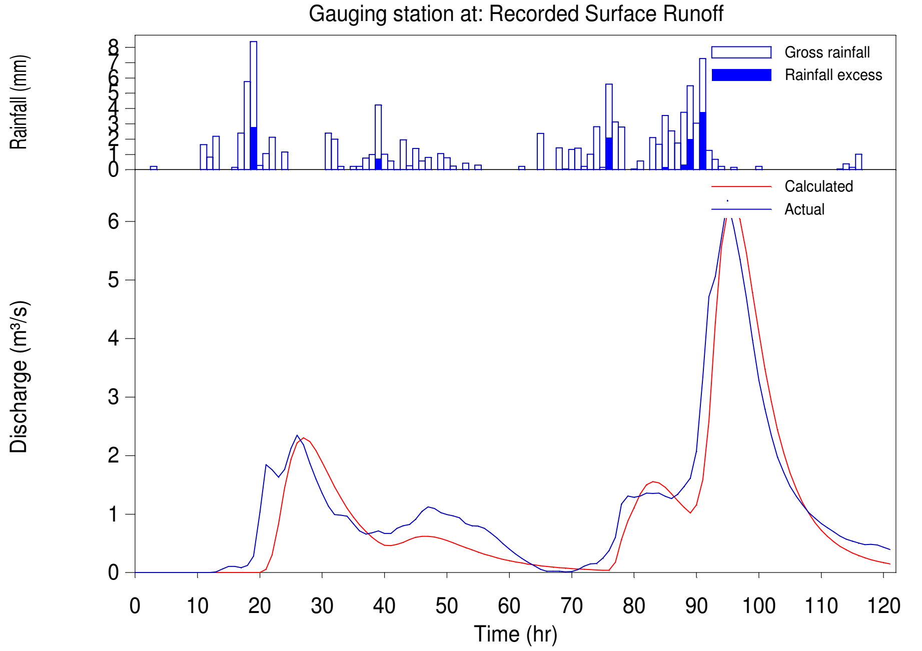
Gauge	Catchment	Event No.	Month and Year	Peak Flow[1] (m³/s)
614005	Dirk Brook @ Kentish Farm (WA)	1	July 1974	6.4
		2	July 1985	6.5
		3	April 1987	7.1
		4	July 1987	8.2
		5	July 1988	6.4
125006	Finch Hatton Creek @ Dam Site (Qld)	1	Jan 1980	262.9
		2	March 1990	266.3
		3	Dec 1990	318.1
		4	Feb 1991	329.3
		5	Jan 2008	505.1
410743	Jerrabomberra Creek @ Four Mile Creek (ACT)	1	Feb 1971	97.8
		2	July 1988	124.1
		3	March 1989	112.6
		4	April 1989	107.6
		5	January 1995	119.2
		6	January 1995	218.0
G8170075	Manton River upstream Manton Dam (NT)	1	March 1981	87.0
		2	March 1997	87.4
		3	Jan 1988	100.1
		4	Feb 2001	83.4
		5	April 2006	115.2
141009	North Maroochy River @ Eumundi (Qld)	1	June 1983	122.5
		2	March 1989	163.2
		3	March 1997	138.9
		4	Feb 1999	147.3
		5	June 2008	124.3
		6	May 2009	127.2
A5040523	Sixth Creek @ Castambul (SA)	1	June 1987	25.7
		2	Sept 1991	22.6
		3	Aug 1993	57.5
		4	July 1995	26.6
		5	Nov 2005	69.5
422321	Spring Creek @ Killarney (Qld)	1	Feb 1976	42.7
		2	April 1988	45.1
		3	Jan 2008	118.9
		4	Jan 2011	111.1
2219	Swan River upstream Hardings Falls (Tas)	1	Dec 1995	104.6
		2	Jan 2000	109.8
		3	April 2003	117.7
		4	Aug 2003	143.4
228217	Toomuc Creek @ Pakenham (Vic)	1	Sept 1984	33.4
		2	July 1996	26.8
		3	Nov 2004	25.4
		4	Feb 2005	30.1

Gauge	Catchment	Event No.	Month and Year	Peak Flow[1] (m^3/s)
603190	Yates Flat Creek @ Woonanup (WA)	1	June 1978	24.4
		2	June 1988	31.6
		3	July 1991	16.3
		4	Aug 2003	20.1
		5	April 2005	17.9

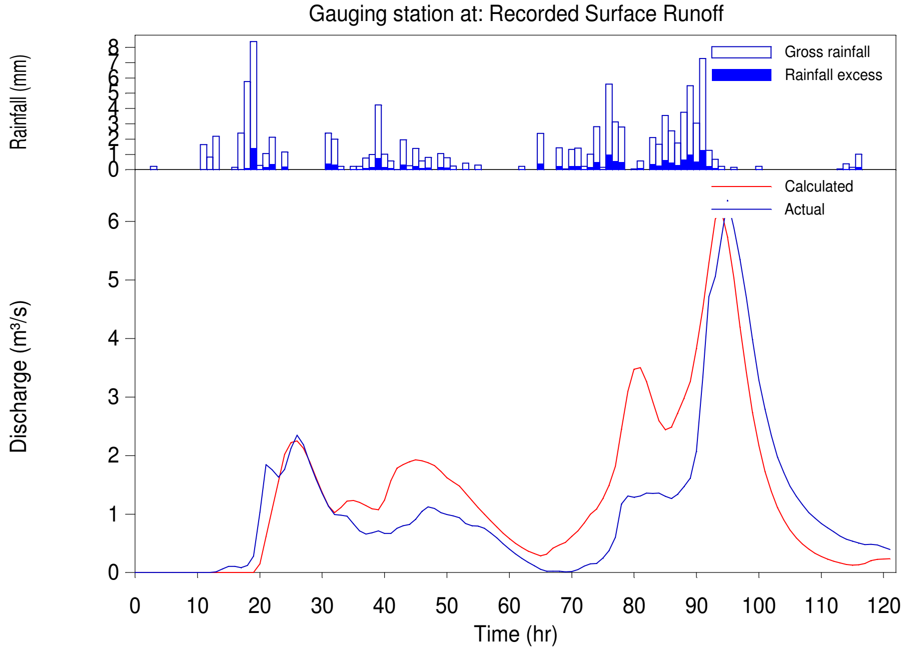
[1] The peak flow quoted is the peak surface runoff which is the recorded flow minus the baseflow. See Section 3.4 for more information on baseflow separation.

614005 Dirk Brook at Kentish Farm

Event 1 – 15/07/1974 9:00:00 AM - 20/07/1974 9:00:00 AM

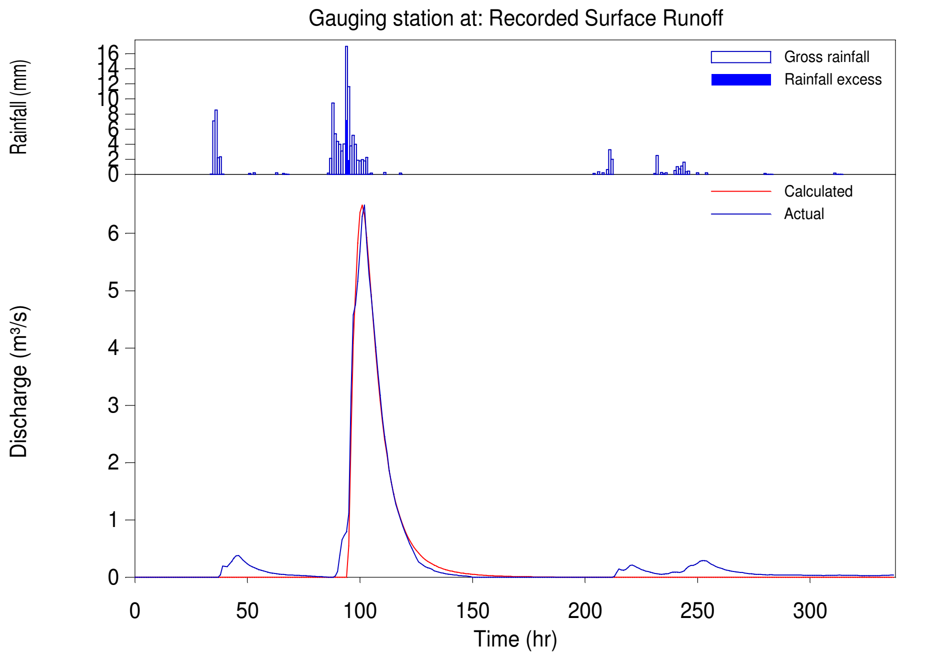
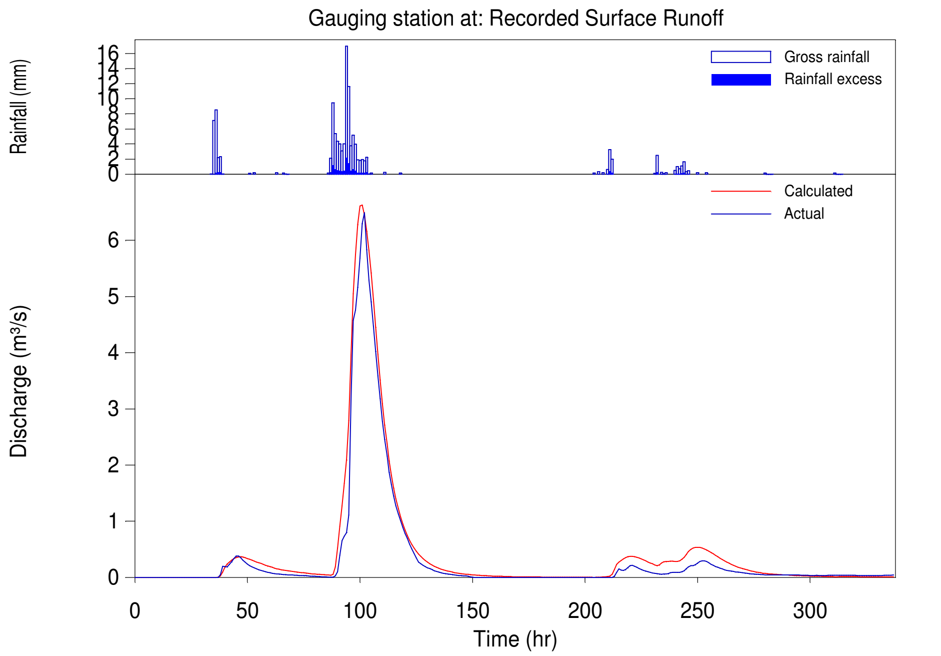


k_c = 9.5
IL = 15.3
CL = 3.49

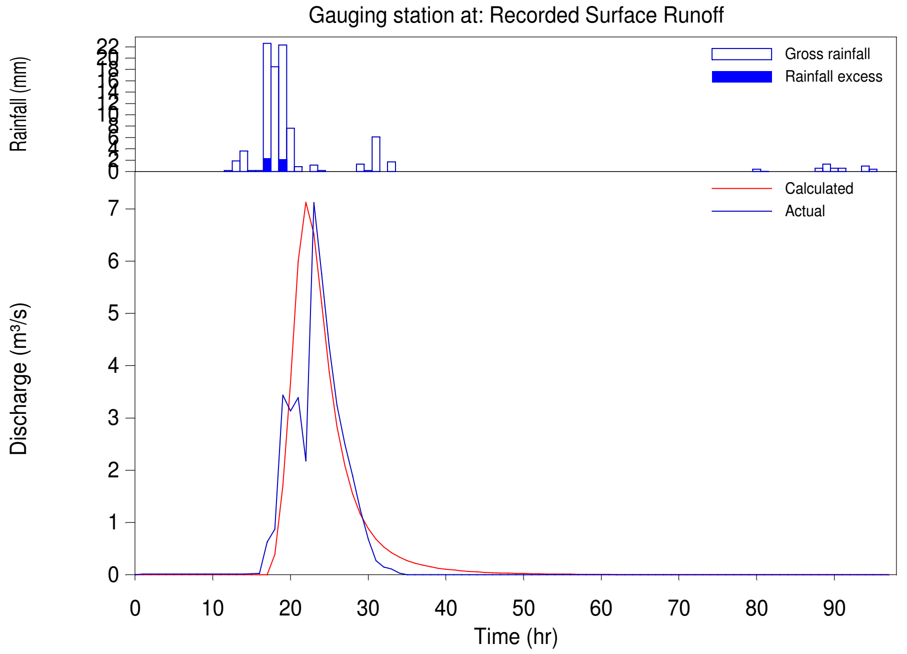
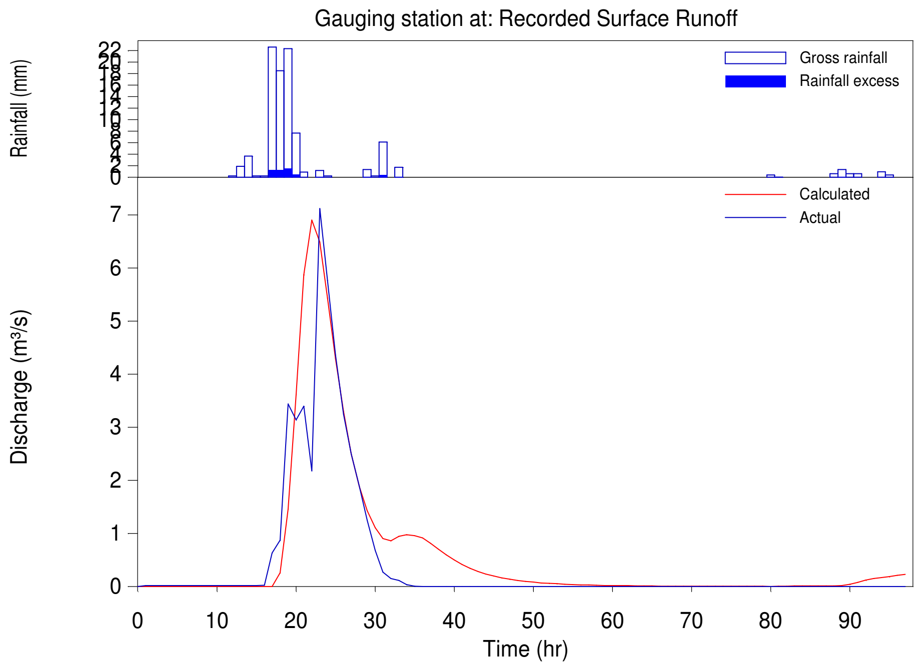


k_c =7
IL = 13.0
RoC = 0.18

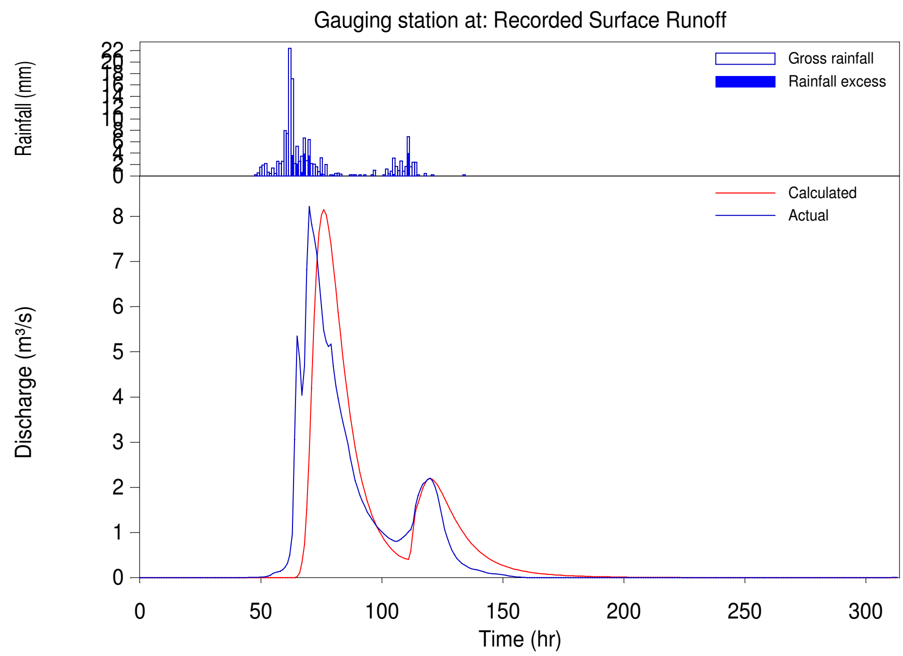
Event 2 – 9/07/1985 9:00:00 AM - 23/07/1985 9:00:00 AM

	k_c =13.6 IL = 20.0 CL = 9.69
	k_c =12 IL = 14.0 RoC =0.13

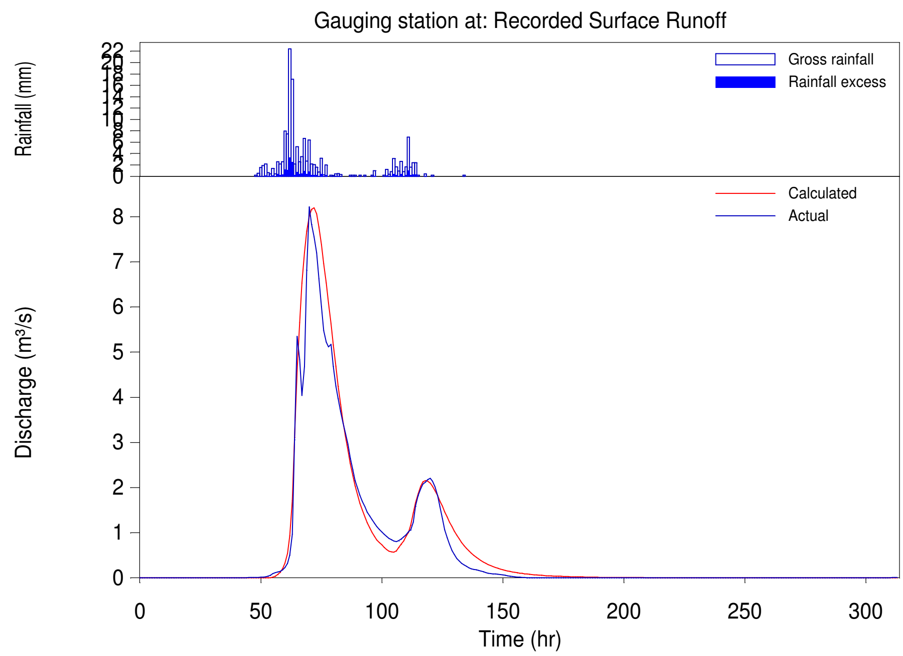
Event 3 – 7/04/1987 9:00:00 AM - 11/04/1987 9:00:00 AM

	k_c = 7.0 IL = 6 CL = 20.1
	k_c = 6.00 IL = 10.1 RoC =0.07

Event 4 – 26/07/1987 9:00:00 AM - 8/08/1987 9:00:00 AM

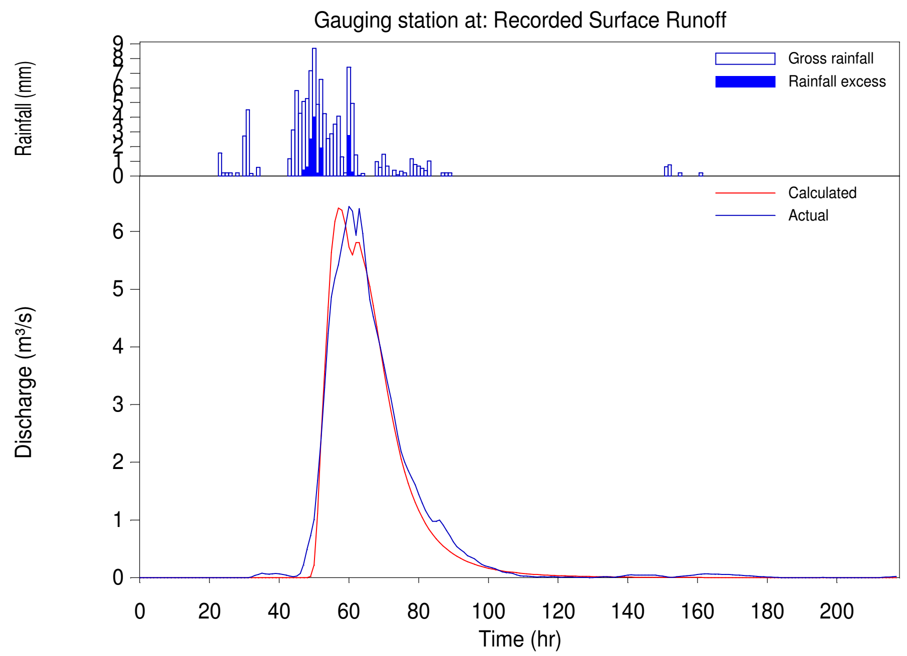


k_c = 16.5
IL = 66.0
CL =2.8

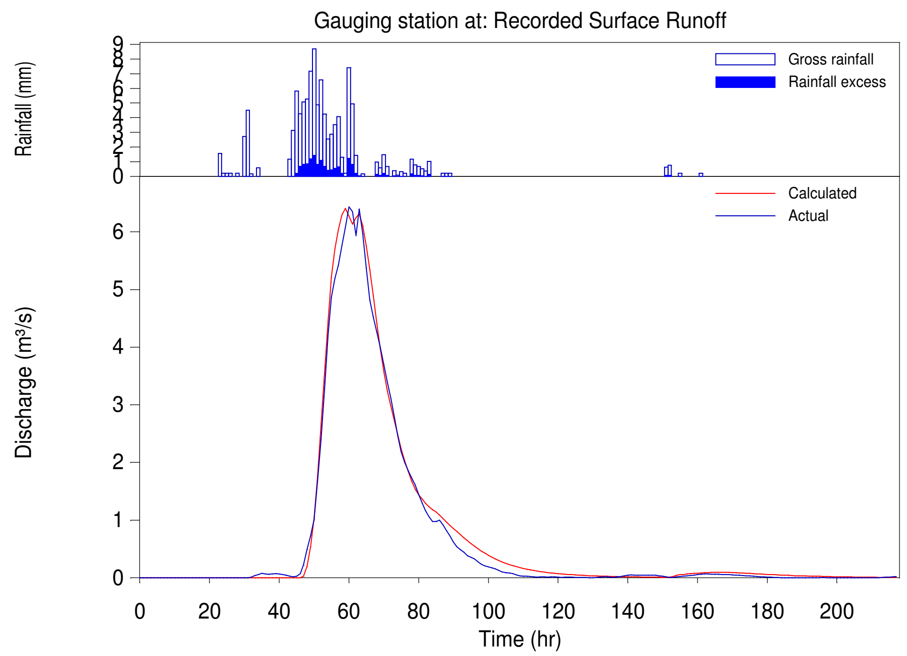


k_c = 14
IL = 5.0
RoC =0.15

Event 5 – 21/07/1988 9:00:00 AM - 30/07/1988 9:00:00 AM



k_c = 14.00
IL = 20
CL =4.64



k_c = 12.5
IL = 19.1
RoC =0.17

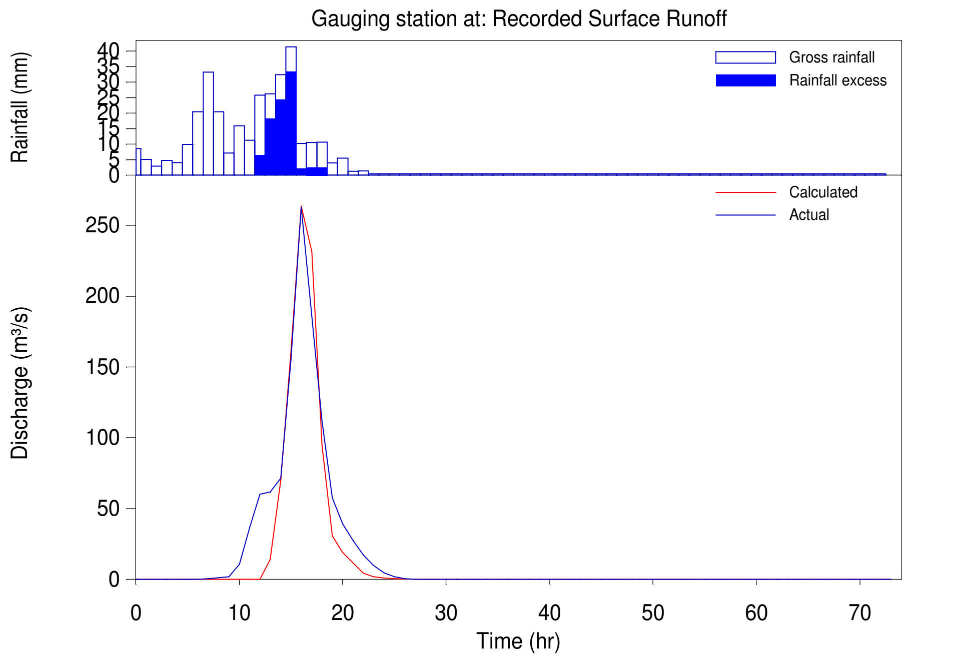
Event	Peak Q[1] (m^3/s)	k_c	IL (mm)	CL or PL (mm/h or %)	% difference in Peak Q	% difference in Volume	Error in time to centroid (hrs)	Comments
1	6.4	9.5	15.3	3.49	-0.5	-12.0	2.9	Good fit. CL provides better fit.
		7	13.0	82%	-3.0	20.4	-3.7	
2	6.5	13.6	20.0	9.69	0.0	-14.9	-10.7	Good fit. PL provides better fit.
		12	14.0	87%	2.1	28.3	6.2	
3	7.1	7	6.0	20.1	0.1	13.4	1.0	Average fit. Similar fit for both. Slightly better for CL?
		6.0	10.1	93%	-3.2	36.9	4.5	
4	8.2	16.5	66.0	2.80	-0.9	1.6	8.0	Good fit. PL provides better fit.
		14.0	5.0	85%	-0.3	12.0	1.5	
5	6.4	14.0	20	4.64	-0.4	-6.0	-1.3	Good fit. Similar fit for both. PL slightly better?
		12.5	19.1	83%	-0.4	7.9	2.6	

[1] Surface runoff ie. total recorded flow – baseflow.

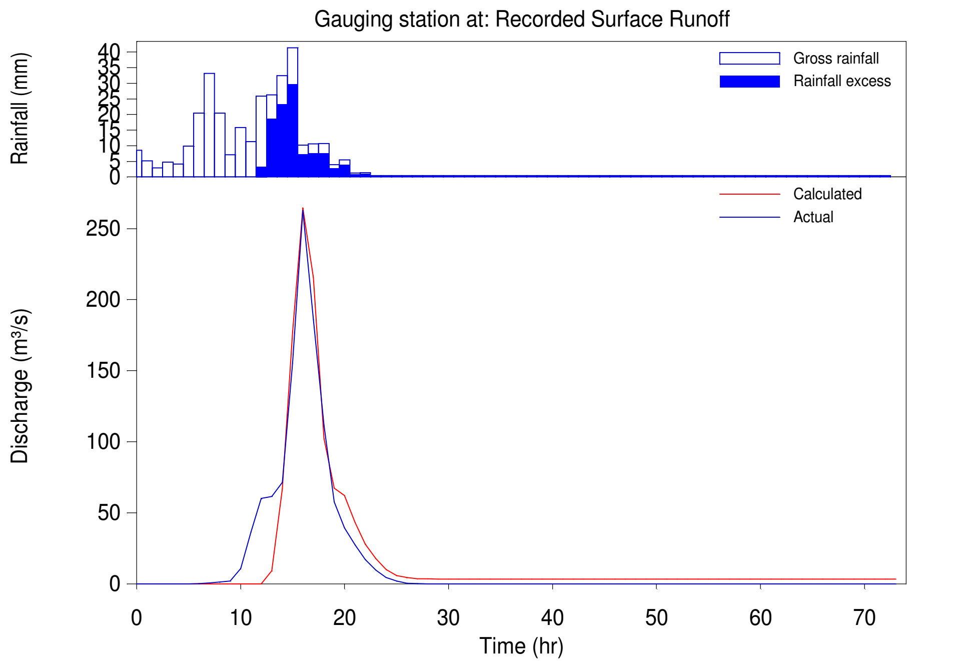
[2] **d_{av}=6.07km**

125006 Finch Hatton Creek at Dam Site

Event 1 – 9:00am 6-9 January 1980 (pluvio 533010 not available)

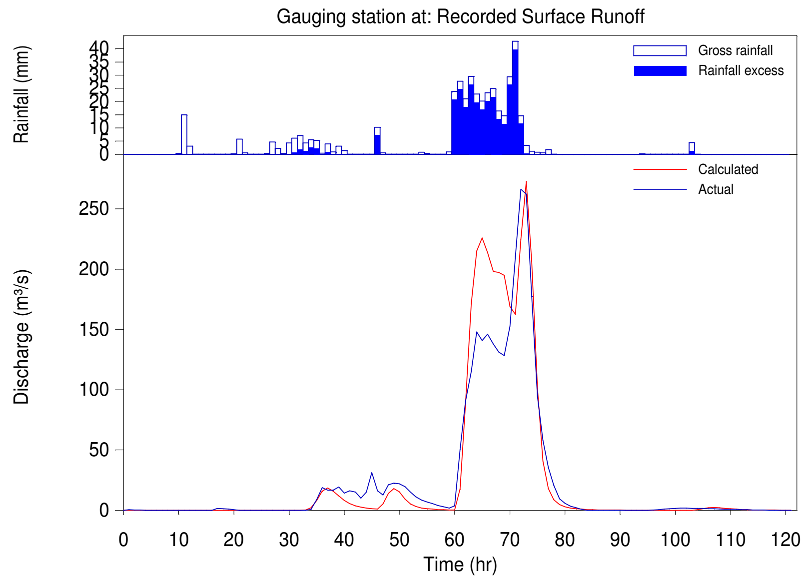
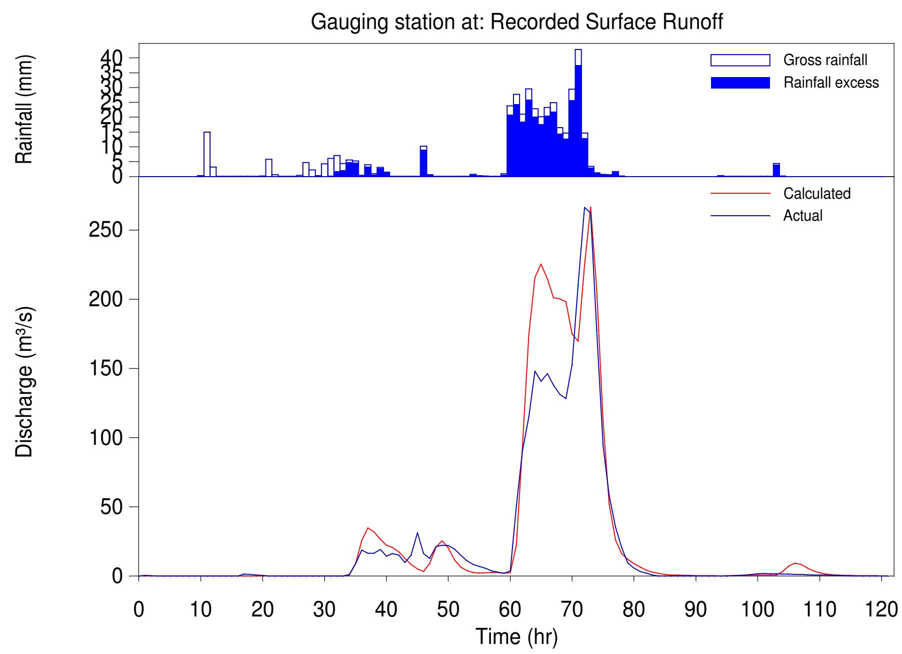


k_c =2.5
IL = 155
CL = 8.0

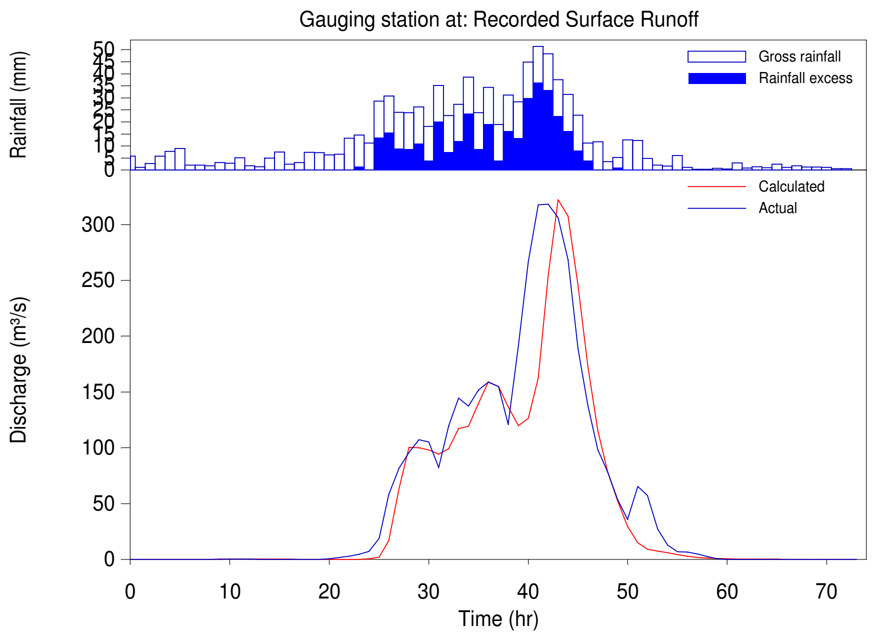
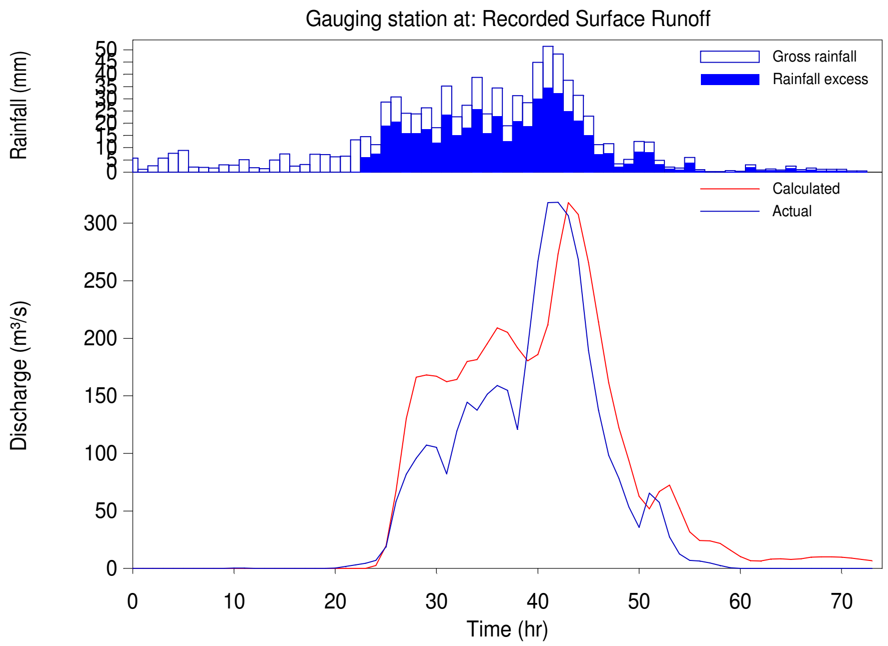


k_c =2.0
IL = 165
RoC =0.72

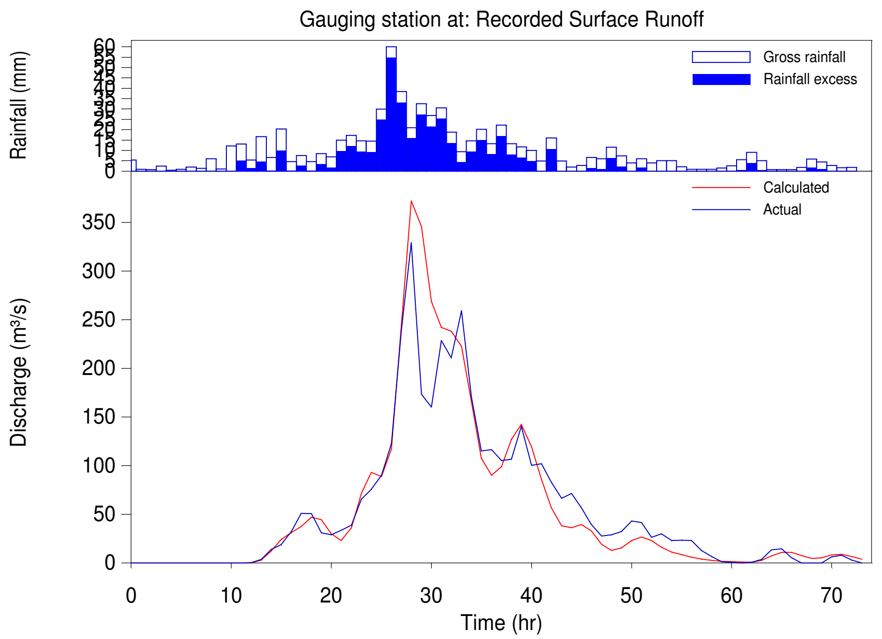
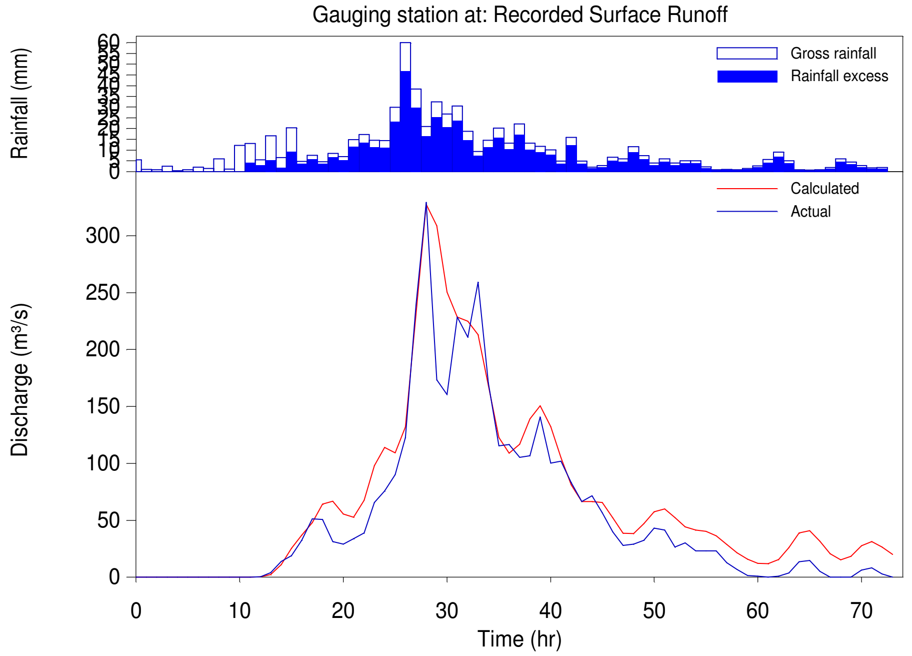
Event 2 – 9:00am 22-27 March 1990 (pluvio 533010 only)

	k_c =4 IL =45 CL = 3
	k_c =4 IL = 50 PL =0.88

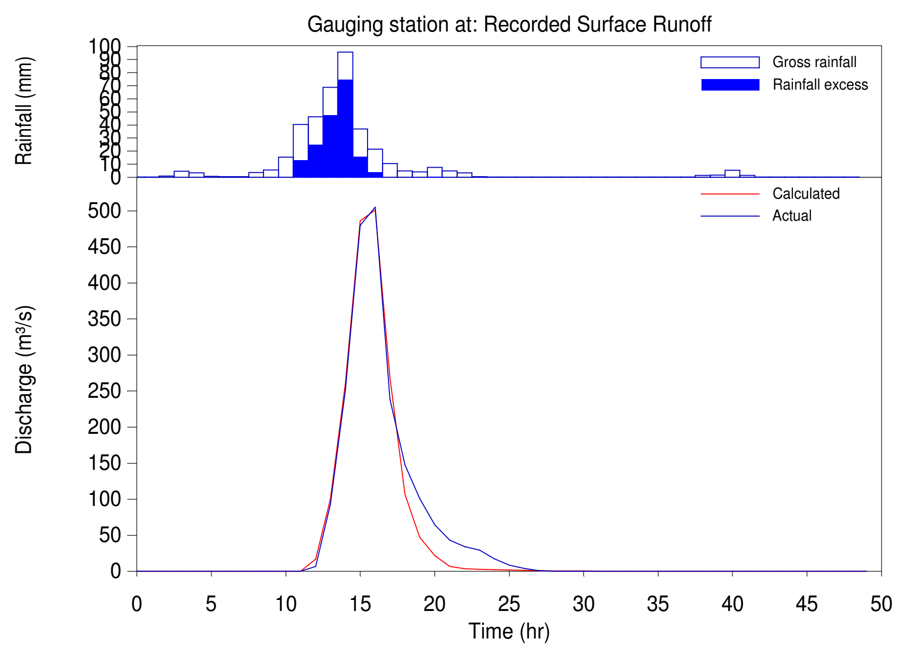
Event 3 – 9:00am 25-28 December 1990 (2 pluvios)

	k_c =4 *IL* = 100 *CL* = 15
	k_c =4.0 *IL* = 115 *RoC* =0.67

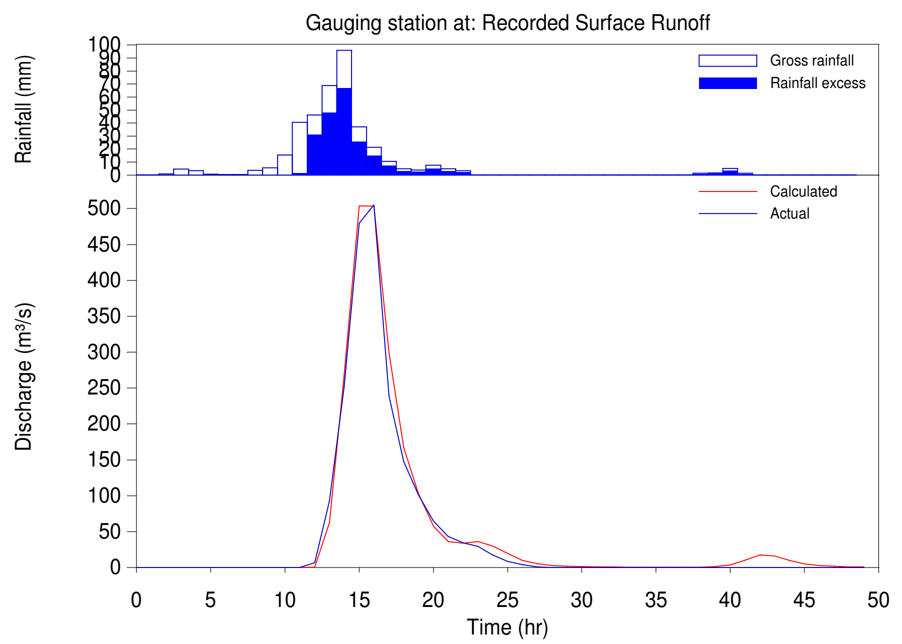
Event 4 – 9:00am 1-4 February 1991

<table>
<tr><td>
</td><td>k_c =4
IL = 60
CL = 5.0</td></tr>
<tr><td>
</td><td>k_c =4.0
IL = 65
RoC =0.78</td></tr>
</table>

Event 5 – 9:00am 17-19 January 2008



k_c =3.3
IL = 40
CL = 21



k_c =3
IL = 75
RoC =0.70

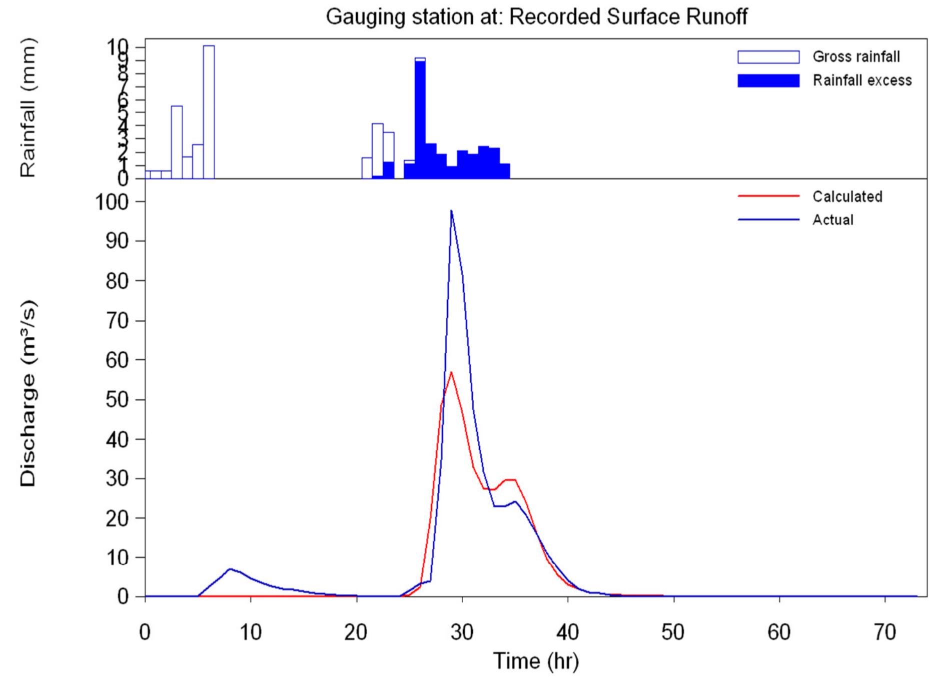
Event	Peak Q[1] (m^3/s)	k_c	IL (mm)	CL or PL (mm/h or %)	% difference in Peak Q	% difference in Volume	Error in time to centroid (hrs)	Comments
1	262.9	2.5	155	8.0 mm/h	0.3	-19.1	0.3	OK fit. Similar fit for CL and PL. Only 1 pluvio available
		2.0	165	28% loss	0.6	10.6	5.4	
2	266.3	4	45	3.0mm/h	2.4	5.7	1.0	Good fit. Similar fit for CL and PL. 533010 used only (this provided a better fit).
		4	50	12% loss	0.1	16.3	0.6	
3	318.1	4	100	15mm/h	1.3	-14.0	0.1	Poor fit. Similar fit for CL and PL. Both pluvios used
		4	115	33% loss	-0.1	27.2	2.4	
4	329.3	4	60	5.0mm/h	12.9	2.0	-1.1	Good fit. Similar fit for CL and PL. Both pluvios used
		4	65	22% loss	-0.5	25.4	2.1	
5	505.1	3.3	40	21mm/h	-0.7	-9.6	-0.6	Good fit. PL better on falling limb. Both pluvios used
		3.0	75	30% loss	-0.6	9.3	1.2	

[1] Surface runoff ie. total recorded flow – baseflow.

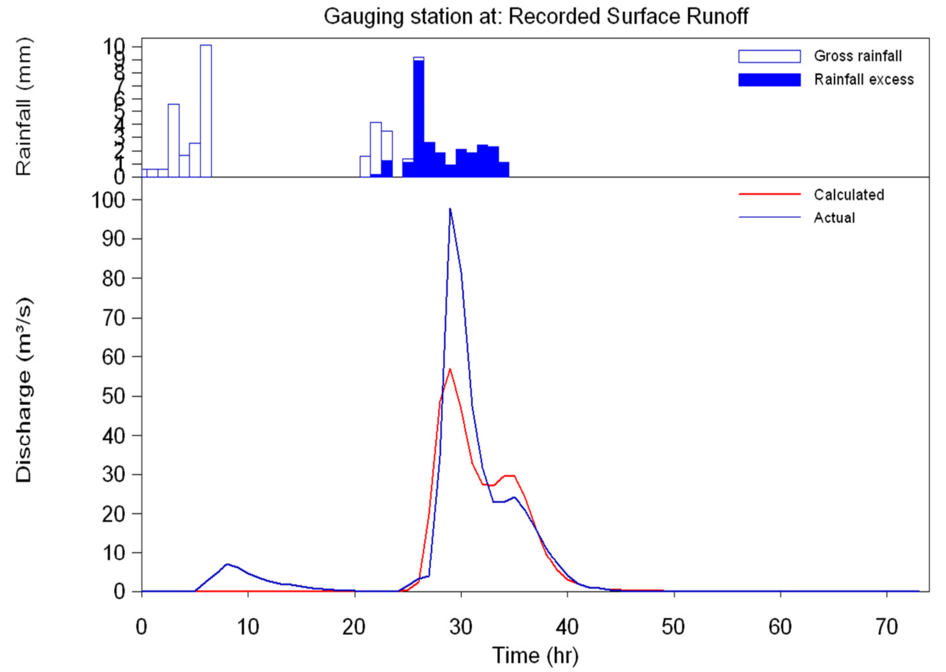
d_{av}=5.59km

410743 Jerrabomberra Creek at Four Mile Creek

Event 1 – 9:00am 9-12 February 1971

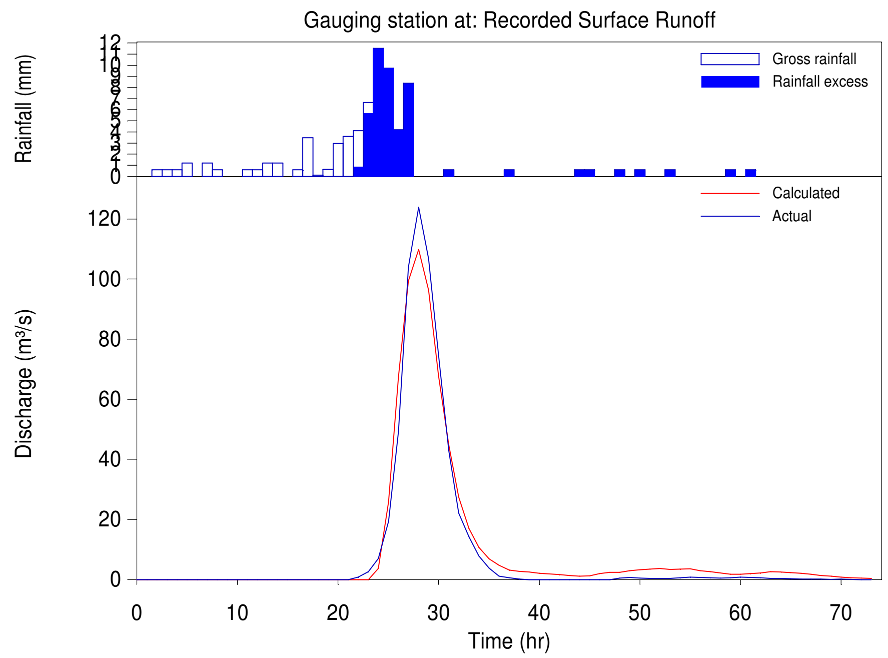


k_c =4
IL = 30
CL = 0

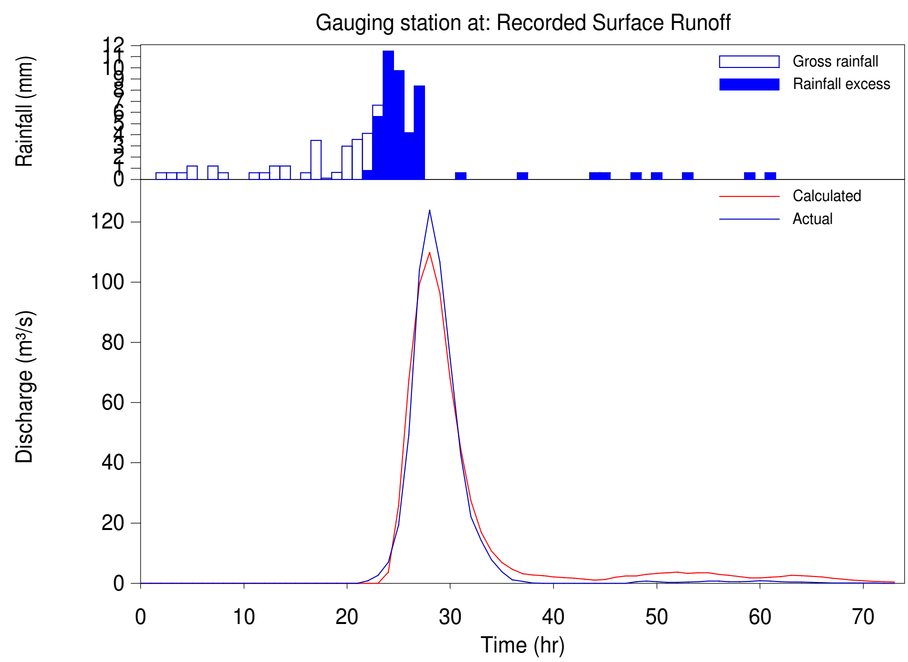


k_c =4
IL = 30
RoC =1

Event 2 – 9:00am 5-8 July 1988

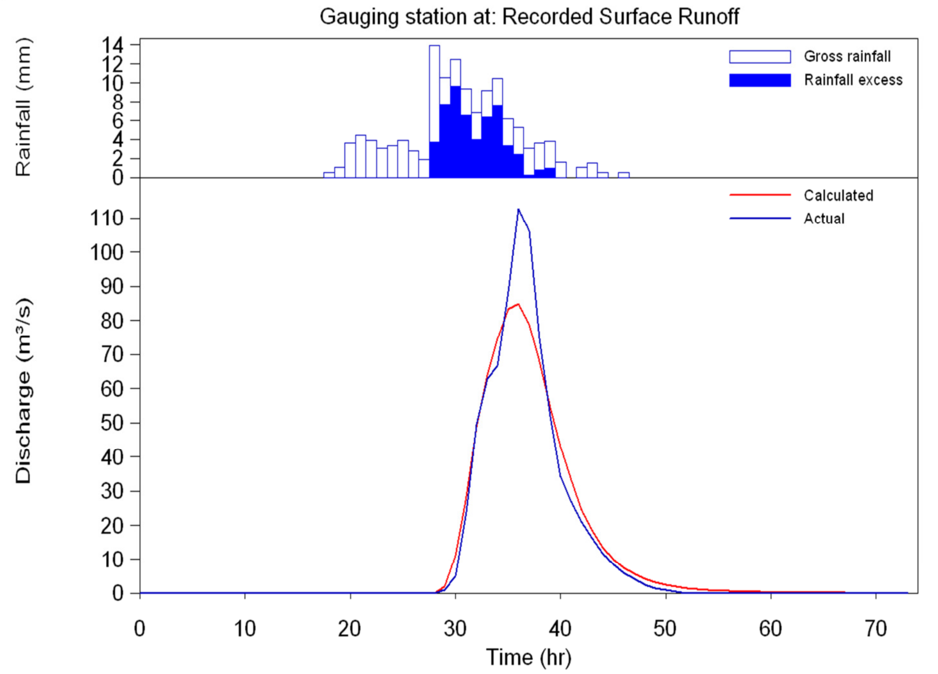


k_c =5.4
IL = 24
CL = 0.0

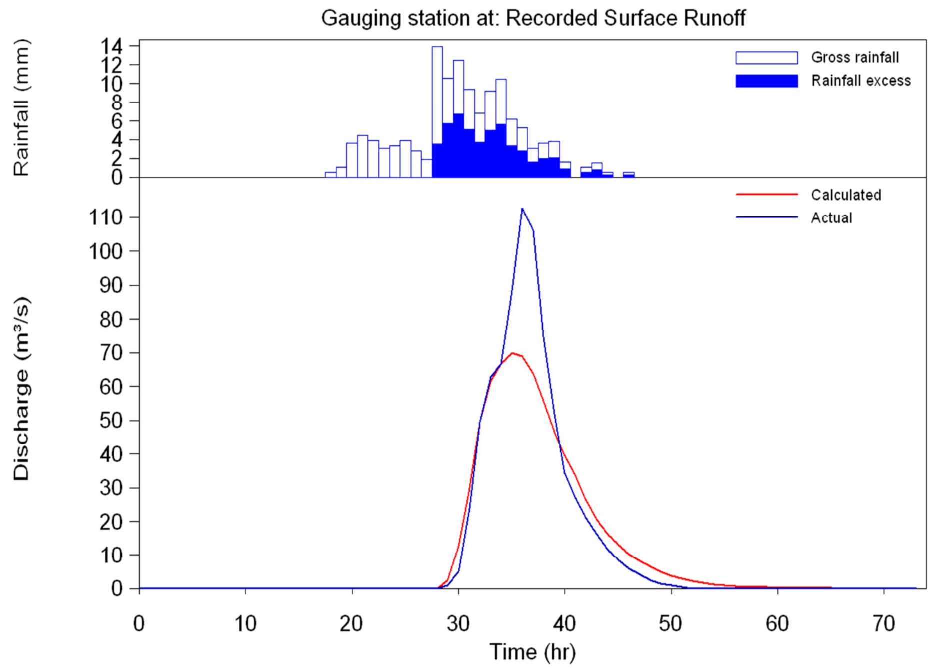


k_c =5.4
IL = 24
RoC =1.0

Event 3 – 9:00am 13-16 March 1989

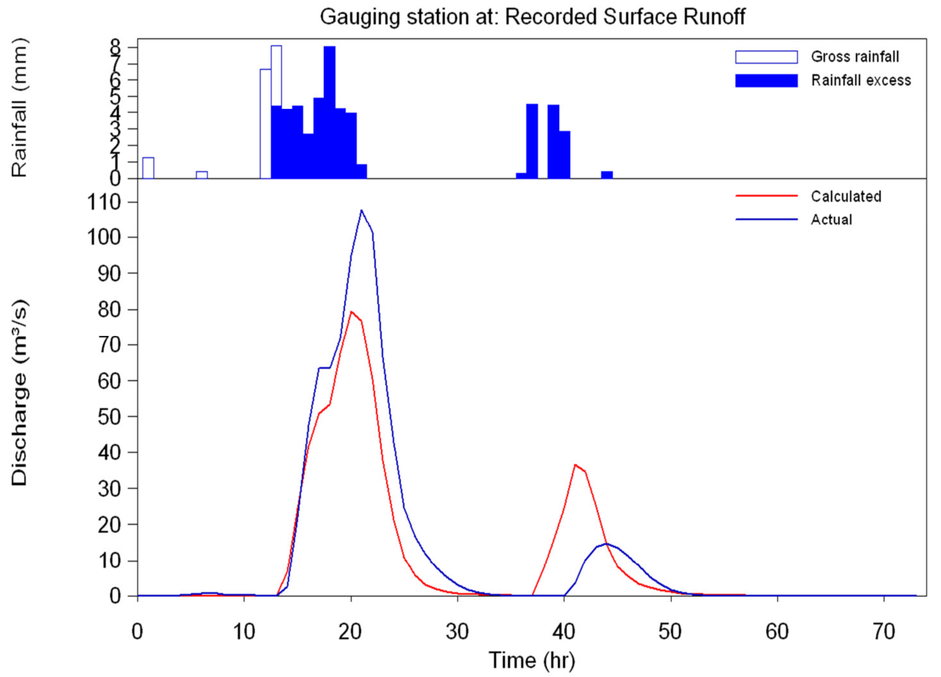
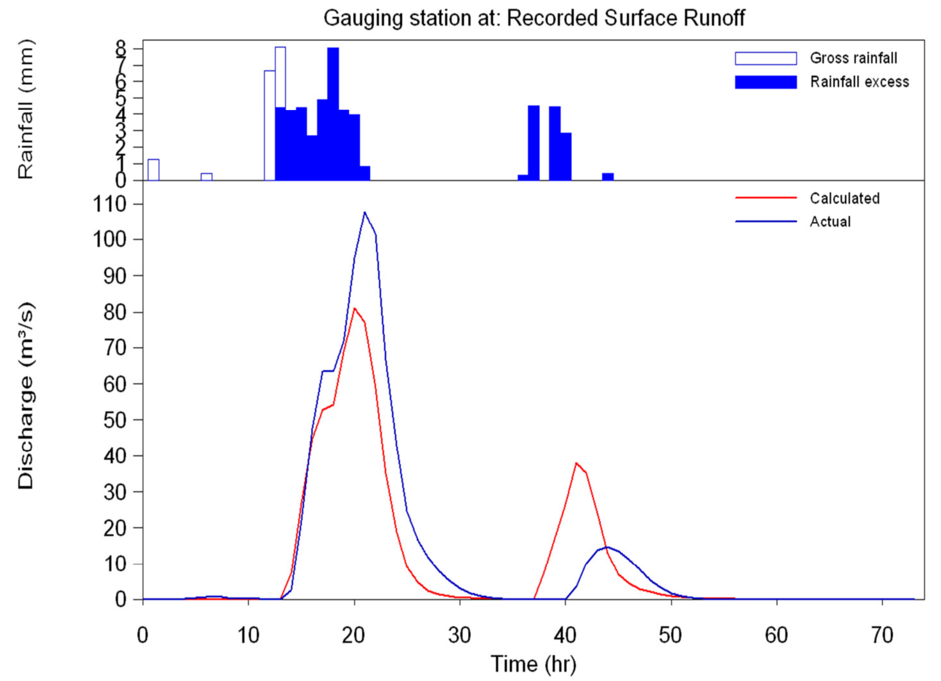


k_c =8
IL = 36
CL = 2.82

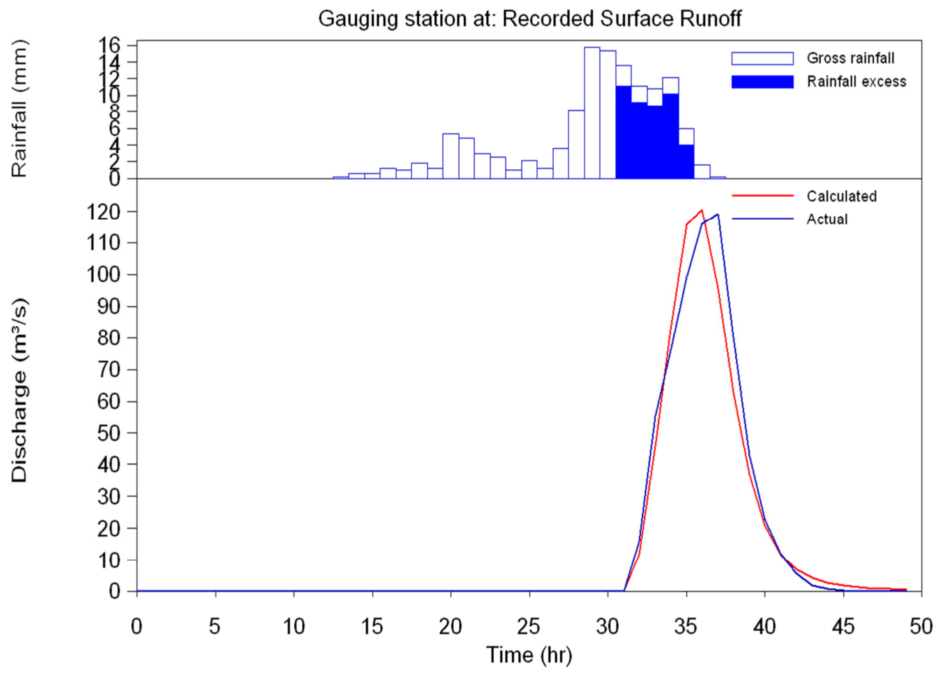


k_c =6
IL = 36
RoC =0.54

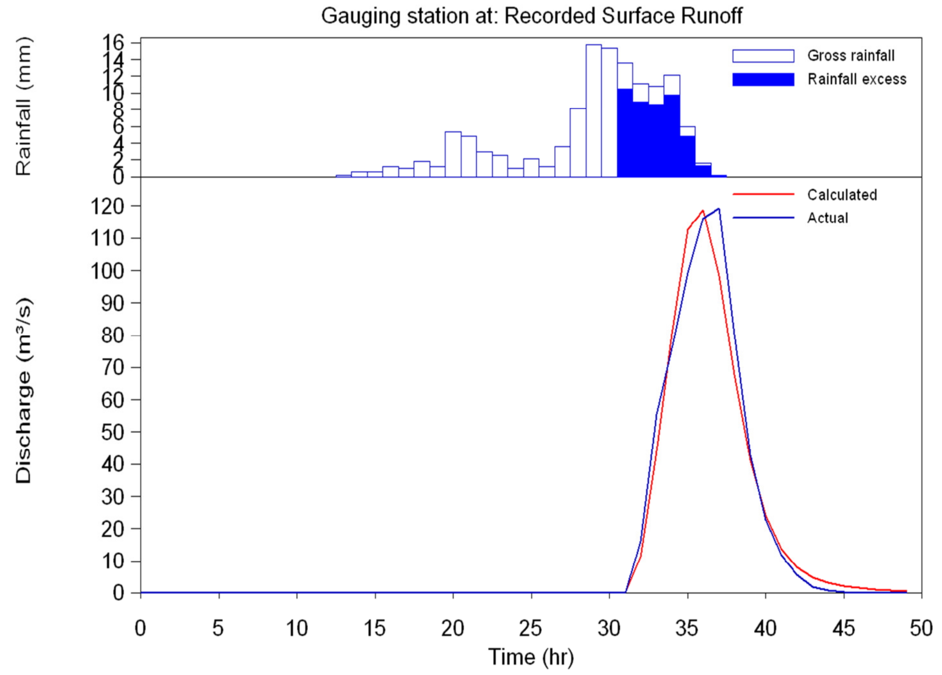
Event 4 – 9:00am 31 March - 5 April 1989

	k_c =4 IL = 12 CL = 0
	k_c =4 IL = 12 RoC =1

Event 5 – 9:00am 19-21 January 1995

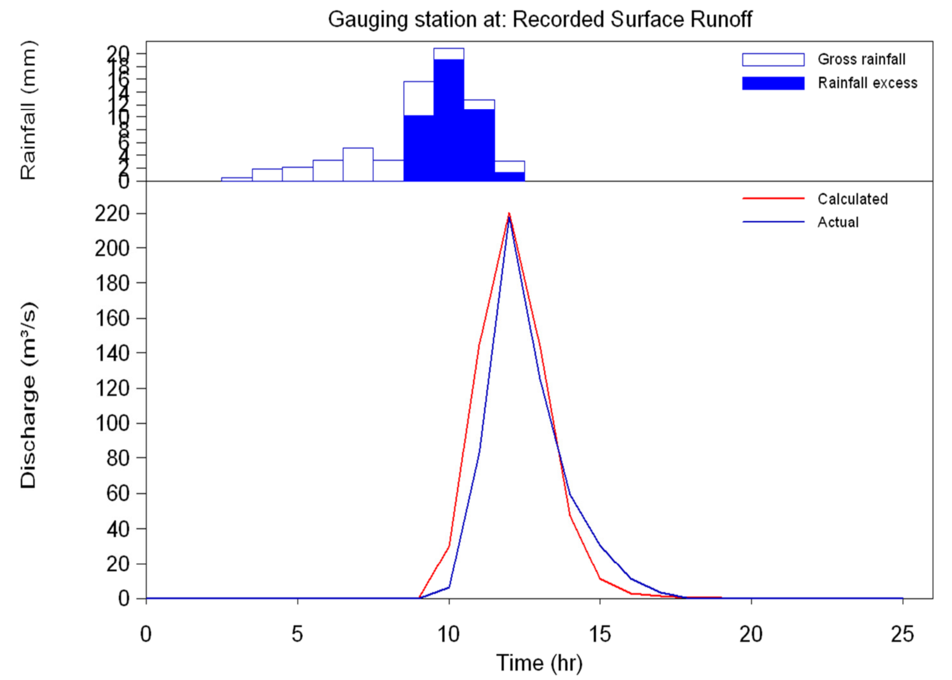


k_c =5.2
IL = 70
CL = 2

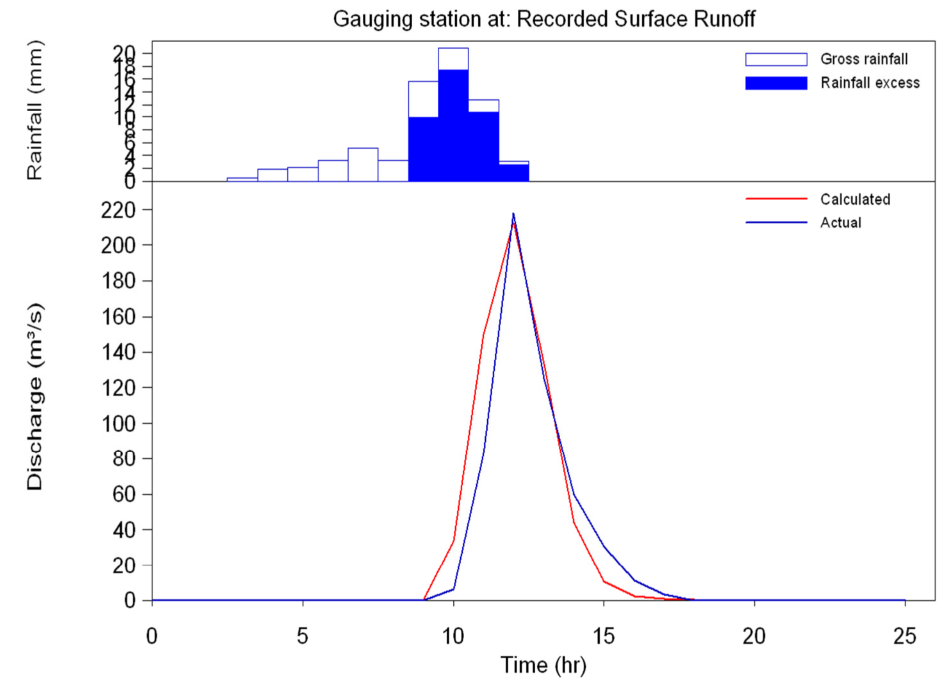


k_c =5.1
IL = 70
PL =0.8

Event 6 – 9:00am 28-29 January 1995



k_c =2.5
IL = 20
CL = 1.7



k_c =2.2
IL = 20
PL =0.84

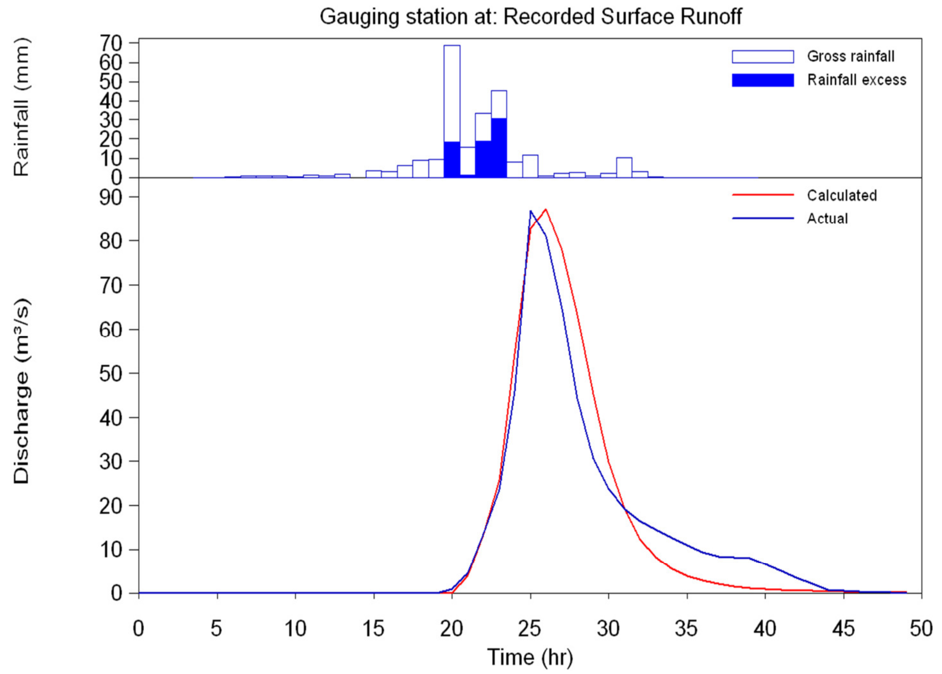
Event	Peak Q[1] (m^3/s)	k_c	IL (mm)	CL or PL (mm/h or %)	% difference in Peak Q	% difference in Volume	Error in time to centroid (hrs)	Comments
1	97.8	4	30	0mm/h	-41.7	-18.8	2.0	Good fit – not enough rainfall. Same result for CL and PL.
		4	30	0% loss	-41.7	-18.8	2.0	
2	124.1	5.4	24	0.0mm/h	-11.3	11.9	2.5	Good fit – not enough rainfall. Same result for CL and PL.
		5.4	24	0% loss	-11.3	11.9	2.5	
3	112.6	8	36	2.82mm/h	-24.7	-0.2	0.4	Good fit – not enough rainfall. Same result for CL and PL.
		6	36	46% loss	-37.9	-6.8	0.7	
4	107.6	4	12	0mm/h	-26.3	-14.2	2.3	Good fit – not enough rainfall. Same result for CL and PL.
		4	12	0% loss	-26.3	-14.2	2.3	
5	119.2	5.2	70	2mm/h	1.1	-3.8	0.0	Good fit – not enough rainfall. Similar result for CL and PL
		5.1	70	20% loss	-0.4	-2	0.2	
6	218	2.5	20	1.7mm/h	1	12.4	-0.4	Ok fit – short duration means that hourly time-step may not be fine enough resolution.
		2.2	20	16%	-2.4	9.7	-0.5	

[1] Surface runoff ie. total recorded flow – baseflow.

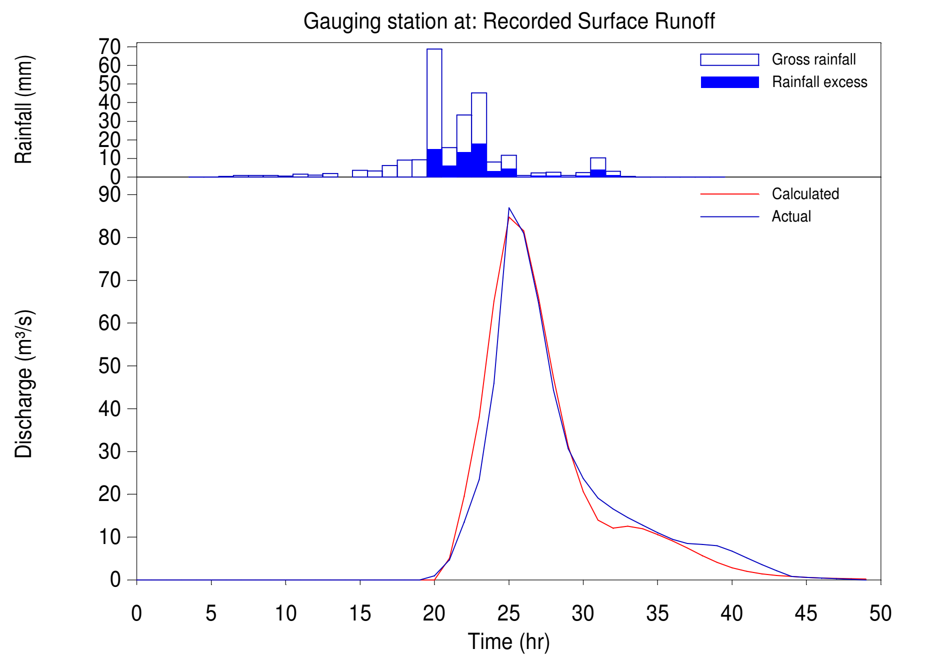
d_{av}=8.28km

G8170075 Manton River upstream Manton Dam

Event 1 – 9:00am 11-13 March 1981

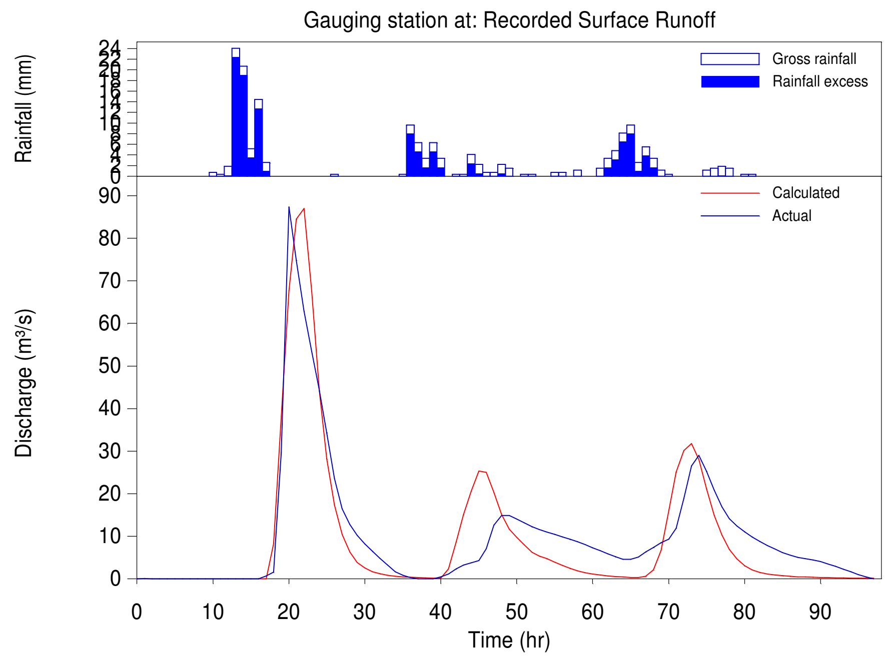


k_c =8
IL = 75
CL = 14.71



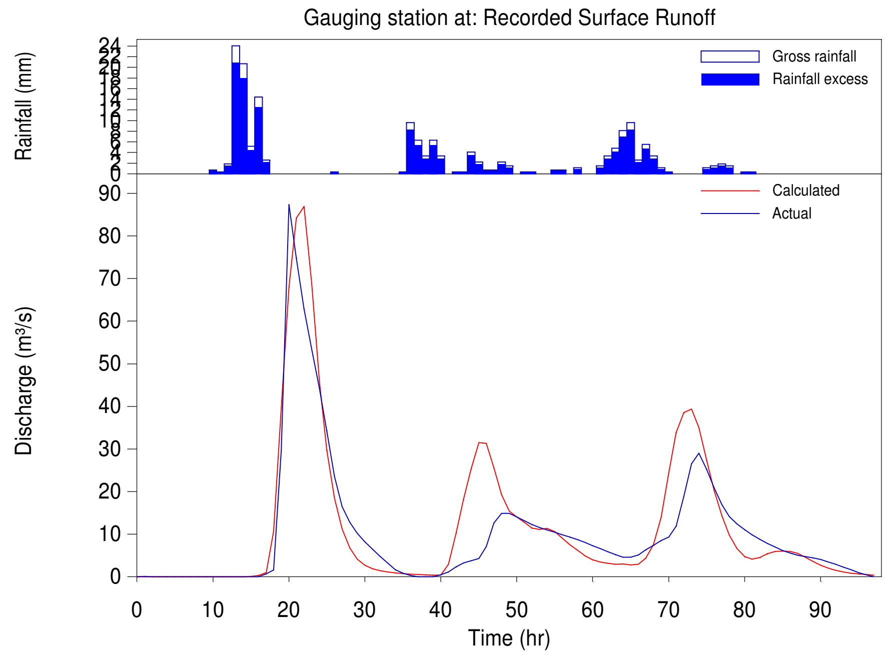
k_c =6
IL = 70
RoC =0.4

Event 2 – 9:00am 1-5 March 1997



k_c =6
IL = 1
CL = 1.6

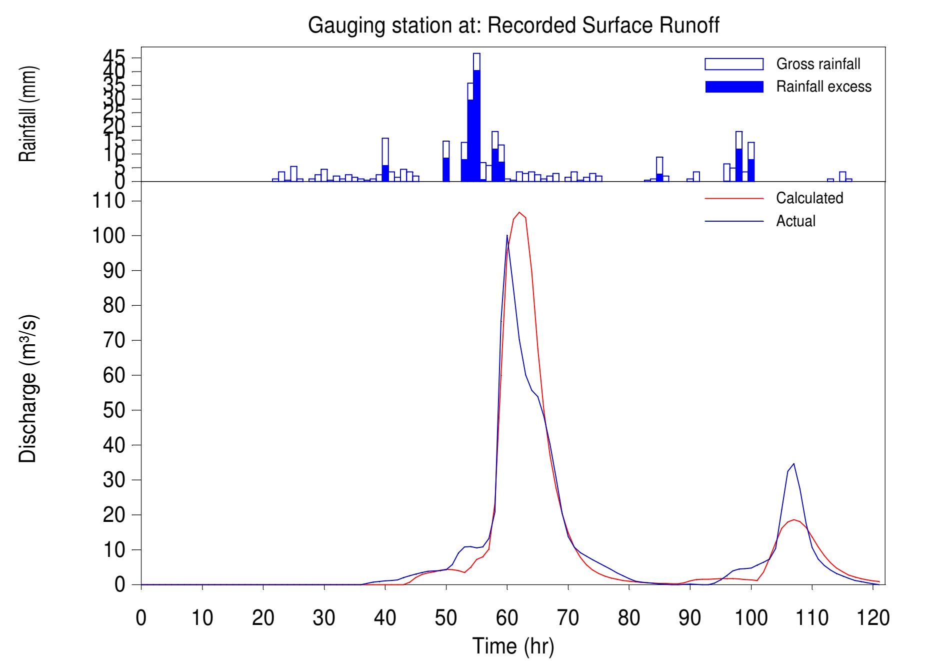
Translation of 4 hrs applied



k_c =6
IL = 1
RoC =0.87

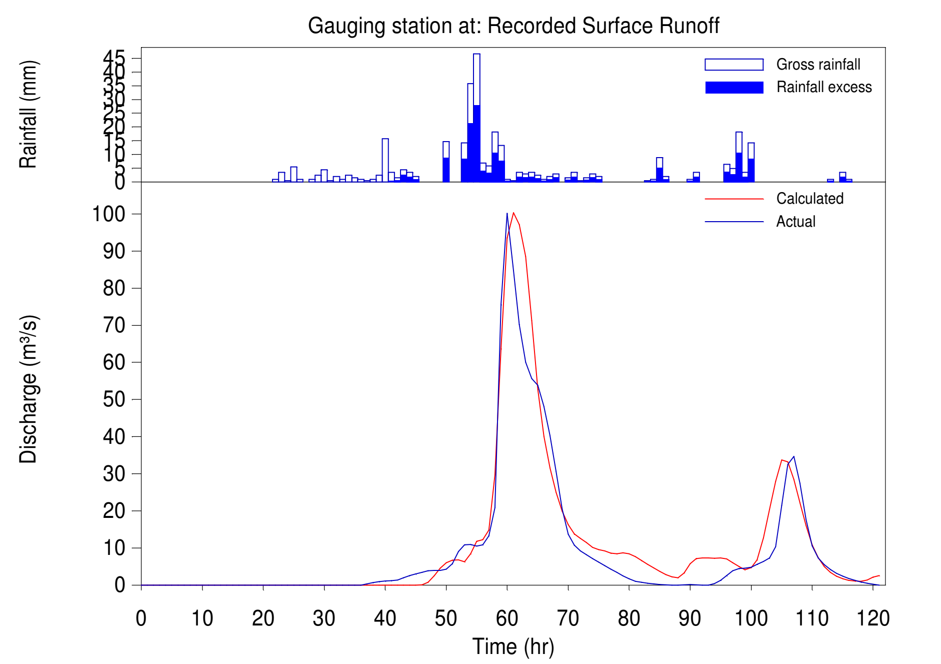
Translation of 4 hrs applied

Event 3 – 9:00am 25-30 January 1998



k_c =9
IL = 35
CL = 6.0

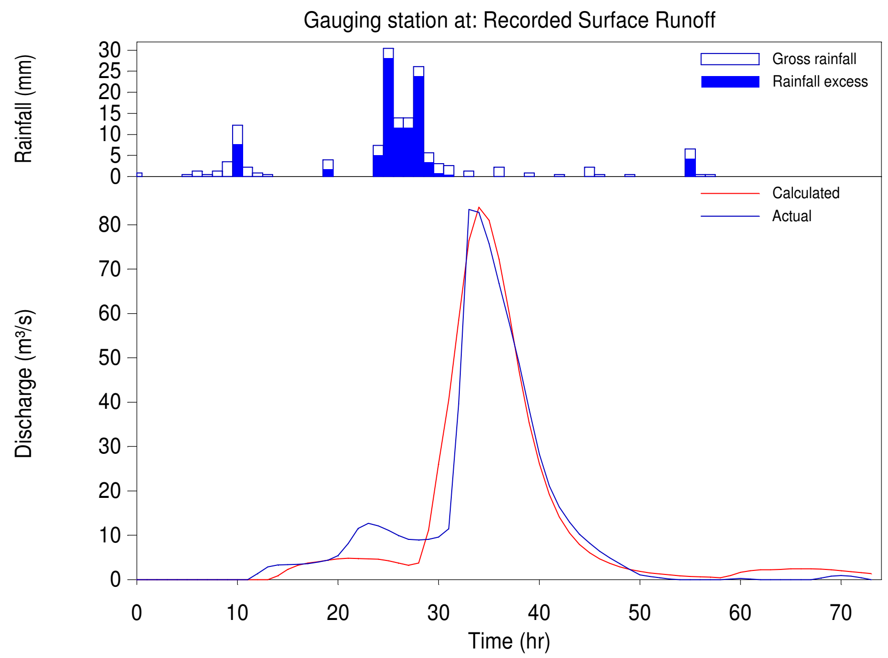
TRANSLATED 3 hrs



k_c =7
IL = 50
RoC =0.6

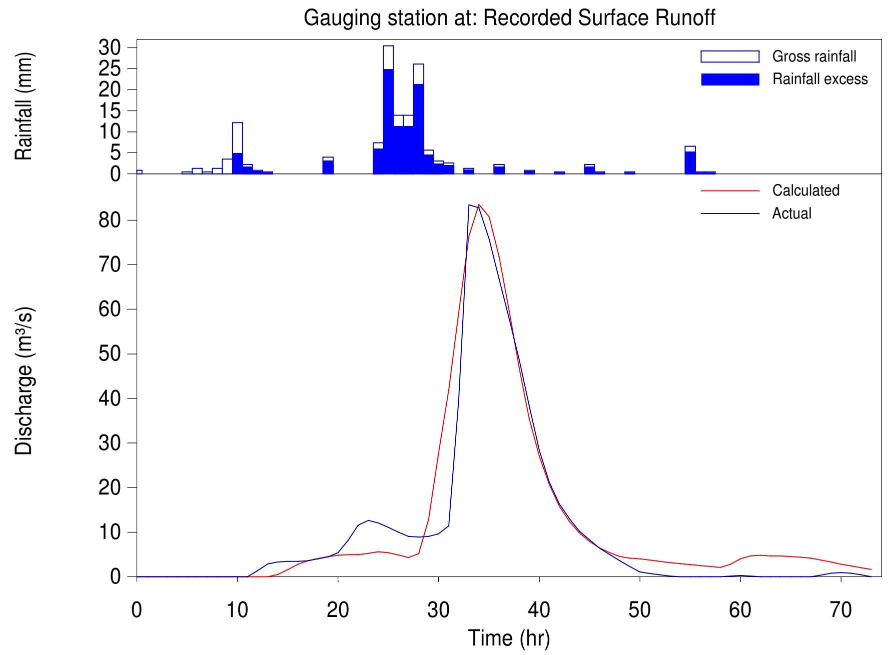
TRANSLATED 3 hrs

Event 4 – 9:00am 12-15 February 2001



k_c =10.5
IL = 10
CL = 2.2

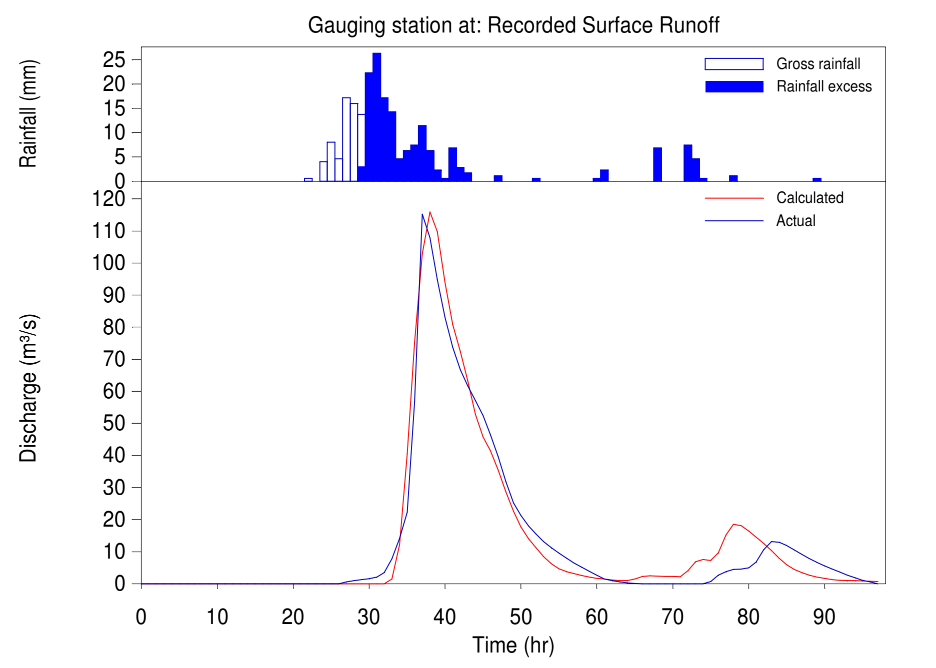
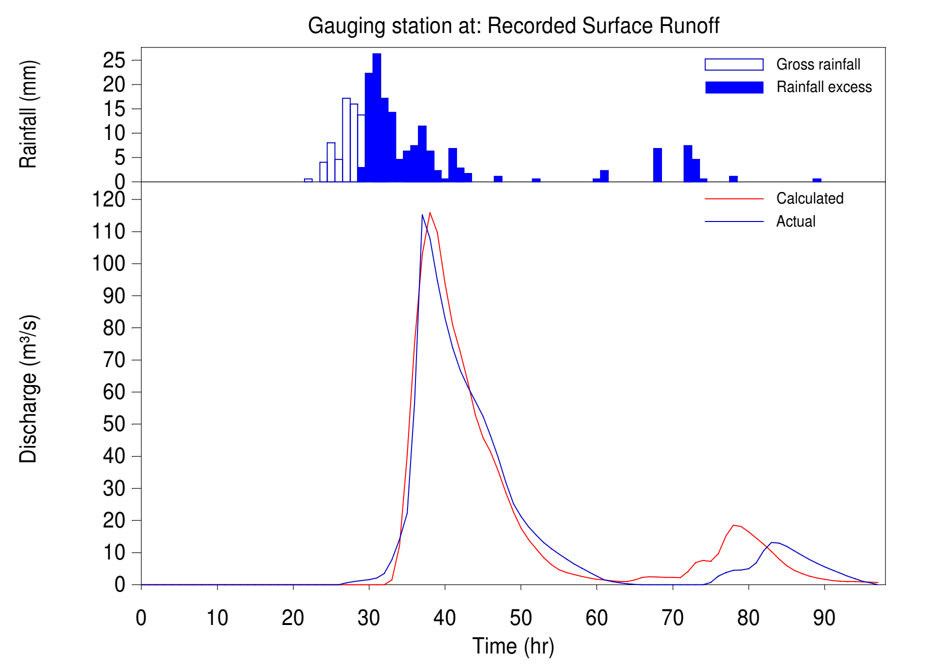
Calculated hydrograph TRANSLATED 3 hrs



k_c =10
IL = 14
RoC =0.82

Calculated hydrograph TRANSLATED 3 hrs

Event 5 – 9:00am 24-28 April 2006

	*k_c* =7.5 *IL* = 61 *CL* = 0 Calculated hydrograph TRANSLATED 3 hrs
	*k_c* =7.5 *IL* = 61 *RoC* =1 Calculated hydrograph TRANSLATED 3 hrs

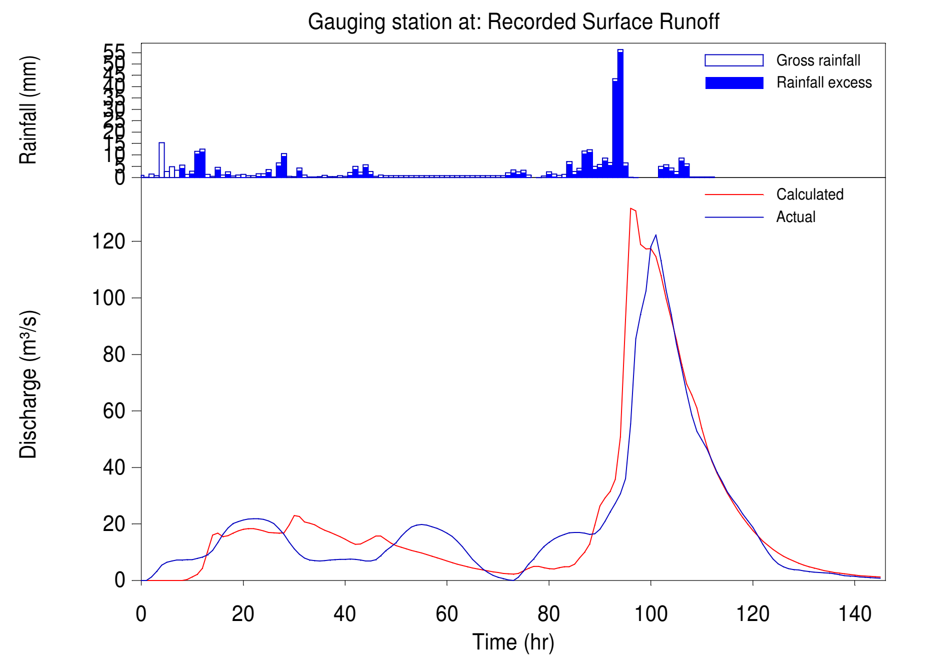
Event	Peak Q[1] (m³/s)	k_c	IL (mm)	CL or PL (mm/h or %)	% difference in Peak Q	% difference in Volume	Error in time to centroid (hrs)	Comments
1	87	8	75	14.71mm/h	0.3	-0.4	-1.1	Good fit. Similar results for CL and PL.
		6	70	60% loss	-2.5	1.6	-0.8	
2	87.4	6	1	1.6mm/h	-0.5	-10.7	-5.4	Average fit. Calculated hydrograph translated 4 hrs. Similar fit for CL and PL.
		6	1	13% loss	-0.5	14.2	-0.3	
3	100.1	9	35	6mm/h	6.6	5.7	-1.8	Good fit. Calculated hydrograph translated 3 hrs. Similar results for CL and PL.
		7	50	40% loss	0.2	18.6	2.4	
4	83.4	10.5	10	2.2mm/h	0.7	3.5	1.6	Good fit. Calculated hydrograph translated 3 hrs. Similar results for CL and PL.
		10	14	18% loss	0.1	12.4	2.8	
5	115.2	7.5	61	0 mm/hr	0.6	4.2	0.5	Good fit. Calculated hydrograph translated 3 hrs. Similar results for CL and PL.
		7.5	61	0% loss	0.6	4.2	0.5	

[1] Surface runoff ie. total recorded flow – baseflow.

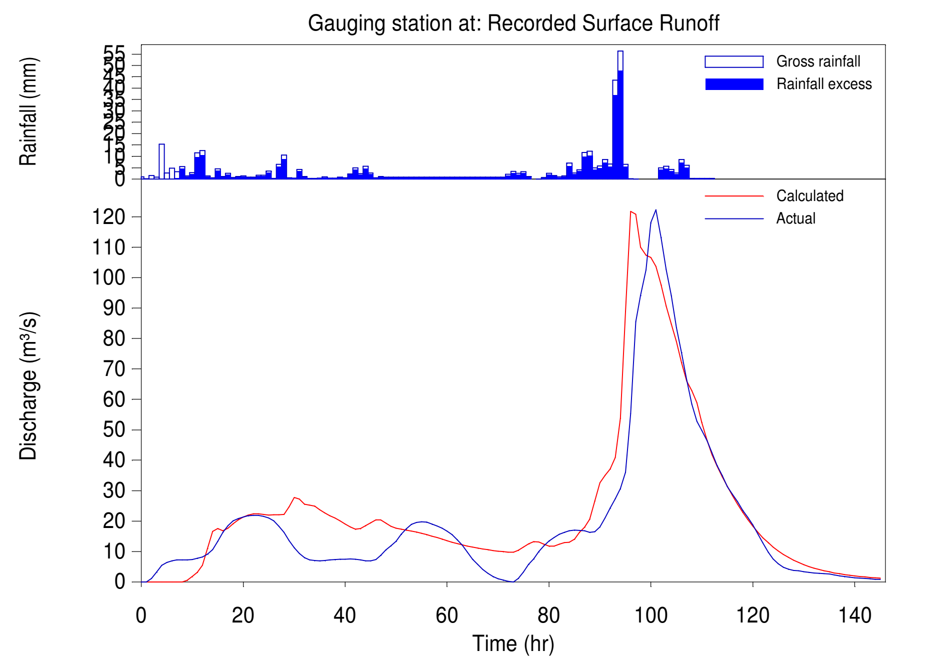
d_{av}=7.4km

141009 North Maroochy River at Eumundi

Event 1 – 18/06/1983 9:00 - 24/06/1983 9:00

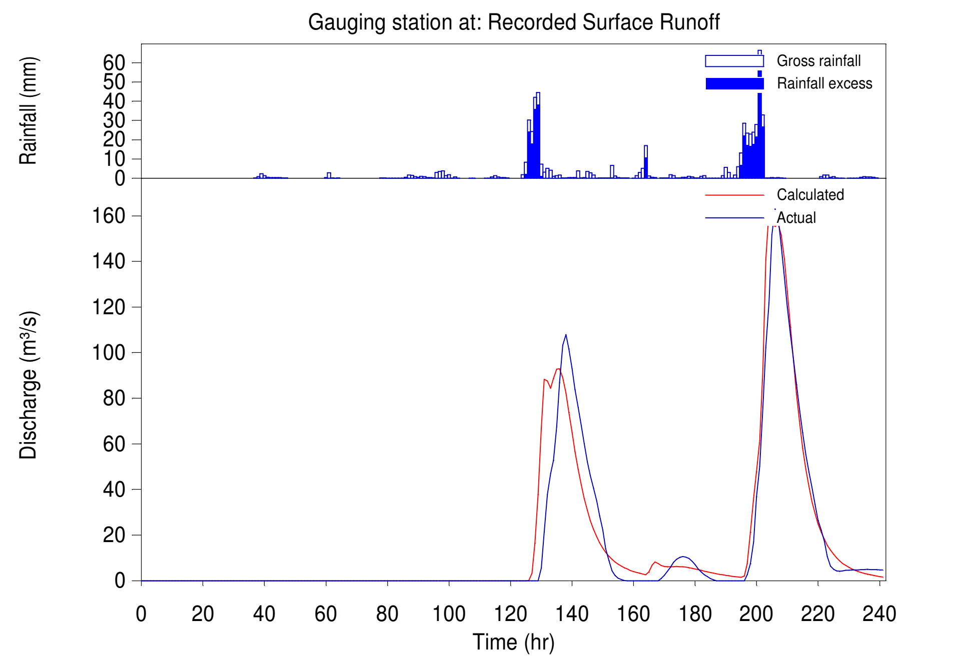
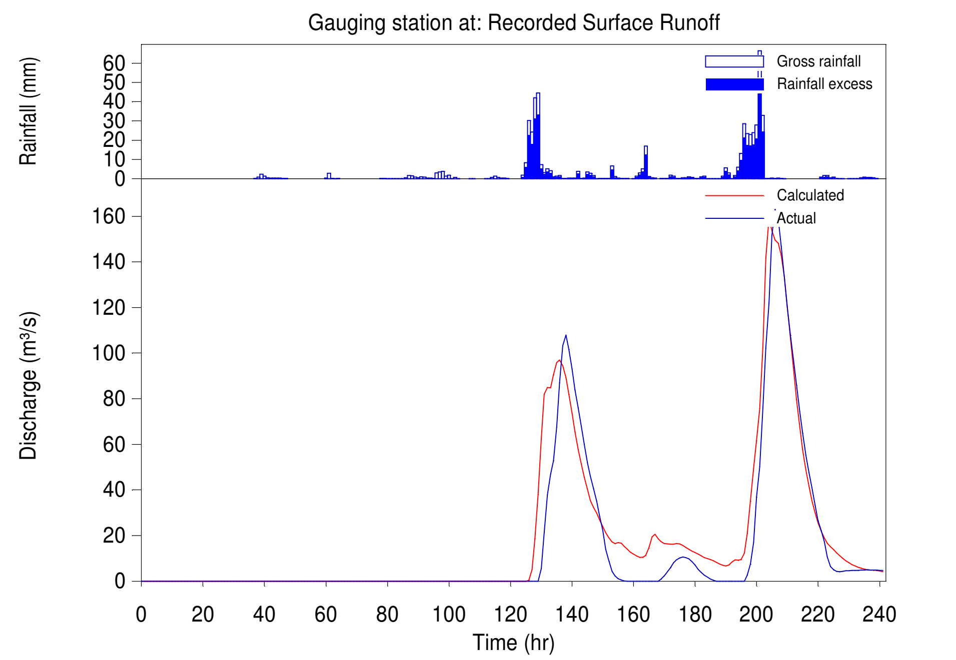


k_c = 20
IL = 30
CL = 1.00

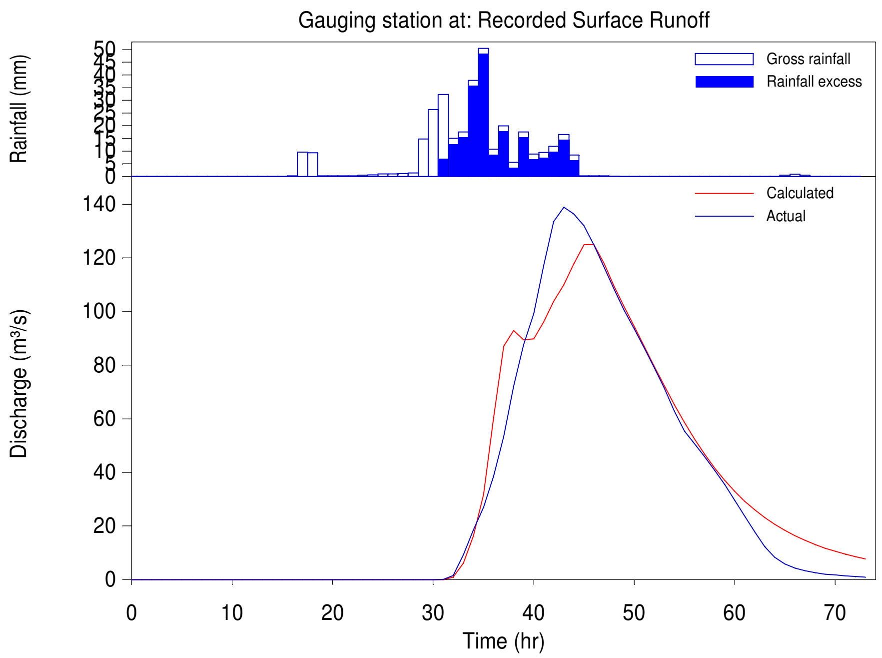
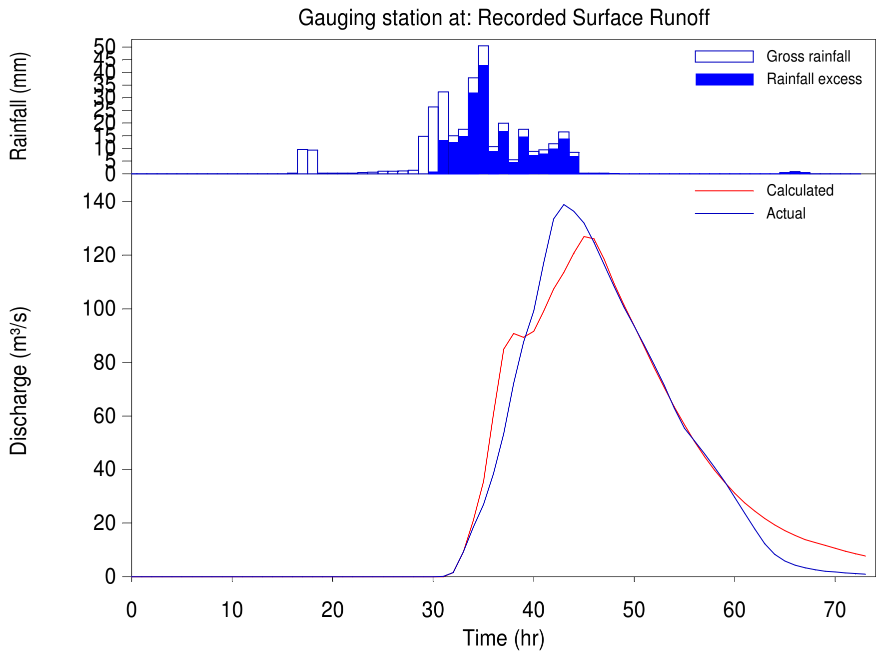


k_c = 20.00
IL = 29.0
PL = 0.85

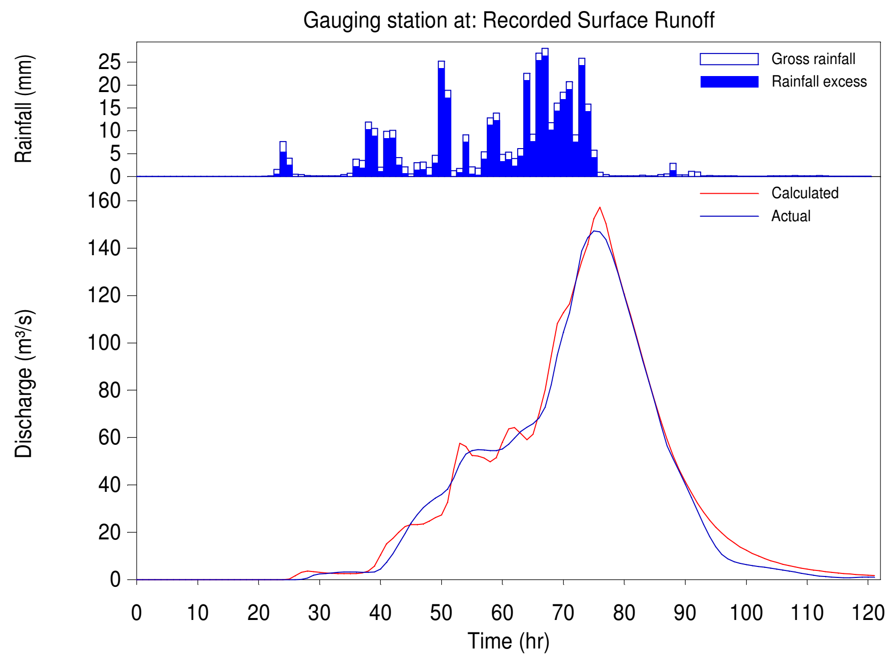
Event 2 – 25/03/1989 9:00 - 4/04/1989 9:00

	k_c = 19.5 *IL* = 35.0 *CL* = 6.0
	k_c = 20 *IL* = 36 *RoC* = 0.75

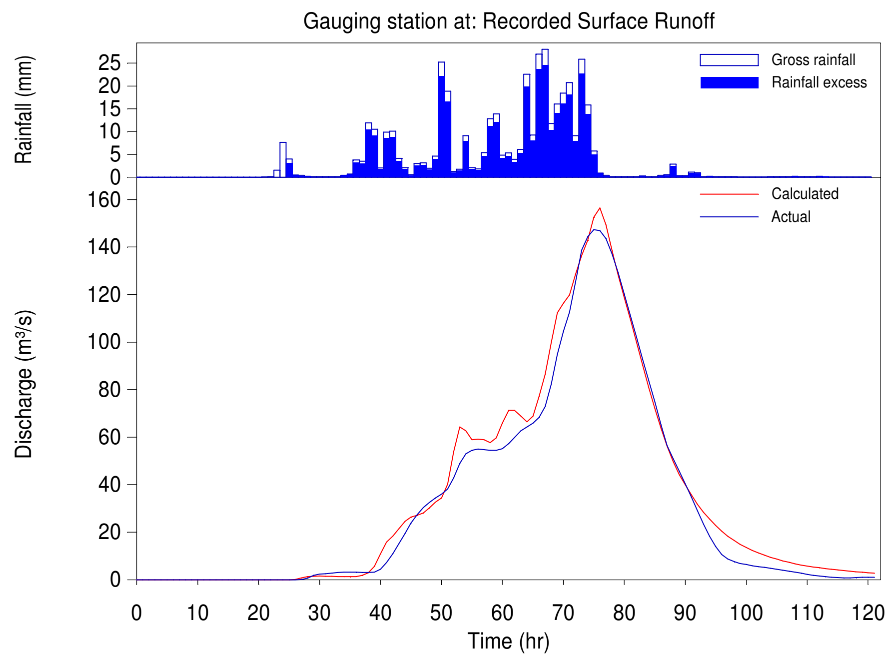
Event 3 – 4/03/1997 9:00 - 7/03/1997 9:00

	k_c = 25.00 IL = 90.0 CL = 1.90
	k_c = 24.00 IL = 82.0 RoC =0.85

Event 4: 6/02/1999 9:00 - 11/02/1999 9:00

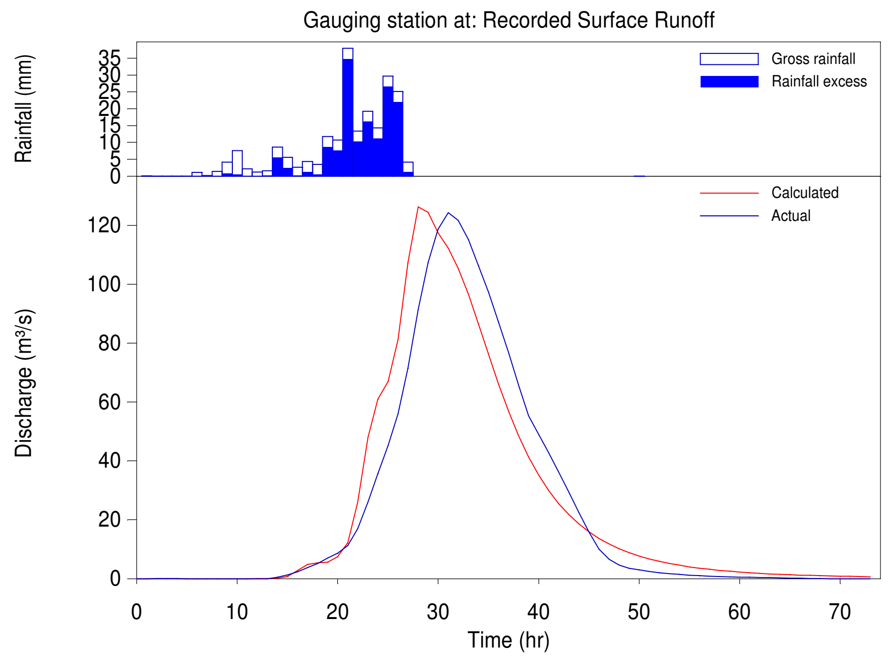


k_c = 24.00
IL = 2.0
CL = 1.5

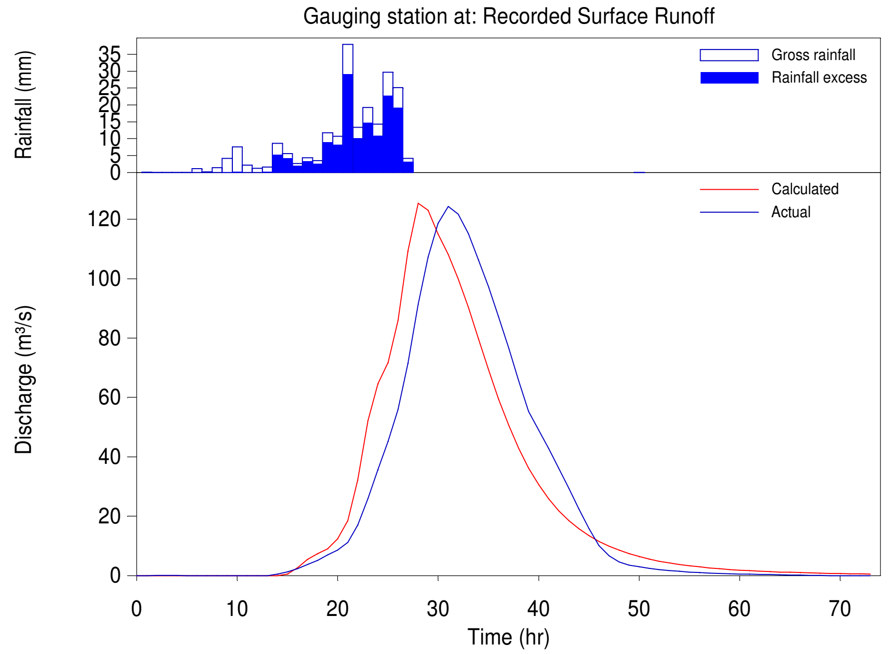


k_c = 23.0
IL = 10.0
RoC =0.88

Event 5: 1/06/2008 9:00 - 4/06/2008 9:00

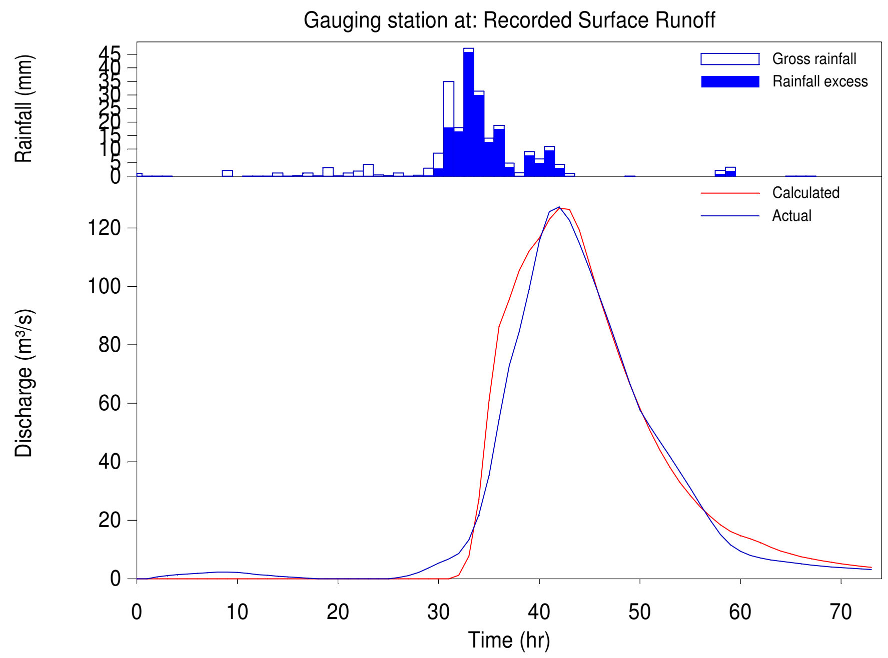


k_c = 19.00
IL = 10.0
CL = 3.00

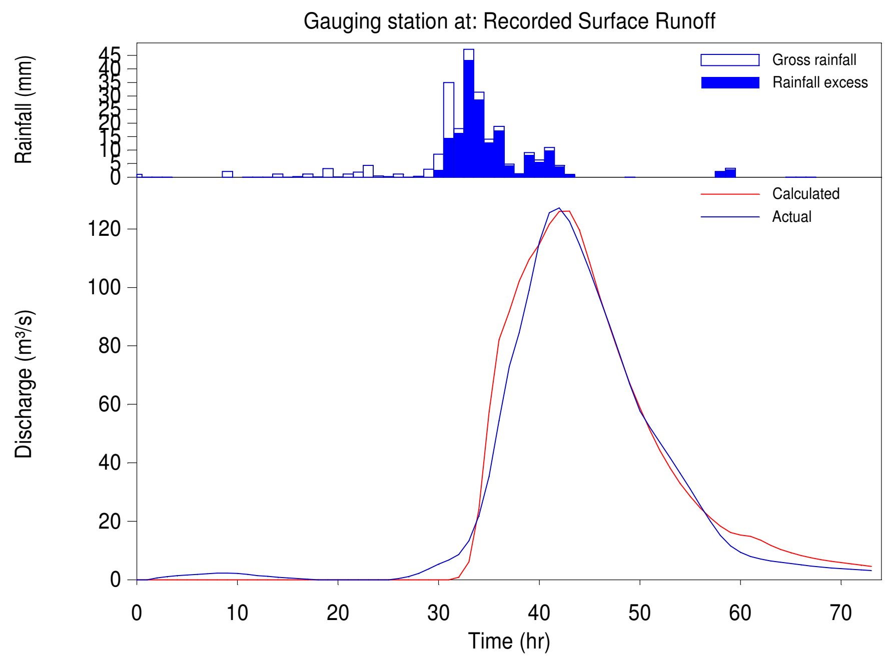


k_c = 18
IL = 20
RoC =0.77

Event 6: 12/04/2009 9:00 - 15/04/2009 9:00



k_c = 20
IL = 42
CL = 1.3



k_c = 19.5
IL = 46
RoC=0.92

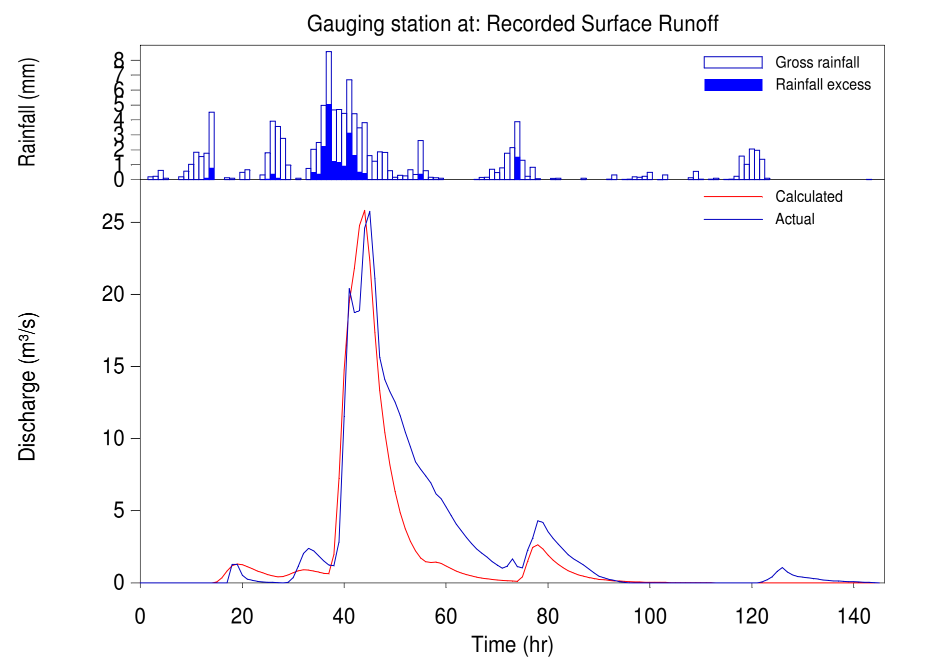
Event	Peak Q[1] (m^3/s)	k_c	IL (mm)	CL or PL (mm/h or %)	% difference in Peak Q	% difference in Volume	Error in time to centroid (hrs)	Comments
1	122.5	20	30	1.00	7.7	6.5	2.0	OK calibration. Similar fit with CL and PL. NOTE: only 1 pluvio available outside catchment
		20.0	29.0	15%	-0.5	19.4	-2.1	
2	163.2	19.5	35	6.0	-0.6	8.5	-1.3	OK fit. Similar fit with CL and PL. NOTE: only 1 pluvio available outside catchment
		20	36.0	25%	-2.4	25.3	-2.7	
3	138.9	25.0	90.0	1.9	-10.1	4.7	1.0	OK fit. Similar fit with Cl and PL.
		24.0	82.0	15%	-8.6	4.7	0.8	
4	147.3	24	2.0	1.5	6.8	4.9	0.7	Good fit. Similar fit with Clan d PL.
		23	10.0	12%	6.3	9.2	0.5	
5	124.3	19	10.0	3	1.6	2.7	-0.4	OK fit – lag required. Similar fit with CL and PL.
		18	20	23%	0.9	-0.5	-1.0	
6	127.2	20	42.0	1.3	-0.4	5.5	0.5	Good fit. Similar fit with CL and PL.
		19.5	16.0	8%	-0.9	5.0	0.8	

[1] Surface runoff ie. total recorded flow – baseflow.

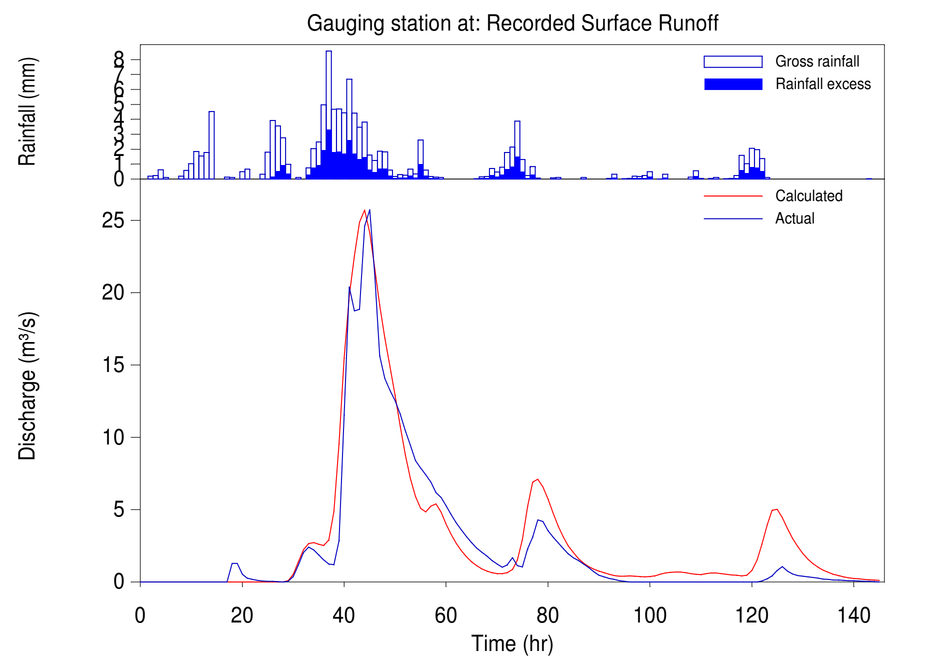
k_c = 8.01 km

A5040523 Sixth Creek at Castambul

Event 1 – 22/06/1987 9:00 - 28/06/1987 9:00

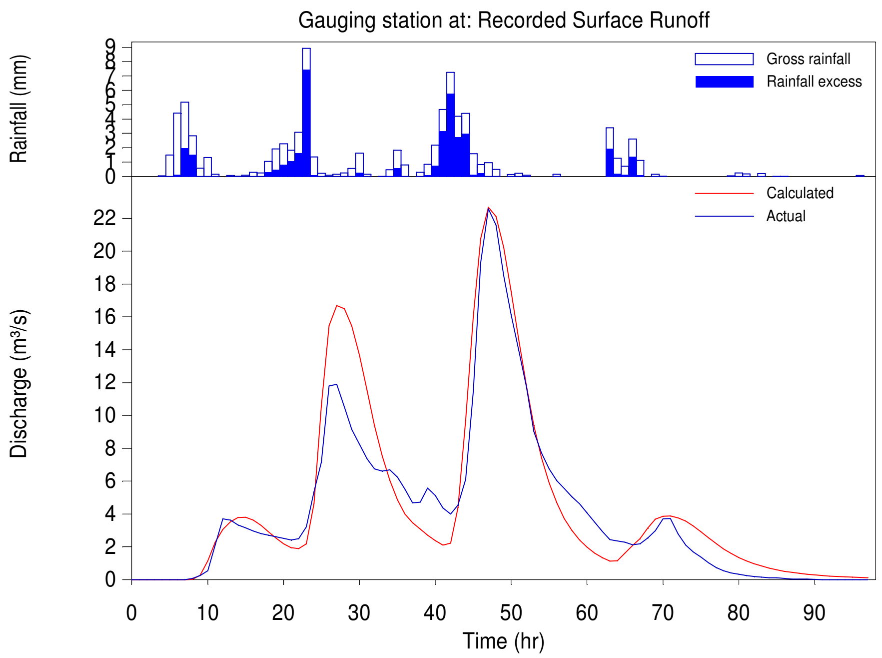


k_c = 8.0
IL = 7.8
CL = 3.5

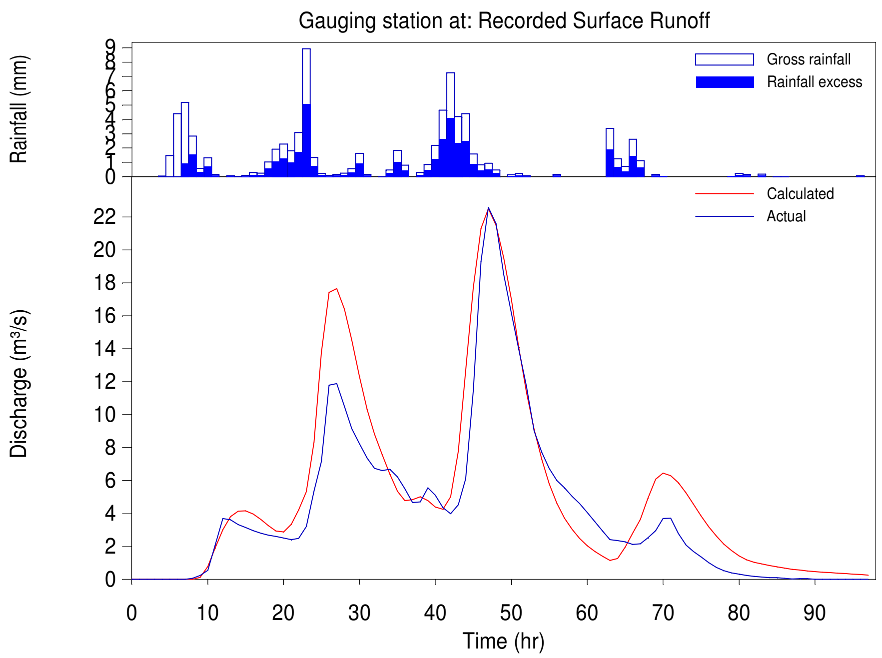


k_c = 8.00
IL = 22
RoC =0.39

Event 2 – 16/09/1991 9:00 - 20/09/1991 9:00

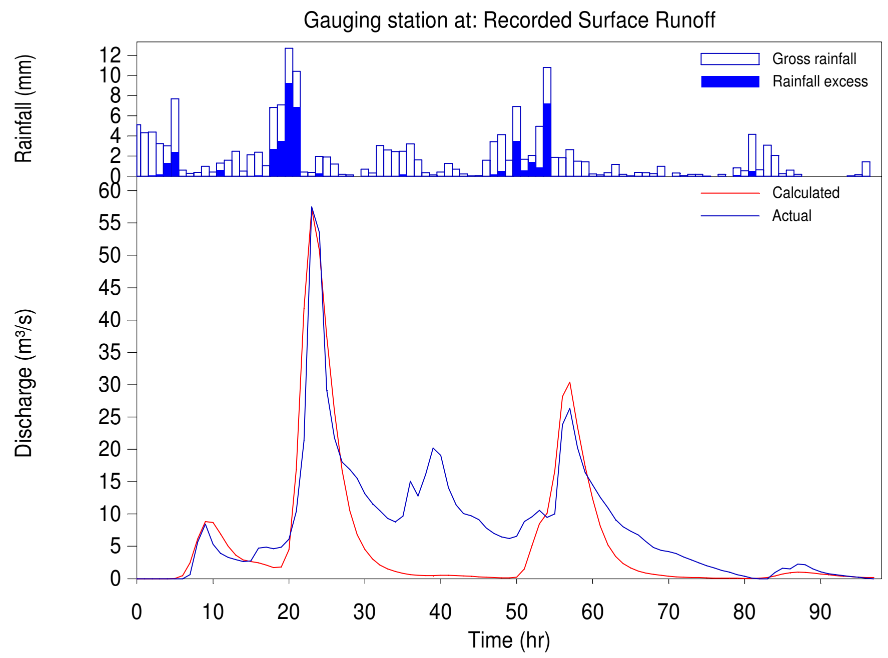


k_c = 10
IL = 7.2
CL = 1.45

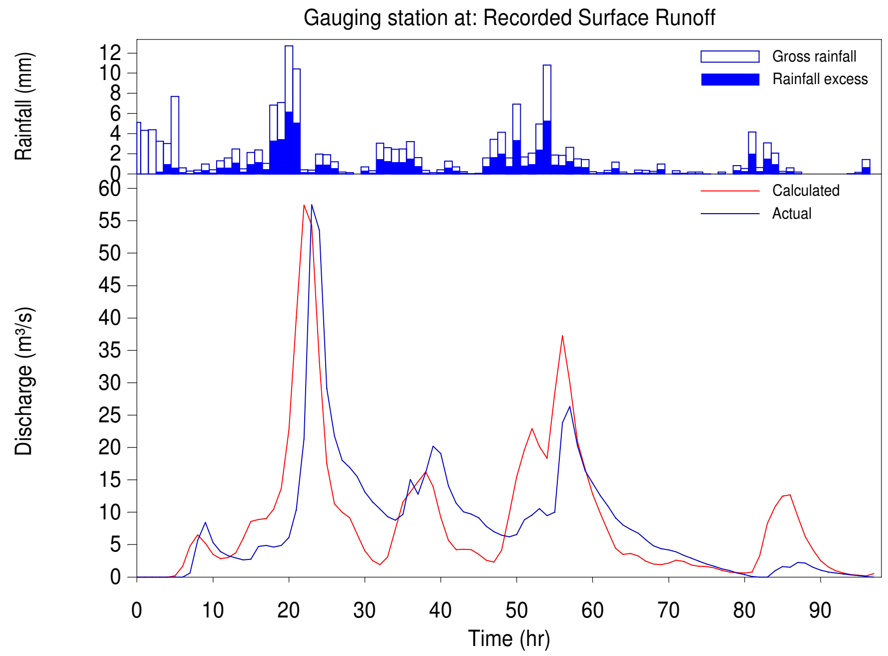


k_c = 9.0
IL = 9.5
RoC = 0.57

Event 3 – 29/08/1992 9:00:00 AM - 2/09/1992 9:00:00 AM

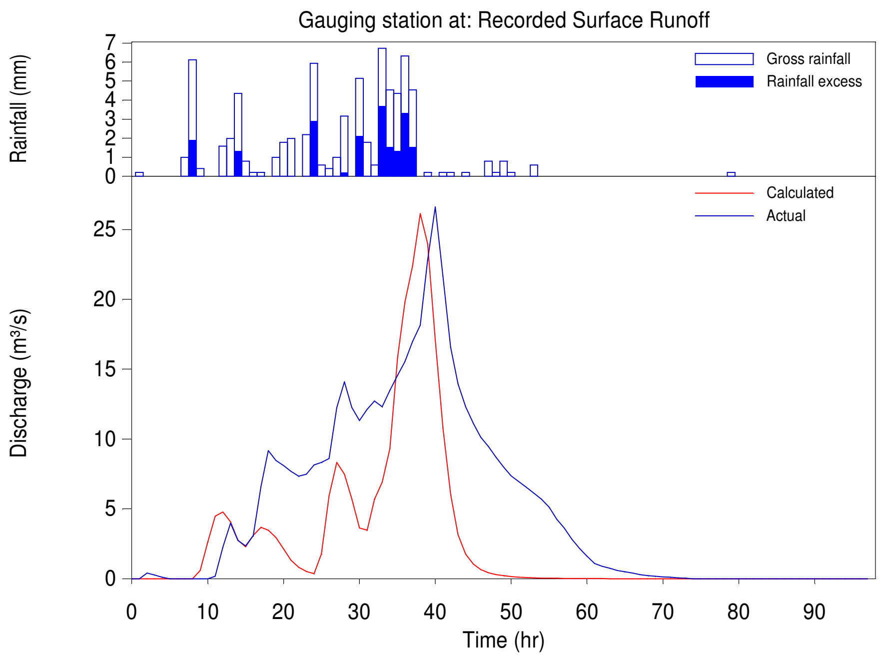
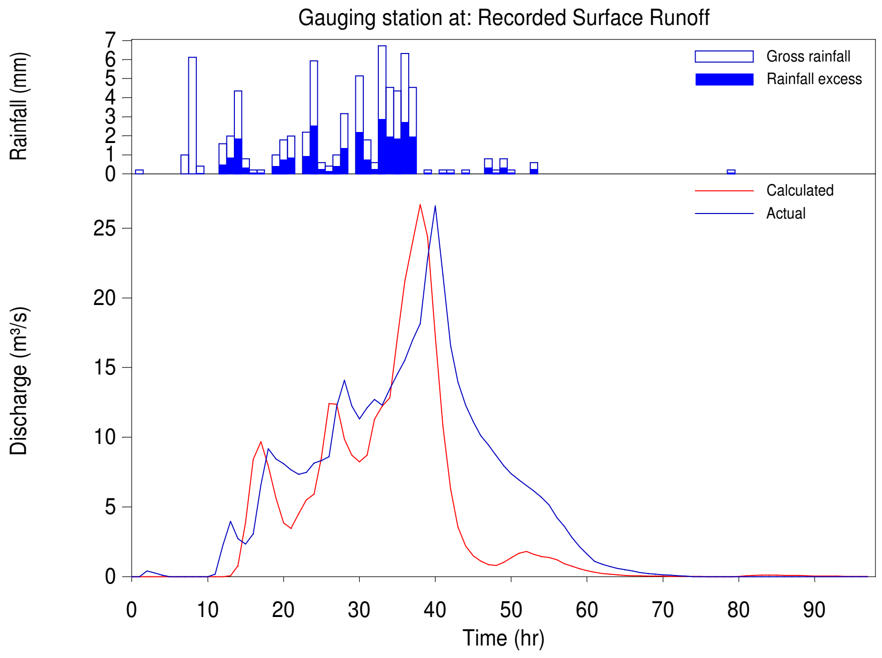


k_c = 6
IL = 18
CL = 4.1

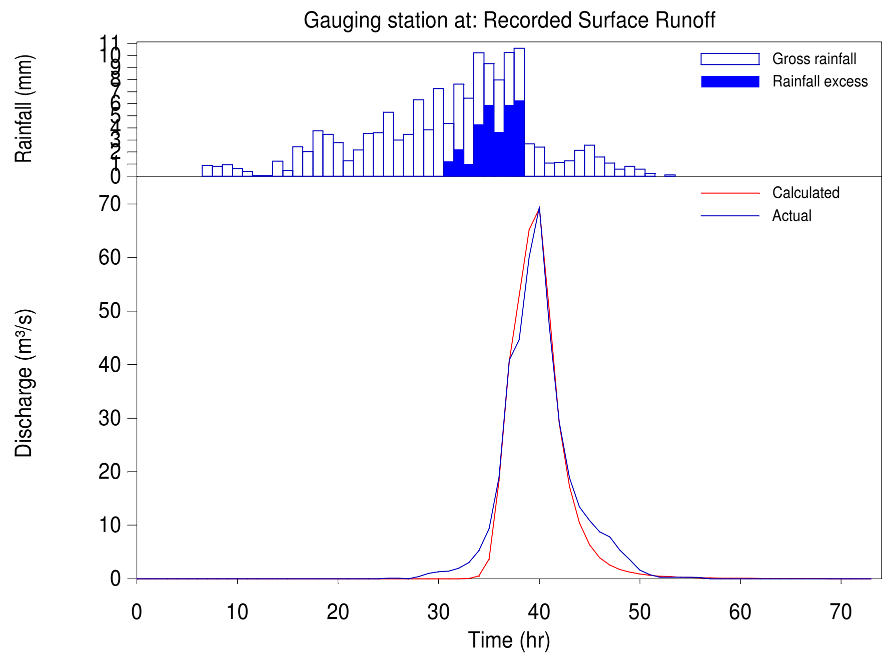


k_c = 3.5
IL = 25
RoC = 0.49

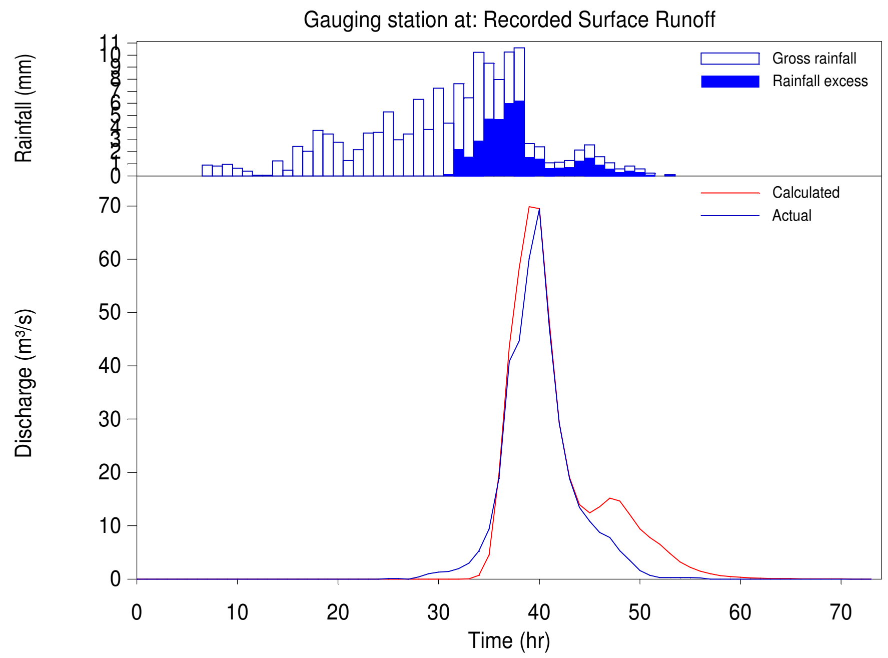
Event 4 – 21/07/1995 9:00:00 AM - 25/07/1995 9:00:00 AM

<table>
<tr><td>
</td><td>k_c = 4
IL = 2.4
CL = 3</td></tr>
<tr><td>
</td><td>k_c = 4
IL = 8
RoC = 0.43</td></tr>
</table>

Event 5 – 6/11/2005 9:00:00 AM - 9/11/2005 9:00:00 AM



k_c = 6
IL = 69
CL = 4.3



k_c = 4.5
IL = 78
RoC = 0.59

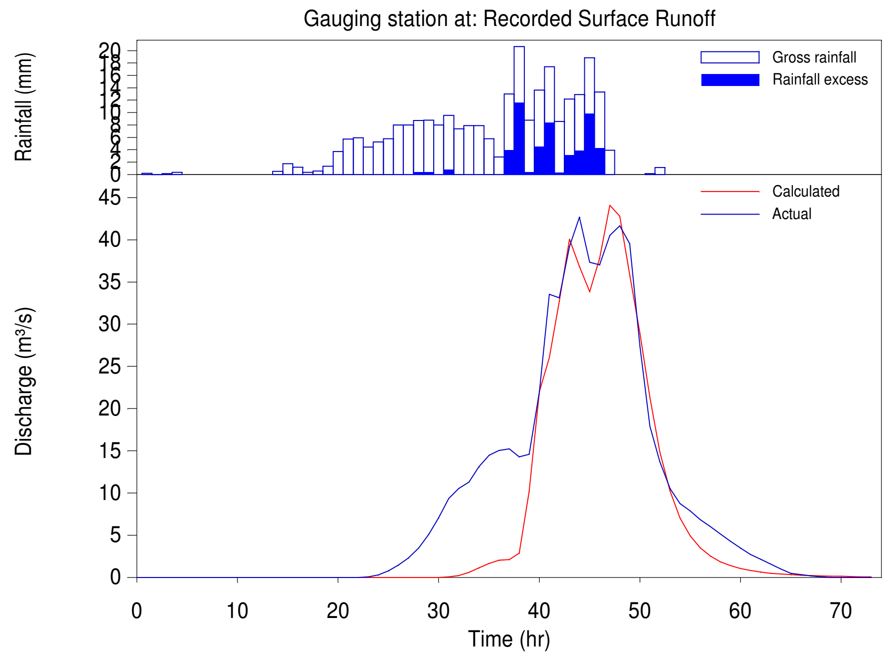
Event	**Peak Q[1] (m^3/s)**	**k_c**	**IL (mm)**	**CL or PL (mm/h or %)**	**% difference in Peak Q**	**% difference in Volume**	**Error in time to centroid (hrs)**	**Comments**
1	25.7	8	7.8	3.5	0.3	-30.2	-6.1	Average fit. PL has better fit.
		8	22	61% (PL)	-0.1	19.7	7.7	
2	22.6	10	7.2	1.45	0.5	9.3	0.0	Good fit. CL has better fit
		9	9.5	43% (PL)	-0.3	23.1	0.6	
3	57.5	6	18	4.1	-0.6	-33.3	-4.5	Average fit, could do better with multiple bursts - PL has better fit, and would be better with translation. CL has poor fit!
		3.5	24	51% (PL)	-0.1	8.9	1.8	
4	26.6	4	2.4	3	-1.8	-48.2	-3.6	Average fit, could do better with multiple bursts - PL has better fit, and would be better with translation. CL has poor fit!
		4	8	57% (PL)	0.3	-29.3	-3.2	
5	69.5	6	69	4.3	-0.4	-7.3	-0.1	Good fit. CL has better fit, but dependent on BF separation
		4.5	78	41% (PL)	0.6	19	1.6	

[1] Surface runoff ie. total recorded flow – baseflow.

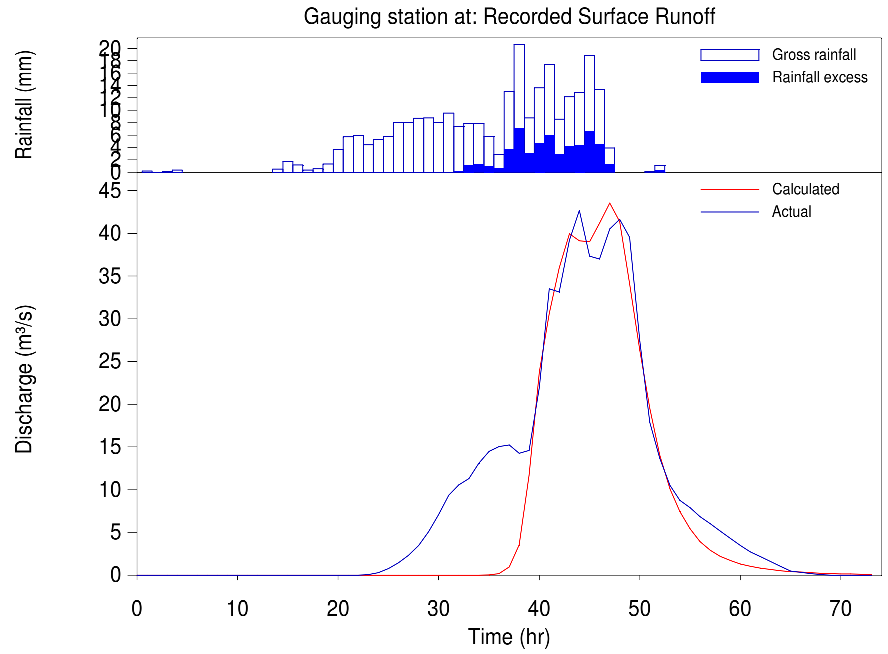
d_{av} = 8.31km

422321 Spring Creek at Killarney

Event 1 – 9:00am 9-12 February 1976

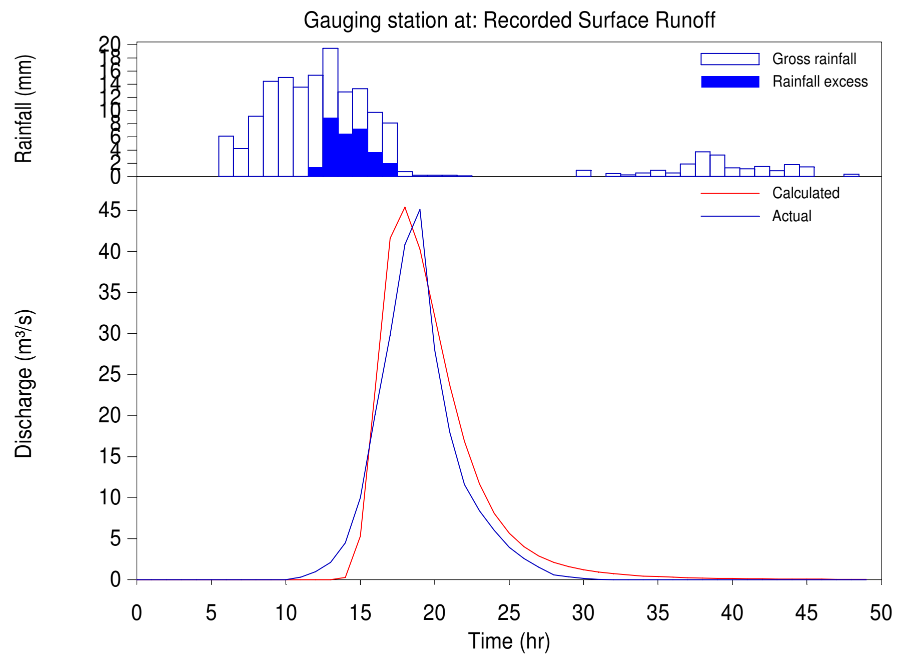


k_c =6
IL = 40
CL = 9

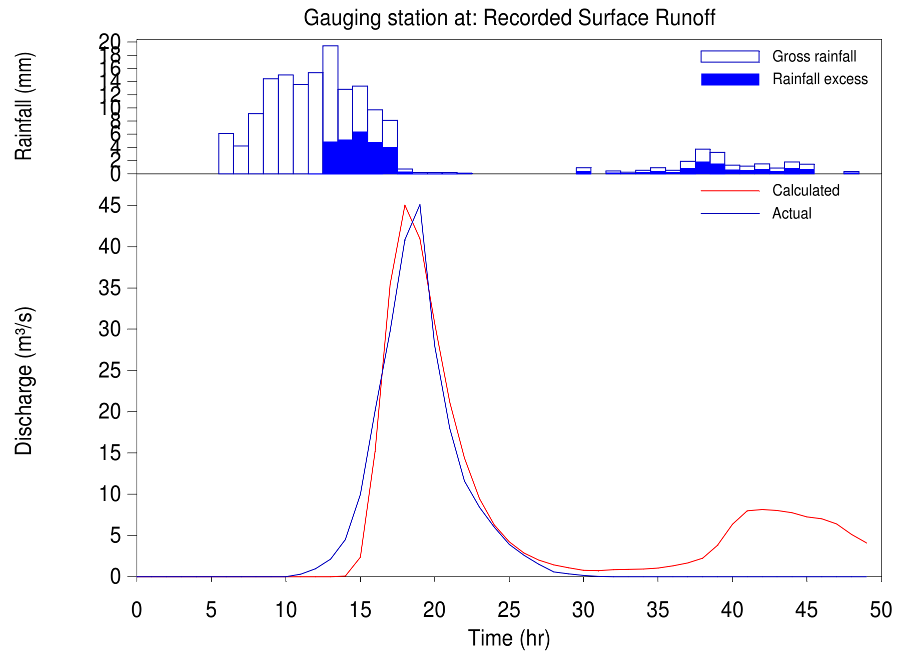


k_c =6
IL = 110
RoC =0.35

Event 2 – 9:00am 3-5 April 1988

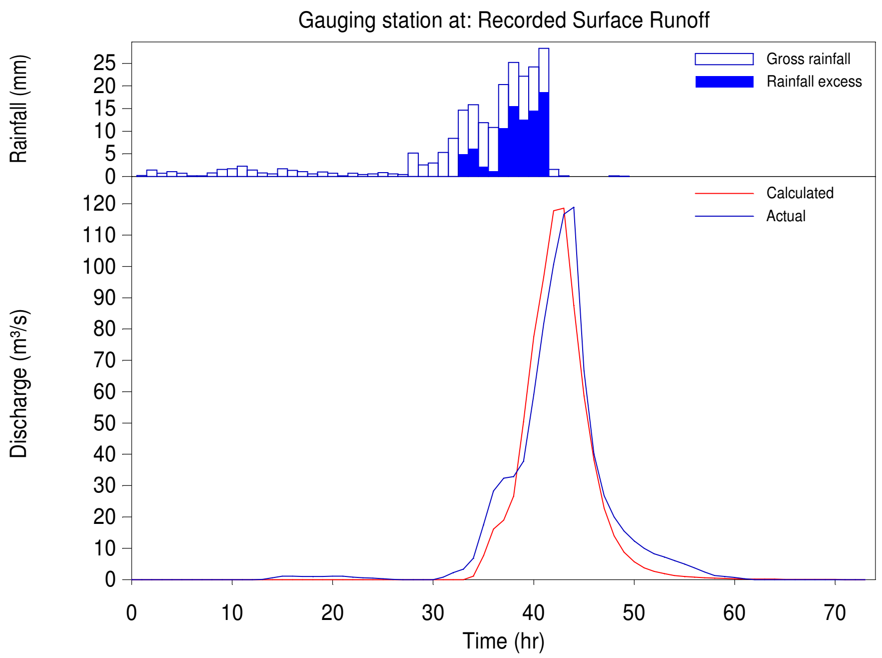


k_c =6.0
IL = 80
CL = 6.0

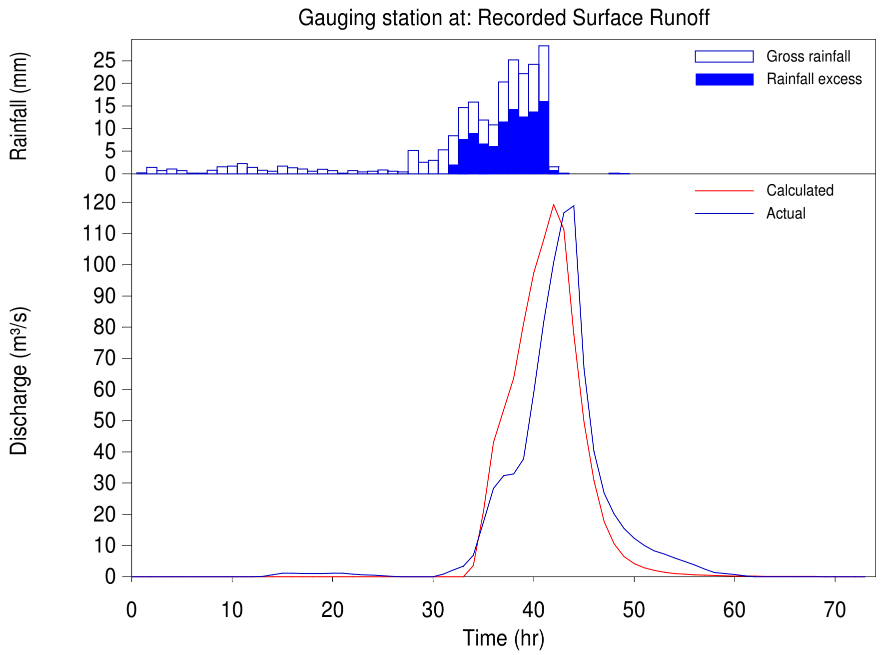


k_c =5
IL = 90
RoC =0.5

Event 3 – 9:00am 3-6 January 2008

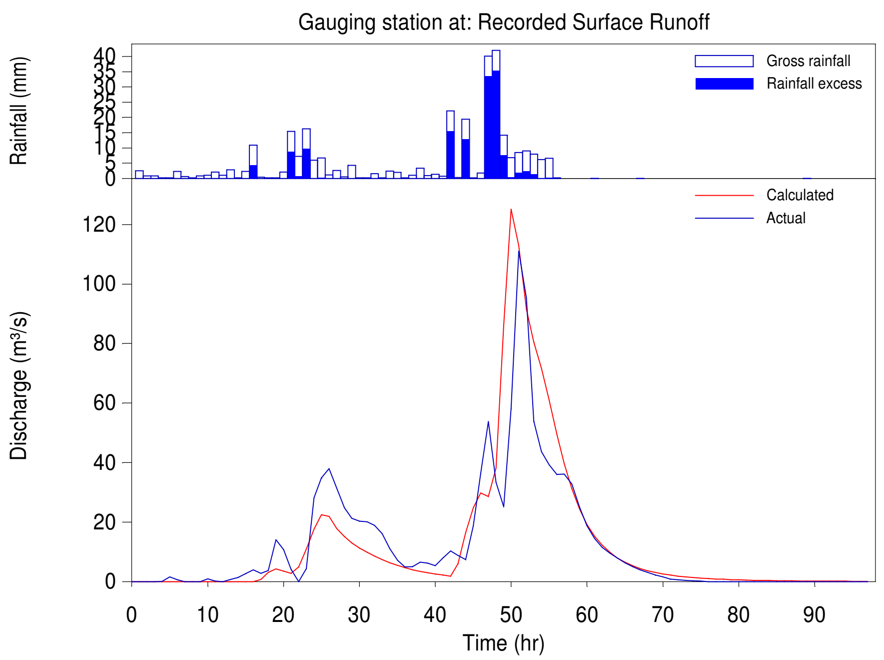
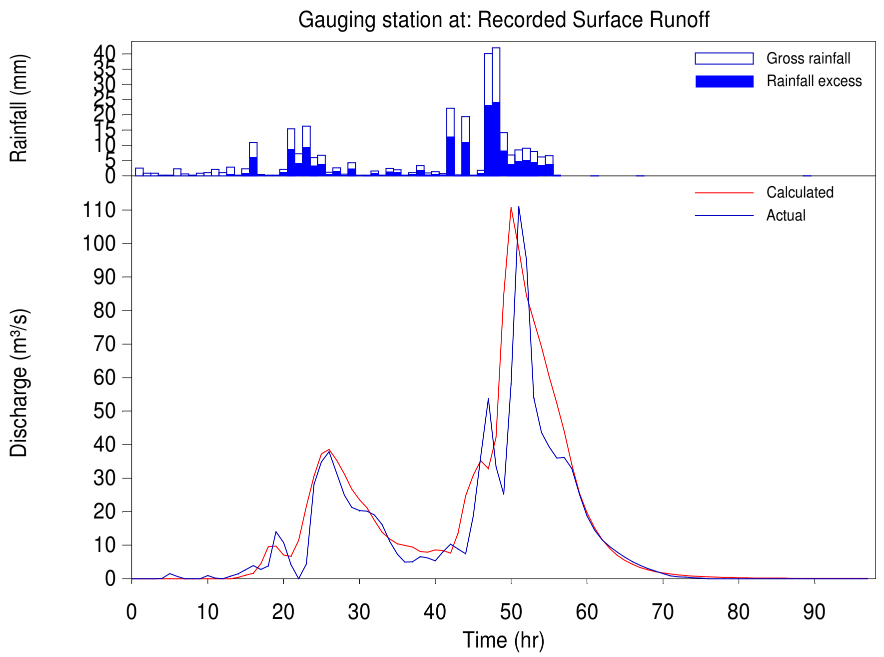


k_c =5.5
IL = 40
CL = 9.6



k_c =5
IL = 45
RoC =0.57

Event 4 – 9:00am 9-13 January 2011

	k_c = 11 IL = 15 CL = 6.5
	k_c =8 IL = 15 RoC =0.58

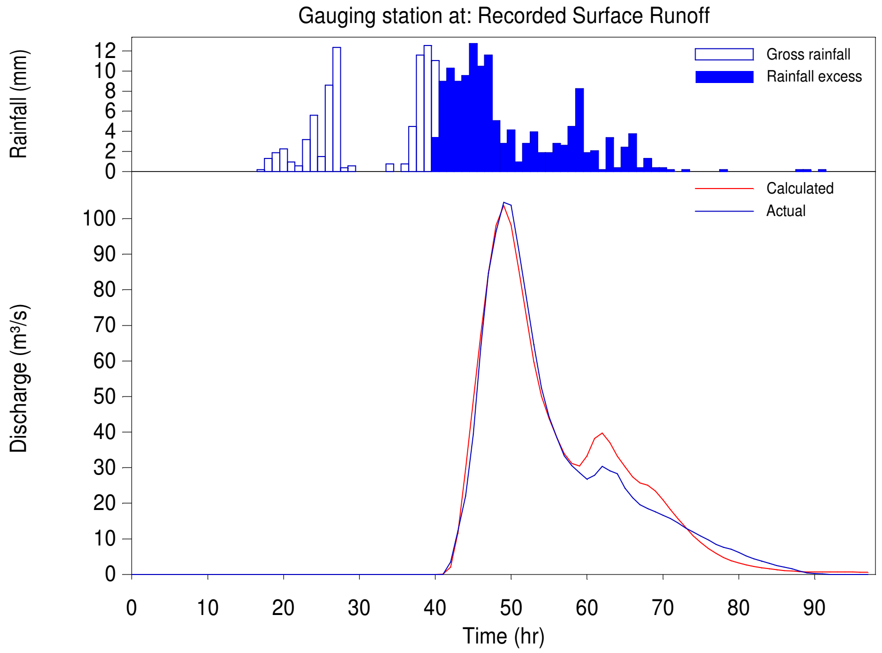
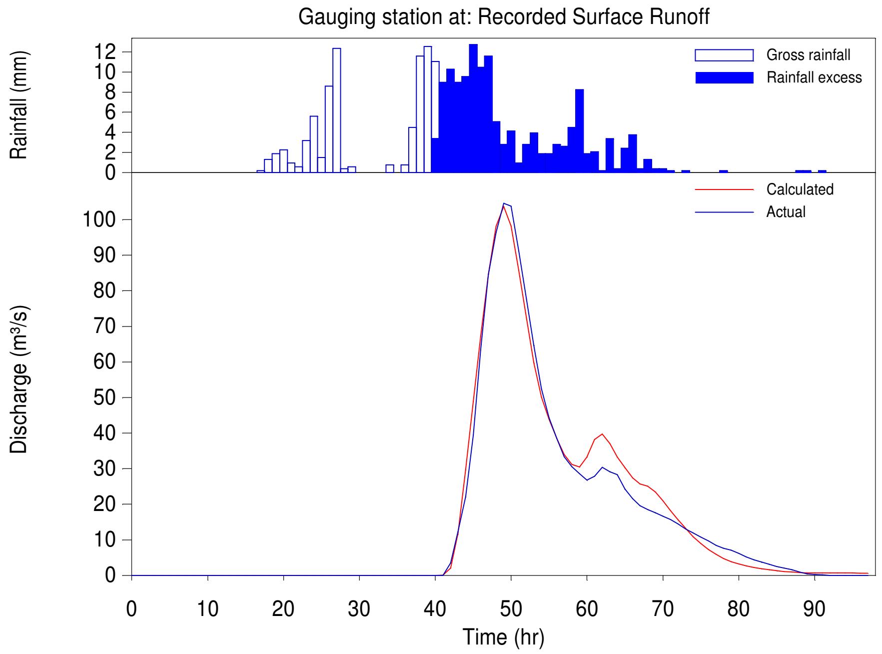
Event	Peak Q[1] (m³/s)	k_c	IL (mm)	CL or PL (mm/h or %)	% difference in Peak Q	% difference in Volume	Error in time to centroid (hrs)	Comments
1	42.7	6	40	9 mm/h	3.3	-24.2	2	Good fit, hard to fit rising limb. Similar fit between CL and PL.
		6	110	65%	0.9	-22.4	2	
2	45.1	6	80	6 mm/h	0.6	15.2	0.8	OK fit. Similar fit between CL and PL.
		5	90	50%	-0.1	34.1	6.6	
3	118.9	5.5	40	9.6 mm/h	-0.3	-10.9	-0.1	OK fit. CL has better fit.
		5	45	43%	0.3	3.8	-1.2	
4	111.1	11	15	6.5 mm/h	12.7	5.1	3.8	OK fit. PL has better fit.
		8	15	42%	-0.3	23	0.3	

[1] Surface runoff ie. total recorded flow – baseflow.

d_{av}=5.82km

2219 Swan River upstream Harding Falls

Event 1 – 17/12/1995 9:00 - 21/12/1995 9:00

<table>
<tr><td>
</td><td>k_c = 9.00
IL = 77.0
CL = 0.0</td></tr>
<tr><td>
</td><td>k_c = 9
IL = 77
RoC = 1.00</td></tr>
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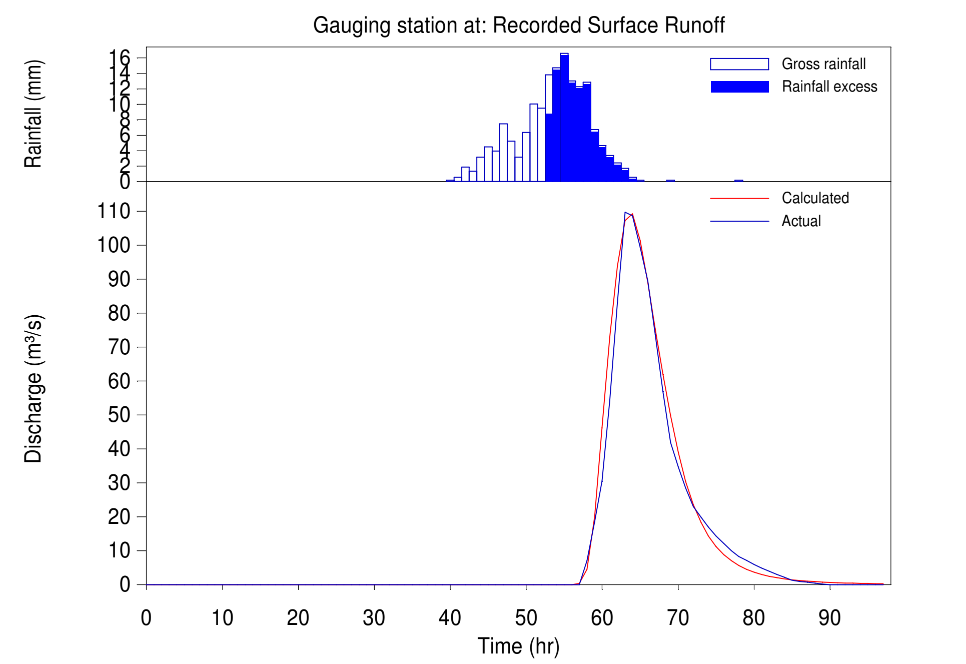
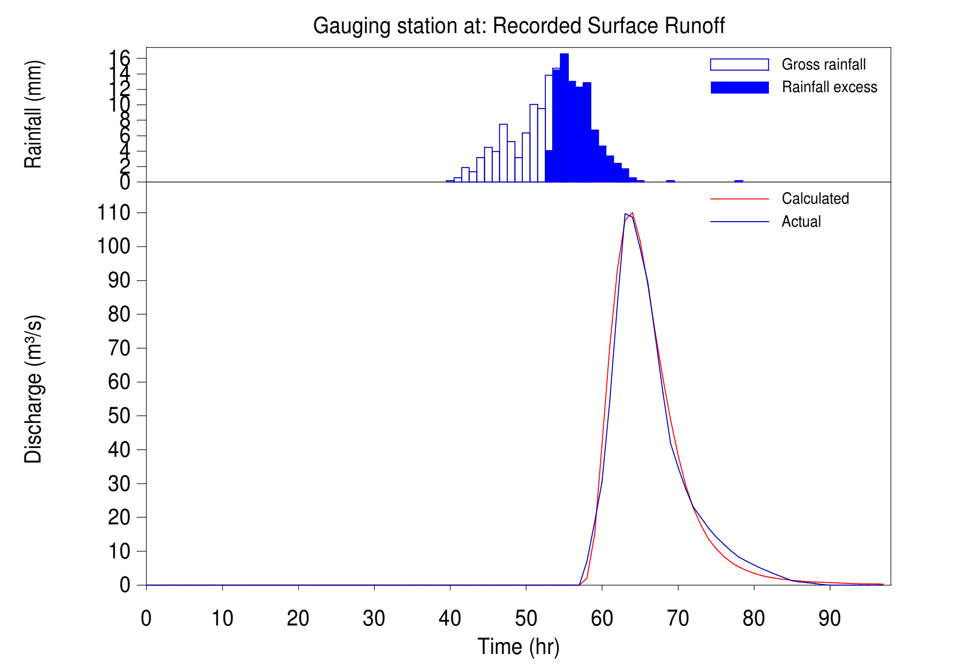
Event 2 – 2/01/2000 9:00 - 6/01/2000 9:00



k_c =10.5
IL = 62.0
CL = 0.2

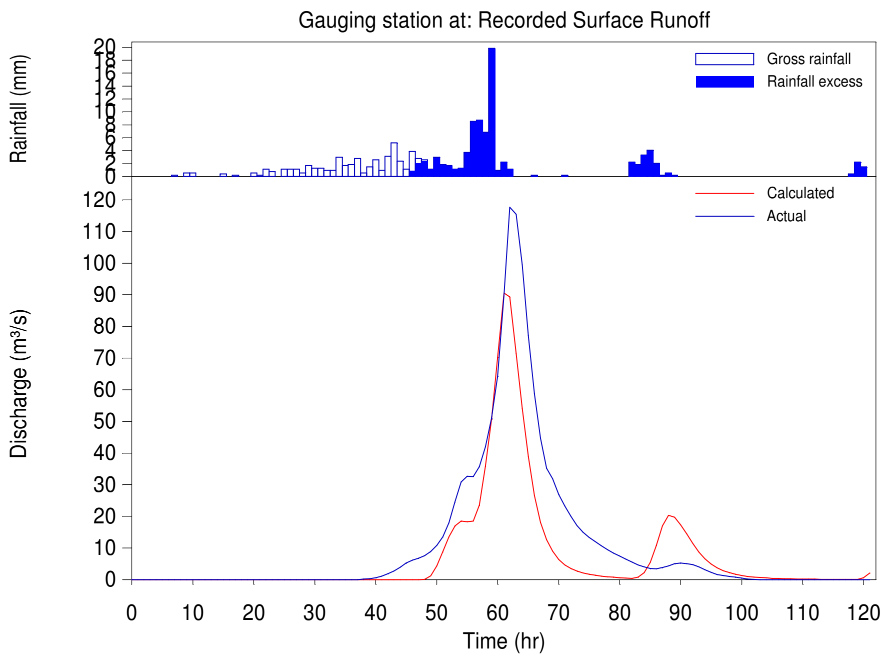
Calculated hydrograph TRANSLATED 2 hrs forwards



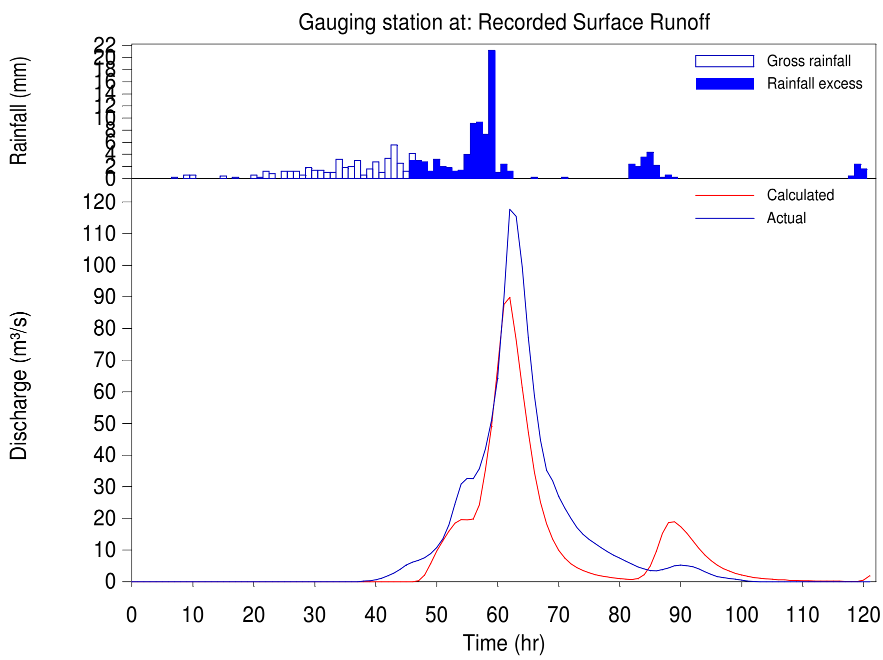
k_c =10
IL = 67
RoC = 1

Calculated hydrograph TRANSLATED 2 hrs forwards

Event 3 – 10/04/2003 9:00 - 15/04/2003 9:00

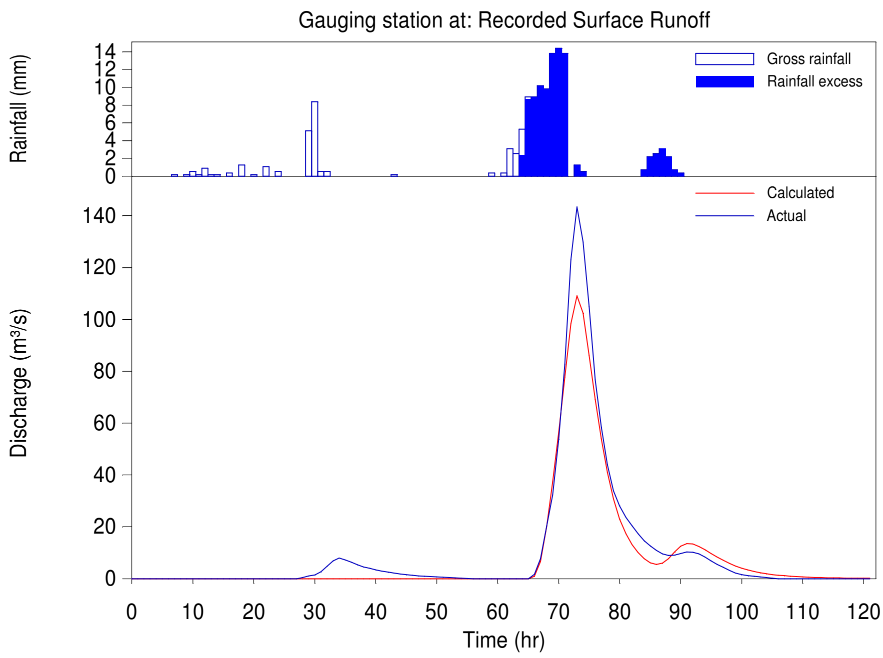


k_c = 7.2
IL = 45.0
CL = 0.00

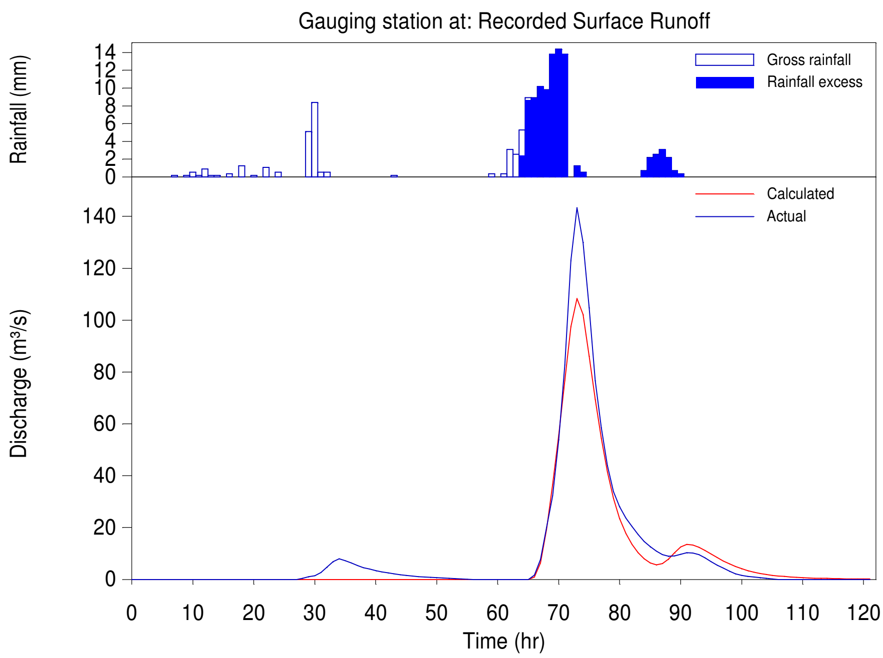


k_c = 7.20
IL = 45
RoC = 0.00

Event 4 – 21/08/2003 9:00 - 26/08/2003 9:00



k_c = 10.0
IL = 30.0
CL = 0.00



k_c =10.0
IL = 30.0
RoC = 0.00

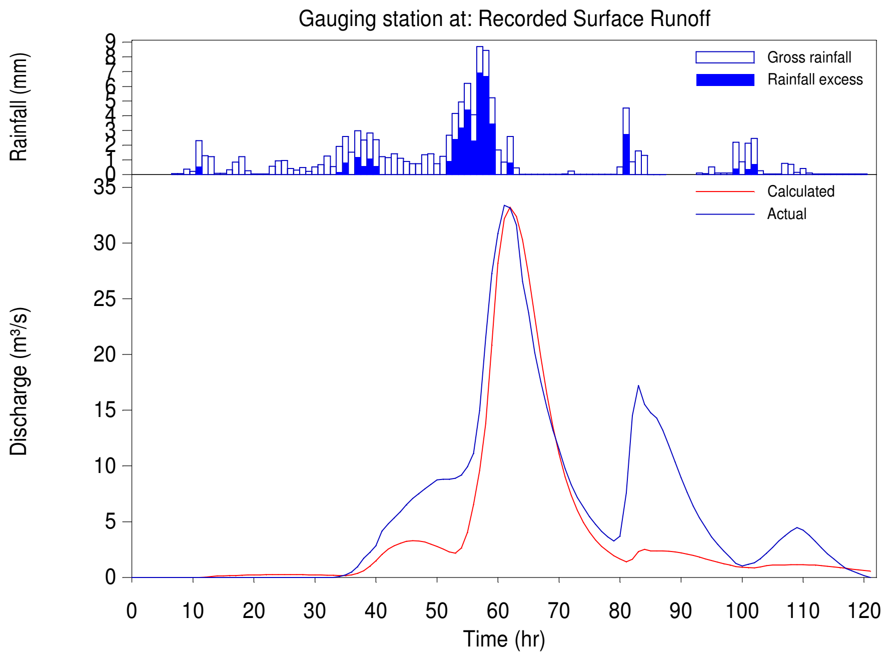
Event	Peak Q[1] (m^3/s)	k_c	IL (mm)	CL or PL (mm/h or %)	% difference in Peak Q	% difference in Volume	Error in time to centroid (hrs)	Comments
1	104.6	9.00	77.0	0.0 (CL)	-0.9	3.9	0.1	Good fit. Similar fit for CL and PL.
		9.00	77.0	0.0 (CL)	-0.9	3.9	0.1	
2	109.8	10.5	62	0.2 (CL)	-0.4	4.6	-0.3	Good fit. Calculated hydrograph translated 2hrs forwards. Similar fit for CL and PL.
		10	67.0	0% (PL)	0.2	2.3	-0.3	
3	117.7	7.2	45.0	0.00 (CL)	-23.1	-32.8	2.8	Poor fit. Seems to be not enough rain on falling limb. Same fit for both.
		7.2	45.0	0% (PL)	-23.1	-32.8	2.8	
4	143.4	10.0	30.0	0.00 (CL)	-24	-16.2	3.4	Average fit. Seems to be not enough rain to match peak. Same fit for both
		10.0	30.0	0% (PL)	-24	-16.2	3.4	

[1] Surface runoff ie. total recorded flow – baseflow.

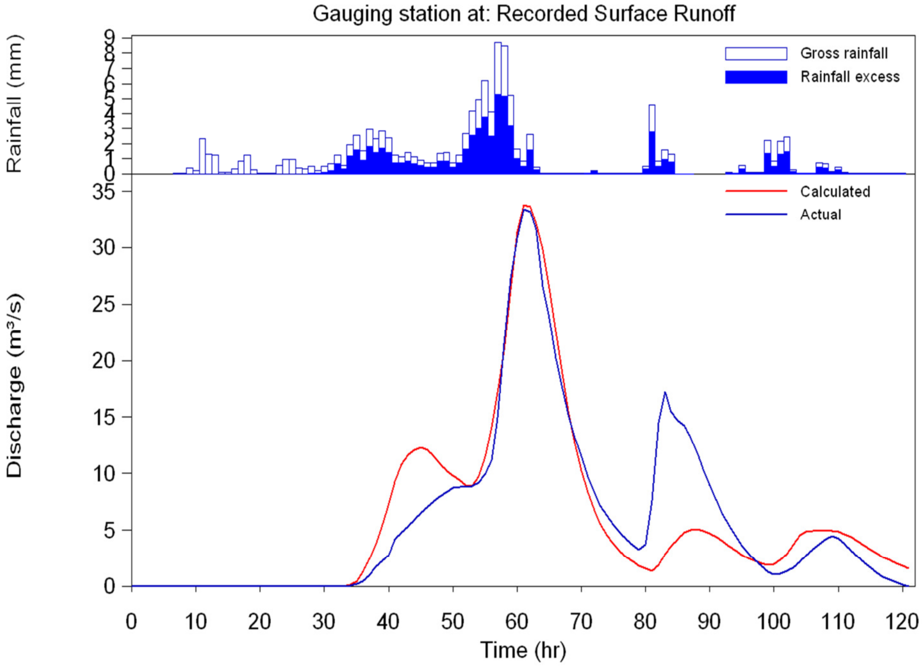
d_{av} = 7.09km

228217 Toomuc Creek at Pakenham

Event 1 – 9:00am 16-19 September 1984

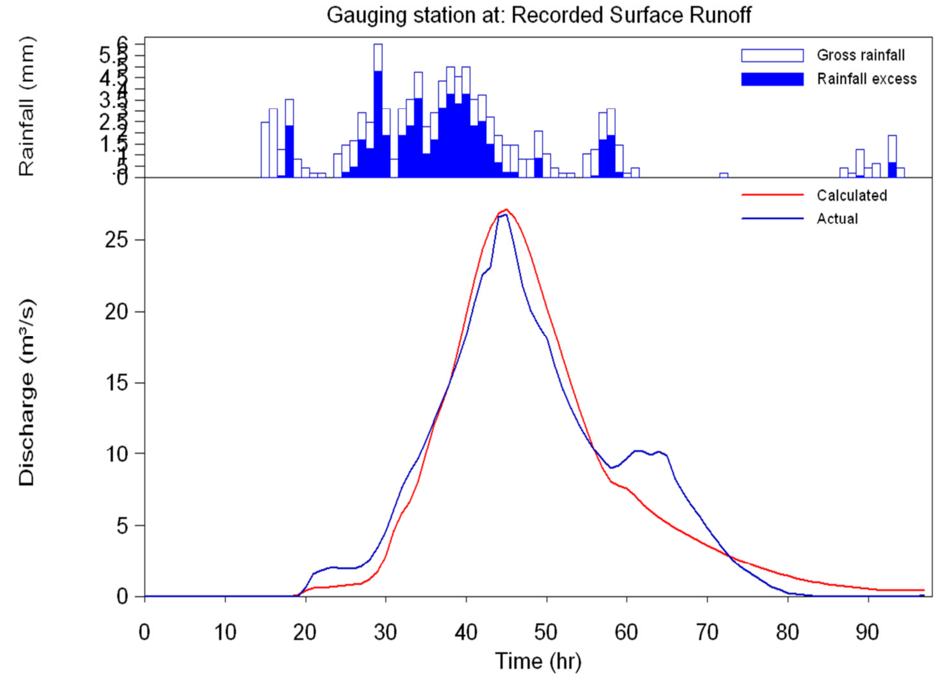


k_c =12
IL = 0
CL = 1.75

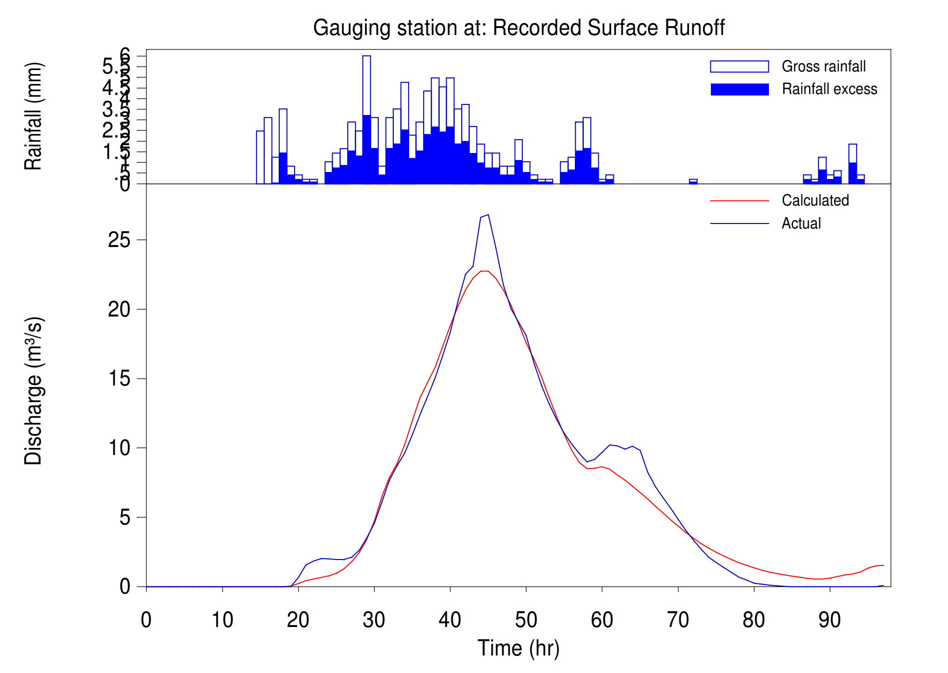


k_c =11
IL = 13
RoC =0.61

Event 2 – 9:00am 28 July – 1 August 1996

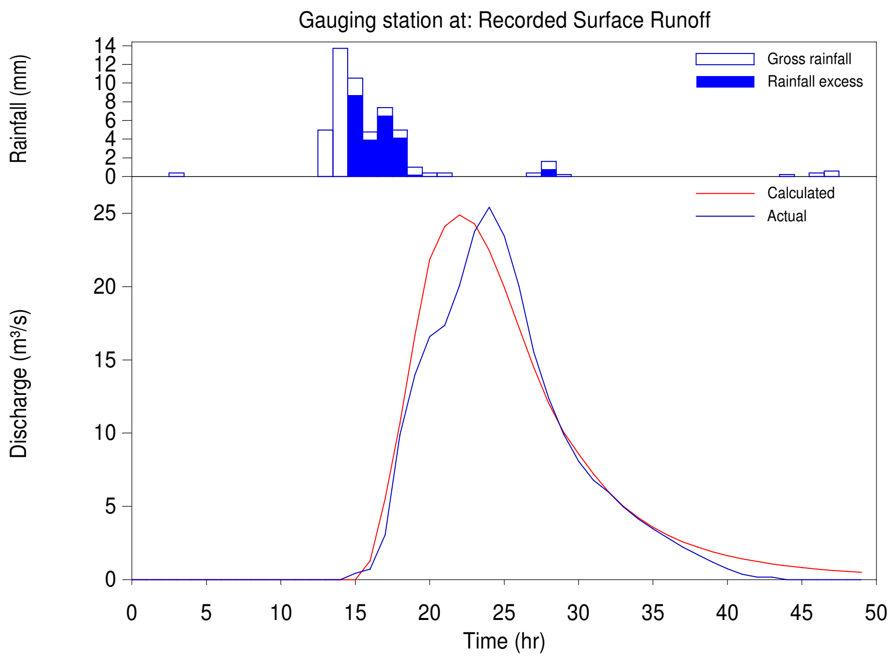


k_c =16
IL = 6
CL = 1.21

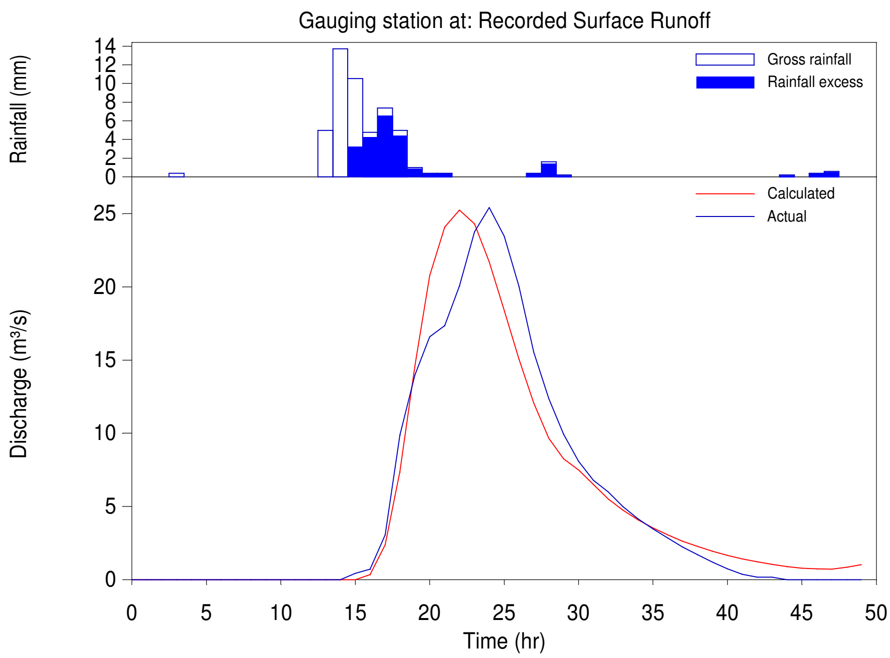


k_c =14
IL = 7.5
RoC =0.54

Event 3 – 9:00am 12-14 November 2004

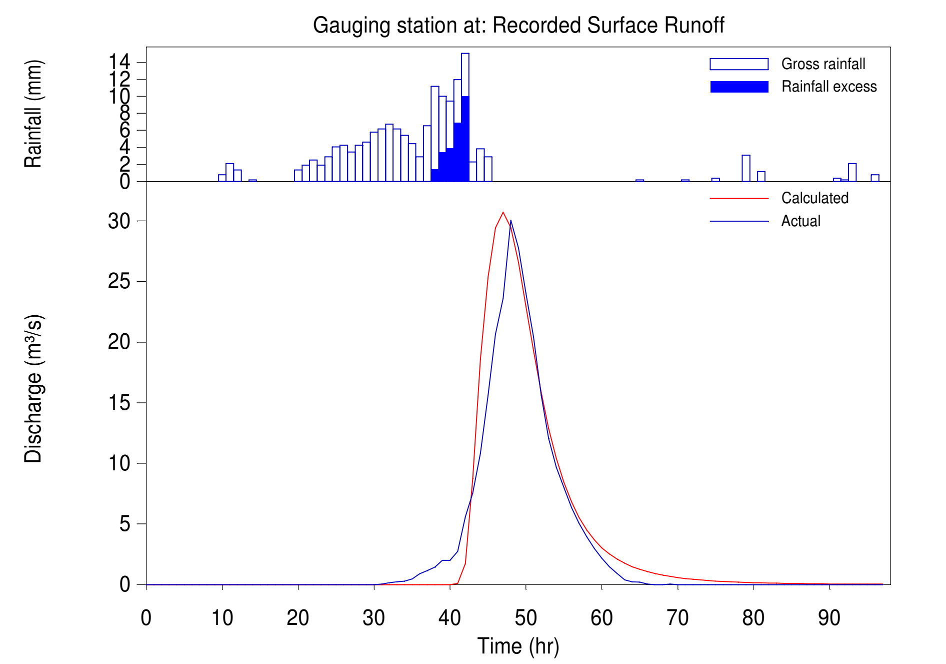


k_c =12
IL = 20
CL = 0.8

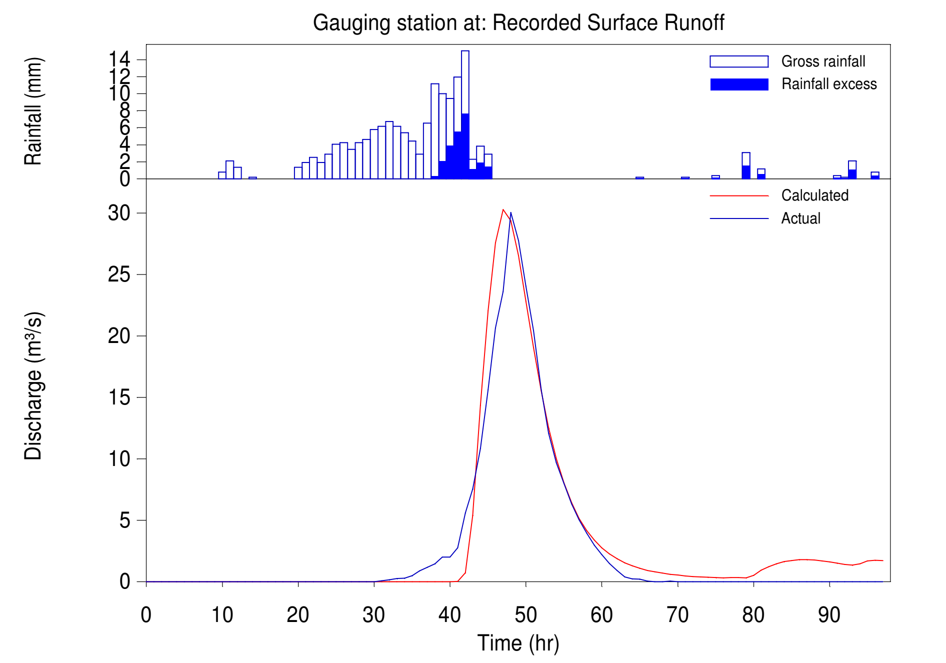


k_c =10
IL = 26
RoC =0.9

Event 4 – 9:00am 1-5 February 2005



k_c =12
IL = 91
CL = 5



k_c =11
IL = 99
RoC =0.51

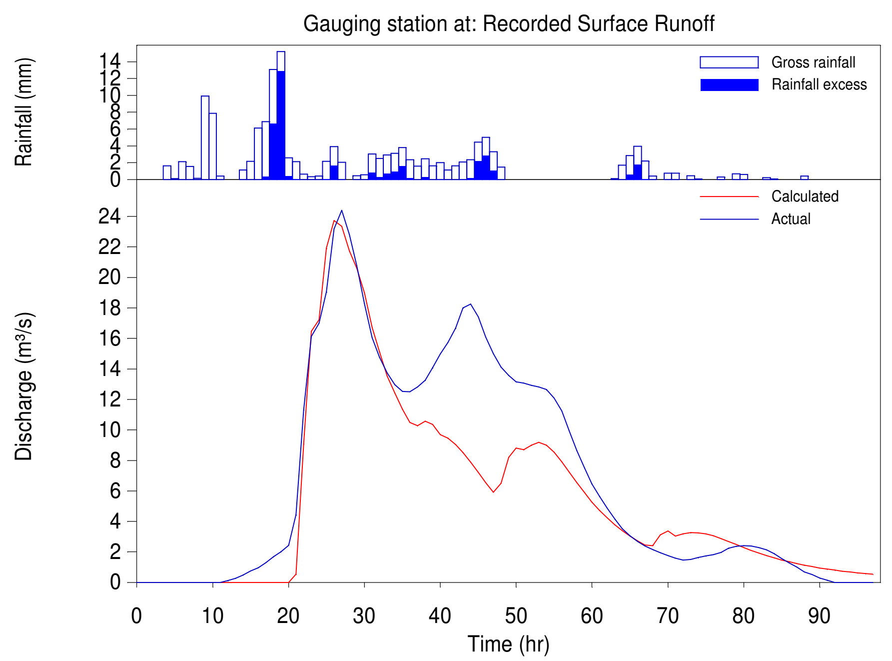
Event	Peak Q[1] (m^3/s)	k_c	IL (mm)	CL or PL (mm/h or %)	% difference in Peak Q	% difference in Volume	Error in time to centroid (hrs)	Comments
1	33.4	12	0	1.75 mm/h	-0.6	-34.7	-3.5	Good calibration to peak. PL has better fit.
		11	13	39% loss	1.3	-1.3	-2.8	
2	26.8	16	6	1.21mm/h	1.3	-1.7	0.7	Good calibration. PL has better fit.
		14	7.5	46% loss	-15.2	-2	1.2	
3	25.4	12	20	0.8 mm/h	-2.1	9.4	0.2	OK calibration. Similar fit for CL and PL.
		10	26	10% loss	-0.7	0.3	0.5	
4	30.1	12	91	5.0 mm/h	2.2	13	1.1	OK calibration. Similar fit for CL and PL.
		11	99	49% loss	0.8	15.4	4.5	

[1] Surface runoff ie. total recorded flow – baseflow.

d_{av}=8.94km

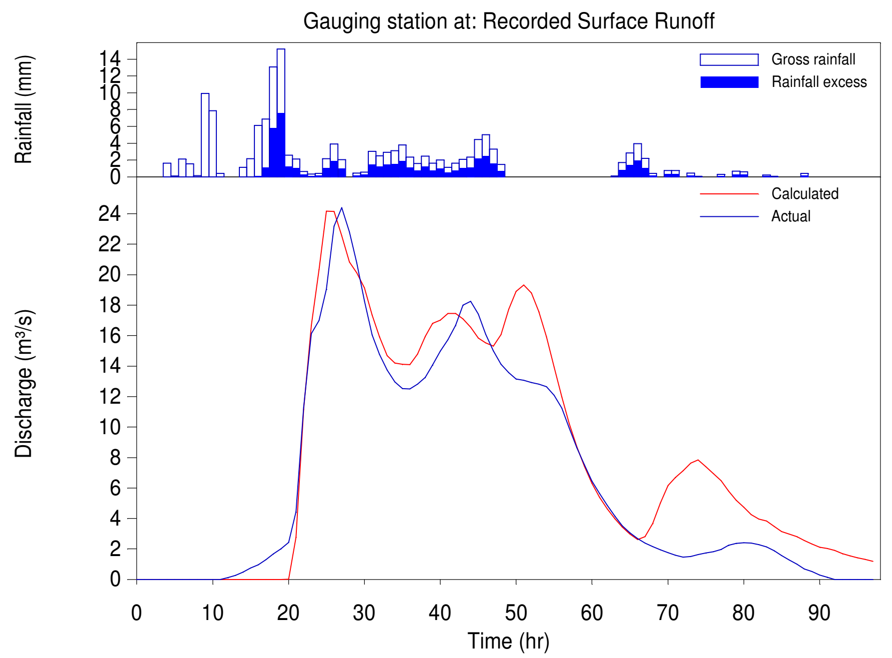
603190 Yates Flat Creek at Woonanup

Event 1 – 28/06/1978 9:00:00 AM - 2/07/1978 9:00:00 AM



k_c = 14
IL = 44.0
CL = 2.20

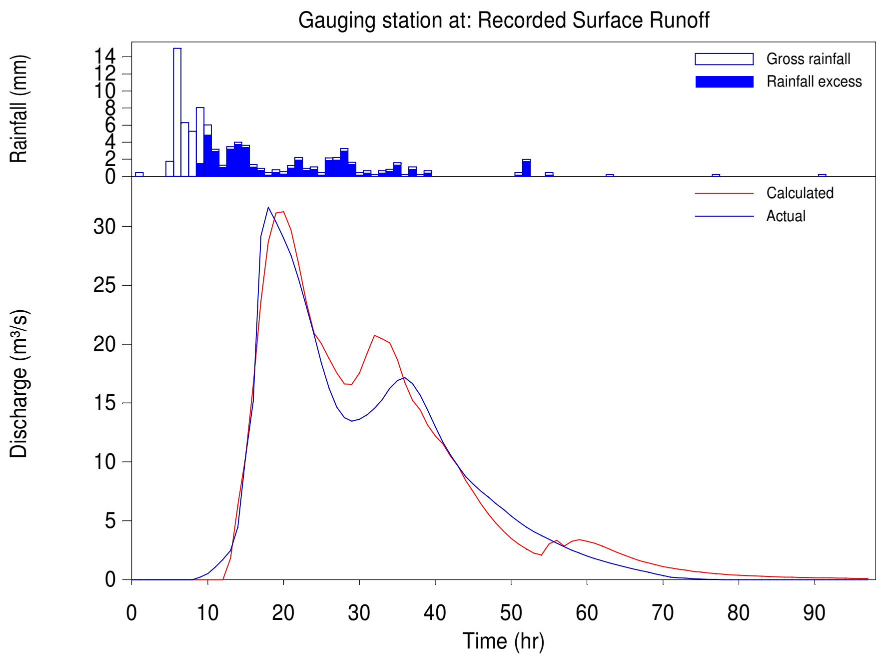
*Includes 2hr translation of calculated hydrograph.



k_c = 11
IL = 39
RoC = 0.5

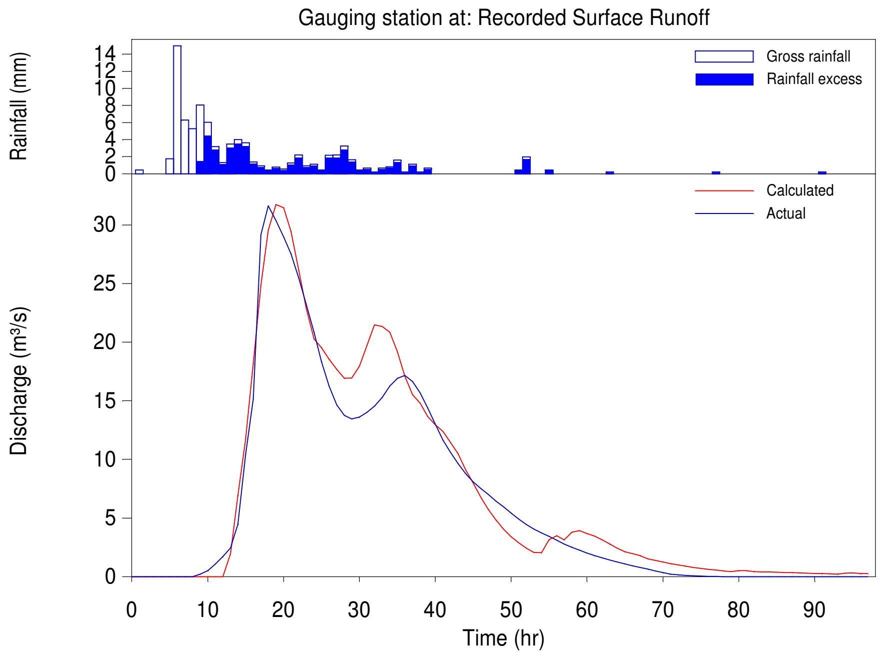
*Includes 2hr translation of calculated hydrograph.

Event 2 – 24/06/1988 9:00:00 AM - 24/06/1988 9:00:00 AM



k_c = 10
IL = 36.0
CL = 0.2

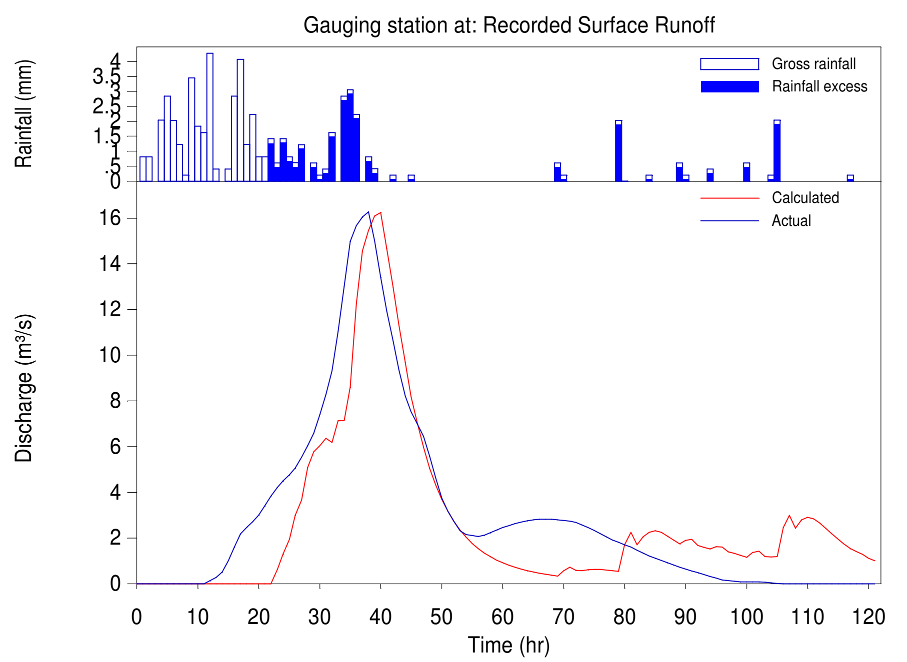
*Includes 2hr translation of calculated hydrograph.



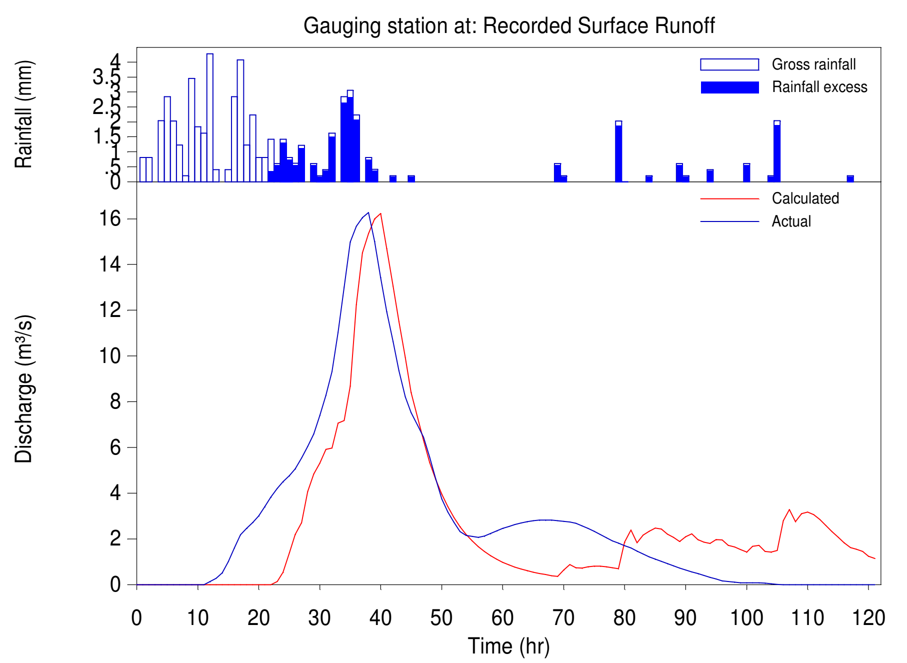
k_c =9
IL = 36.0
RoC = 0.89

*Includes 2hr translation of calculated hydrograph.

Event 3 – 20/07/1991 9:00:00 AM - 25/07/1991 9:00:00 AM

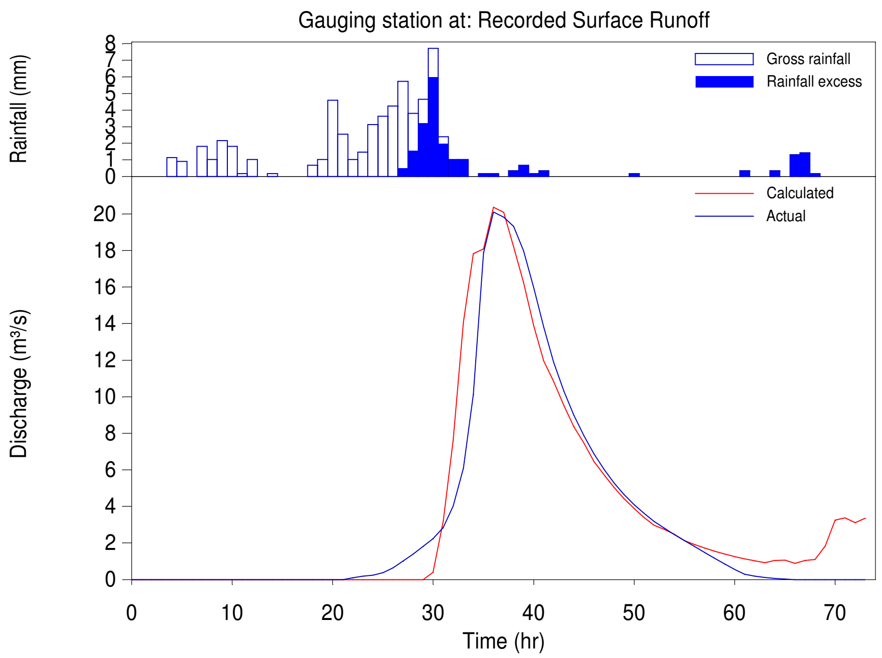


k_c = 9.00
IL = 32.0
CL = 0.21



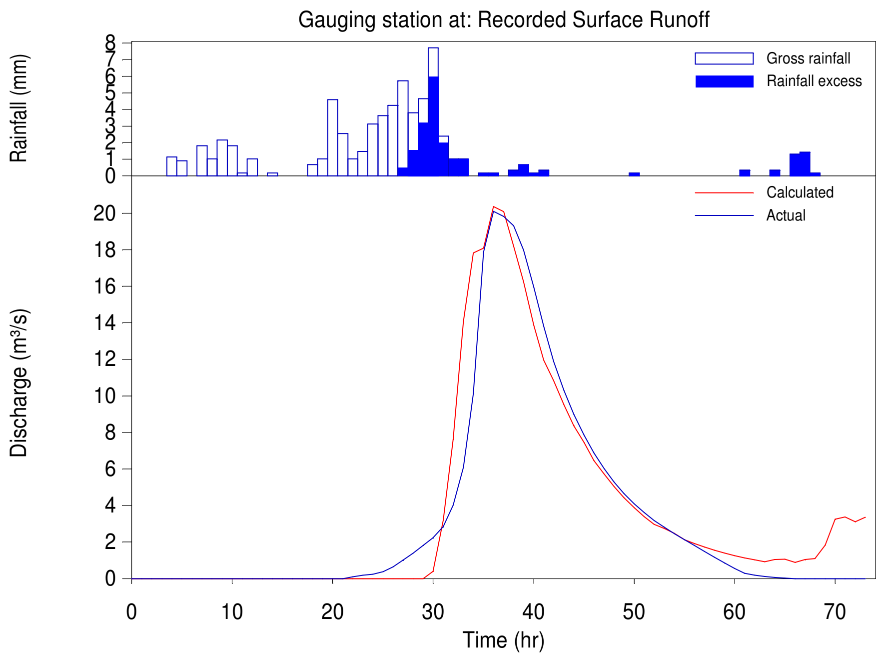
k_c = 10
IL = 35.0
RoC =0.93

Event 4 – 21/08/2003 9:00:00 AM - 24/08/2003 9:00:00 AM



k_c = 12.00
IL = 43.5
CL = 0

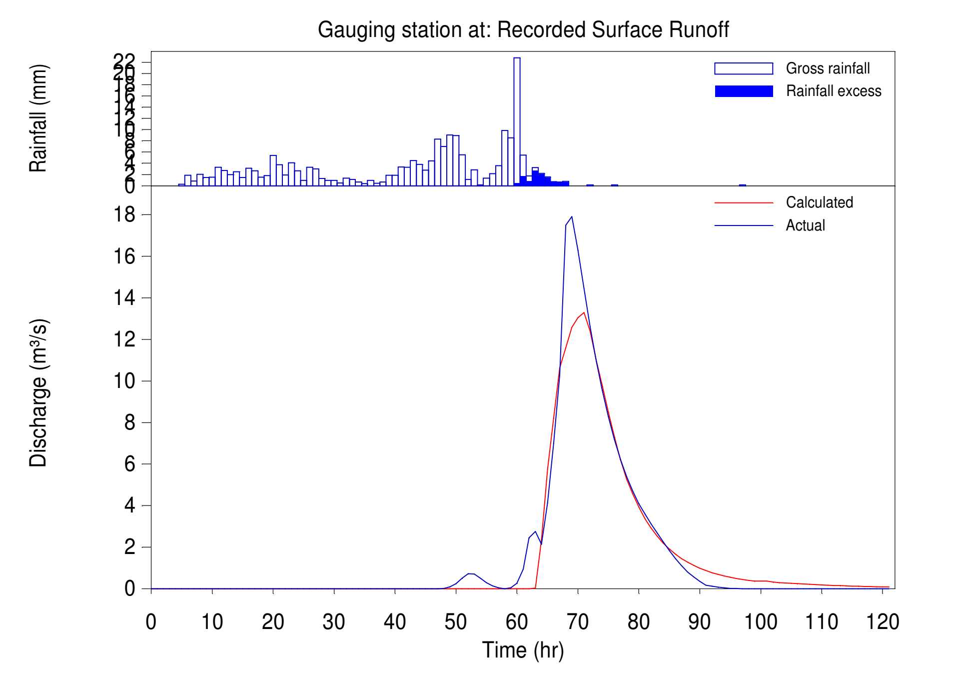
*Includes 2hr translation of calculated hydrograph.



k_c = 12.00
IL = 43.5
RoC =1.0

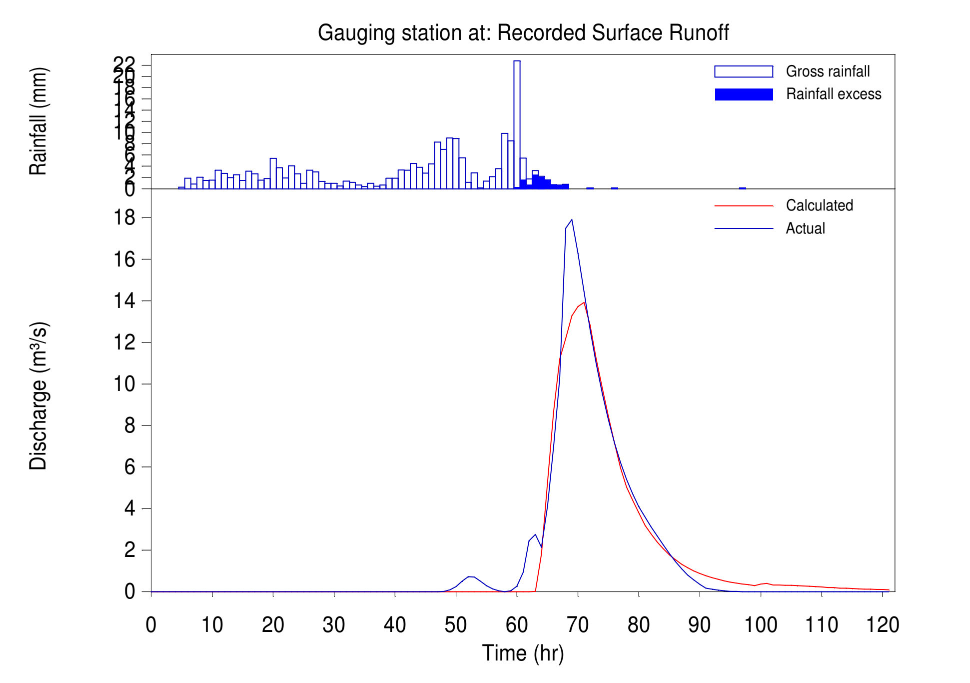
*Includes 2hr translation of calculated hydrograph.

Event 5 – 30/03/2005 9:00:00 AM - 4/04/2005 9:00:00 AM



k_c = 10
IL = 185.0
CL = 0.1

*Includes 2hr translation of calculated hydrograph.



k_c = 9
IL = 186
RoC =1
*Includes 2hr translation of calculated hydrograph.

Event	Peak Q1 (m³/s)	kc	IL (mm)	CL or PL (mm/h or %)	% difference in Peak Q	% difference in Volume	Error in time to centroid (hrs)	Comments
1	24.4	14	44	2.2	-2.8	-18.9	0.7	Good fit. PL provides better fit to whole hydrograph. 2hr translation applied to calculated hydrograph.
		11	39	50%	-1	19.6	4.5	
2	31.6	10	36	0.2	-1.2	6	0.9	OK fit. Similar fit between CL and PL. 2hr translation applied to calculated hydrograph
		9	36	11%	0.3	9.3	1.3	
3	16.3	10	34	0.12	-0.2	-9.5	11.4	OK fit. Pluvio data seems off.
		10	35	7%	-0.2	-7.4	13.3	
4	20.1	12	43.5	0	1.3	10.6	2.3	Poor fit. Same fit for CL and PL. 2hr translation applied to calculated hydrograph
		12	43.5	0%	1.3	10.6	2.3	
5	17.9	10	185	0.1	-25.8	-6.1	2.5	OK fit. Can't get the peak. Similar fit for CL and PL. 2 hr translation applied to calculated hydrograph.

[1] Surface runoff ie. total recorded flow – baseflow.

d_{av}= 6.14km

Appendix C Generalisation of catchment lag

In order to determine the rainfall that contributes to the runoff, it is necessary to determine the lag between when the rainfall falls and the surface runoff is detected at the gauge. The calibration results were analysed in order to determine whether the catchment lag can be predicted by catchment characteristics.

The RORB manual states that the model lag applied is based on the following equation:

$L = k_c Q^p$ (equation C-1)

Where *L* is the lag (hrs), *Q* is the mean outlet discharge (m^3/s), k_c is the routing parameter and *p* is a constant with a value in the order of -0.25.

The lag between the centroid of the rainfall hyetograph to the centroid of the recorded runoff hydrograph was extracted from the RORB calibration events. This analysis was performed using the calculated lag, which is based on the calculated hydrograph obtained from the calibration parameters, rather than the recorded hydrograph. The main reason for using the calculated hydrograph was to be able to compare the lag to the k_c parameter.

Initially, the RORB formulation for lag was investigated (equation C-1), replacing the average flow with the peak flow. The exponent *p* was estimated by fitting the equation for each of the catchments individually. This yielded a *p* value of between -0.02 and -0.13, a median value of -0.1 and an average of -0.097. A *p* value of -0.1, and k_c parameters obtained from the continuing loss calibration fits for each event were applied to equation C-1 to derive estimates of lag for each event, as shown in Figure C-1. This shows that this equation is generally quite good at estimating the lag, although it slightly over-predicts compared to RORB's lag calculations. The design k_c parameters for each catchment from the continuing loss model (shown in Table 3-2) were then applied to the equation, and the result is shown in Figure C-2. This shows that there is more spread, but the average lag across the events is close to the 1 to 1 line.

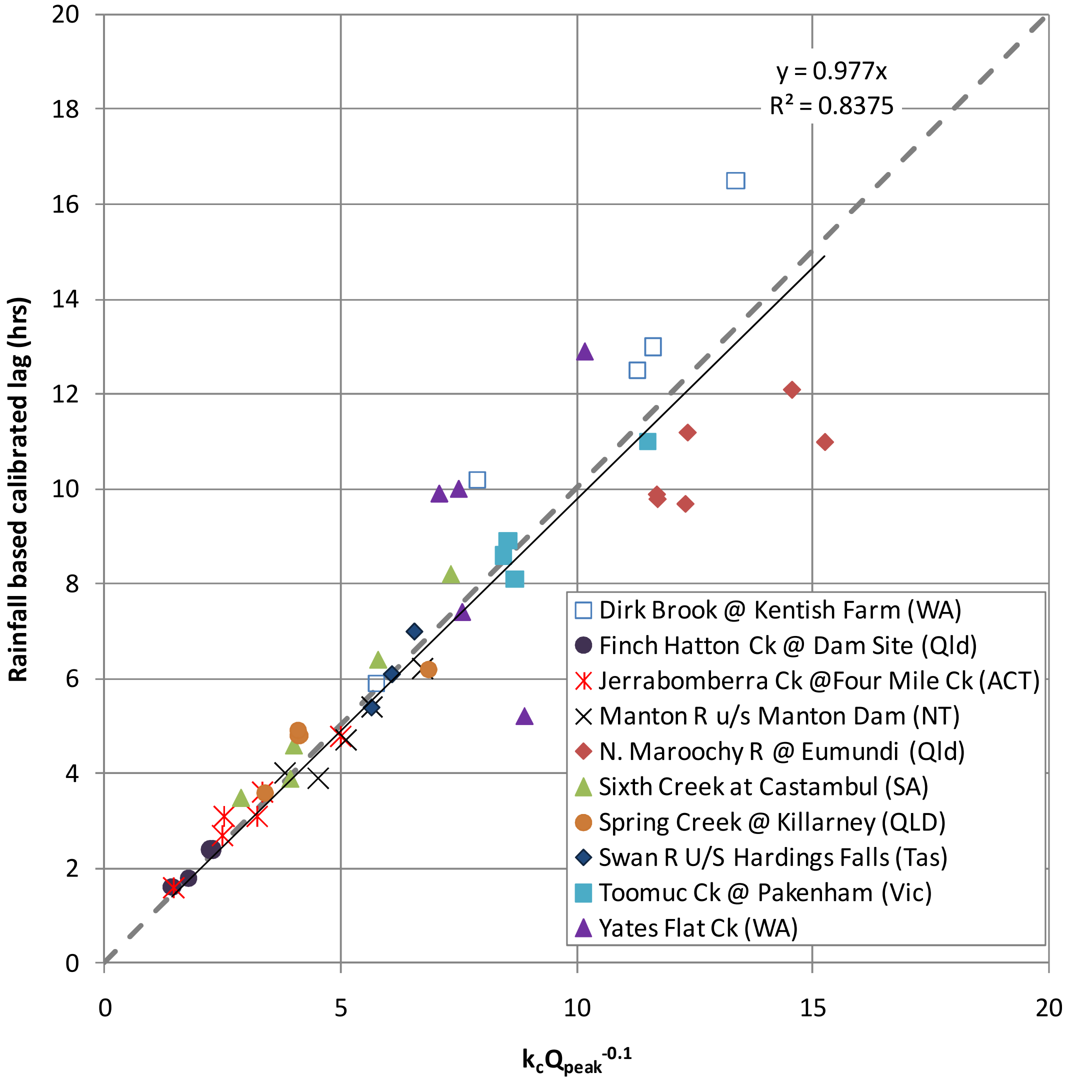


Figure C-1: Comparison of predicted lag using a formula based on the rainfall based lag equation, applying k_c parameters obtained from the continuing loss fit for each event.

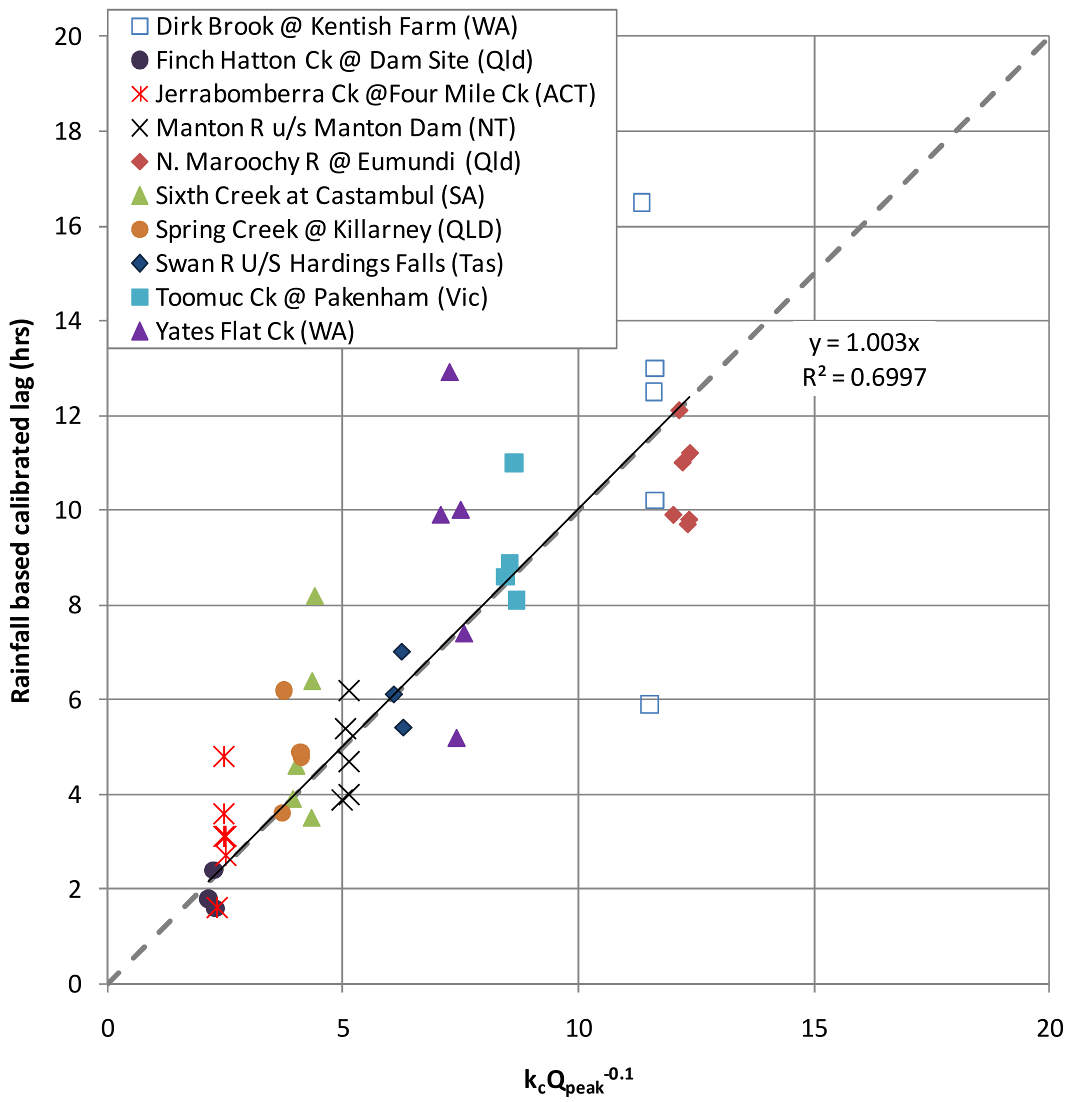


Figure C-2: Comparison of predicted lag using a formula based on the rainfall based lag equation.

As the idea is to apply the lag to catchments that have not been calibrated using a RORB model, and therefore do not have a k_c parameter available, area, d_{av} and flow were considered as variables that could explain the lag. This is shown in Figure C-3, and shows that the fit is not very good for any of the formulations attempted, with the lag being over-predicted for lower lags, and under-predicted for higher lags.

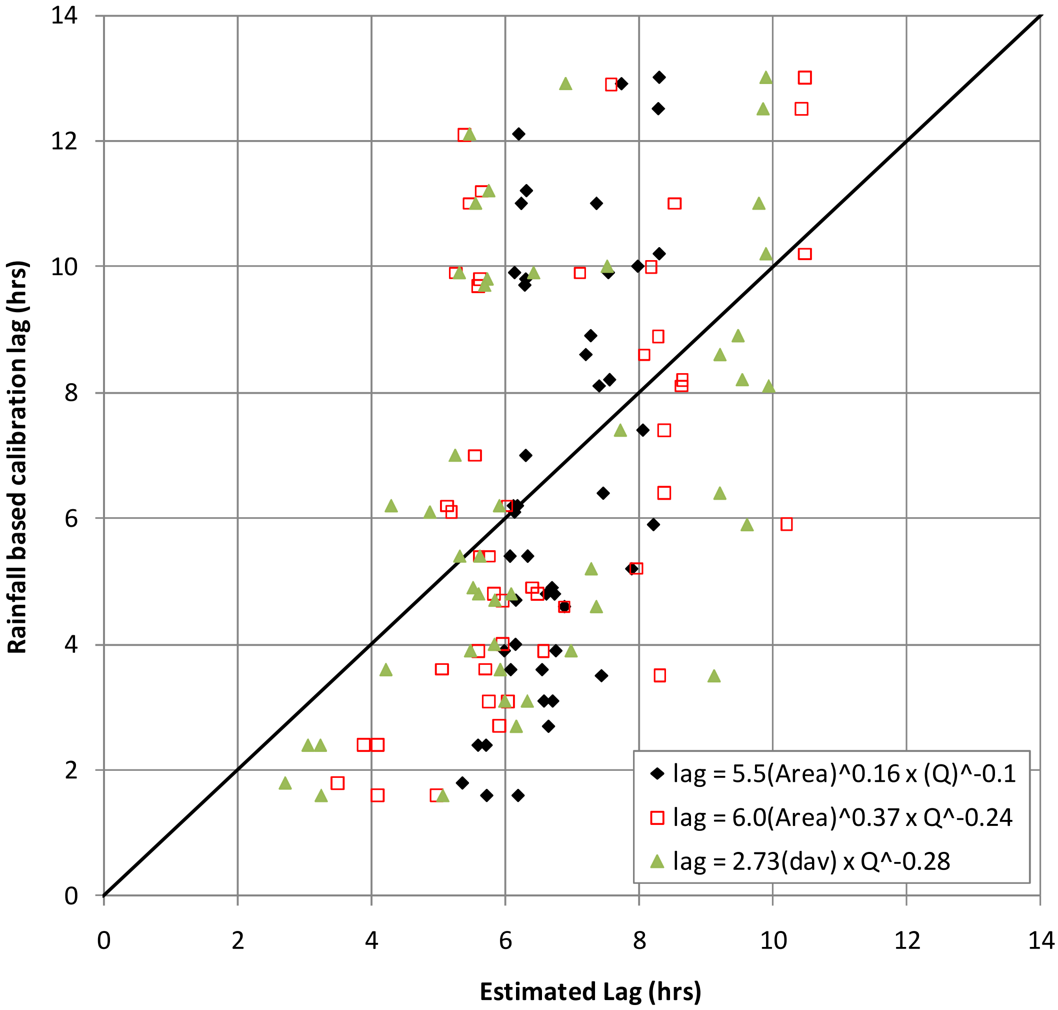


Figure C-3: Area, d_{av} and peak flow as variables to describe lag.

Appendix D Storm durations

This appendix summarises the duration of complete storms analysed to estimated loss values.

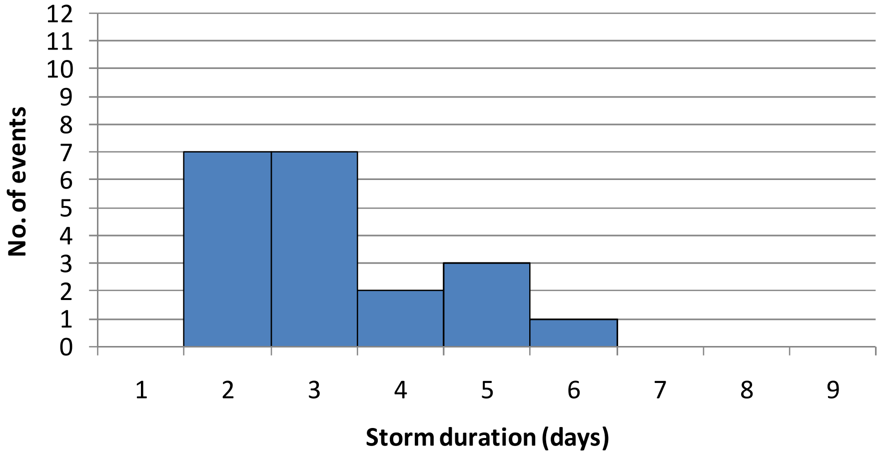


Figure D-1 Duration of storms analysed for Dirk Brook at Kentish Farm

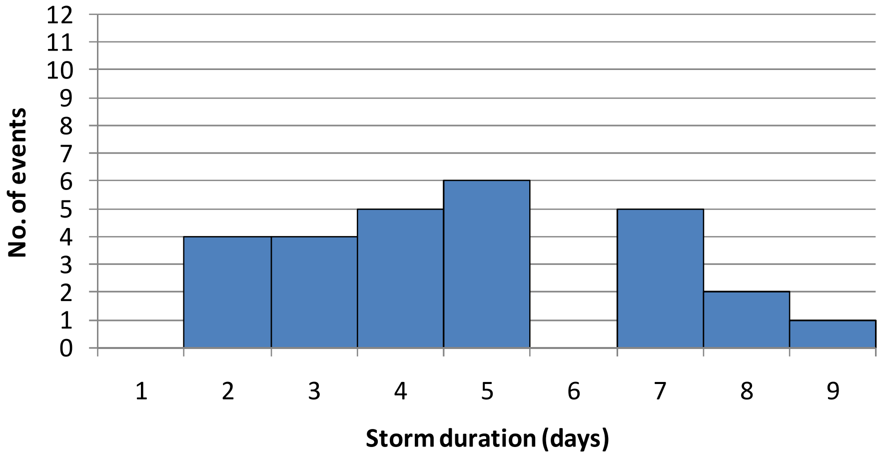


Figure D- 2 Duration of storms analysed for Finch Hatton Creek at Dam Site

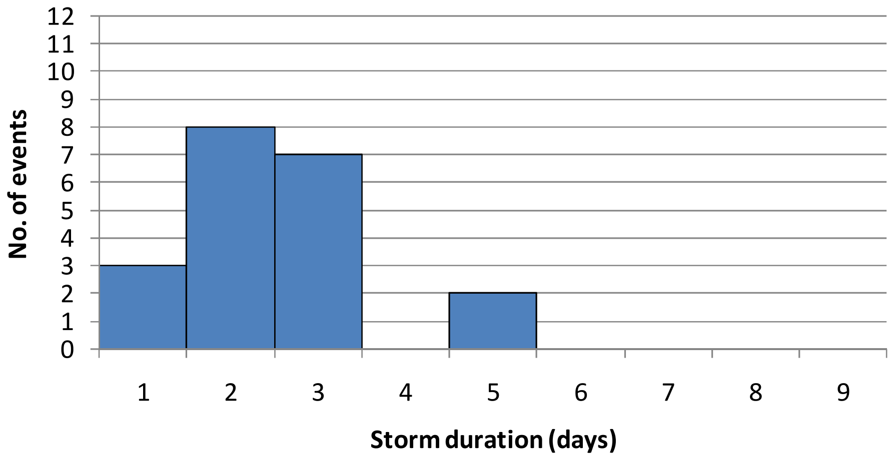


Figure D- 3 Duration of storms analysed for Jerrabomberra Creek at Four Mile Creek

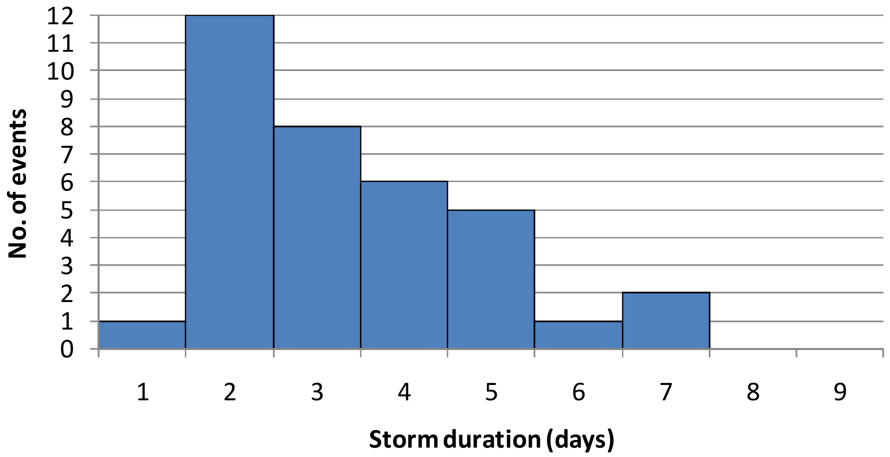


Figure D-4 Duration of storms analysed for Manton River upstream Manton Dam

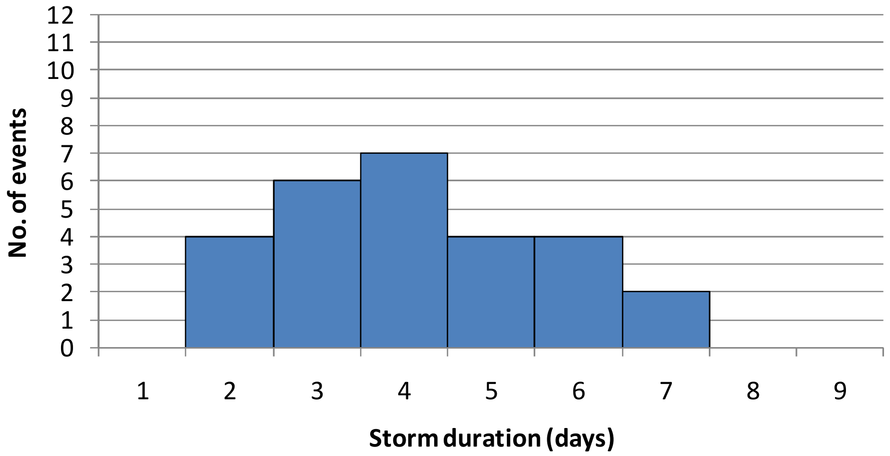


Figure D-5 Duration of storms analysed for North Maroochy River at Eumundi

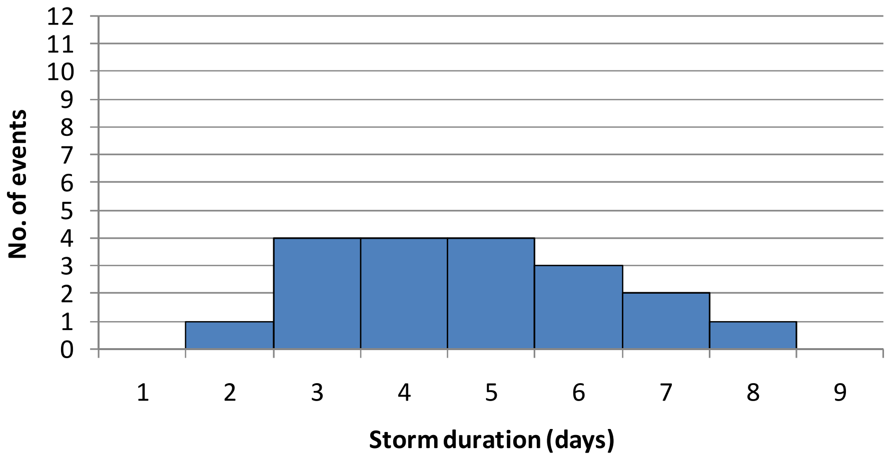


Figure D-6 Duration of storms analysed for Sixth Creek at Castambul

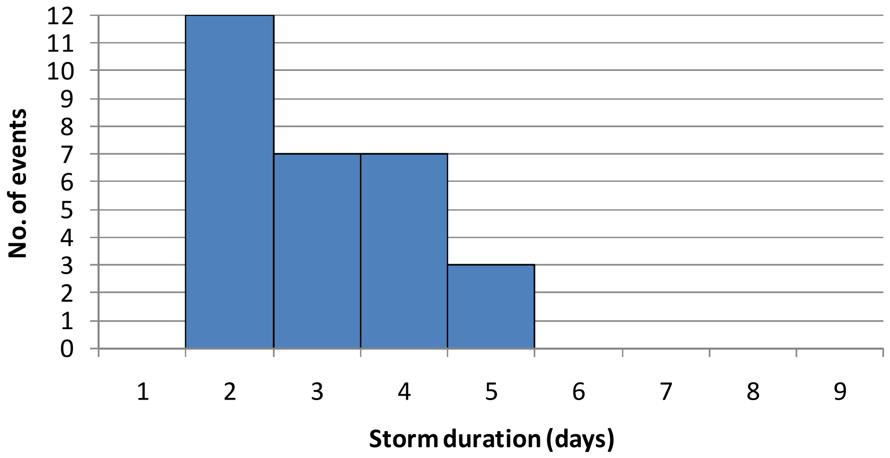


Figure D-7 Duration of storms analysed for Spring Creek at Killarney

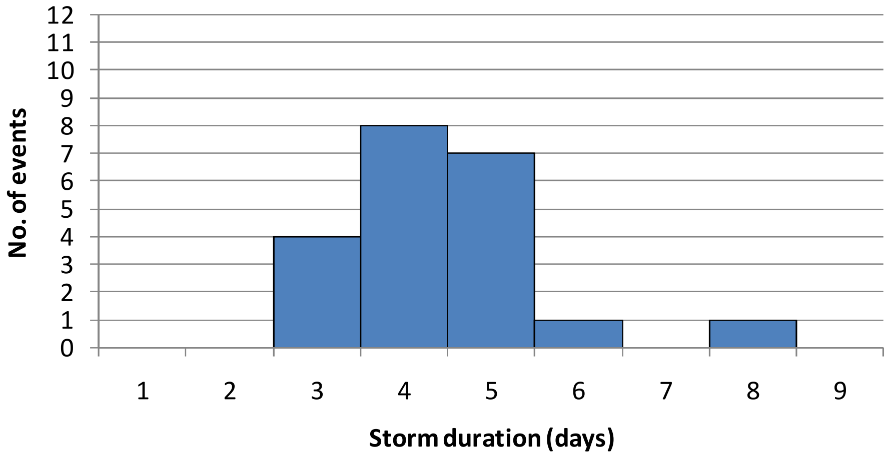


Figure D-8 Duration of storms analysed for Swan River upstream Harding Falls

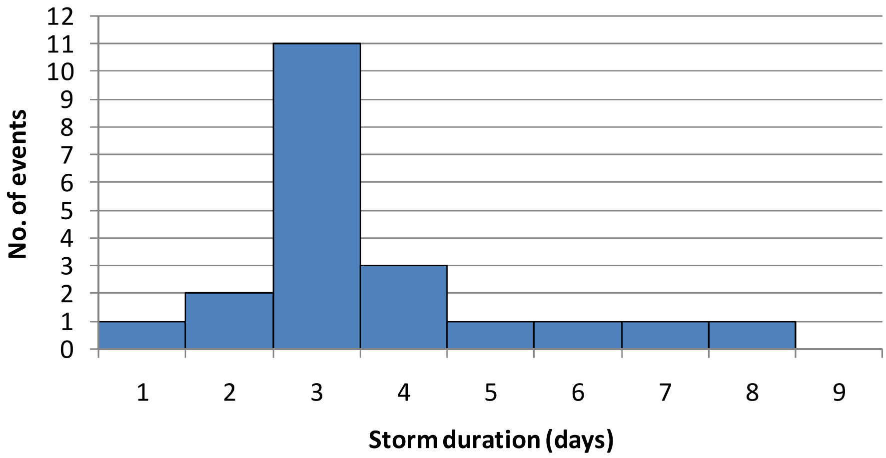


Figure D-9 Duration of storms analysed for Toomuc Creek at Pakenham

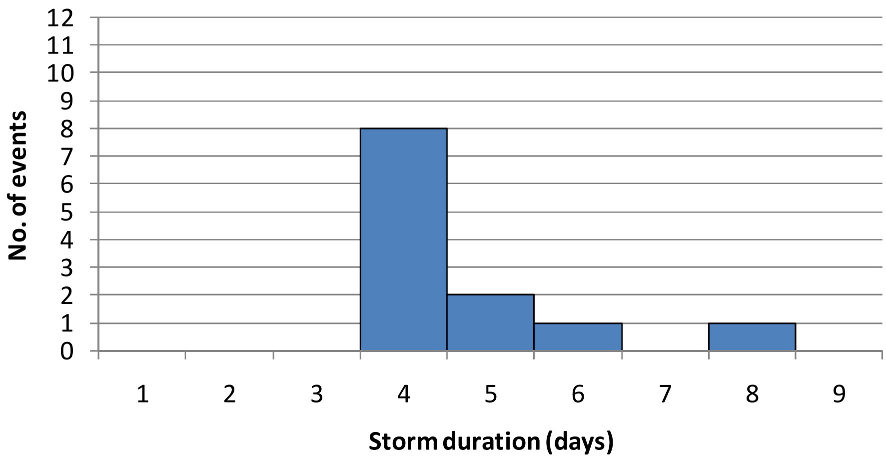
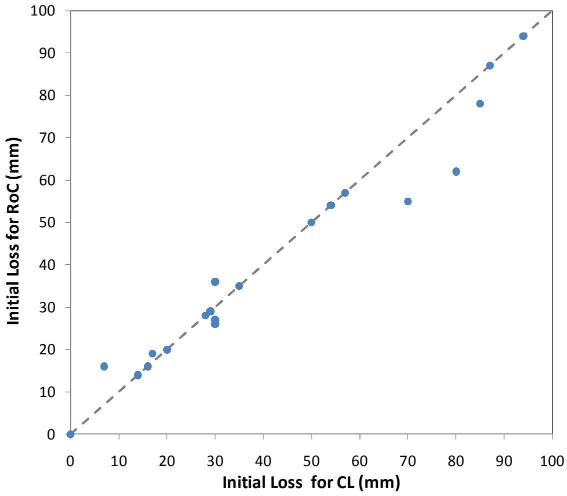
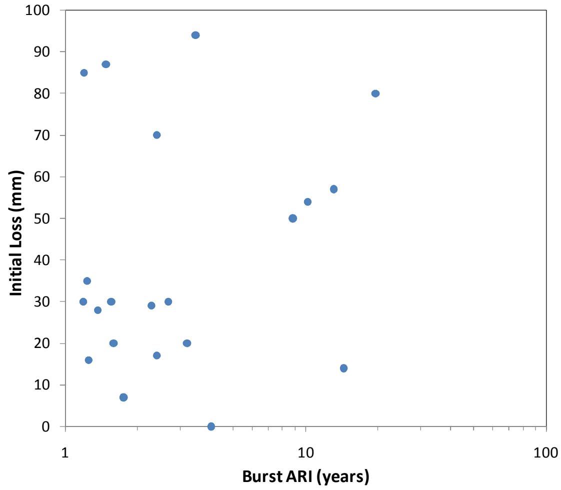


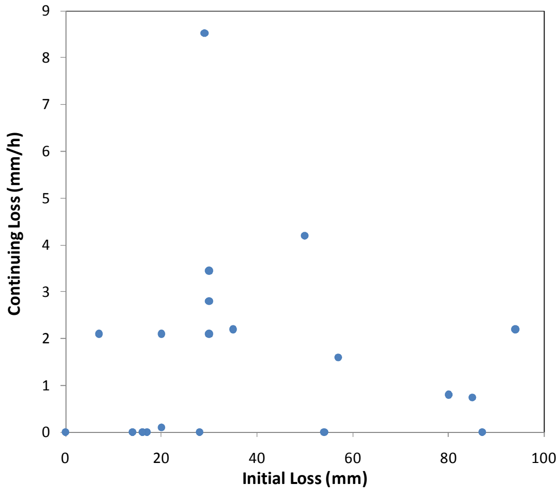
Figure D-10 Duration of storms analysed for Yates Flat Creek at Woonanup

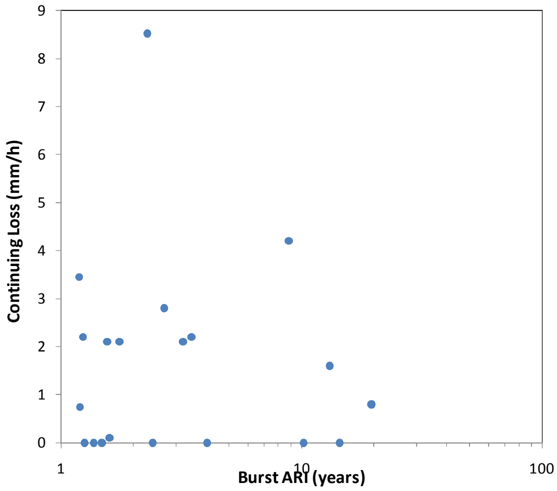
Appendix E Summary of loss values

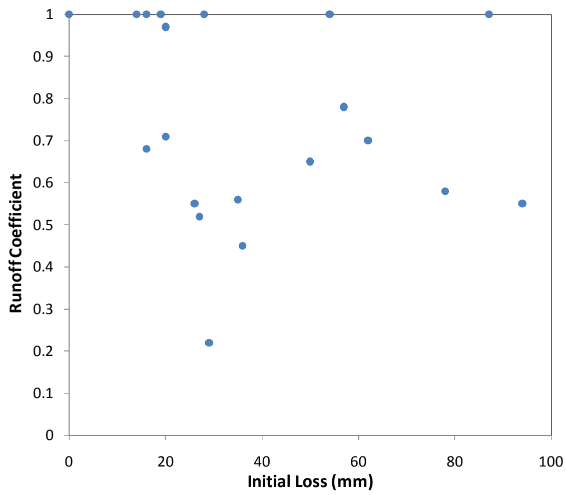
2219 Swan River upstream Harding Falls

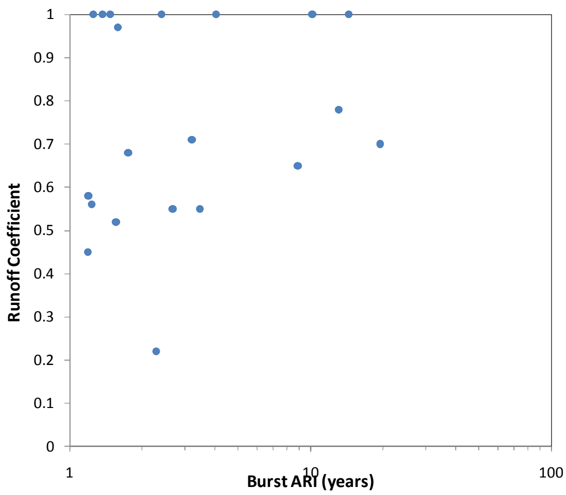


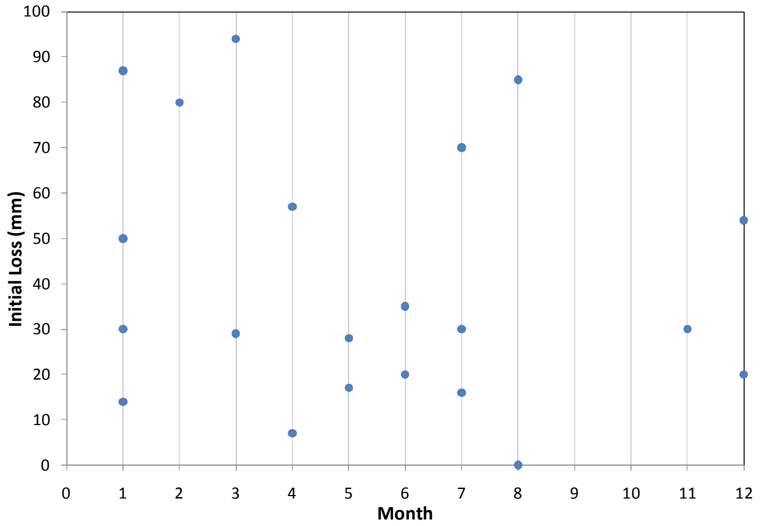


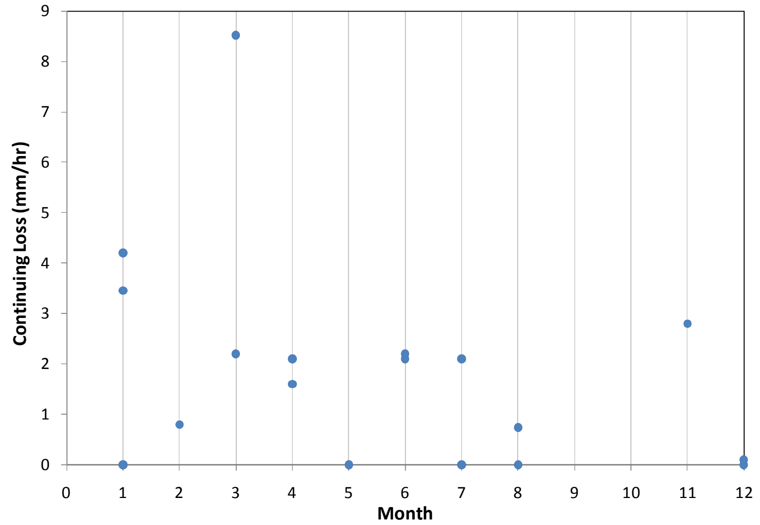


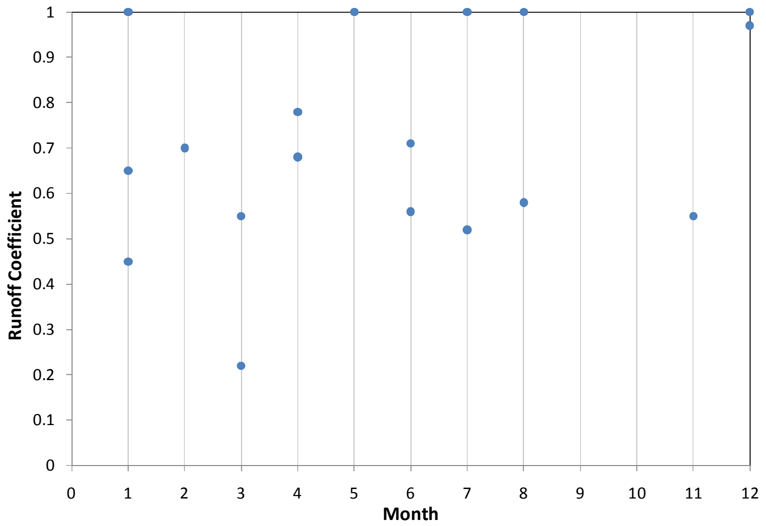




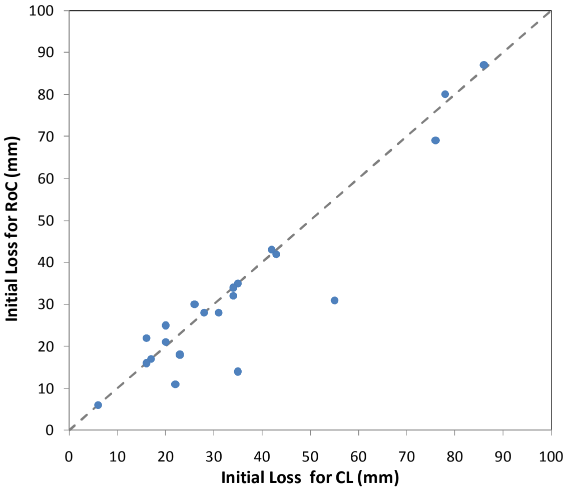


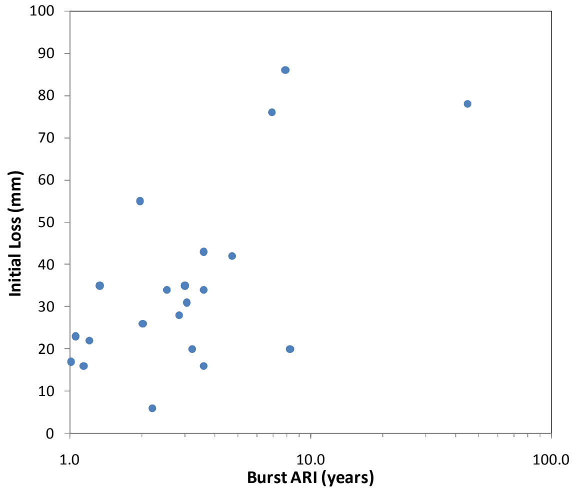

Initial Loss (mm)
Month

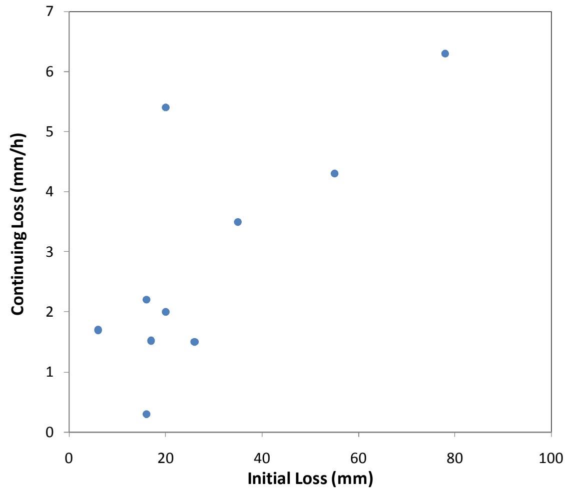

Continuing Loss (mm/hr)
Month

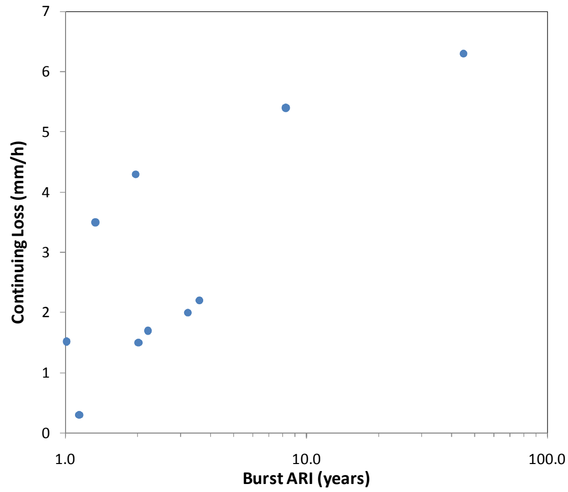

Runoff Coefficient
Month

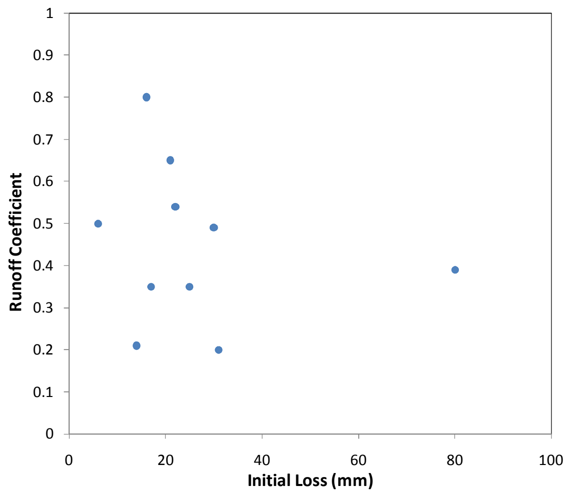
228217 Toomuc Creek at Pakenham

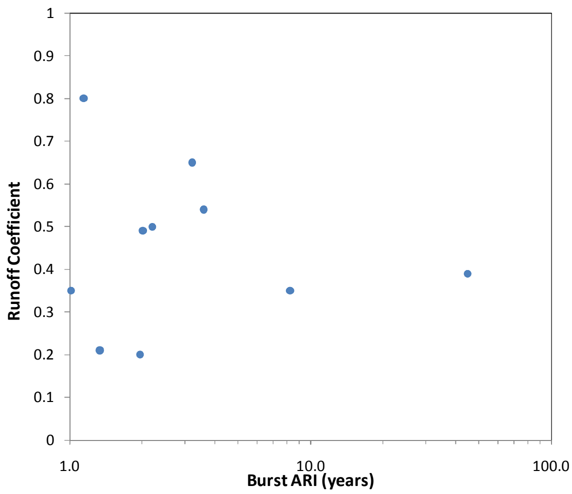


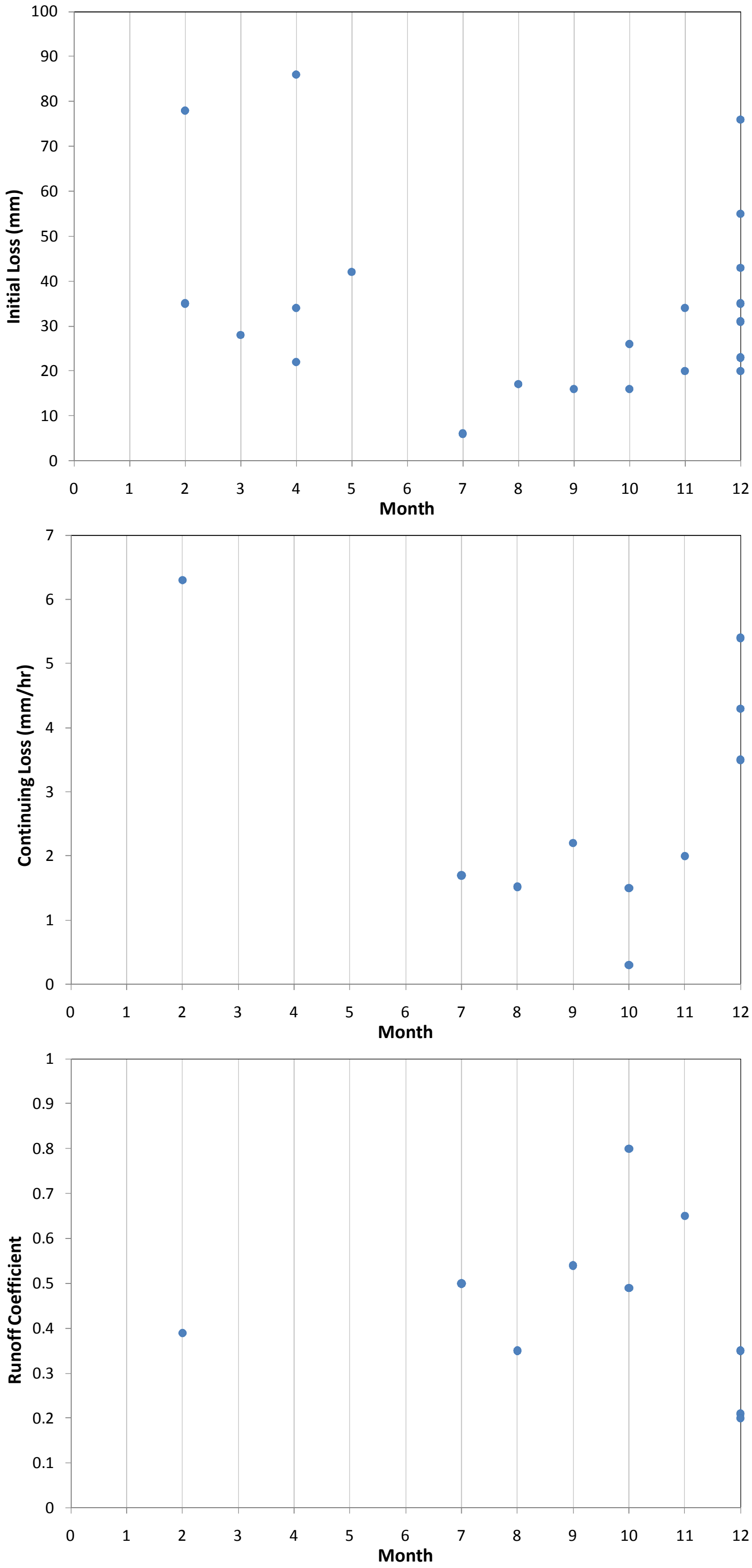




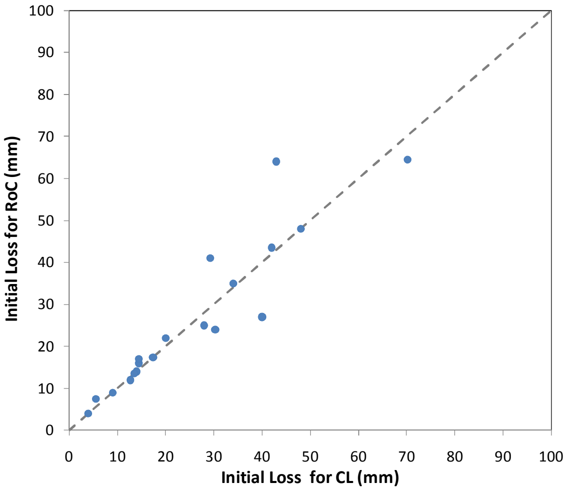


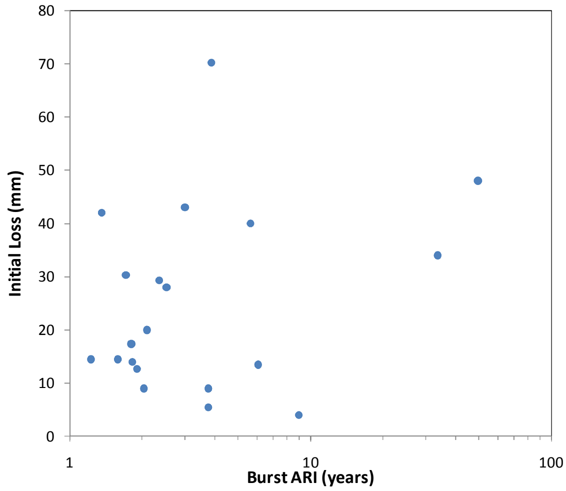


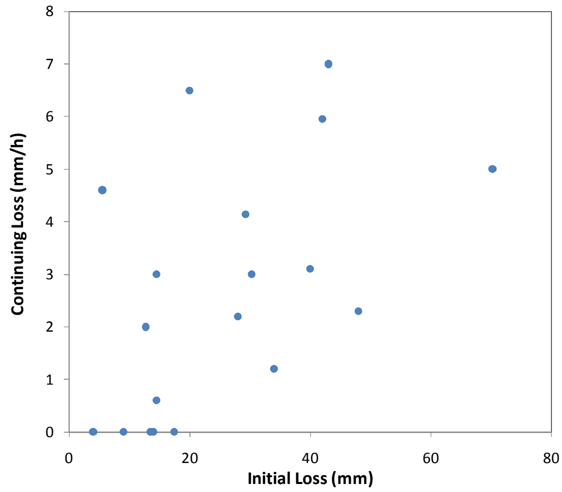


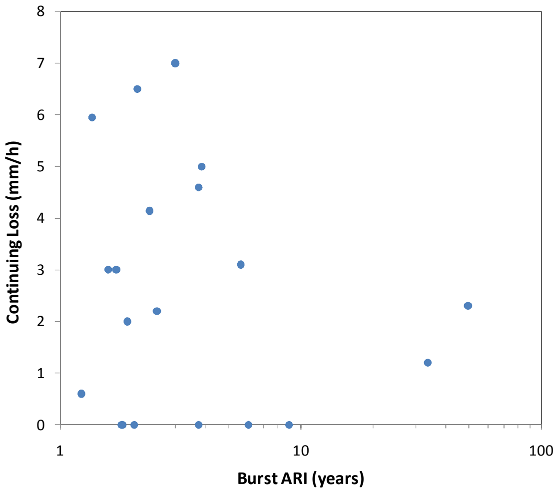

Initial Loss (mm)
Month
Continuing Loss (mm/hr)
Month
Runoff Coefficient
Month

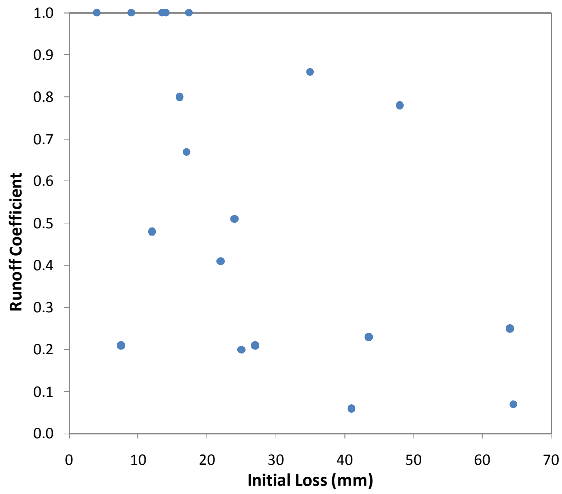
410743 Jerrabomberra Creek at Four Mile Creek

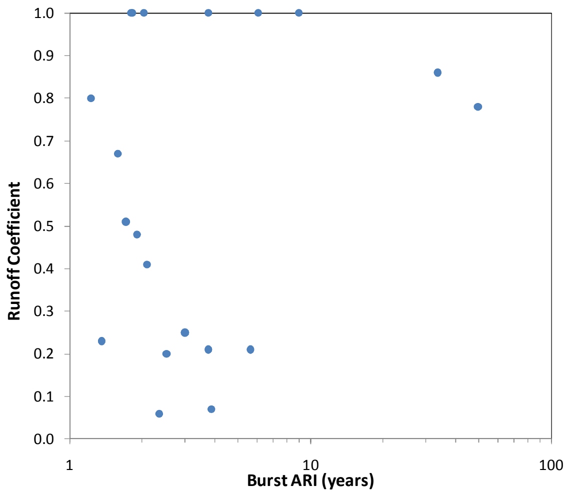


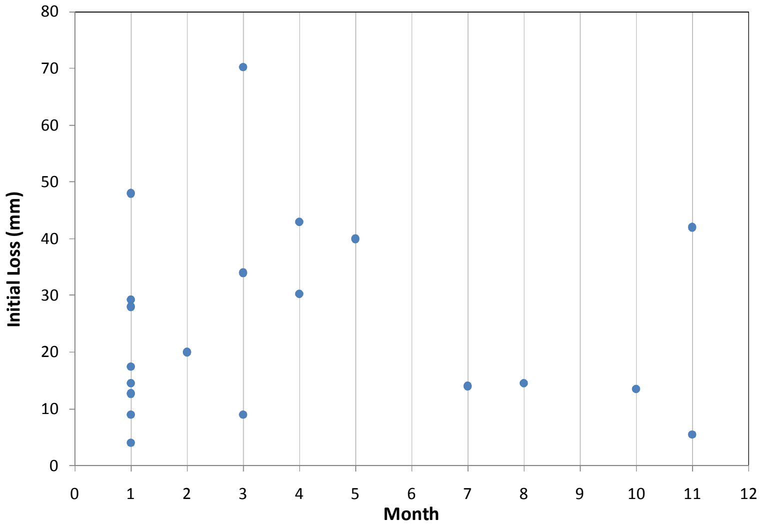




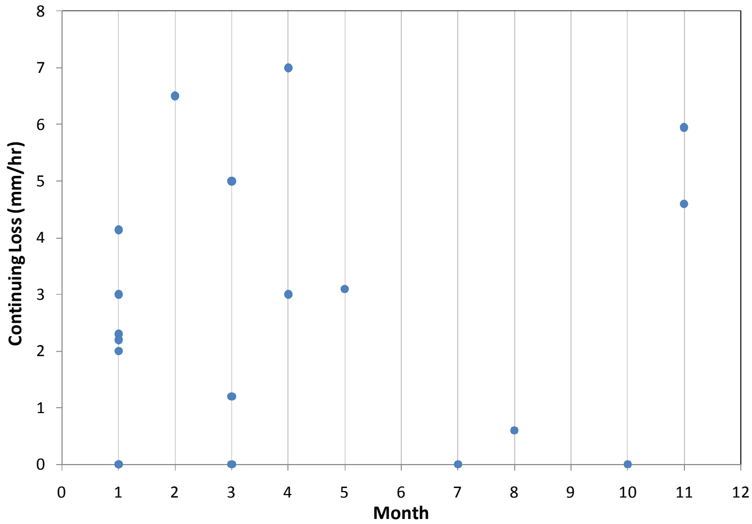




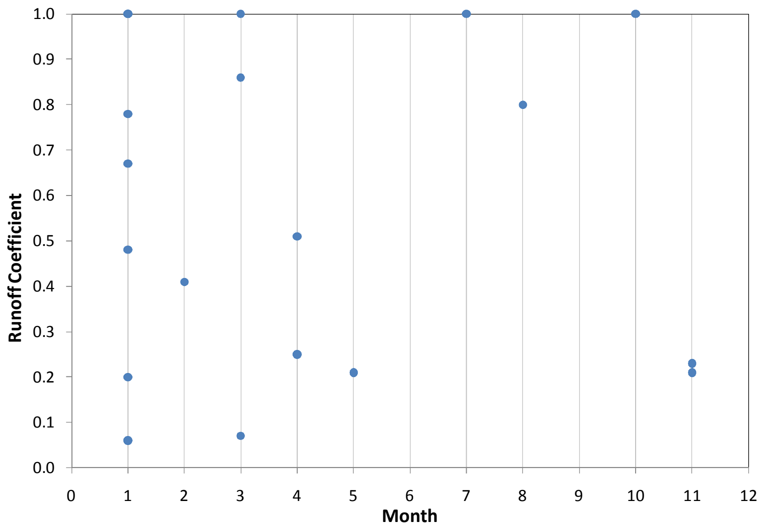




Initial Loss (mm)
0
10
20
30
40
50
60
70
80
0
1
2
3
4
5
6
7
8
9
10
11
12
Month

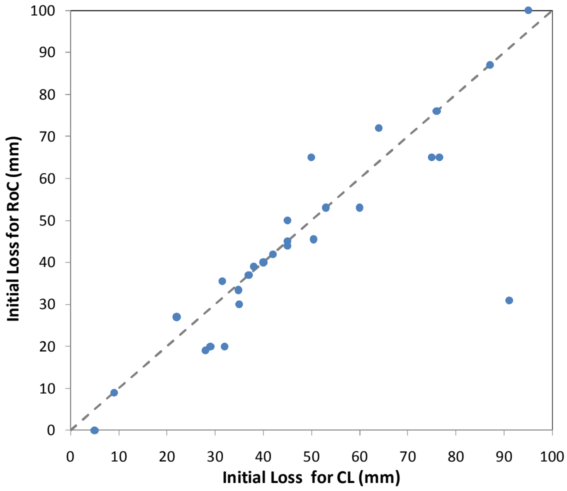


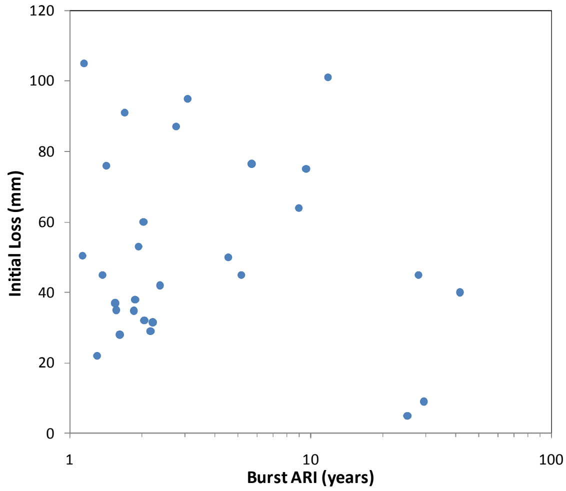
Continuing Loss (mm/hr)
0
1
2
3
4
5
6
7
8
0
1
2
3
4
5
6
7
8
9
10
11
12
Month

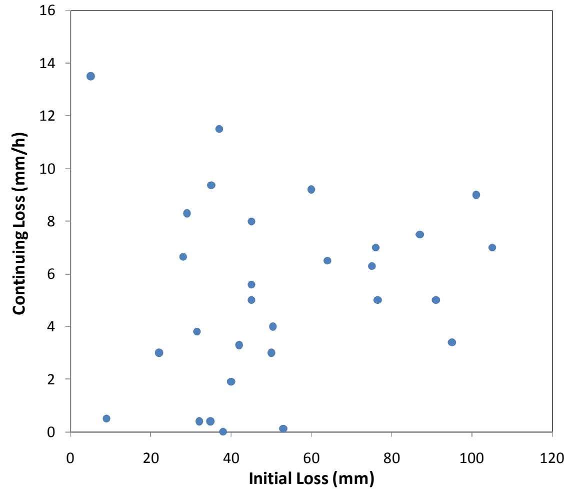


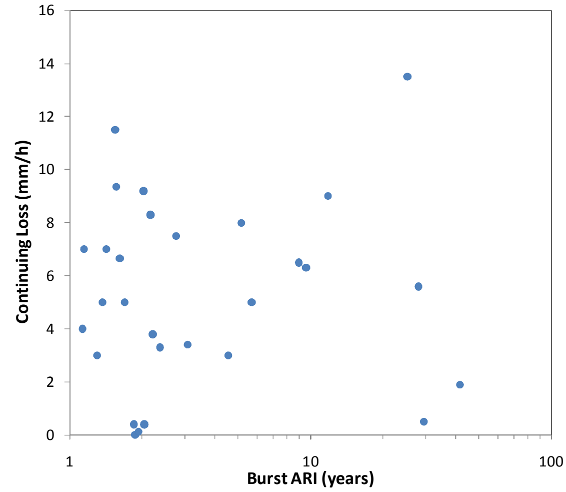
Runoff Coefficient
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
1
2
3
4
5
6
7
8
9
10
11
12
Month

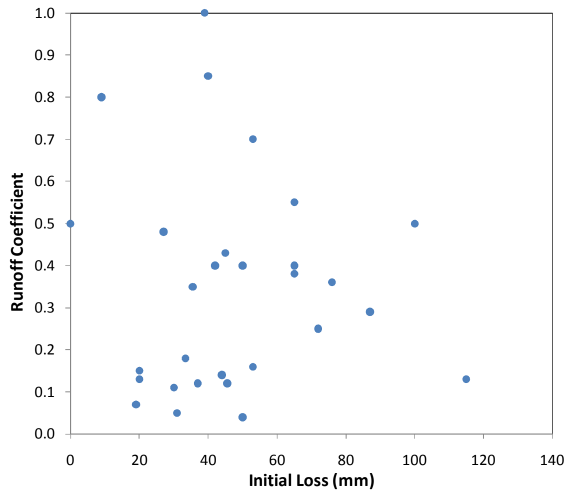
422321 Spring Creek at Killarney

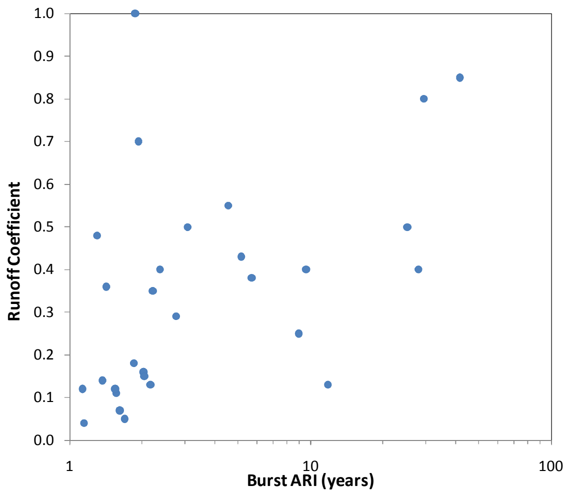


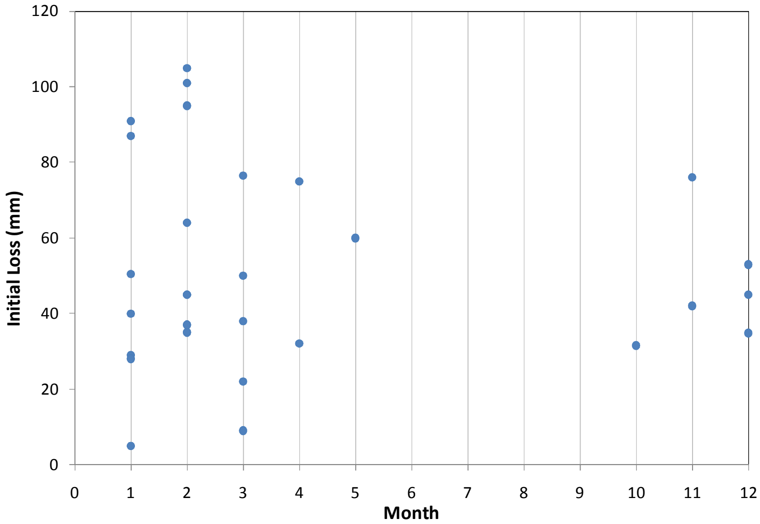


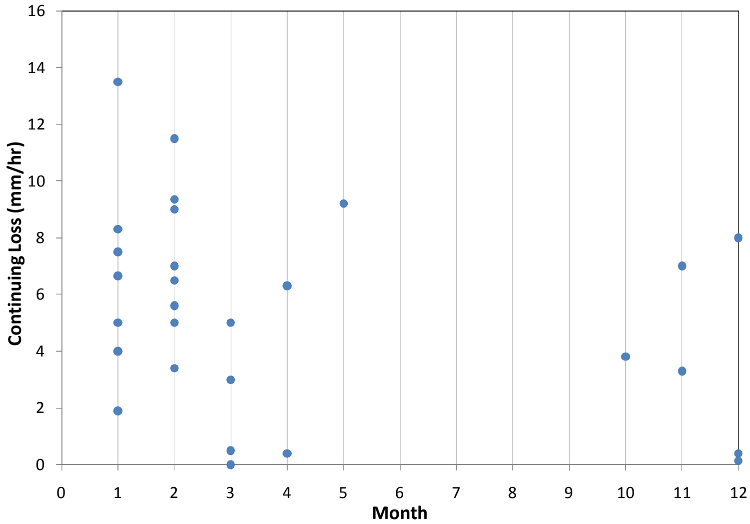


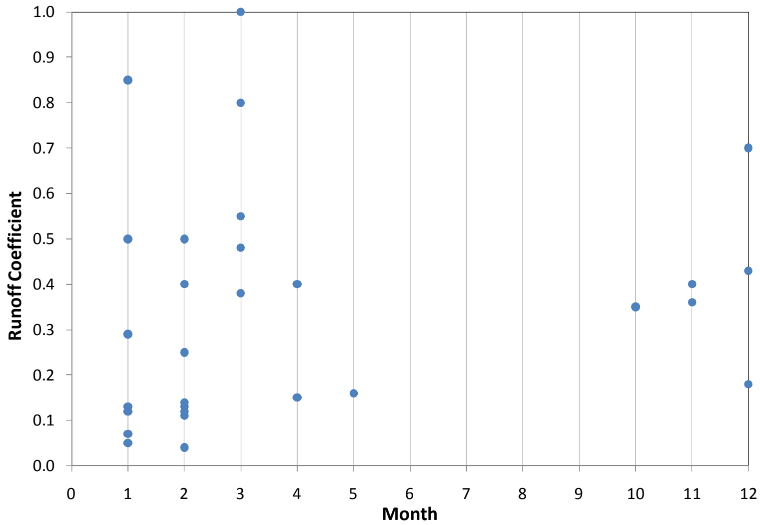




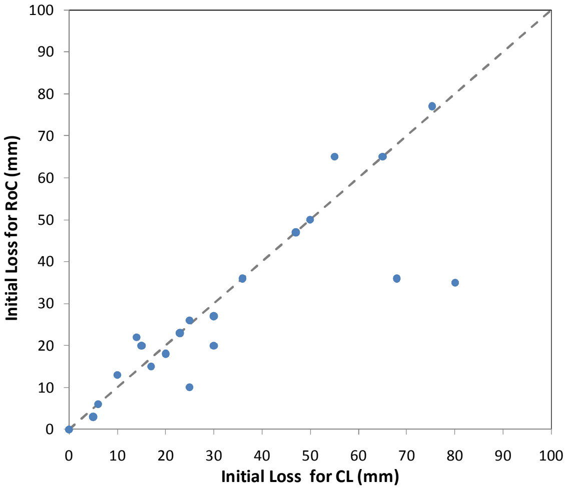


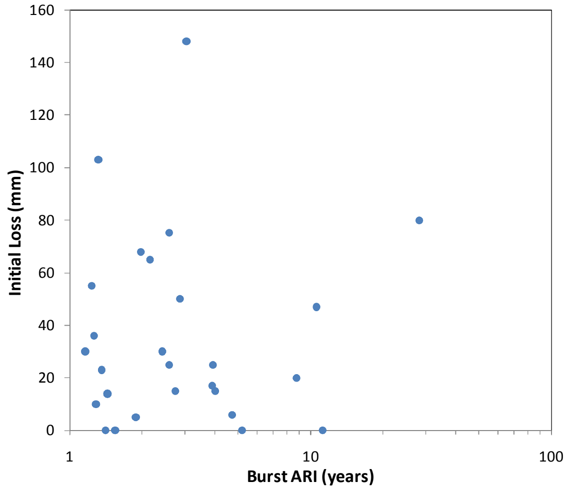

Initial Loss (mm)
Month
0
20
40
60
80
100
120
0 1 2 3 4 5 6 7 8 9 10 11 12

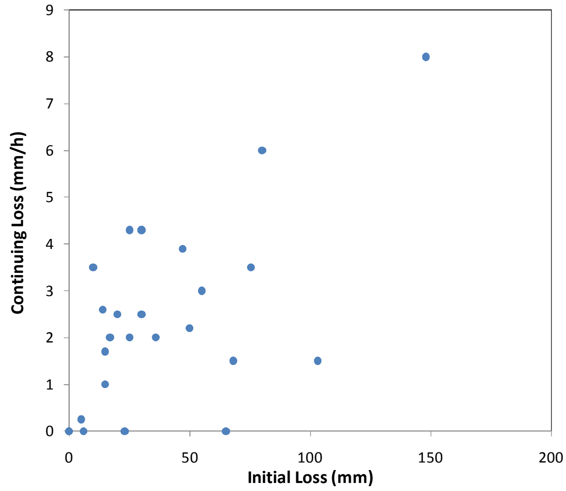

Continuing Loss (mm/hr)
Month
0
2
4
6
8
10
12
14
16
0 1 2 3 4 5 6 7 8 9 10 11 12

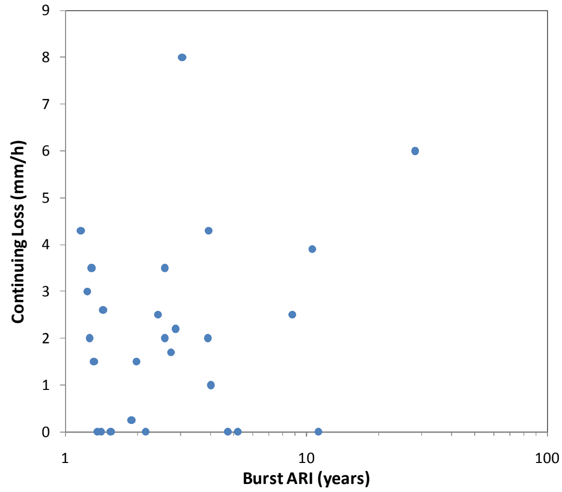

Runoff Coefficient
Month
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0 1 2 3 4 5 6 7 8 9 10 11 12

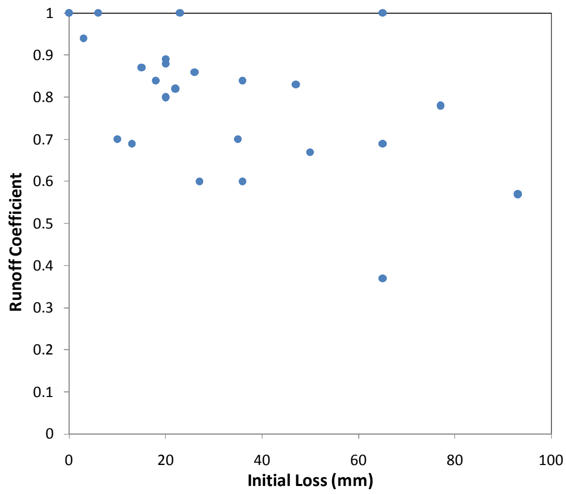
141009 North Maroochy River at Eumundi

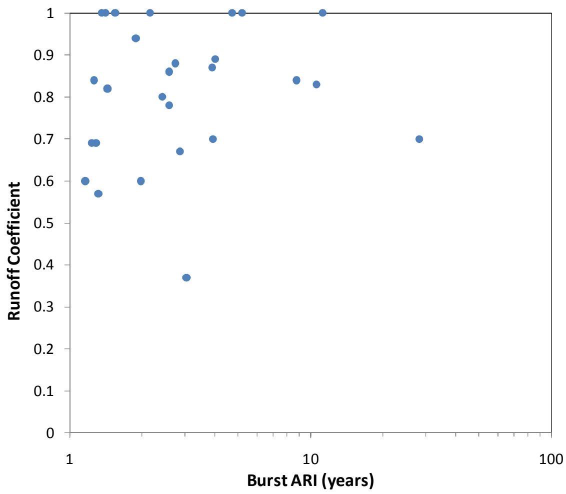


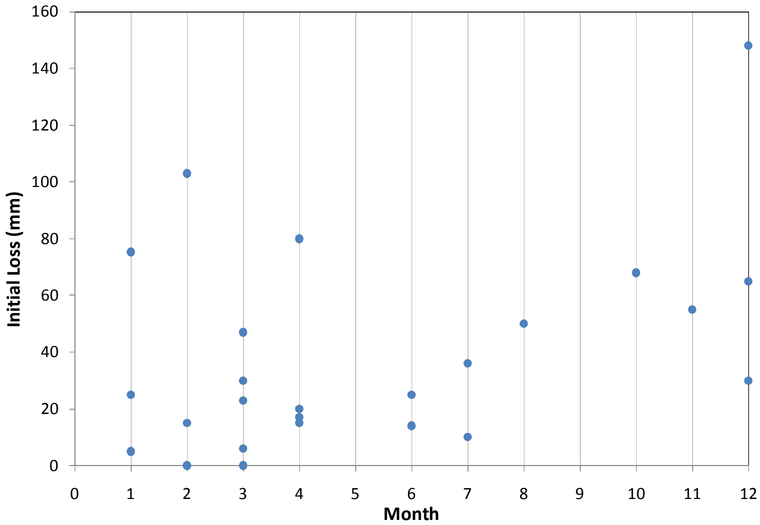


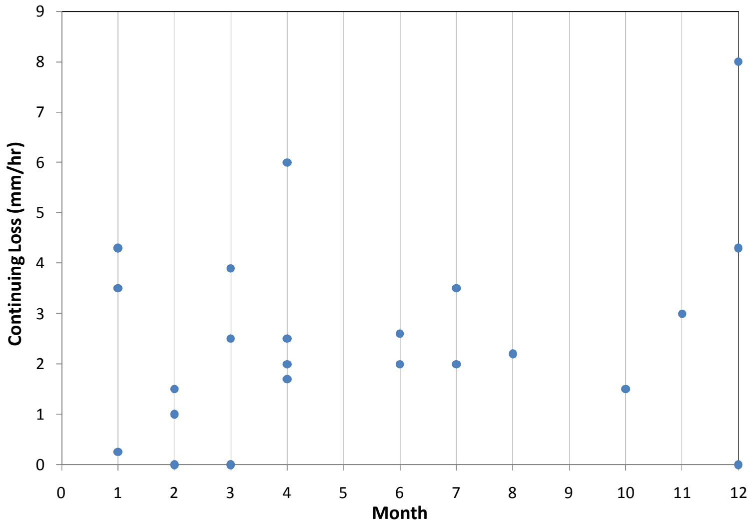


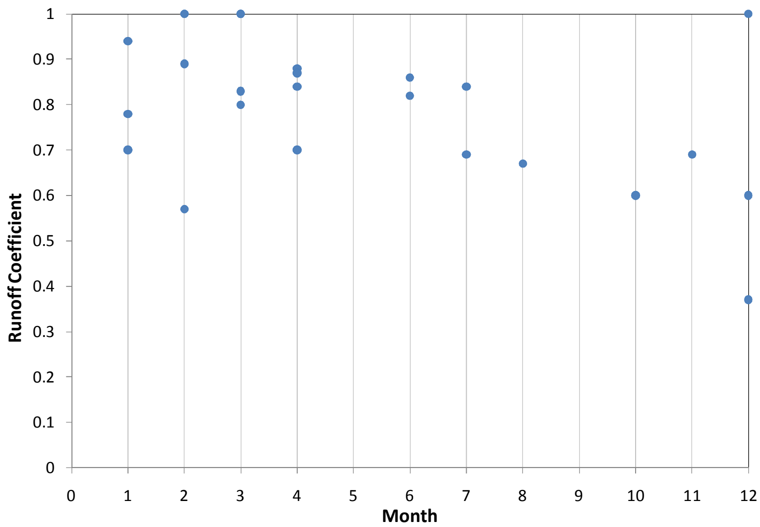




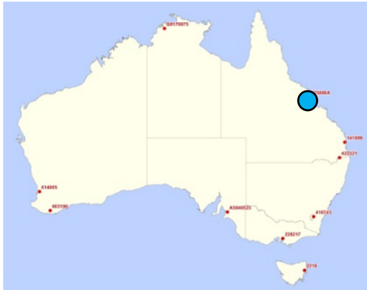


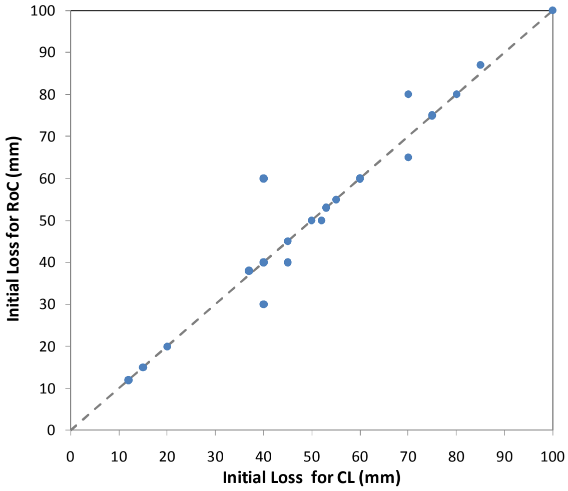

Initial Loss (mm)
Month
0
20
40
60
80
100
120
140
160
0
1
2
3
4
5
6
7
8
9
10
11
12

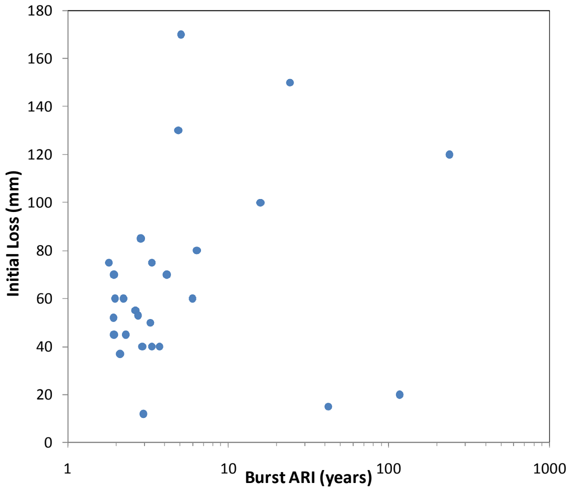

Continuing Loss (mm/hr)
Month
0
1
2
3
4
5
6
7
8
9
10
11
12

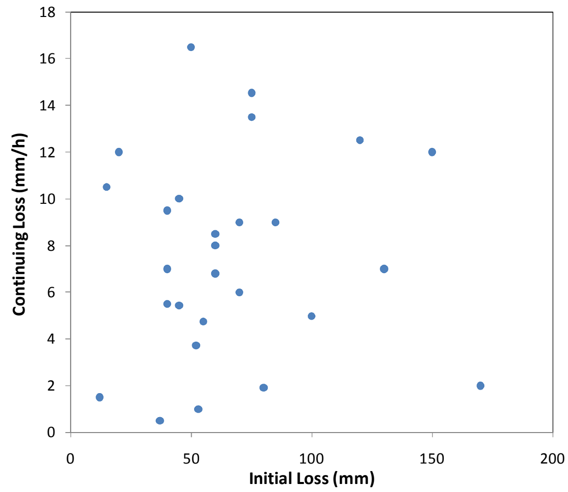

Runoff Coefficient
Month
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
1
2
3
4
5
6
7
8
9
10
11
12

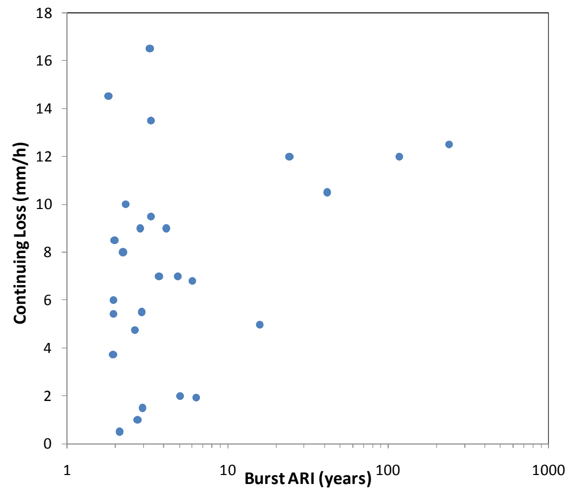
125006 Finch Hatton at Dam Site

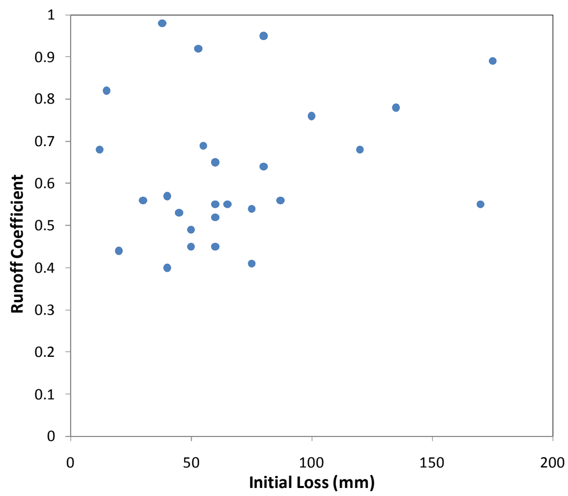


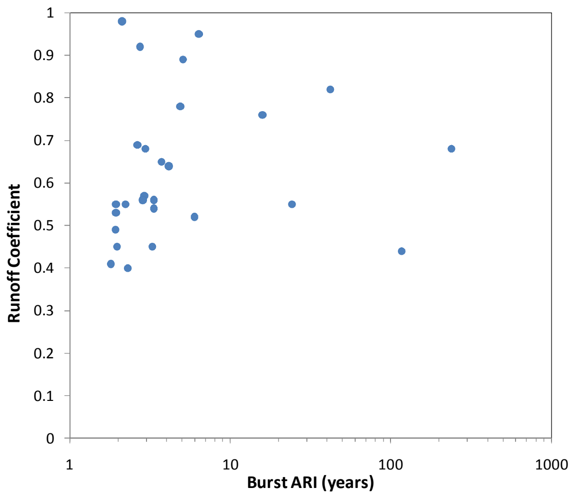


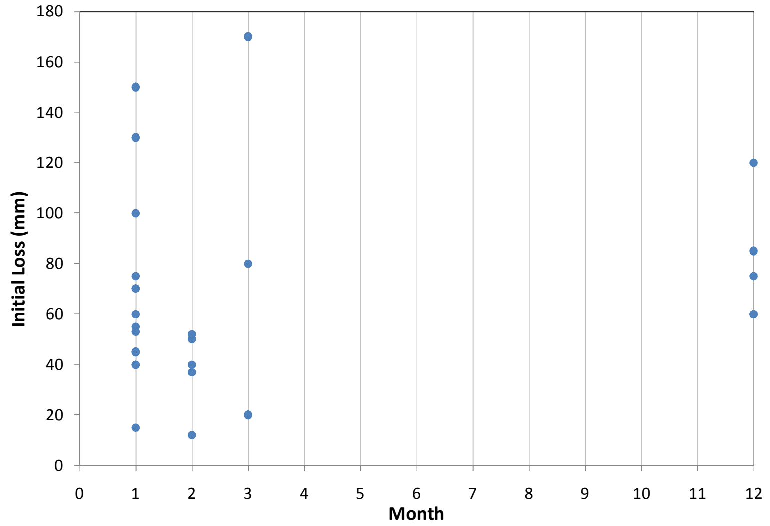


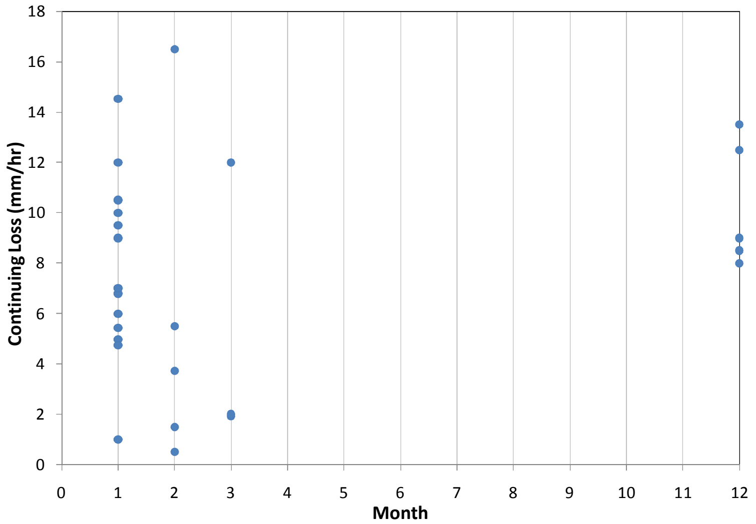


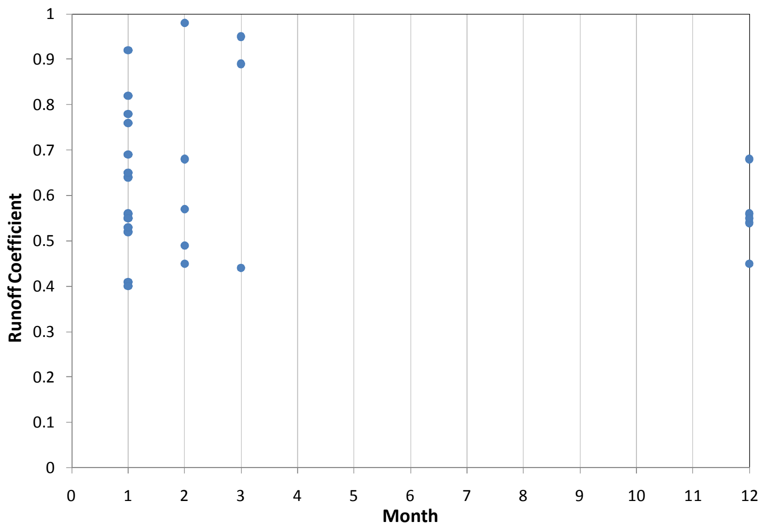




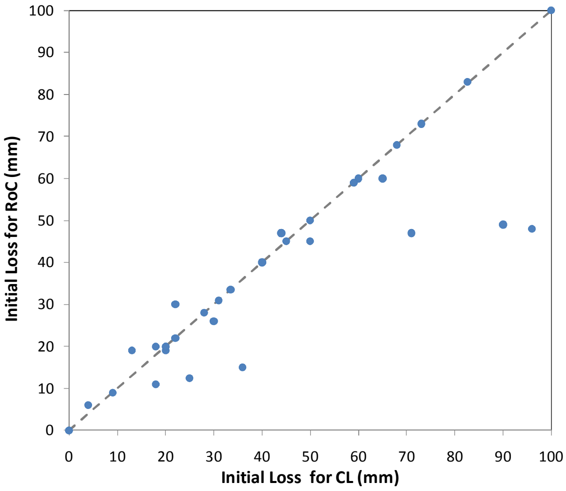


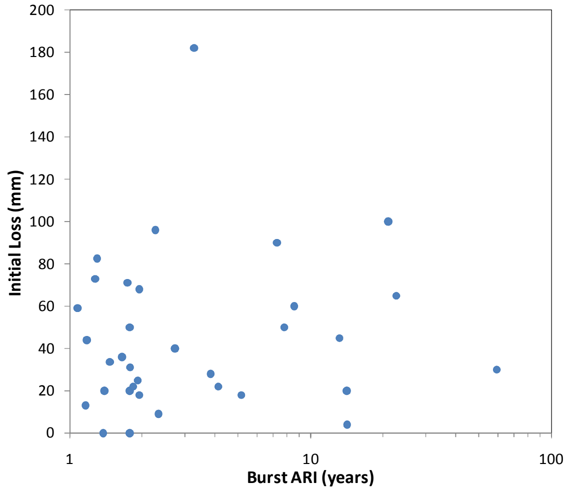

Initial Loss (mm)
Month
0
20
40
60
80
100
120
140
160
180
0 1 2 3 4 5 6 7 8 9 10 11 12

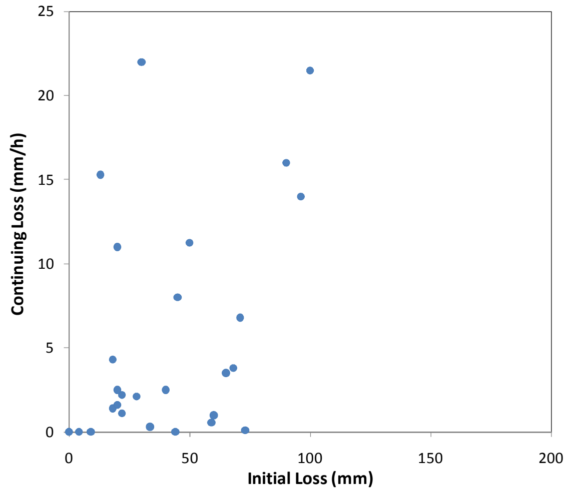

Continuing Loss (mm/hr)
Month
0
2
4
6
8
10
12
14
16
18
0 1 2 3 4 5 6 7 8 9 10 11 12

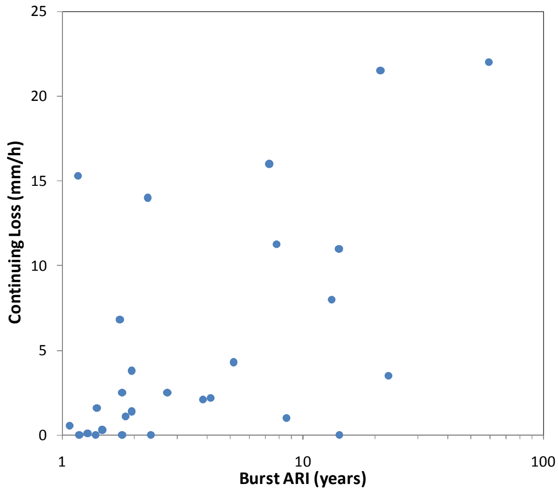

Runoff Coefficient
Month
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0 1 2 3 4 5 6 7 8 9 10 11 12

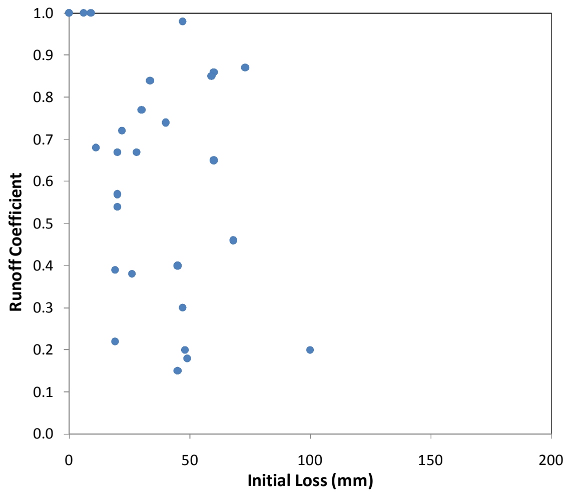
G8170075 Manton River upstream Manton Dam

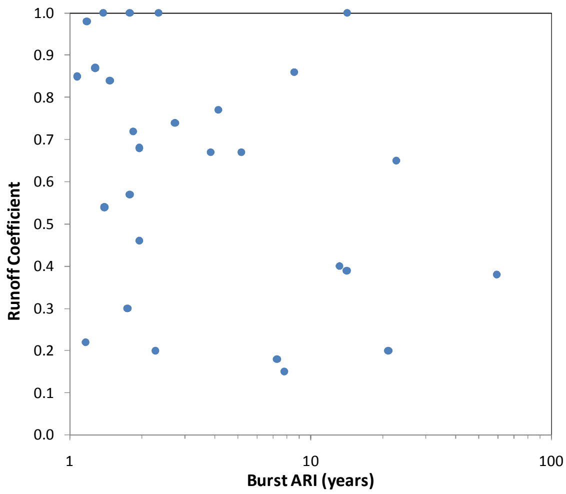


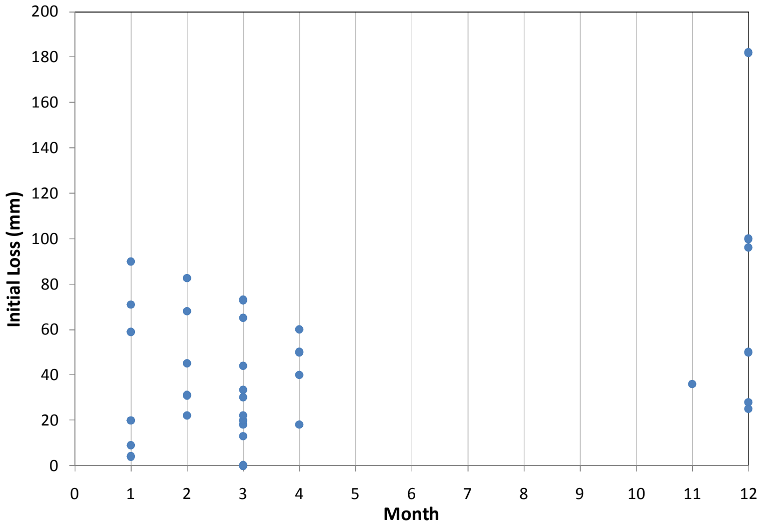


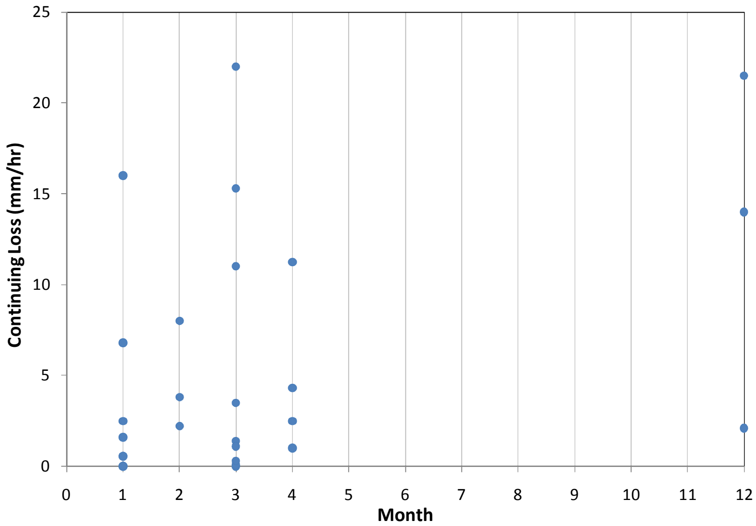


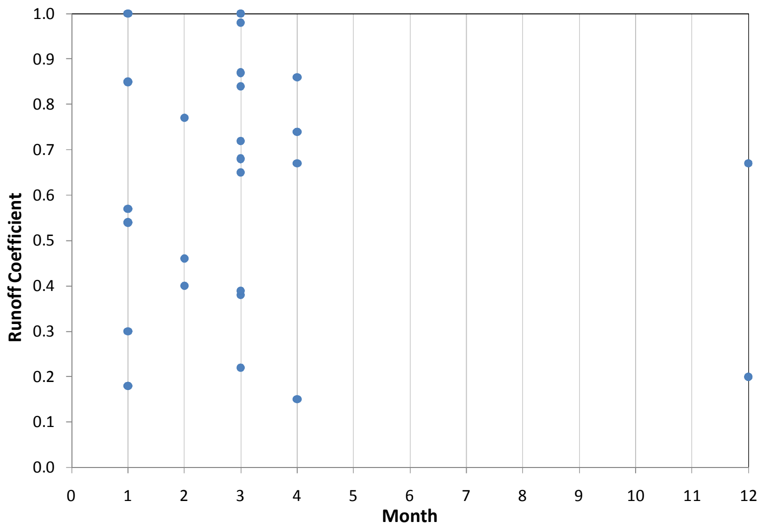




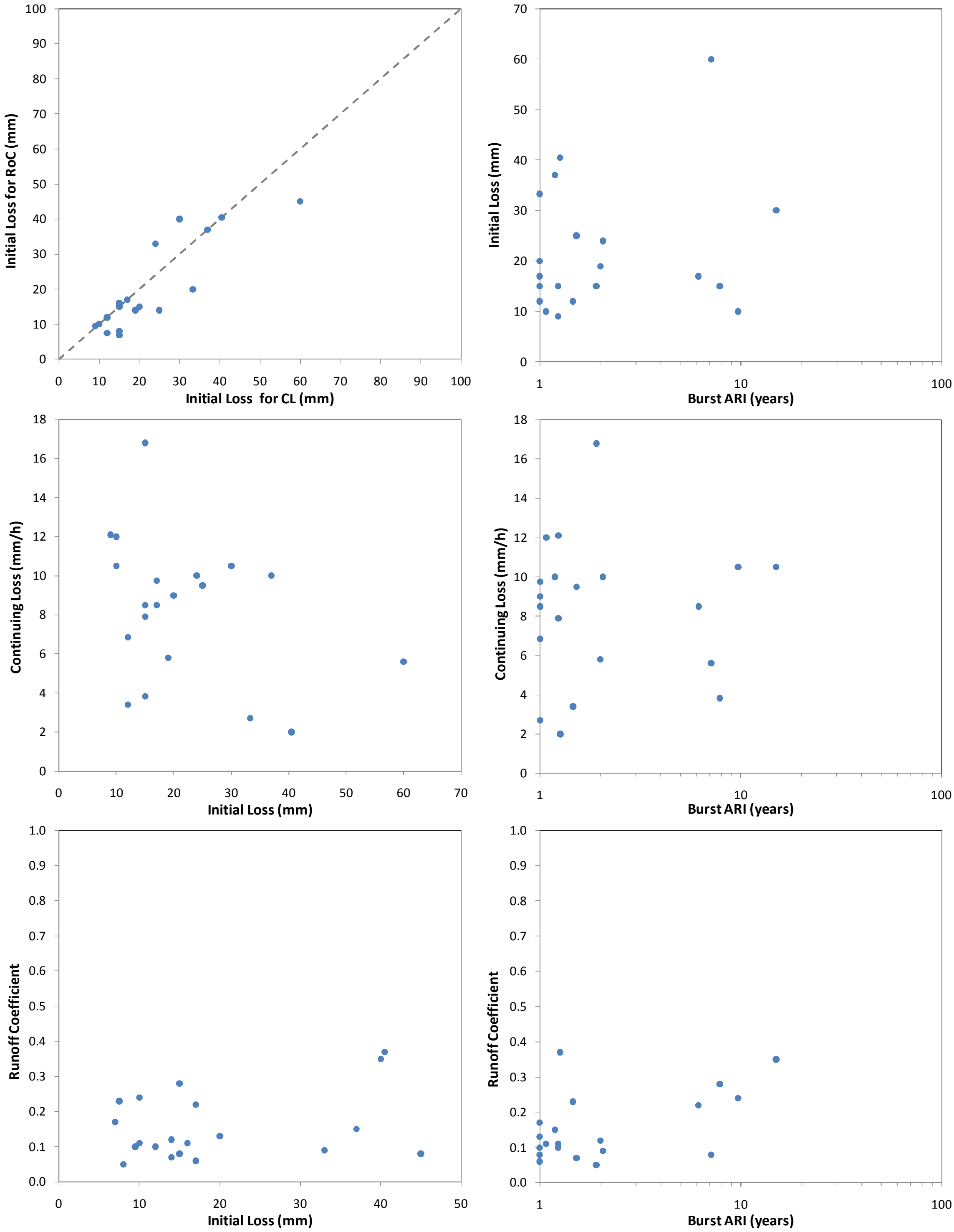


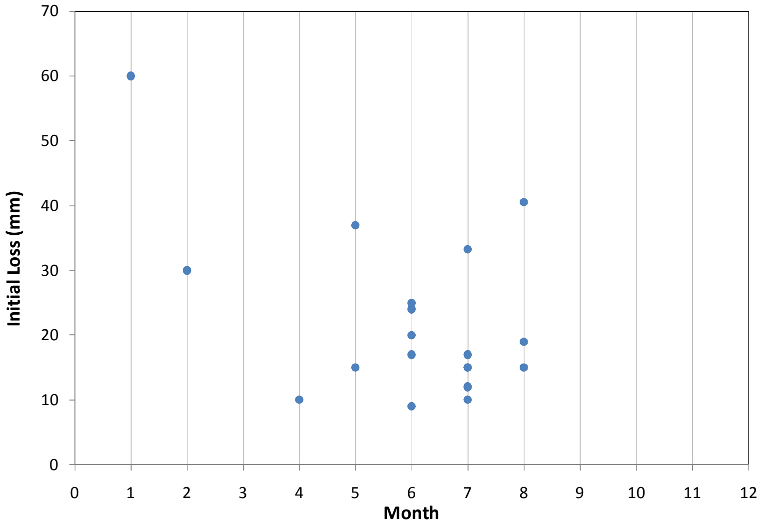

Initial Loss (mm)
Month

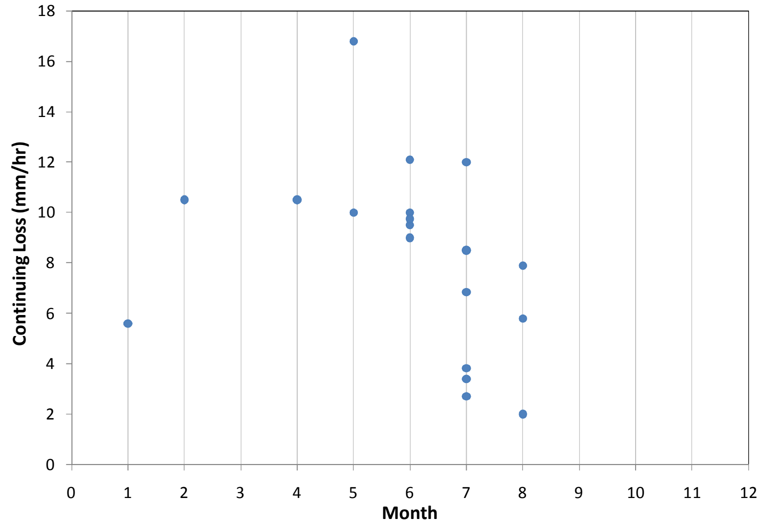

Continuing Loss (mm/hr)
Month

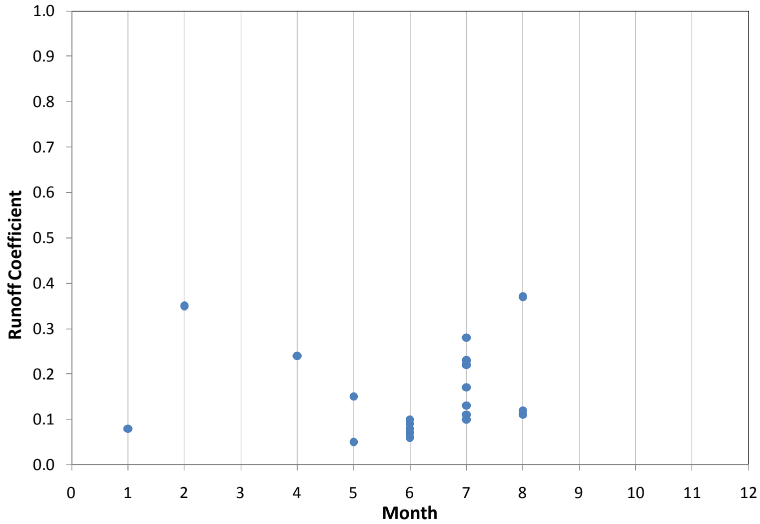

Runoff Coefficient
Month

614005 Dirk Brook at Kentish Farm

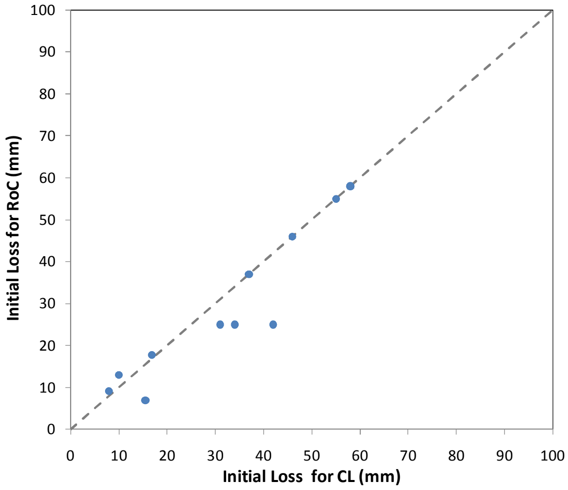


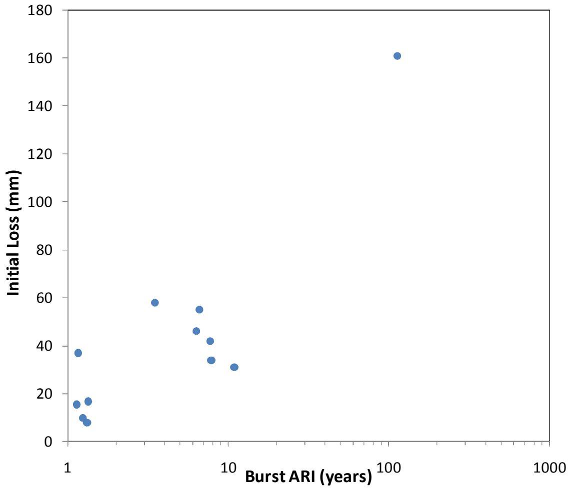

Initial Loss (mm)
Month

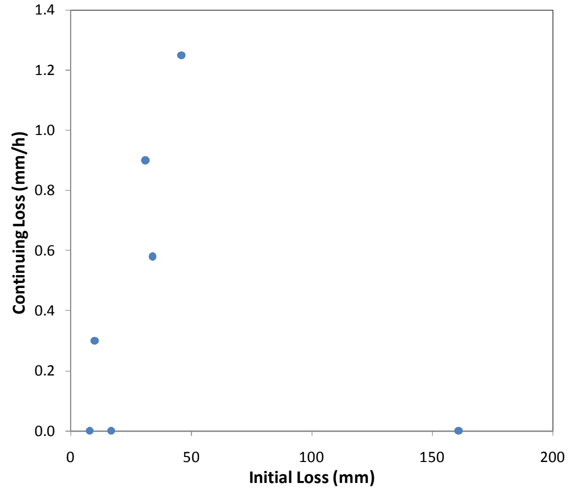

Continuing Loss (mm/hr)
Month

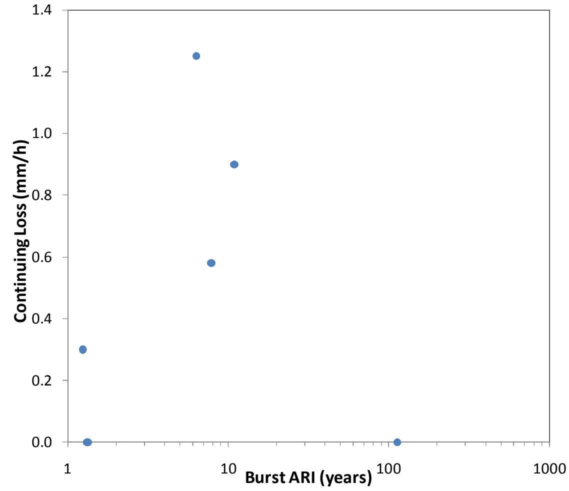

Runoff Coefficient
Month

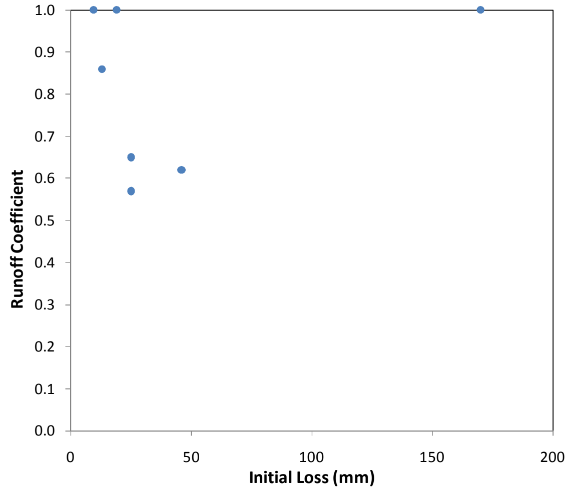
603190 Yates Flat Creek at Woonanup

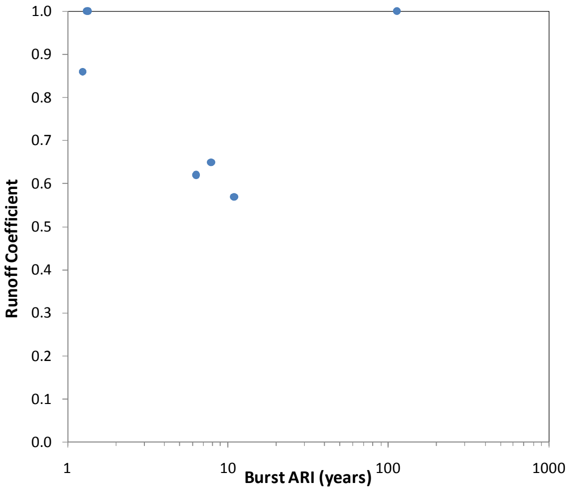


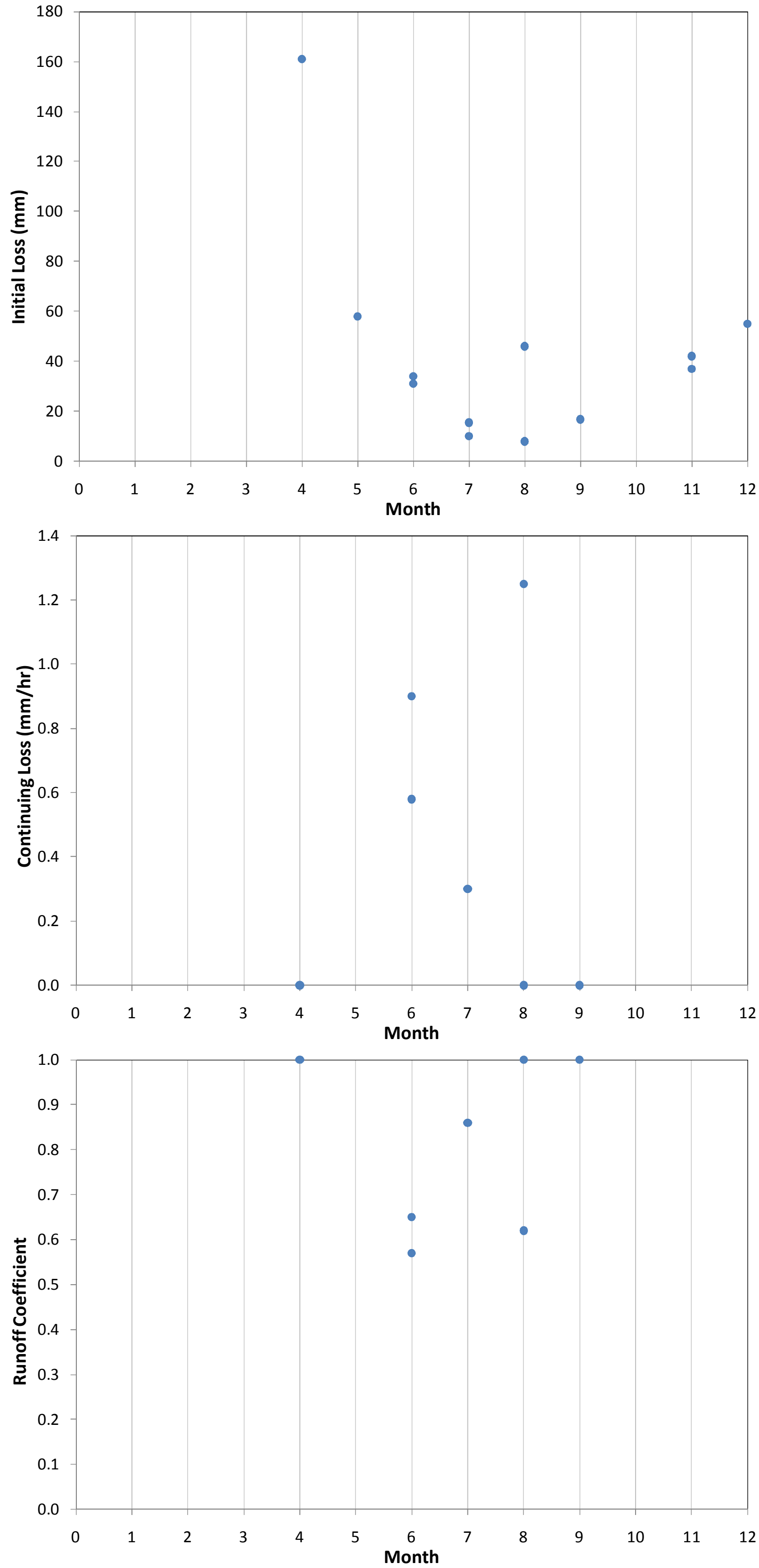






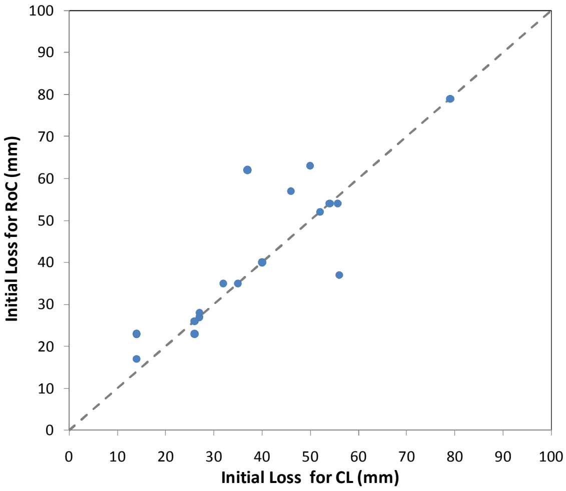


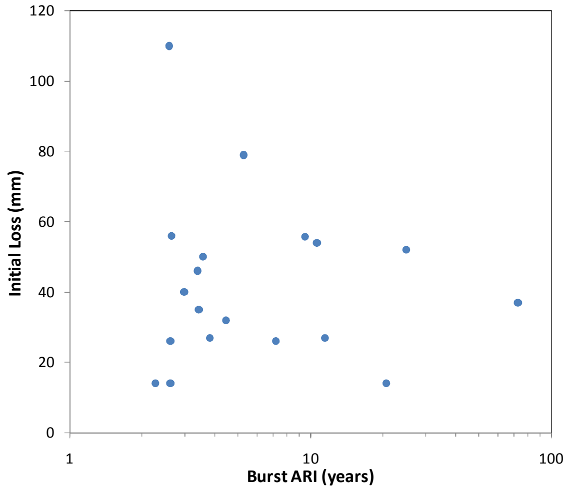


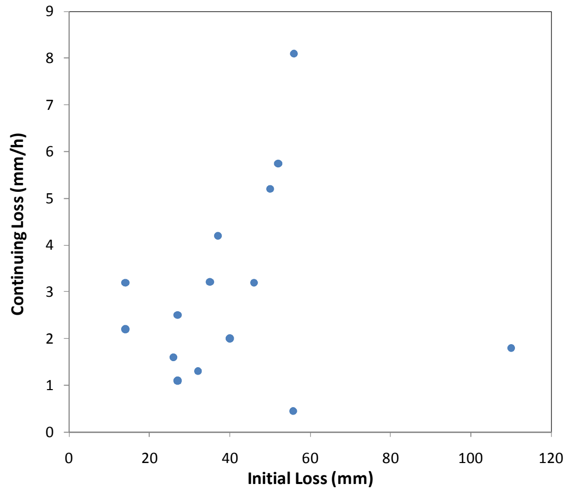


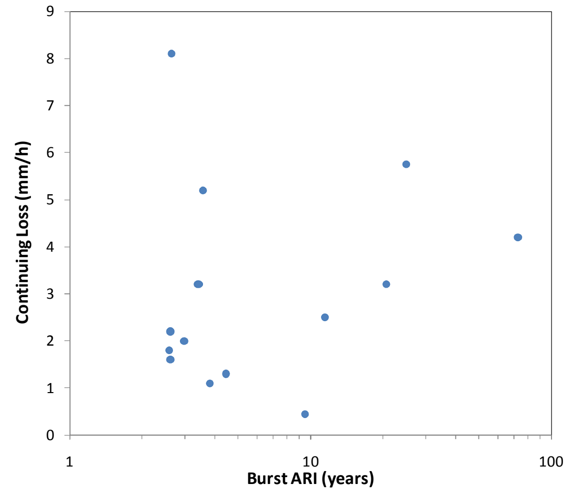
Initial Loss (mm)
180
160
140
120
100
80
60
40
20
0
0 1 2 3 4 5 6 7 8 9 10 11 12
Month
Continuing Loss (mm/hr)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12
Month
Runoff Coefficient
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12
Month

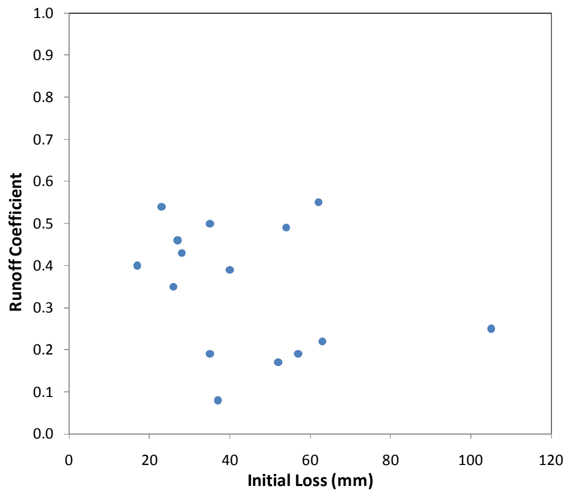
A5040523 Sixth Creek at Castambul

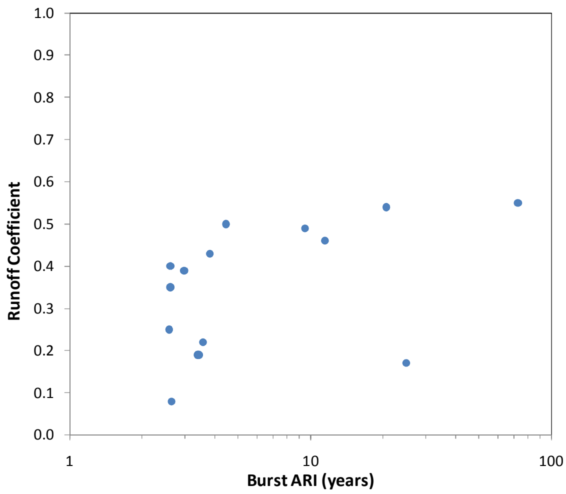


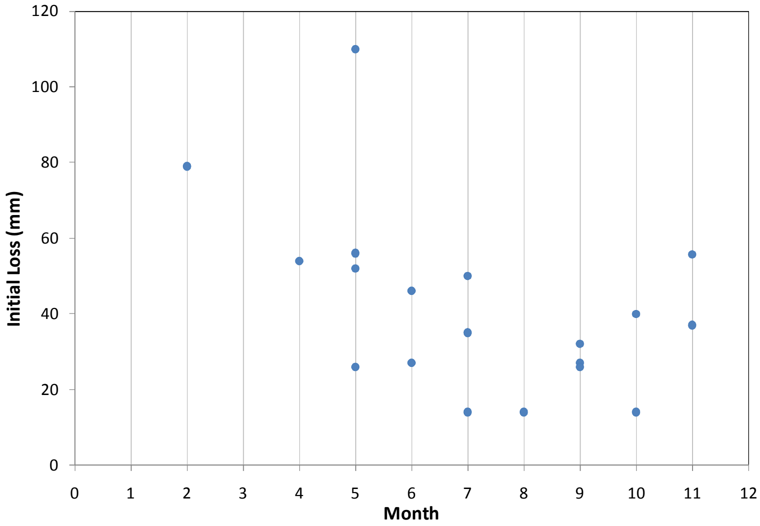




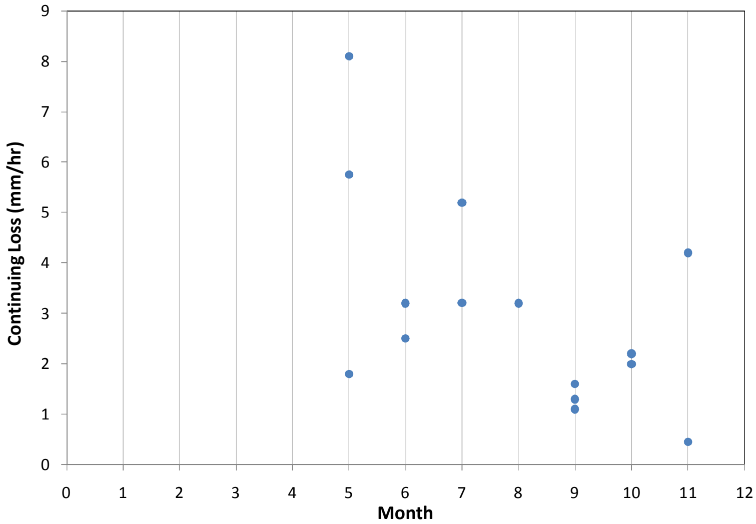




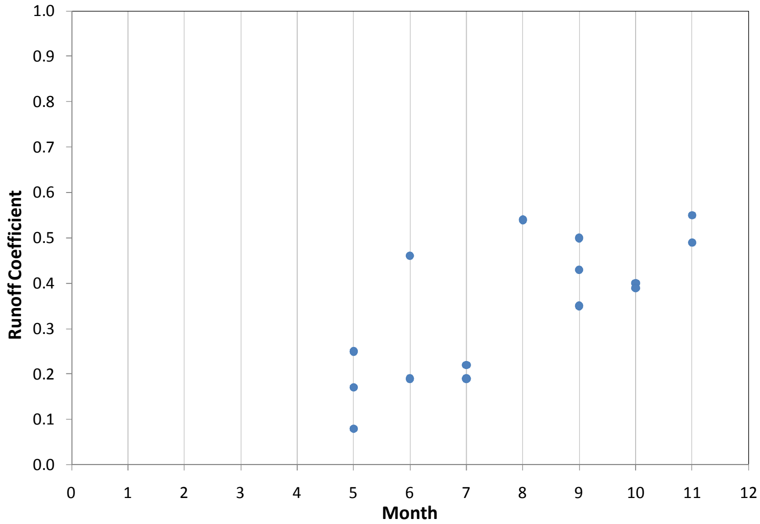




Initial Loss (mm)
Month



Continuing Loss (mm/hr)
Month



Runoff Coefficient
Month

Appendix F Flood frequency data and plots

Extracted annual maximum flood series data for site 2219

Site 2219	
Year	Peakflow (m^3/s)
1983	126.6
1984	82.1
1985	50.8
1986	145.8
1987	11.4
1988	56.9
1989	18.0
1990	7.3
1991	22.9
1992	40.9
1993	85.7
1994	5.3
1995	108.8
1996	55.1
1997	14.8
1998	24.0
1999	11.9
2000	116.6
2001	66.4
2002	1.9
2003	146.4
2004	80.6
2005	70.1
2006	7.3
2007	14.2
2008	17.8
2009	143.9
2010	154.0
2011	197.2

Extracted annual maximum flood series data for site 125006A

Site 125006A	
Year	Peakflow (m^3/s)
1976	297.5
1977	203.2
1978	131.2
1979	206.9
1980	293.9
1981	96.5
1982	65.2
1983	87.7
1984	13.7
1985	121.3
1986	121.3
1987	28.2
1988	172.8
1989	117.5
1990	334.1
1991	363.4
1992	5.3
1993	36.8
1994	41.0
1995	55.3
1996	57.1
1997	174.9
1998	280.9
1999	142.9
2000	276.4
2001	127.2
2002	149.0
2003	38.9
2004	11.4
2005	128.1
2006	20.0
2007	250.7
2008	579.0
2009	174.6
2010	231.1
2011	171.1

Extracted annual maximum flood series data for site 141009A

Site 141009A	
Year	Peakflow (m^3/s)
1982	33.9
1983	127.1
1984	36.4
1985	87.6
1986	25.2
1987	31.1
1988	122.7
1989	170.4
1990	41.0
1991	54.0
1992	154.6
1993	14.7
1994	19.9
1995	113.1
1996	40.9
1997	139.8
1998	32.3
1999	148.3
2000	32.0
2001	63.3
2002	14.8
2003	30.3
2004	91.0
2005	19.9
2006	17.7
2007	107.2
2008	127.0
2009	128.6
2010	43.6
2011	119.5

Extracted annual maximum flood series data for site 228217C

Site 228217C	
Year	Peakflow (m^3/s)
1978	13.2
1979	3.6
1980	6.6
1981	6.4
1982	0.8
1983	12.6
1984	33.5
1985	20.0
1986	7.9
1987	21.0
1988	14.4
1989	19.8
1990	31.2
1991	11.9
1992	16.2
1993	15.7
1994	5.3
1995	16.0
1996	27.4
1997	0.8
1998	7.6
1999	9.0
2000	9.6
2001	6.9
2002	0.4
2003	4.2
2004	26.3
2005	30.6
2006	1.3
2007	7.7
2008	1.8
2009	6.1
2010	13.2
2011	32.8

Extracted annual maximum flood series data for site 410743

Site 410743	
Year	Peakflow (m^3/s)
1968	6.82
1969	24.00
1970	28.87
1971	110.28
1972	57.80
1973	50.87
1974	69.39
1975	40.58
1976	75.52
1977	43.52
1978	38.36
1979	0.19
1980	30.08
1981	27.47
1982	0.32
1983	32.85
1984	72.07
1985	19.56
1986	23.52
1987	1.04
1988	126.47
1989	115.55
1990	22.89
1991	2.97
1992	43.42
1993	30.90
1994	3.61
1995	261.71
1996	13.57
1997	1.43

Extracted annual maximum flood series data for site 422321B

422321B	
Year	Peakflow (m^3/s)
1973	9.4
1974	34.5
1975	15.0
1976	46.7
1977	3.4
1978	5.8
1979	24.6
1980	15.0
1981	15.9
1982	9.9
1983	16.3
1984	21.2
1985	11.7
1986	1.0
1987	12.5
1988	47.4
1989	41.0
1990	31.8
1991	9.1
1992	1.1
1993	1.1
1994	2.2
1995	8.6
1996	84.5
1997	4.5
1998	25.9
1999	42.4
2000	1.6
2001	30.6
2002	1.2
2003	1.2
2004	30.8
2005	1.6
2006	11.0
2007	7.1
2008	142.4
2009	15.8
2010	62.8
2011	131.7

Extracted annual maximum flood series data for site 603190

Site 603190	
Year	Peakflow (m^3/s)
1963	9.9
1964	17.1
1965	12.9
1966	5.5
1967	13.0
1968	26.1
1969	4.4
1970	7.4
1971	12.9
1972	3.5
1973	6.3
1974	5.0
1975	4.3
1976	4.2
1977	8.7
1978	25.0
1979	2.9
1980	12.1
1981	6.5
1982	0.7
1983	8.0
1984	15.0
1985	11.9
1986	3.1
1987	1.3
1988	32.3
1989	2.9
1990	12.0
1991	16.7
1992	12.1
1993	6.1
1994	2.7
1995	4.9
1996	5.7
1997	4.2
1998	9.6
1999	3.5
2000	5.5
2001	2.2
2002	1.0
2003	20.8
2004	1.1
2005	18.9
2006	0.0
2007	0.3
2008	6.2
2009	4.6

Extracted annual maximum flood series data for site 614005

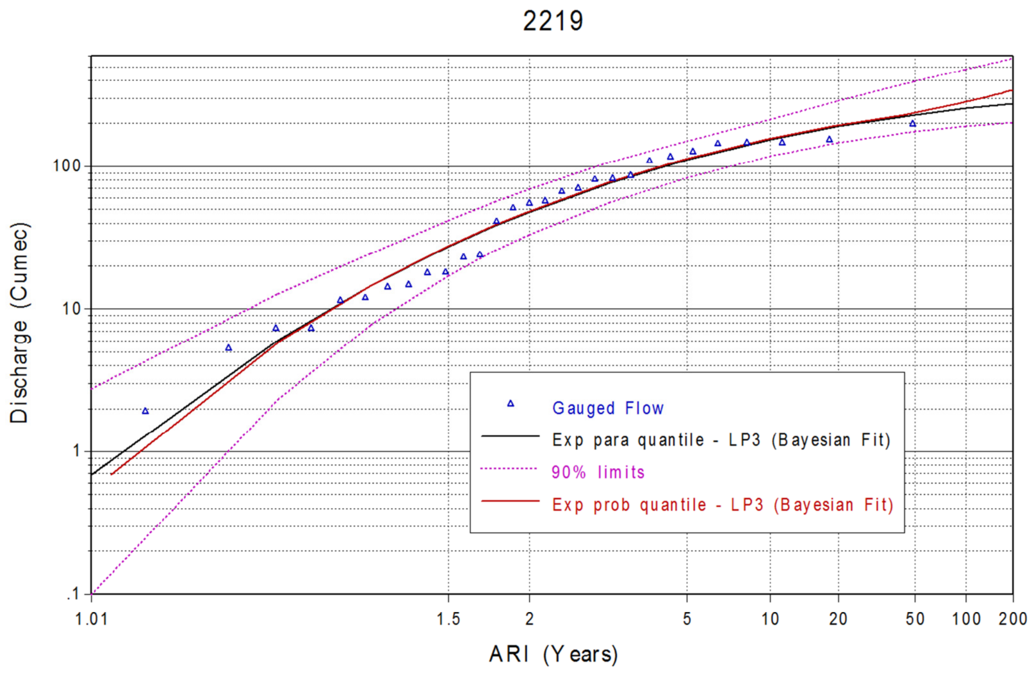
614005	
Year	Peakflow (m^3/s)
1971	2.8
1972	2.2
1973	4.7
1974	7.8
1975	3.5
1976	1.7
1977	4.5
1978	4.9
1979	3.0
1980	3.0
1981	5.9
1982	2.7
1983	3.7
1984	3.8
1985	6.9
1986	1.9
1987	8.4
1988	7.4
1989	4.0
1990	1.9
1991	6.0
1992	4.2
1993	3.8
1994	4.8
1995	2.8
1996	5.7
1997	3.0
1998	2.3
1999	2.2
2000	3.7
2001	0.0

Extracted annual maximum flood series data for site A5040523

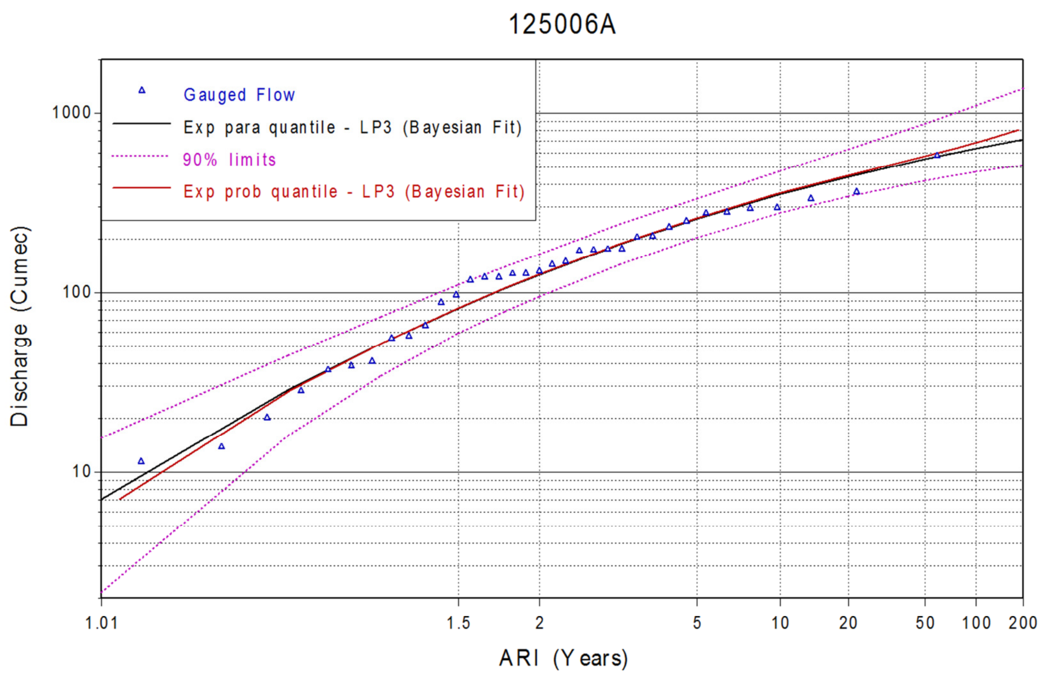
Site A5040523	
Year	Peakflow (m^3/s)
1979	38.0
1980	13.1
1981	81.0
1982	4.8
1983	15.7
1984	10.1
1985	11.4
1986	13.1
1987	28.3
1988	12.1
1989	7.5
1990	13.5
1991	27.1
1992	81.7
1993	19.2
1994	4.0
1995	28.4
1996	17.7
1997	5.0
1998	10.0
1999	8.2
2000	15.0
2001	11.1
2002	2.7
2003	10.1
2004	22.2
2005	77.2
2006	8.2
2007	6.1
2008	4.1
2009	23.3
2010	20.0
2011	1.6

Extracted annual maximum flood series data for site G8170075

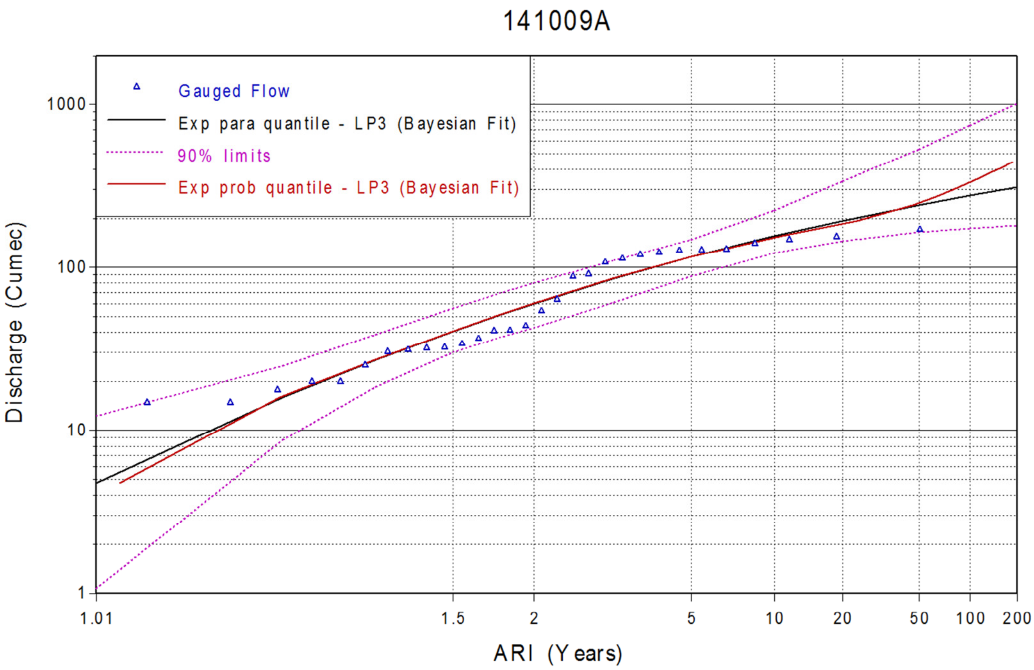
Site G8170075	
Year	Peakflow (m^3/s)
1965	24.4
1966	24.4
1967	26.0
1968	28.5
1969	24.4
1970	2.6
1971	25.1
1972	21.9
1973	19.4
1974	40.8
1975	35.0
1976	26.9
1977	54.7
1978	23.0
1979	6.6
1980	27.2
1981	90.2
1984	20.4
1985	13.1
1986	16.0
1990	0.4
1991	45.5
1992	20.2
1993	28.4
1994	23.6
1995	64.6
1996	67.8
1997	91.3
1998	104.5
1999	76.7
2000	25.3
2001	86.8
2002	17.3
2003	19.2
2004	82.4
2005	11.6
2006	117.4
2007	75.1
2008	27.0
2009	33.9
2010	56.1
2011	139.5

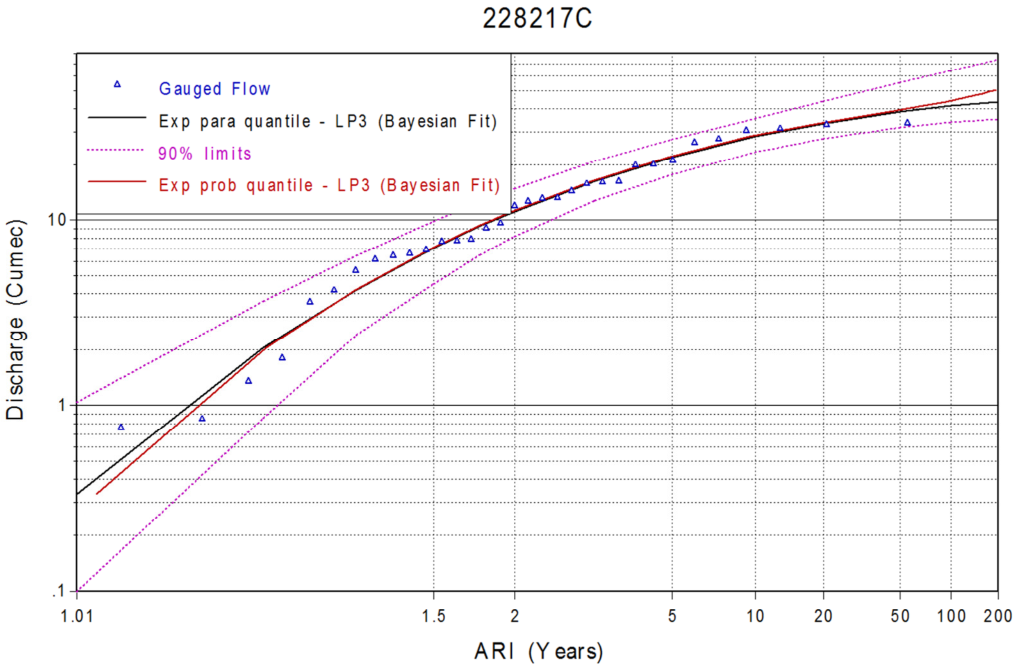


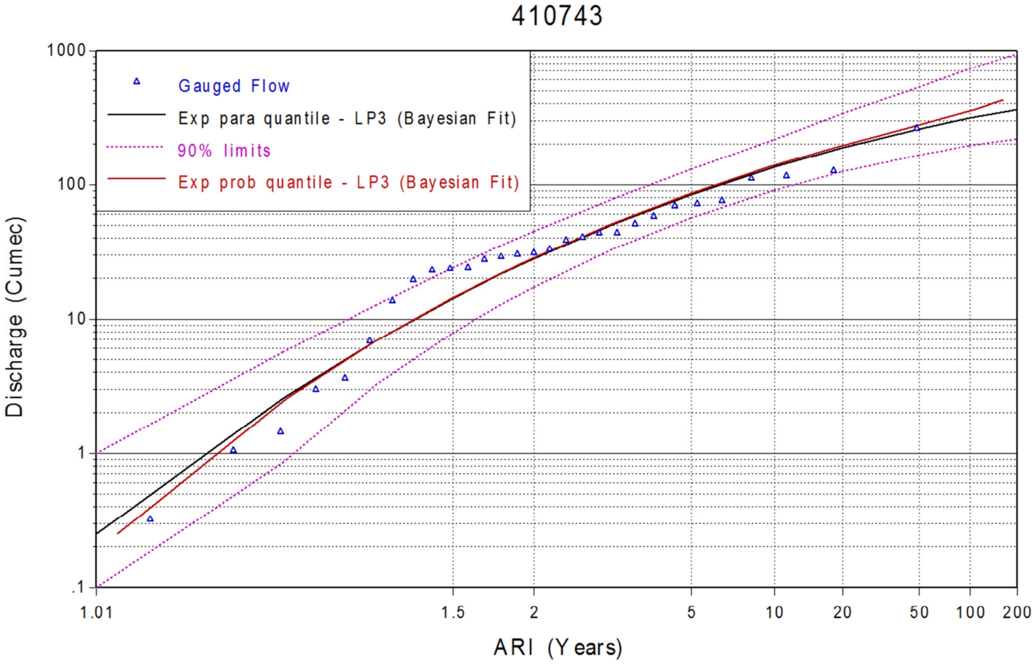
2219
Discharge (Cumec)
ARI (Years)
Gauged Flow
Exp para quantile - LP3 (Bayesian Fit)
90% limits
Exp prob quantile - LP3 (Bayesian Fit)

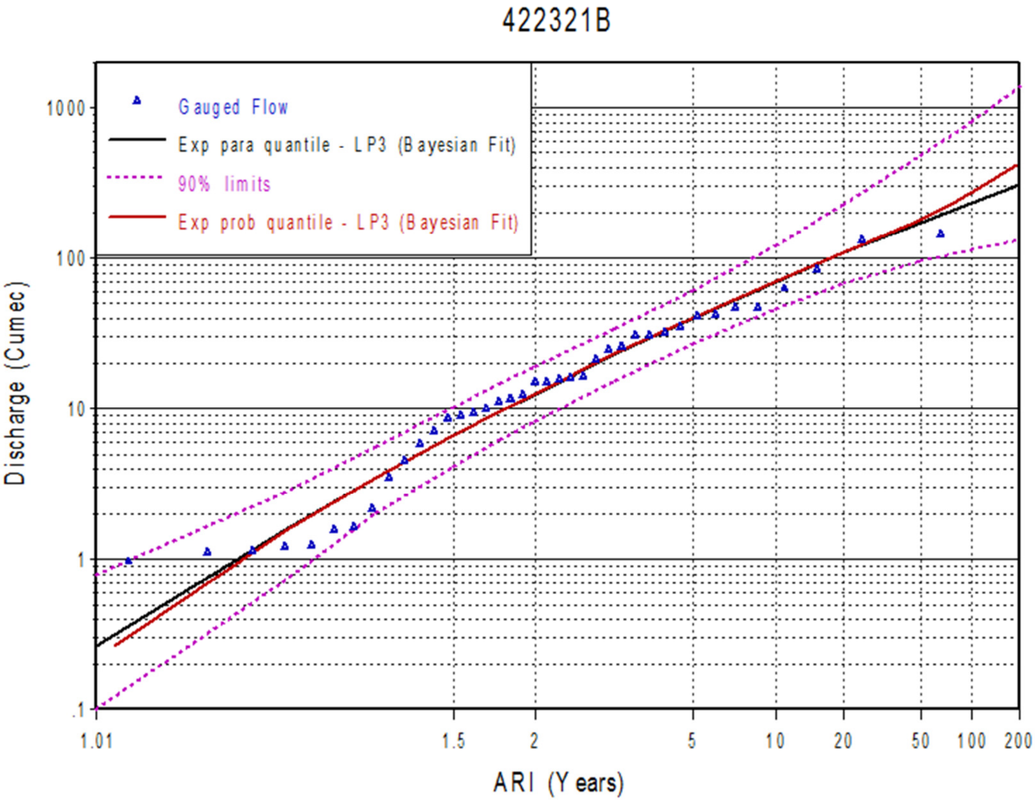


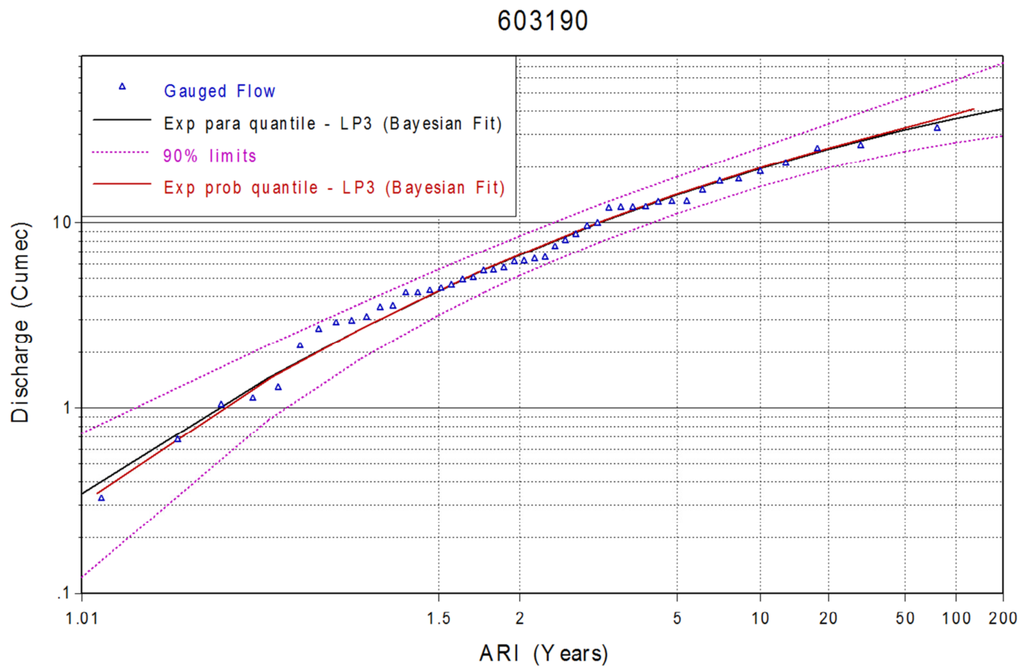
125006A
Discharge (Cumec)
ARI (Years)
Gauged Flow
Exp para quantile - LP3 (Bayesian Fit)
90% limits
Exp prob quantile - LP3 (Bayesian Fit)

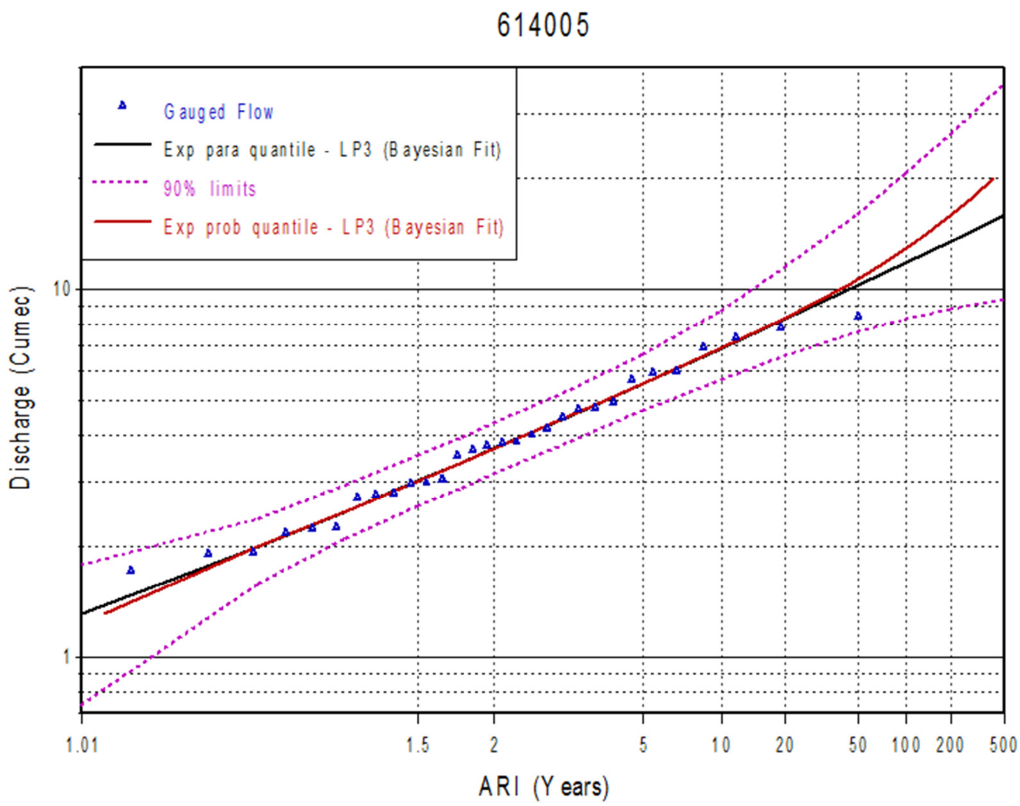

141009A
Gauged Flow
Exp para quantile - LP3 (Bayesian Fit)
90% limits
Exp prob quantile - LP3 (Bayesian Fit)
Discharge (Cumec)
1000
100
10
1
1.01
1.5
2
5
10
20
50
100
200
ARI (Years)

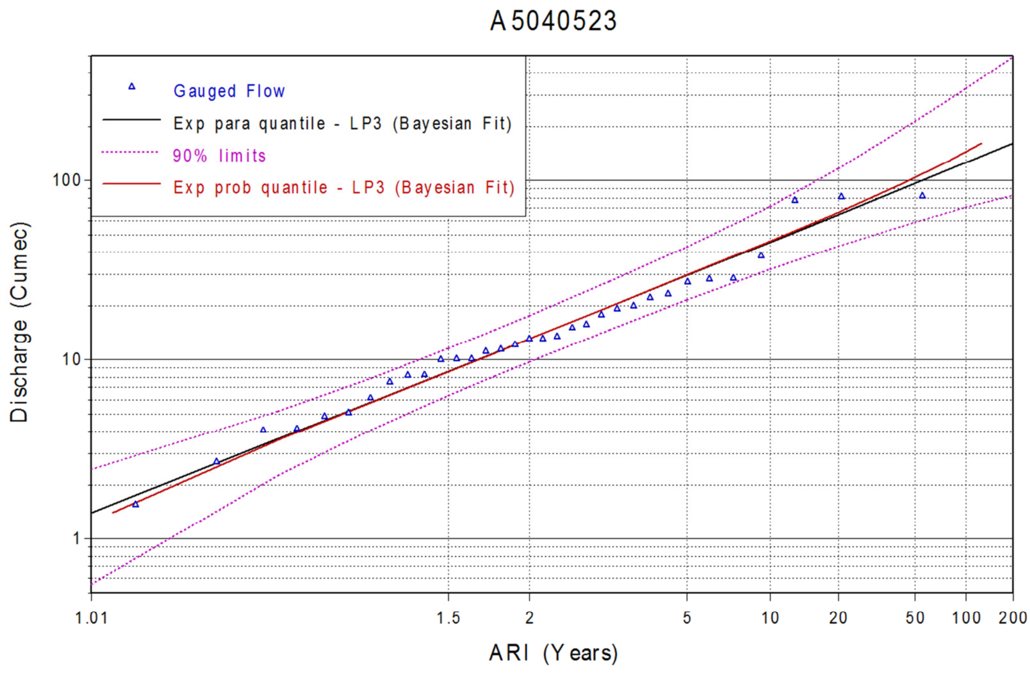

228217C
Gauged Flow
Exp para quantile - LP3 (Bayesian Fit)
90% limits
Exp prob quantile - LP3 (Bayesian Fit)
Discharge (Cumec)
10
1
.1
1.01
1.5
2
5
10
20
50
100
200
ARI (Years)

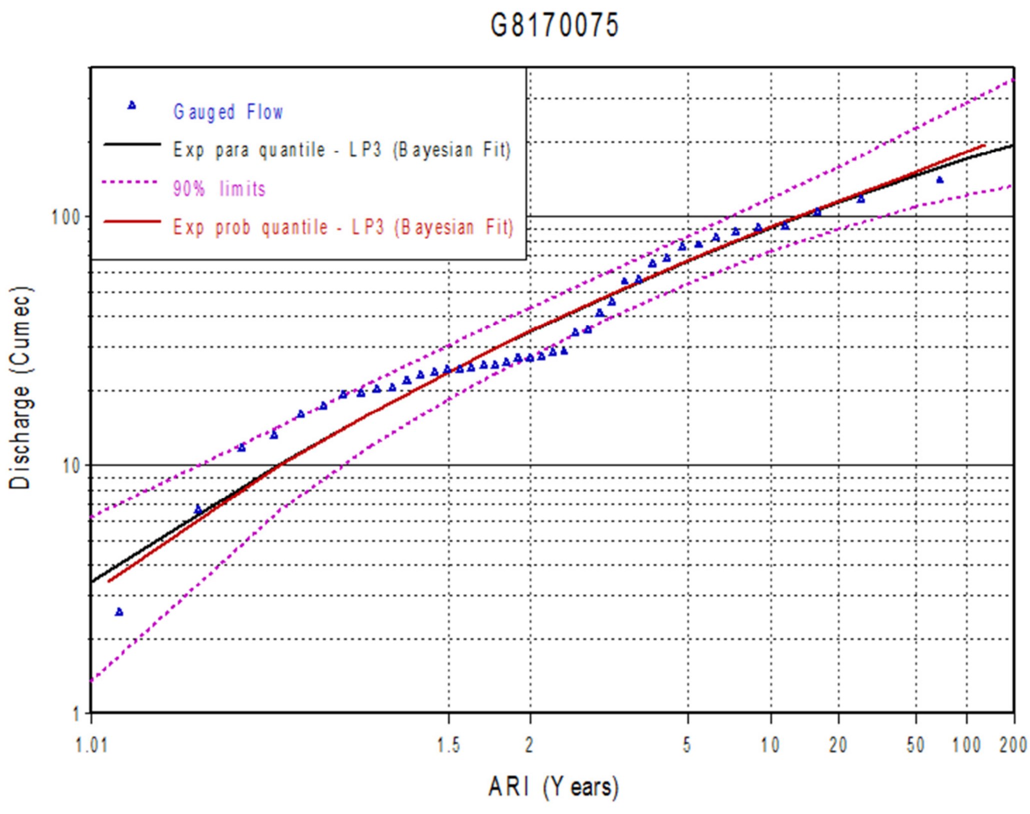

410743
Gauged Flow
Exp para quantile - LP3 (Bayesian Fit)
90% limits
Exp prob quantile - LP3 (Bayesian Fit)
Discharge (Cumec)
1000
100
10
1
.1
1.01
1.5
2
5
10
20
50
100
200
ARI (Years)


422321B
Gauged Flow
Exp para quantile - LP3 (Bayesian Fit)
90% limits
Exp prob quantile - LP3 (Bayesian Fit)
Discharge (Cumec)
1000
100
10
1
.1
1.01
1.5
2
5
10
20
50
100
200
ARI (Years)


603190
Gauged Flow
Exp para quantile - LP3 (Bayesian Fit)
90% limits
Exp prob quantile - LP3 (Bayesian Fit)
Discharge (Cumec)
10
1
.1
1.01
1.5
2
5
10
20
50
100
200
ARI (Years)

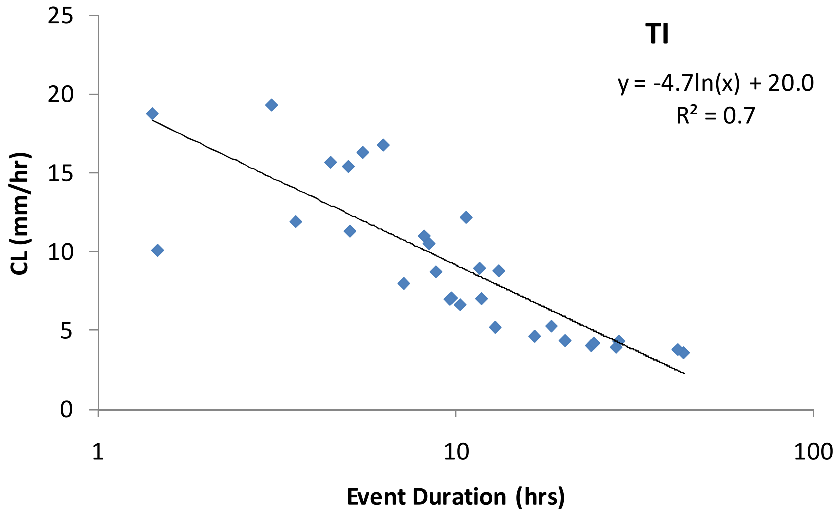

614005
Gauged Flow
Exp para quantile - LP3 (Bayesian Fit)
90% limits
Exp prob quantile - LP3 (Bayesian Fit)
Discharge (Cumec)
10
1
1.01
1.5
2
5
10
20
50
100
200
500
ARI (Years)

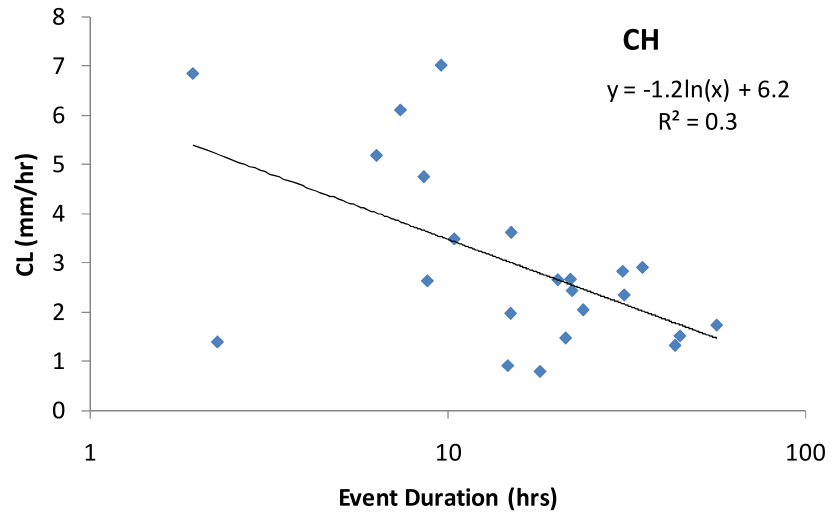

A5040523
Gauged Flow
Exp para quantile - LP3 (Bayesian Fit)
90% limits
Exp prob quantile - LP3 (Bayesian Fit)
Discharge (Cumec)
100
10
1
1.01
1.5
2
5
10
20
50
100
200
ARI (Years)

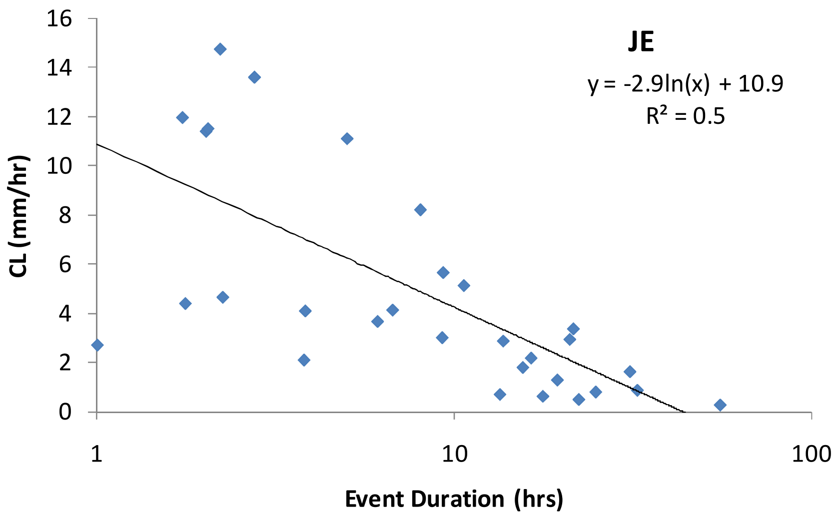

G8170075
Gauged Flow
Exp para quantile - LP3 (Bayesian Fit)
90% limits
Exp prob quantile - LP3 (Bayesian Fit)
Discharge (Cumec)
100
10
1
1.01
1.5
2
5
10
20
50
100
200
ARI (Years)

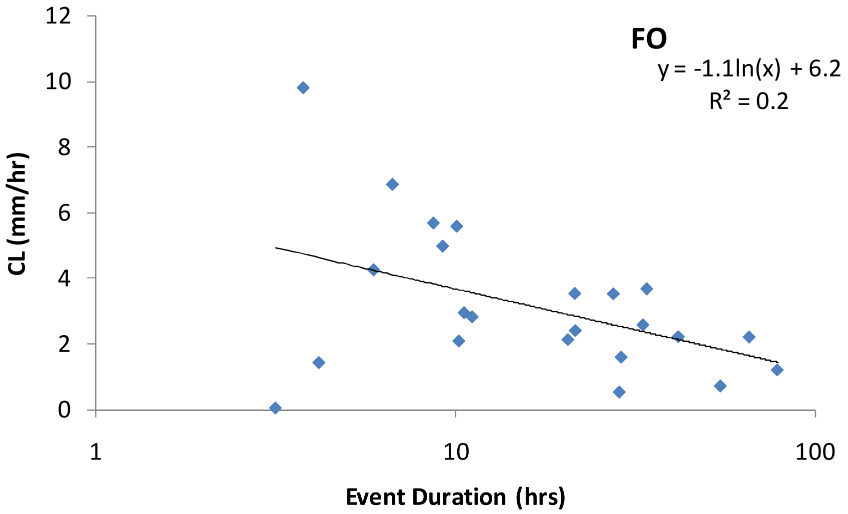
Appendix G Variation of CL with duration

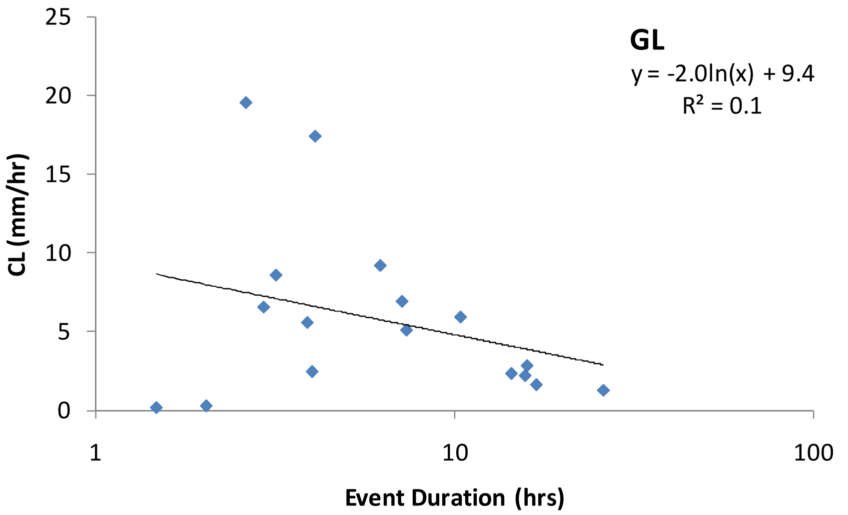
The following figures summarise the relationship between CL and duration for the South-Eastern Australia catchments analysed by Hill et. al (1996).

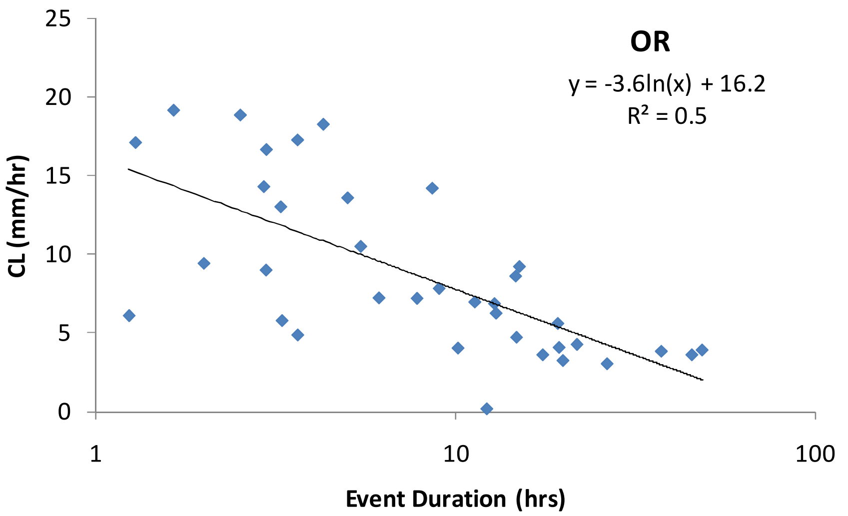

TI
y = -4.7ln(x) + 20.0
R² = 0.7
CL (mm/hr)
25
20
15
10
5
0
1
10
100
Event Duration (hrs)

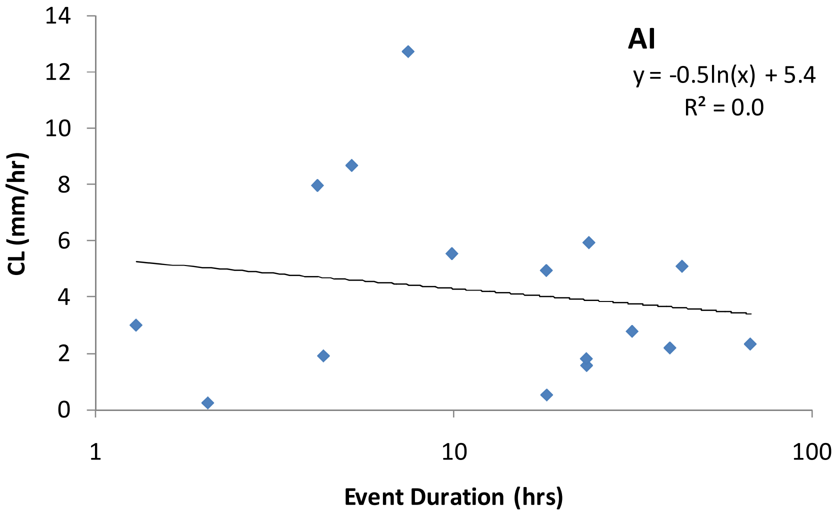

CH
y = -1.2ln(x) + 6.2
R² = 0.3
CL (mm/hr)
8
7
6
5
4
3
2
1
0
1
10
100
Event Duration (hrs)

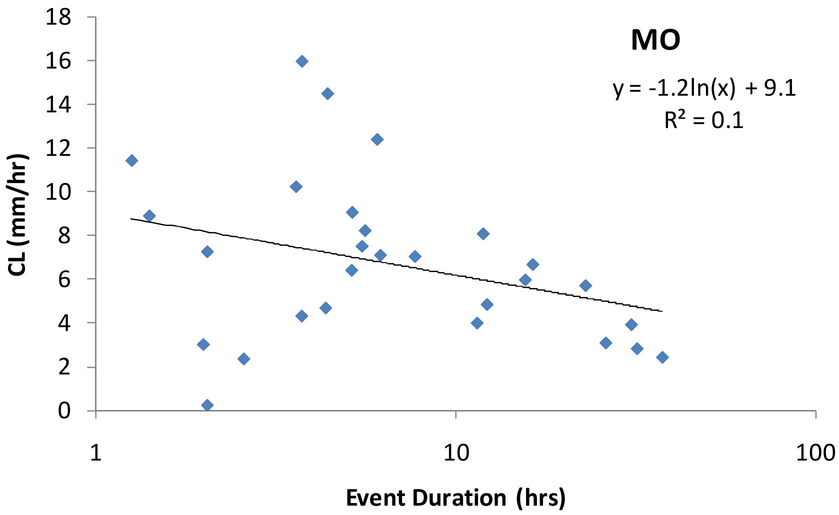

JE
y = -2.9ln(x) + 10.9
R² = 0.5
CL (mm/hr)
16
14
12
10
8
6
4
2
0
1
10
100
Event Duration (hrs)

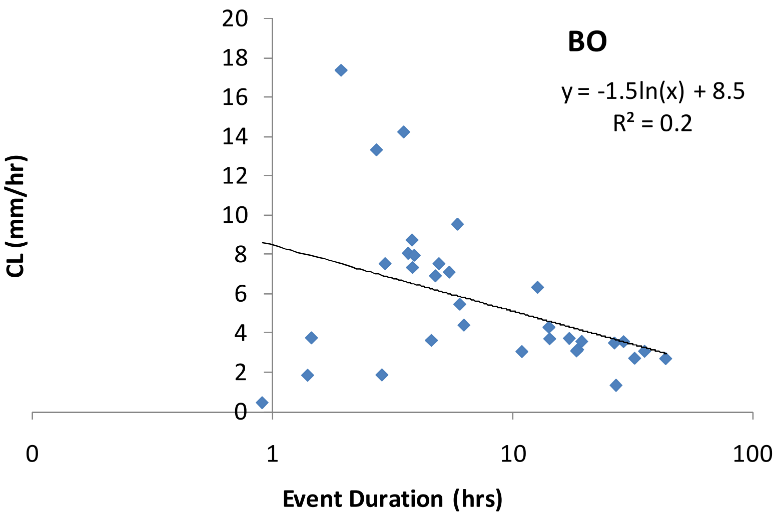

FO
y = -1.1ln(x) + 6.2
R² = 0.2
CL (mm/hr)
Event Duration (hrs)
12
10
8
6
4
2
0
1
10
100


GL
y = -2.0ln(x) + 9.4
R² = 0.1
CL (mm/hr)
Event Duration (hrs)
25
20
15
10
5
0
1
10
100


OR
y = -3.6ln(x) + 16.2
R² = 0.5
CL (mm/hr)
Event Duration (hrs)
25
20
15
10
5
0
1
10
100

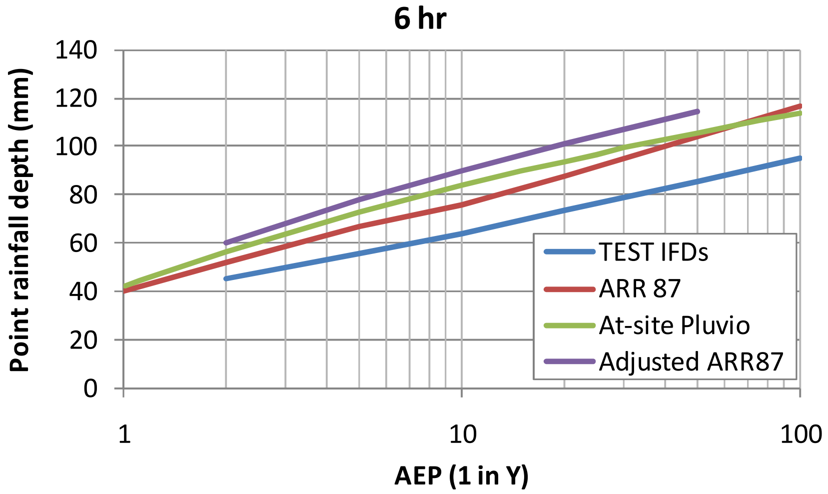

AI
y = -0.5ln(x) + 5.4
R² = 0.0
CL (mm/hr)
Event Duration (hrs)
0
2
4
6
8
10
12
14
1
10
100

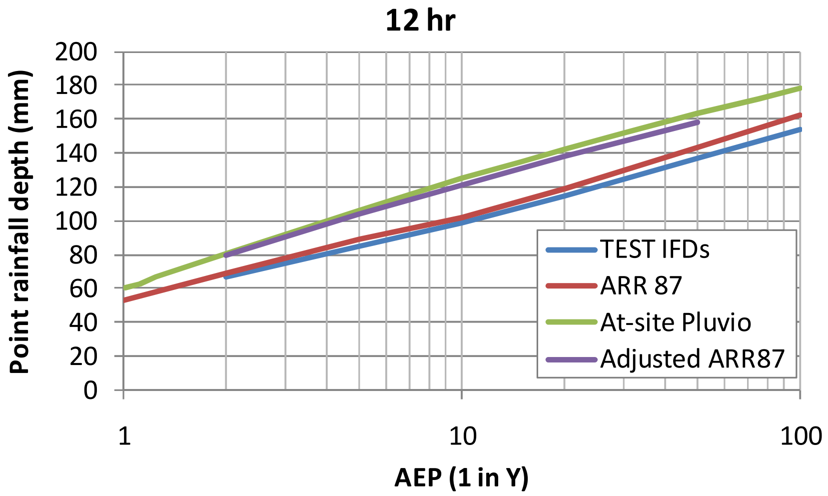

MO
y = -1.2ln(x) + 9.1
R² = 0.1
CL (mm/hr)
Event Duration (hrs)
0
2
4
6
8
10
12
14
16
18
1
10
100

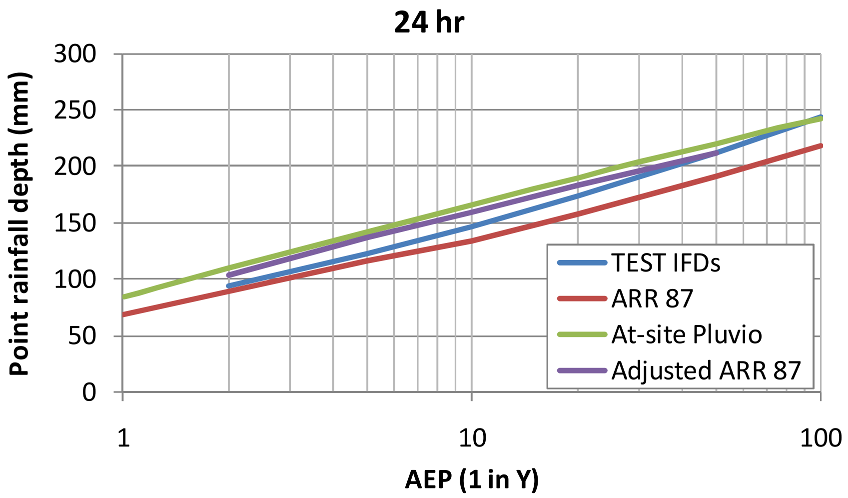

BO
y = -1.5ln(x) + 8.5
R² = 0.2
CL (mm/hr)
Event Duration (hrs)
0
2
4
6
8
10
12
14
16
18
20
0
1
10
100

Appendix H Rainfall frequency comparison graphs

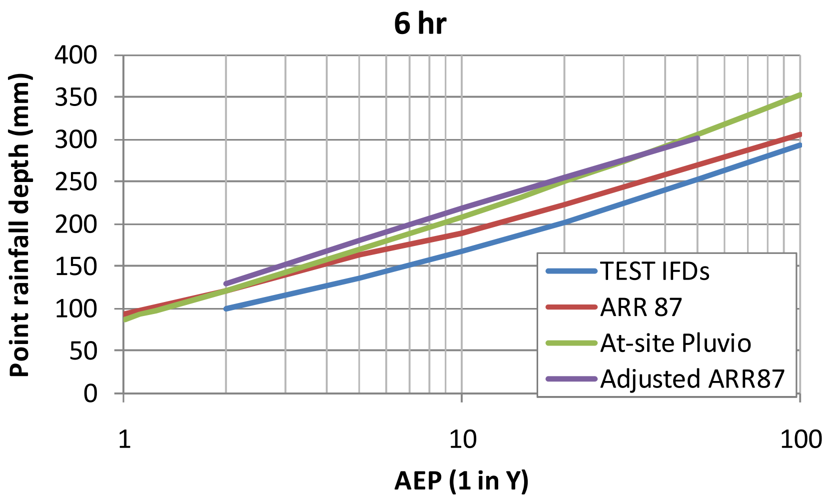
2219 Swan River upstream Harding Falls

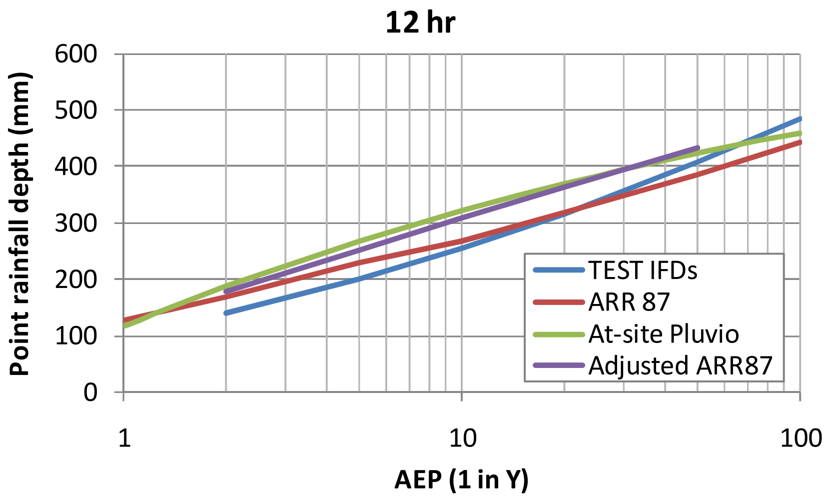


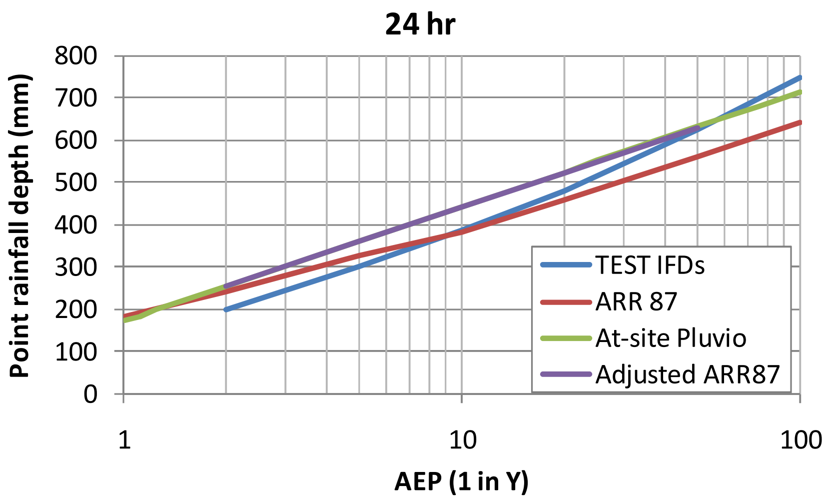




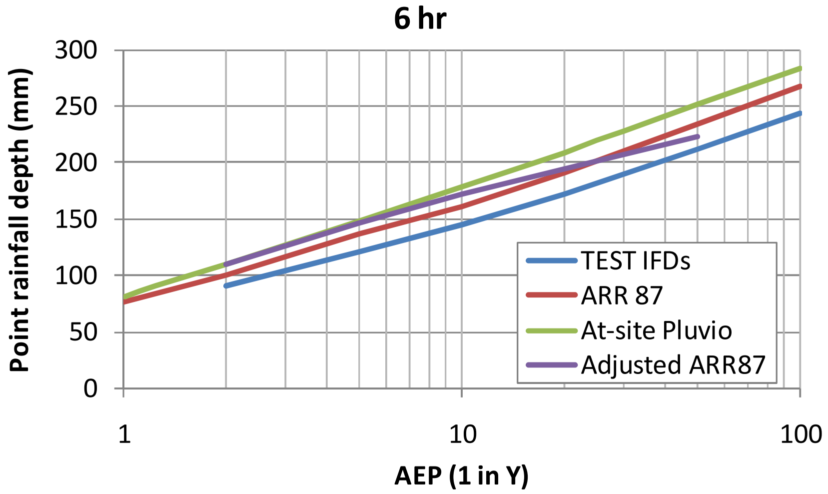
125006 Finch Hatton Creek at Dam Site

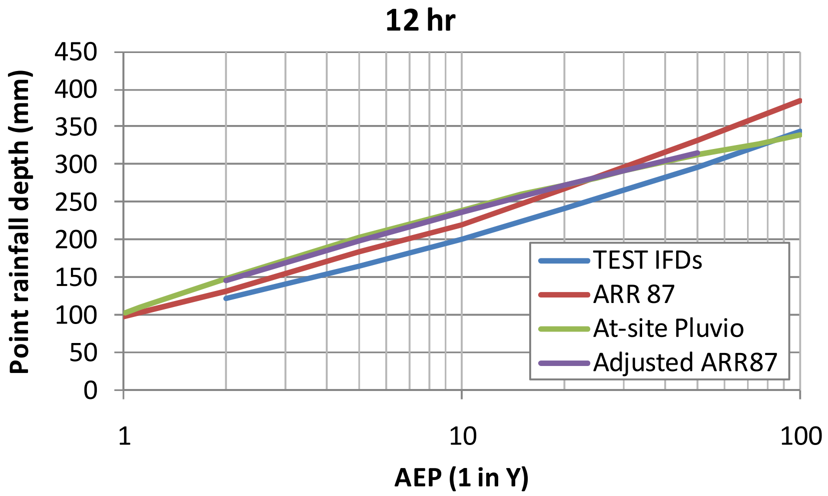


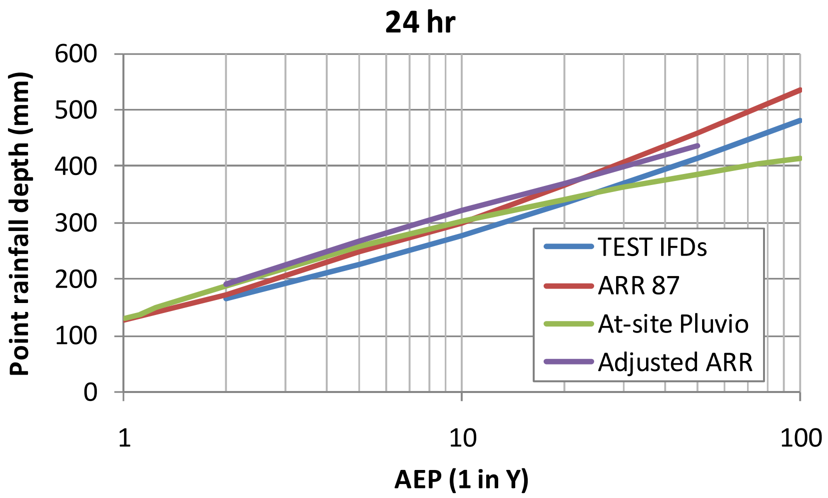




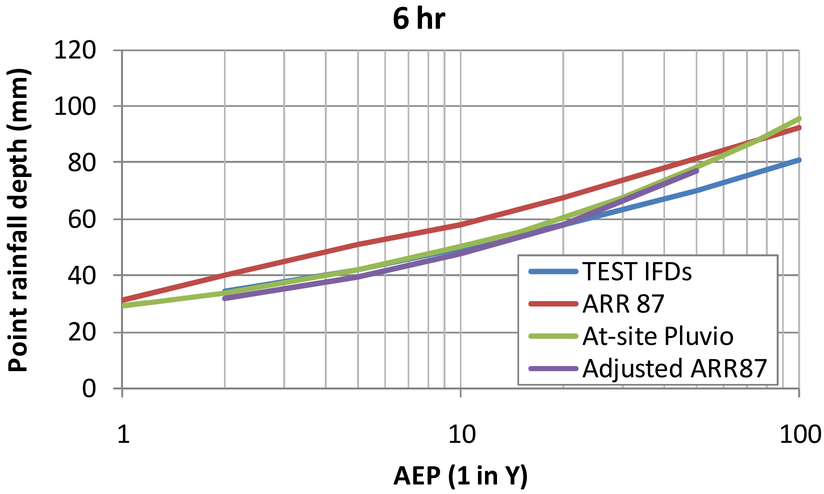
141009 North Maroochy River at Eumundi

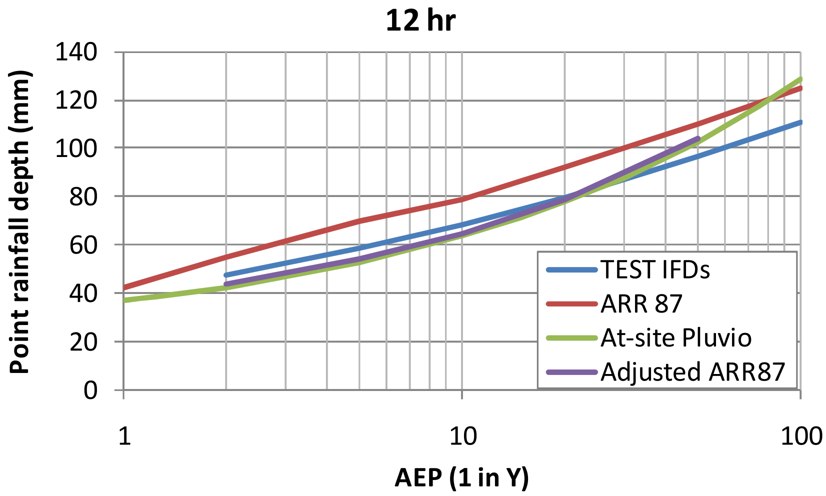


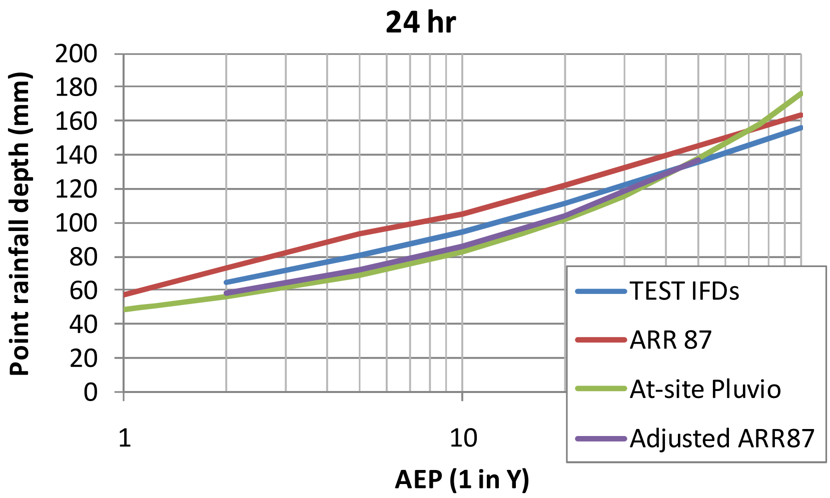




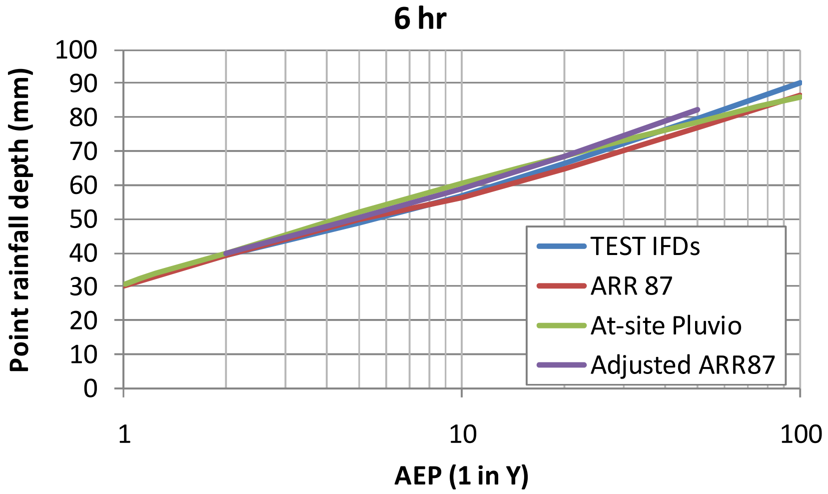
228217 Toomuc Creek at Pakenham

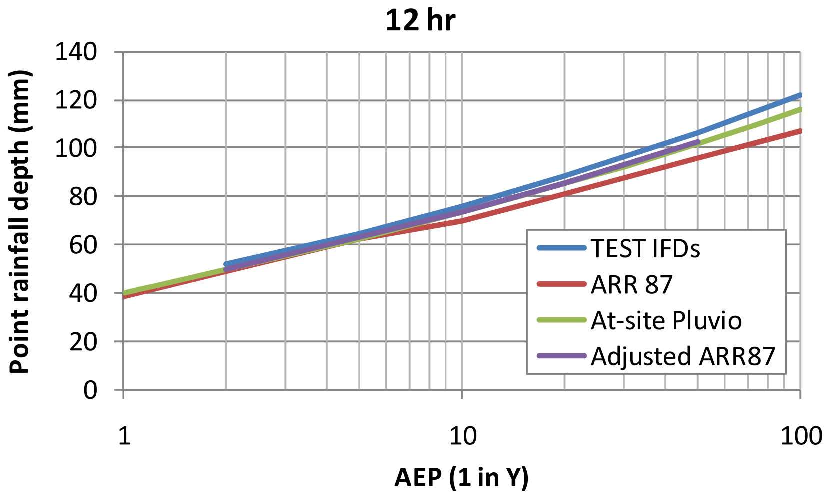


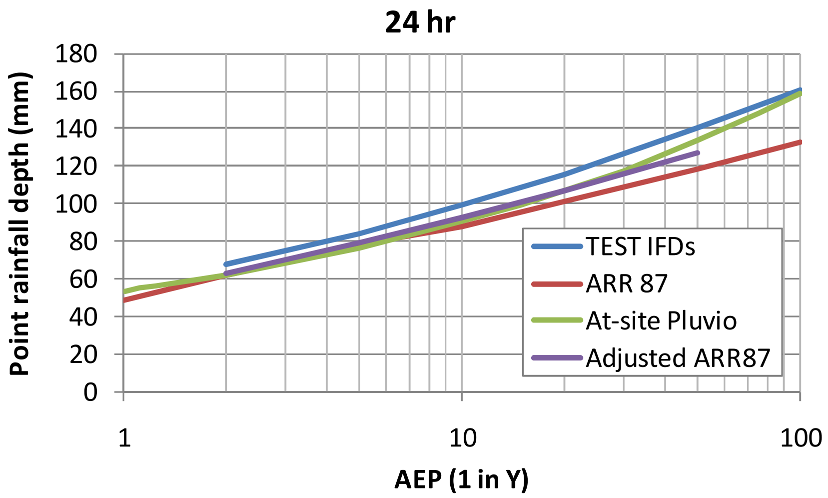




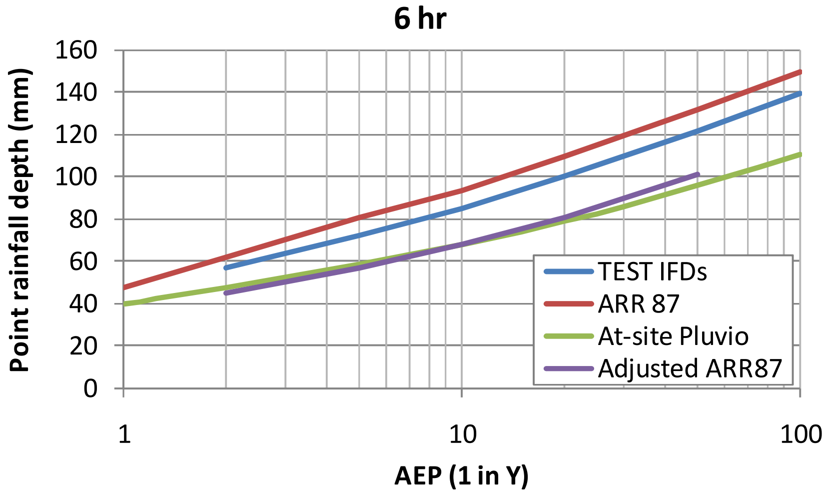
410743 Jerrabomberra Creek at Four Mile Creek

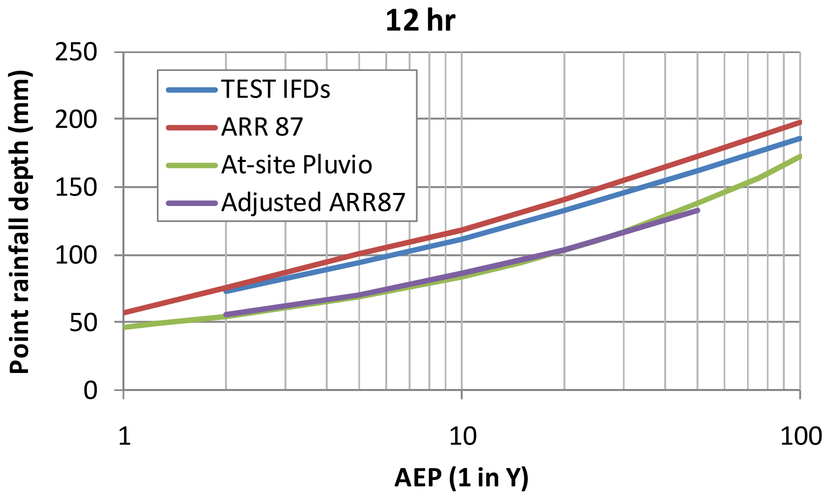


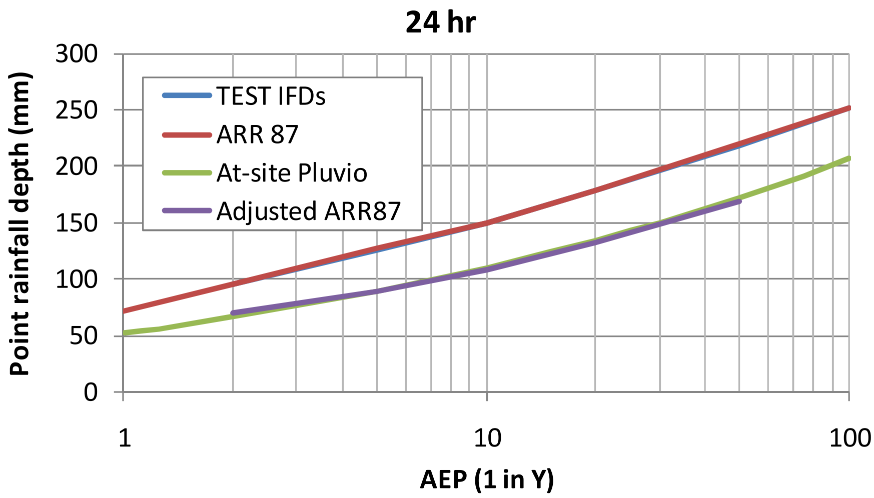




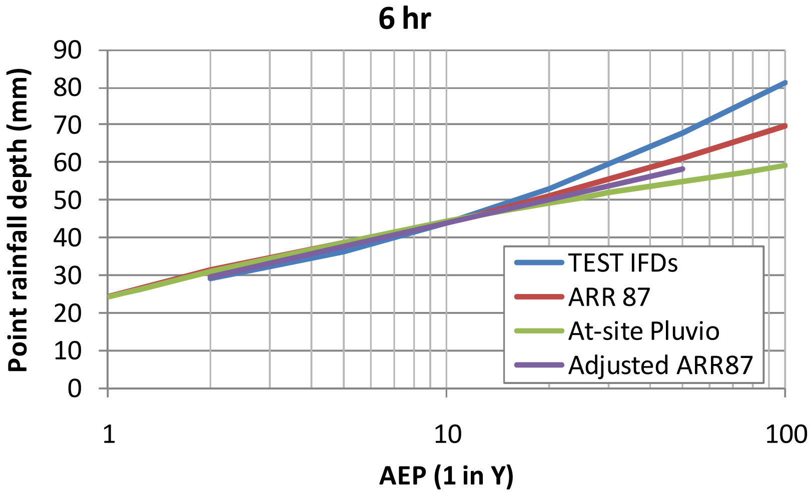
422321 Spring Creek at Killarney

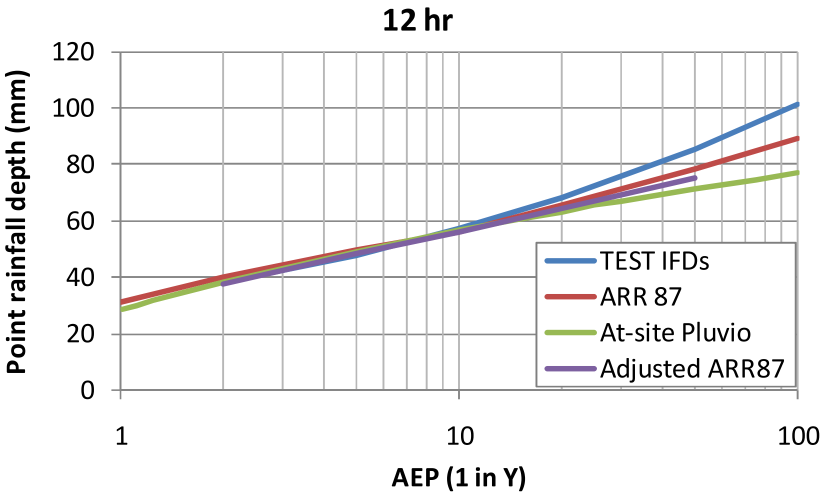


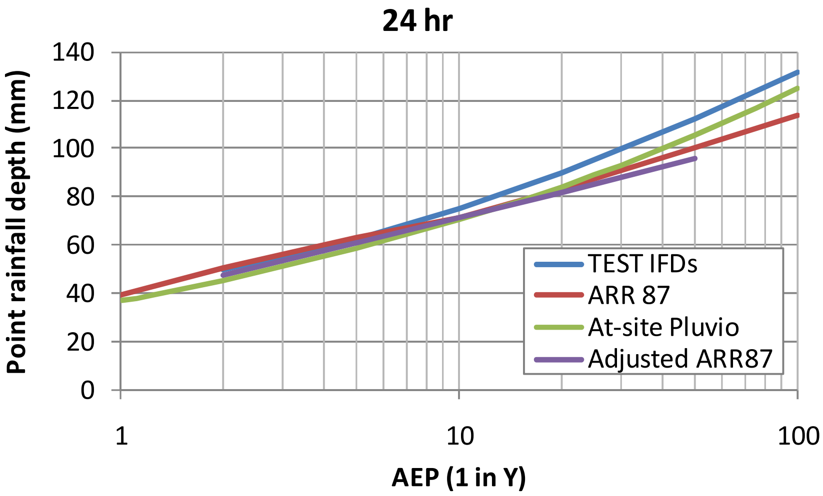




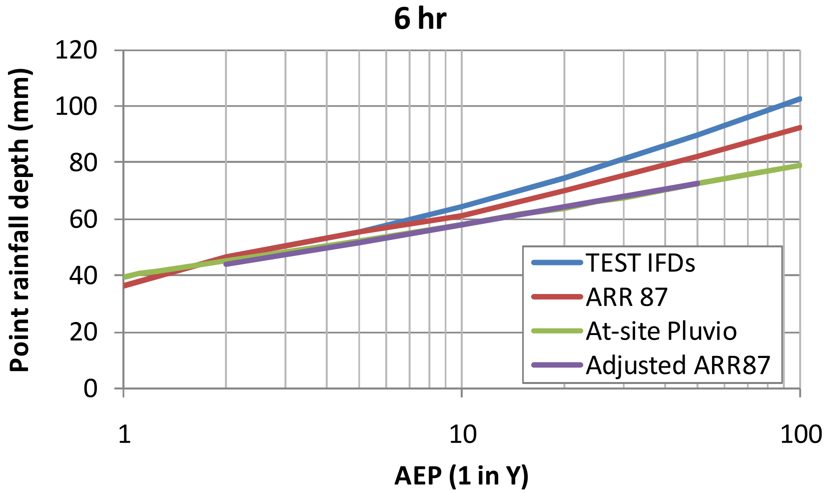
603190 Yates Flat Creek at Woonanup

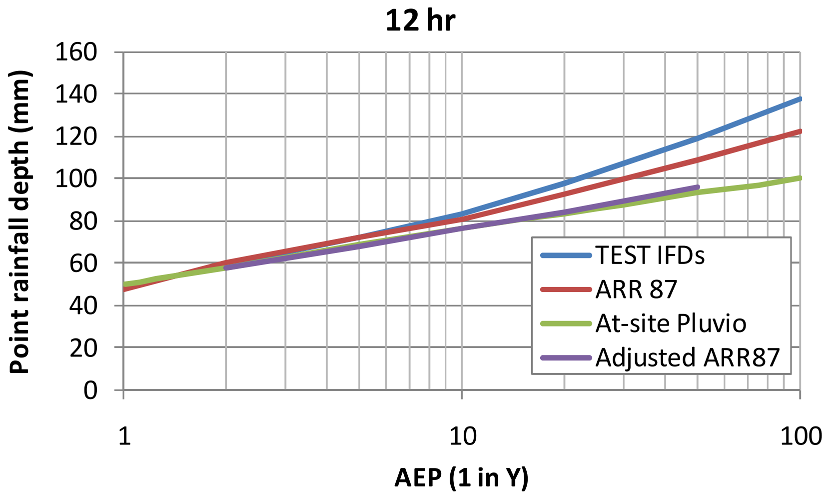


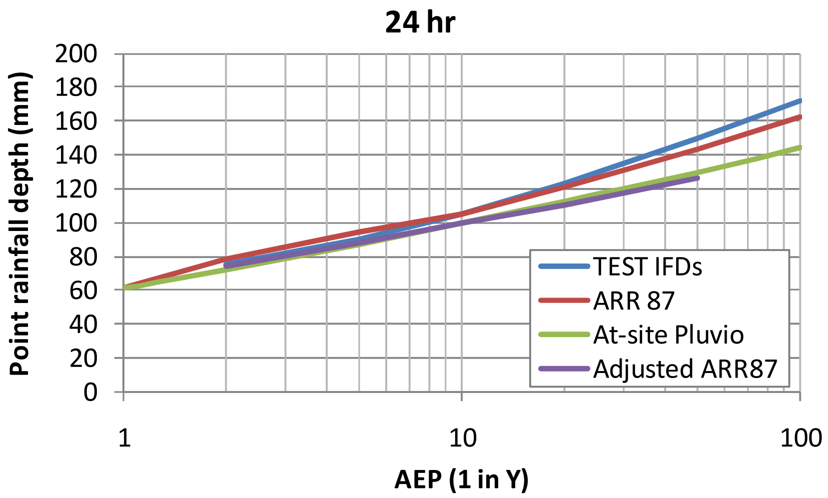




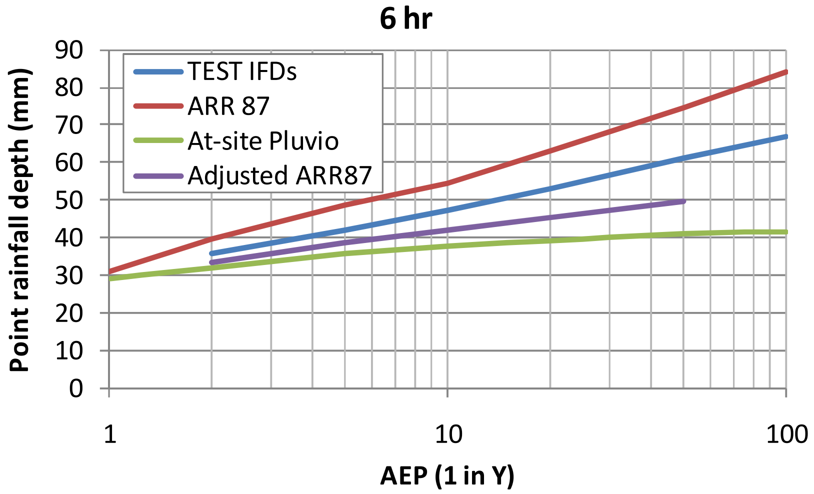
614005 Dirk Brook at Kentish Farm

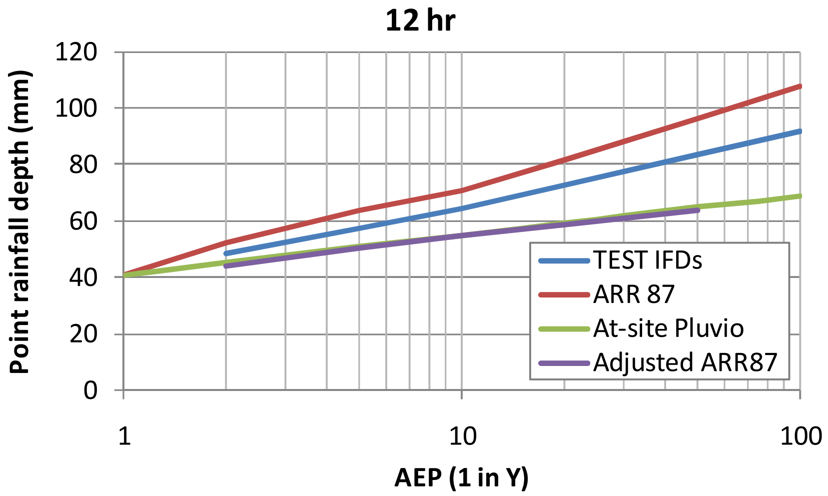


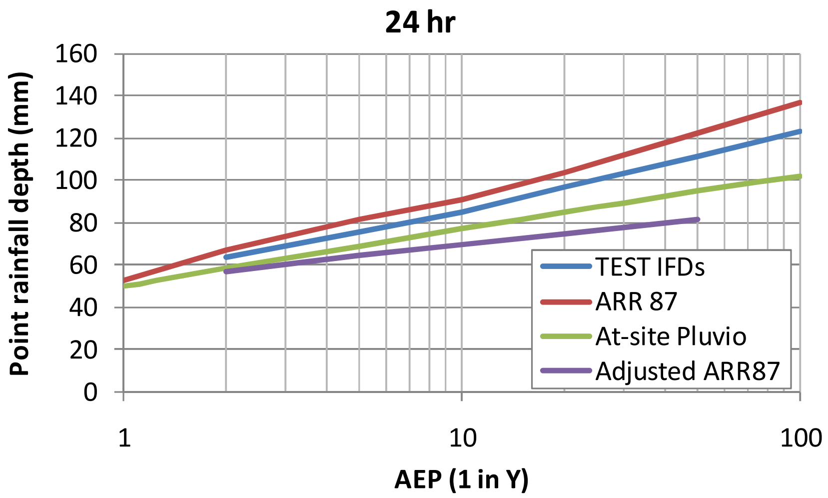




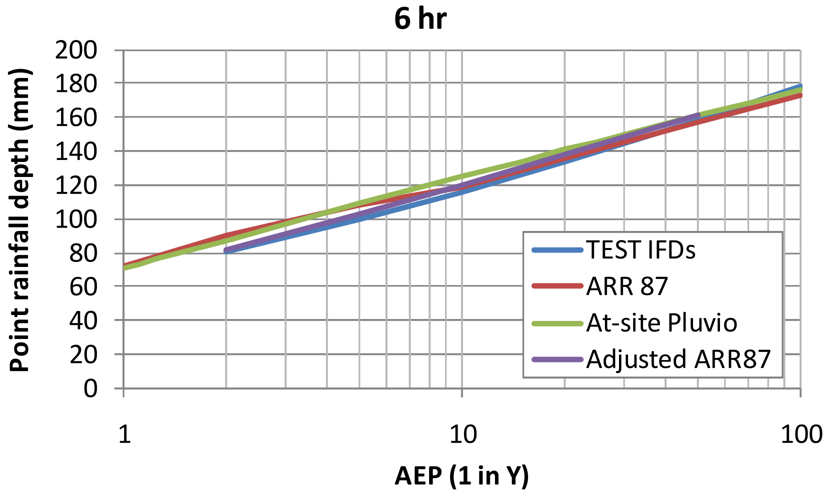
A5040523 Sixth Creek at Castambul

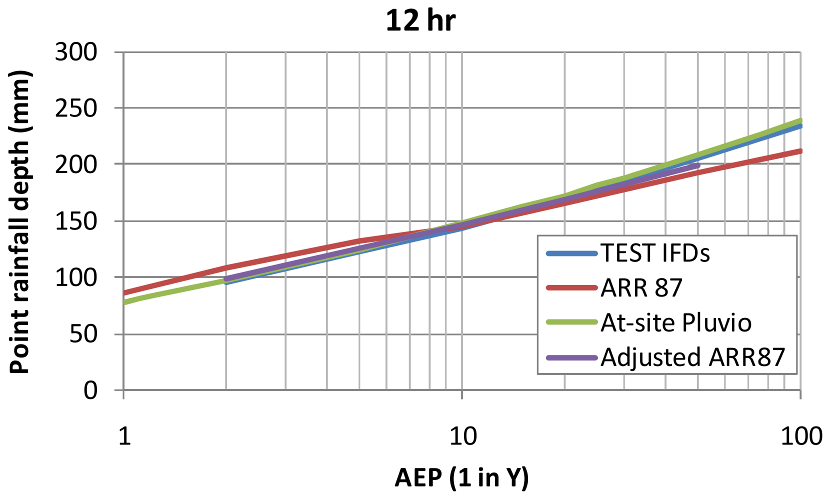


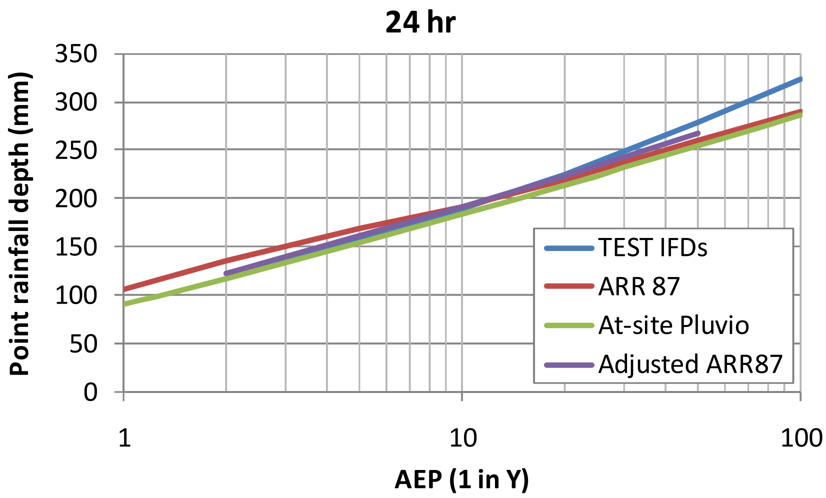




G8170075 Manton River at Manton Dam



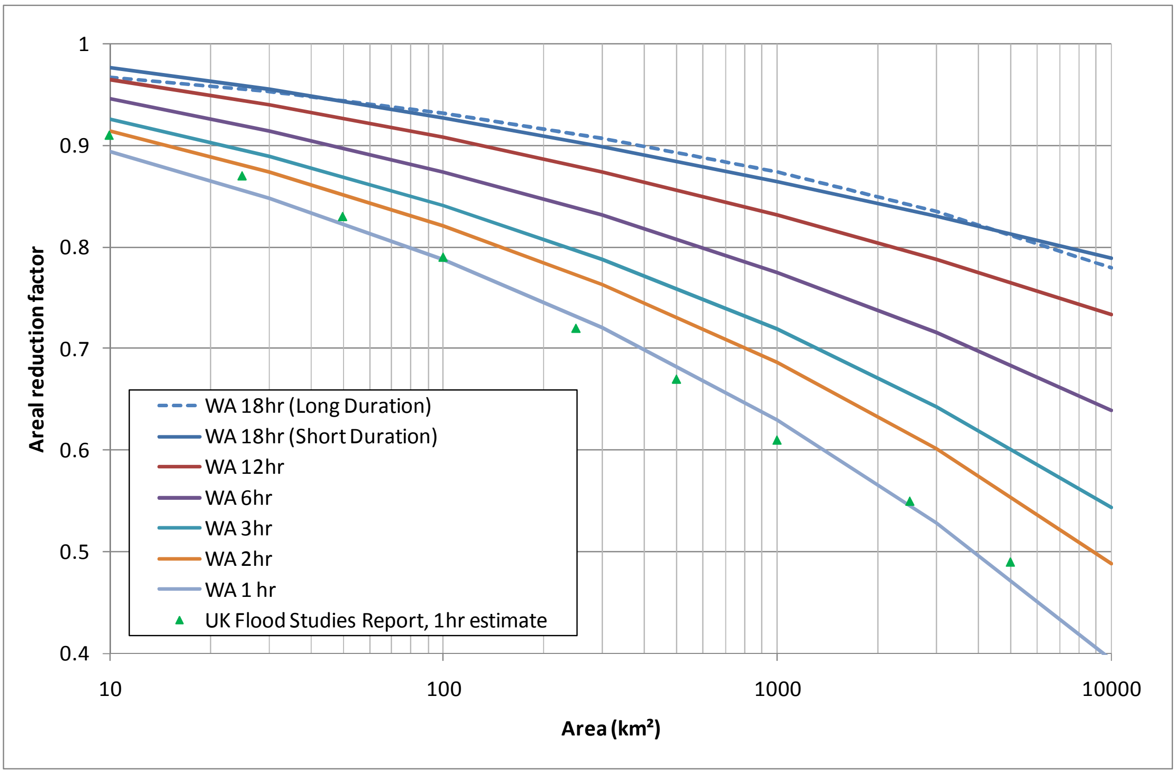




Appendix I WA short duration areal reduction factors

As short duration aerial reduction factors were not available for Western Australia from the CRC-FORGE project, these were derived. It was assumed that the areal reduction factor equation would follow the same form as that derived in the Victorian CRC-FORGE project (Siriwardena and Weinmann, 1996). The 1 hour duration curve was adopted from the UK flood study report, and the 18 hour curve was adopted from the long duration analysis. The parameters from the equation were then chosen to best match these two bounding cures, as shown in the figure below. The adopted short duration equation is:

$$ARF_{0.50} = 1.00 - 0.145\left(Area^{0.174} - 0.756\right) - 0.039\left(Area^{0.226}\right)\left(-0.011 - \log_{10} DUR\right)$$



Appendix J Parametric distributions

Initial Loss (IL/CL model)

Catchment	Selected distribution	Parameters	Median Error
614005 Dirk Bk @ Kentish Farm			
Initial Loss (IL/CL model)	Gamma	a=2.88 b=7.56	11.1%
Continuing Loss (IL/CL model)	Log-Pearson 3	a=3.67 b=0.29 g=3.05	
RoC (IL/PL model)	Beta*	a1=0.12 a2=0.44 a=0.10 b=0.40	-0.0%
IMC (SWMOD)	Generalised Extreme Value	k=-0.156 s=35.0 m=173.5	-2.3%
125006 Finch Hatton Crk @ Dam Site			
Initial Loss (IL/CL model)	Gamma	a=2.99 b=22.4	0.2%
Continuing Loss (IL/CL model)	Gamma	a=3.05 b=2.47	-3.6%
RoC (IL/PL model)	Beta*	a1=0.74 a2=1.07 a=0.40 b=1.00	8.1%
IMC (SWMOD)	Weibull (3P)	a=6.36 b=230.1 g=-138.2	-1.3%
410743 Jerrabomberra Crk @ Four Mile Crk			
Initial Loss (IL/CL model)	Generalised Pareto	k=-0.25 s=26.8 m=3.45	9.3%
Continuing Loss (IL/CL model)	Generalised Pareto	k=-0.398 s=4.55 m=-0.724	-8.2%
RoC (IL/PL model)	Beta	a1=0.312 a2=0.256 a=0.1 b=1.0	4.8%
IMC (SWMOD)	Gumbel max	s=17.9 m=5.52	16.1%
G8170075 Manton R u/s Manton Dam			
Initial Loss (IL/CL model)	Gamma	a=1.56 b=29.0	2.3%
Continuing Loss (IL/CL model)	Gamma	a=0.654 b=8.35	19%
RoC (IL/PL model)	Beta	a1=0.653 a2=0.534 a=0.15 b=1.0	-4.7%
IMC (SWMOD)	Weibull (3P)	a=1.676 b=49.8 g=-13.8	6.6%
141009 N.Maroochy R @ Eumundi			
Initial Loss (IL/CL model)	Gamma	a=0.99 b=35.9	-0.4%
Continuing Loss (IL/CL model)	Gamma	a=1.16 b=1.86	-26.6
RoC (IL/PL model)	Beta	a1=1.53 a2=0.616 a=0.333 b=1.0	1.2%

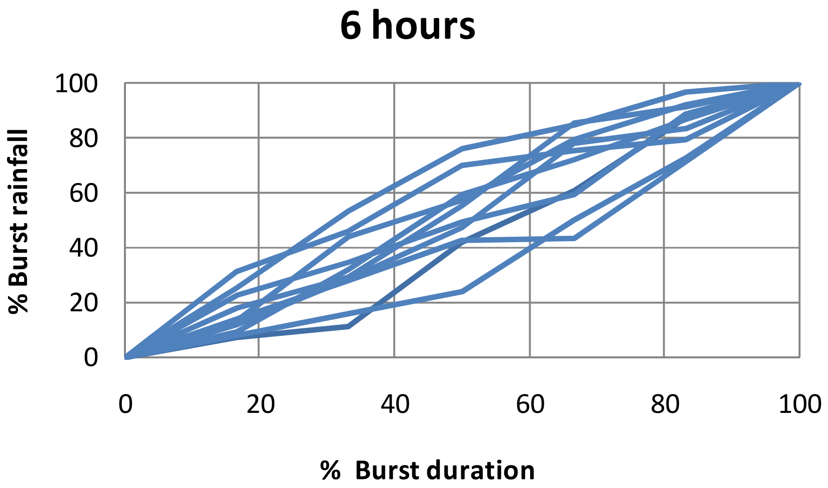
IMC (SWMOD)	Generalised Pareto	k=-1.70 s=178.5 m=-48.0	-1.6%
A5040523 Sixth Crk @ Castambul			
Initial Loss (IL/CL model)	Gamma	a=3.09 b=13.5	1.0%
Continuing Loss (IL/CL model)	Generalised Pareto	k=0.160 s=2.83 m=0.606	-1.2%
RoC (IL/PL model)	Beta	a1=0.762 a2=0.578 a=0.08 b=0.550	-8.3%
IMC (SWMOD)	Generalised Pareto	k=-2.61 s=178.4 m=-16.1	-8.8%
422321 Spring Crk @ Killarney			
Initial Loss (IL/CL model)	Gamma	a=3.76 b=13.8	4.3%
Continuing Loss (IL/CL model)	Generalised Extreme Value	k=-0.207 s=3.41 m=3.94	3.5%
RoC (IL/PL model)	Beta*	a1=0.352 a2=0.594 a=-1.61E-14 b=1.0	-53.8%
IMC (SWMOD)	Beta	a1=2.44 a2=2.25 a=-80.5 b=58.3	-32.3%
2219 Swan R u/s Harding Falls			
Initial Loss (IL/CL model)	Gamma	a=2.05 b=19.8	11.5%
Continuing Loss (IL/CL model)	Generalised Pareto	k=0.0974 s=1.79 m=-0.332	-25.0%
RoC (IL/PL model)	Beta*	a1=0.963 a2=0.121 a=0.155 b=1.0	29.0%
IMC (SWMOD)	Lognormal (3P)	s=0.303 m=4.68 g=-130.5	56.8%
22827 Toomuc Crk @ Pakenham			
Initial Loss (IL/CL model)	Gamma	a=2.65 b=13.3	-0.7%
Continuing Loss (IL/CL model)	Gamma	a=2.22 b=1.30	15.7%
RoC (IL/PL model)	Beta*	a1=0.607 a2=0.861 a=0.2 b=0.800	-4.8%
IMC (SWMOD)	Lognormal (3P)	s=0.0342 m=6.10 g=-435.7	11.2%
603190 Yates Flat Crk @ Woonanup			
Initial Loss (IL/CL model)	Gamma	a=1.10 b=38.8	-13.5%
Continuing Loss (IL/CL model)	Gamma	a=0.756 b=0.573	-15.4%
RoC (IL/PL model)	Beta	a1=0.104 a2=0.0793 a=0.57 b=1.0	8.5%
IMC (SWMOD)	Generalised Pareto*	k=-3.97 s=537.4 m=-86.6	38.4%

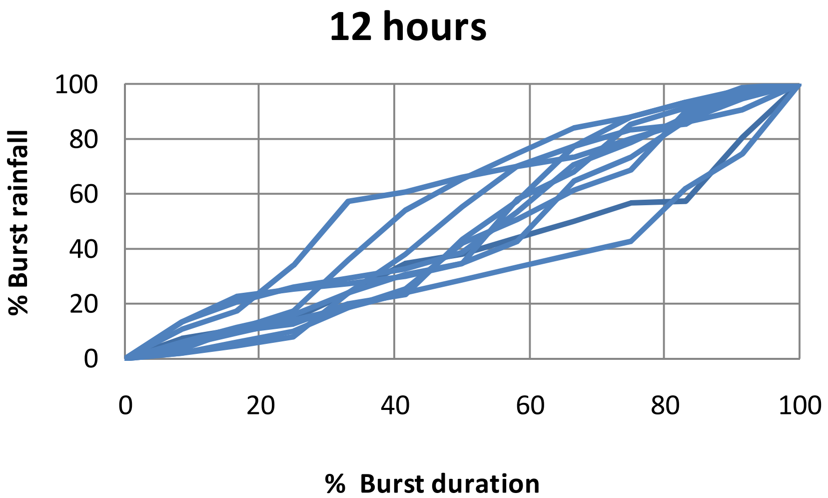
Standardised			
Initial Loss (IL/CL model)	**Generalised Gamma**	**k=0.52 a=8.14 b=0.021**	**5.7%**
Continuing Loss (IL/CL model)	**Gamma**	**a=0.811 b=1.61**	**-17.6%**
RoC (IL/PL model)	**Generalised Gamma**	**k=1.19 a=2.73 b=0.462**	**-3.1%**
IMC (SWMOD)	**Beta**	**a1=19099 a2=67.1 a=-4581.3 b=17.171**	**9.9%**

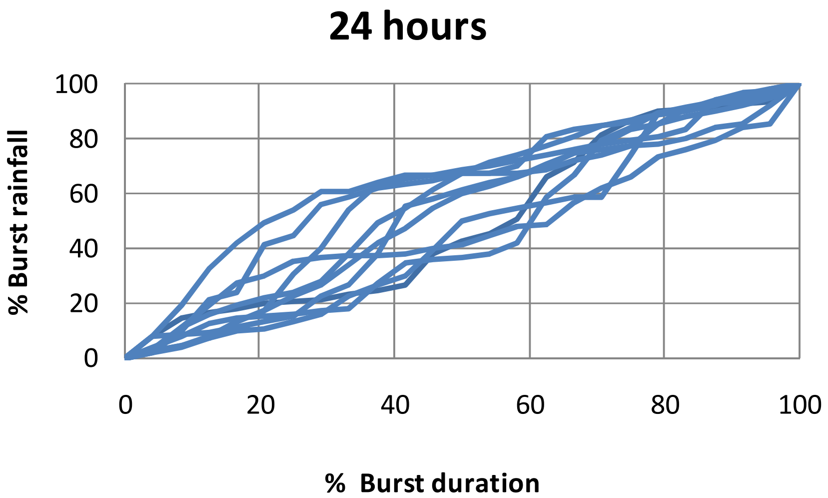
*Issues with goodness of fit tests

Appendix K Temporal patterns

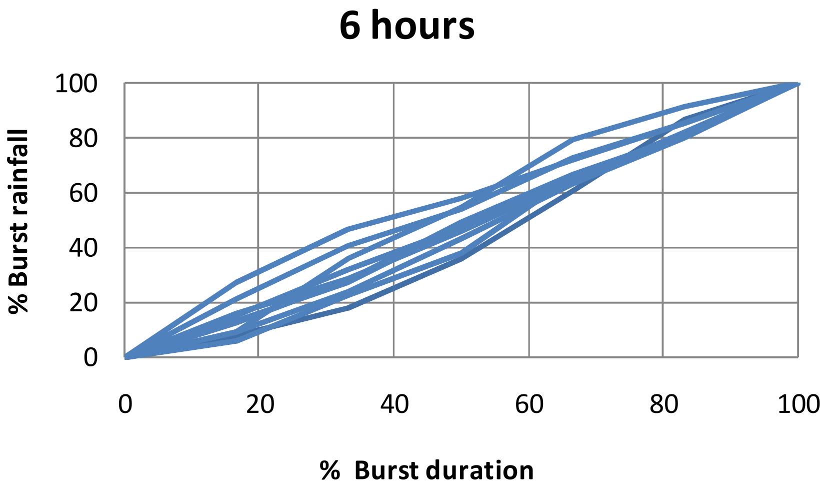
614005 Dirk Brook at Kentish Farm

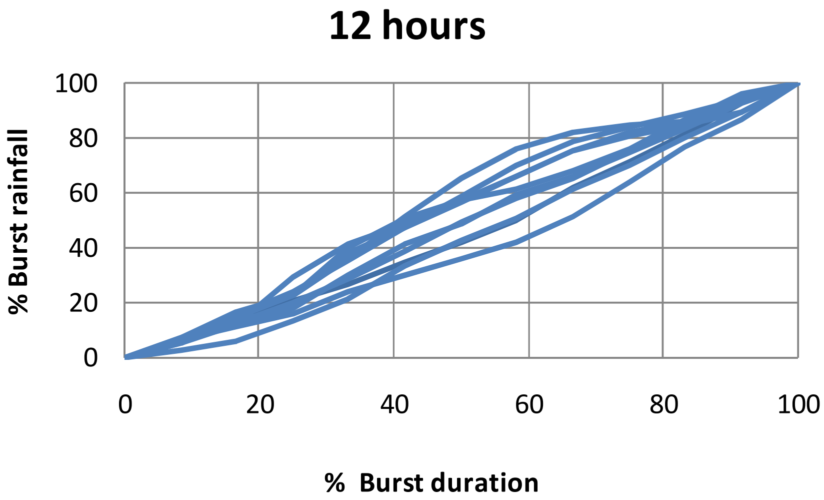


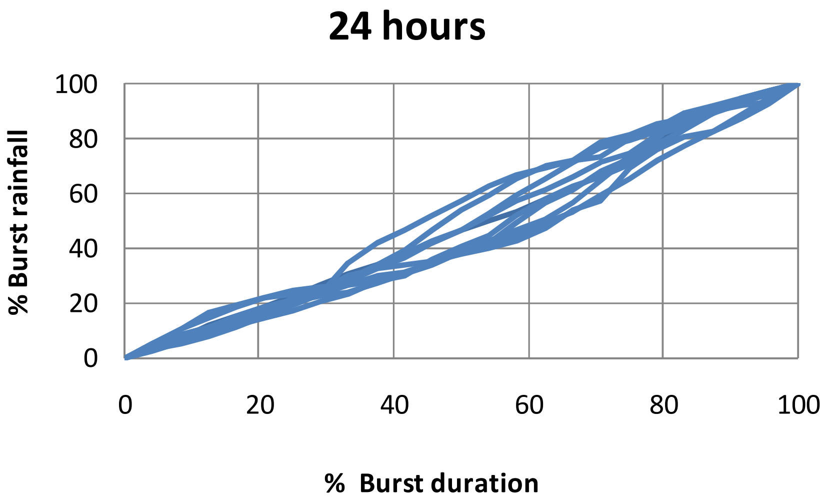




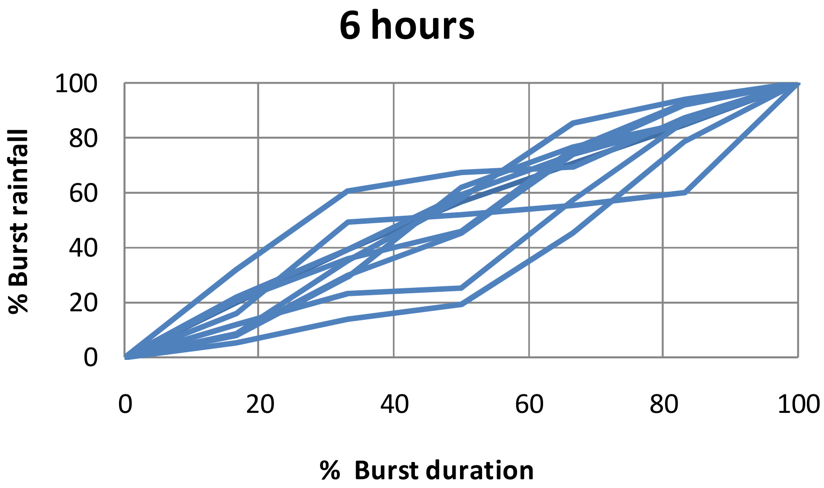
125006 Finch Hatton Creek @ Dam Site

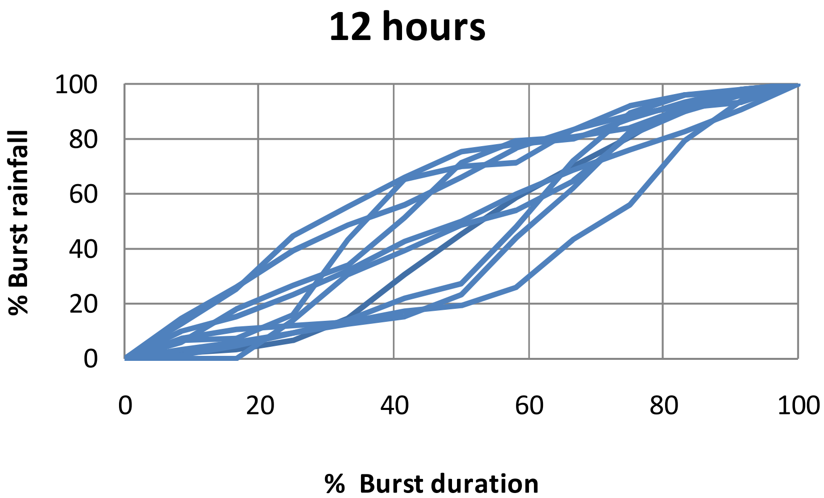


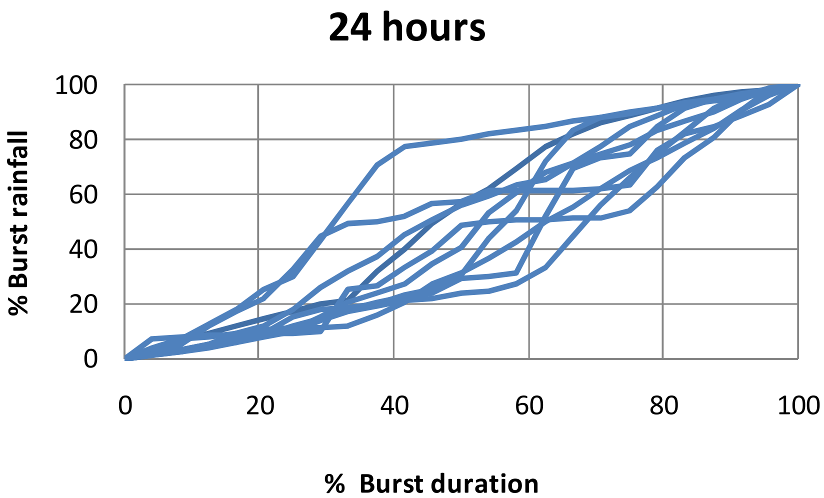




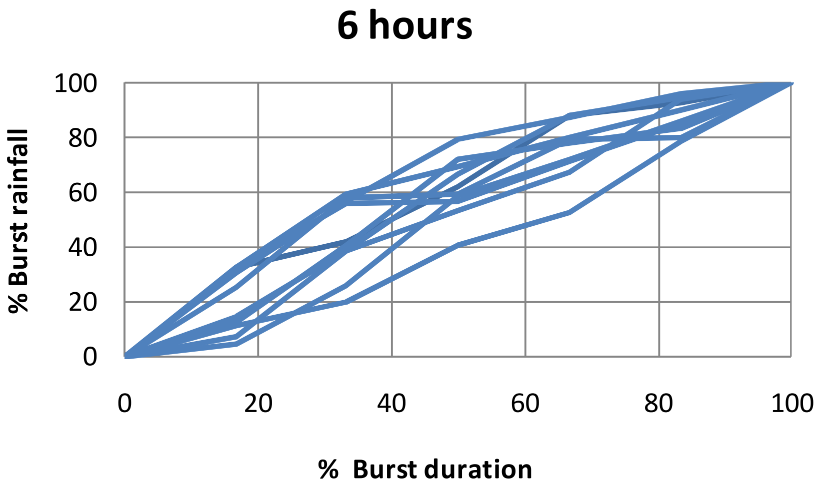
410743 Jerrabomberra Creek @ Four Mile Creek

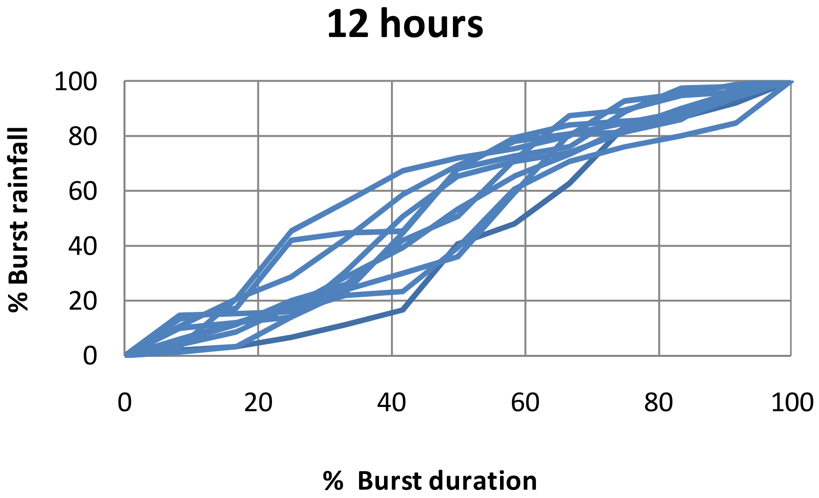


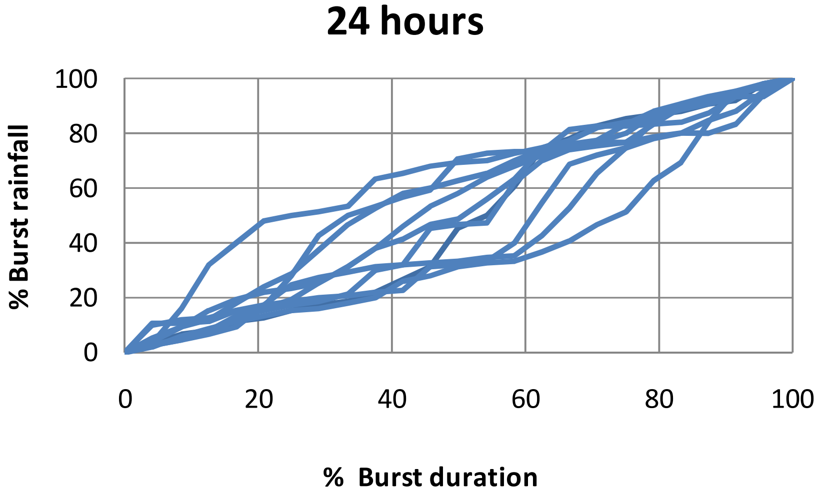




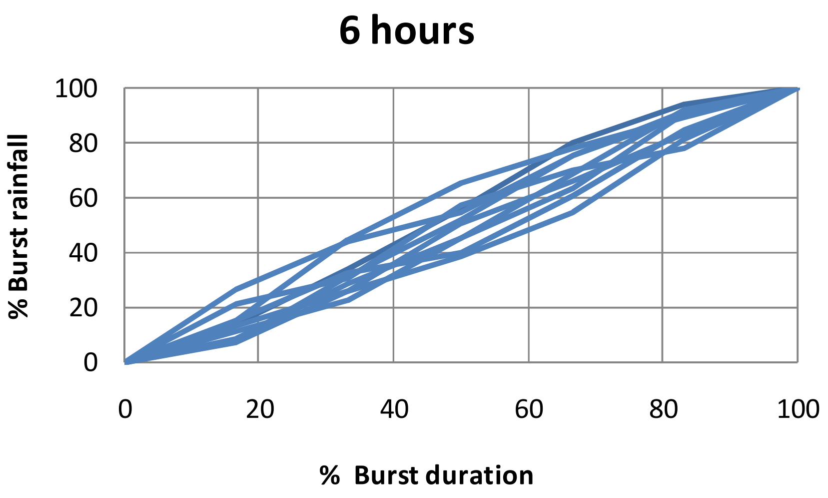
G8170075 Manton River upstream Manton Dam

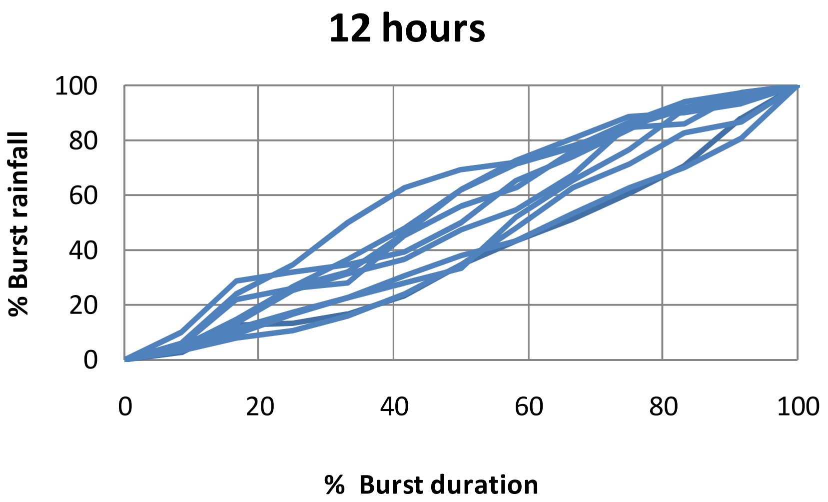


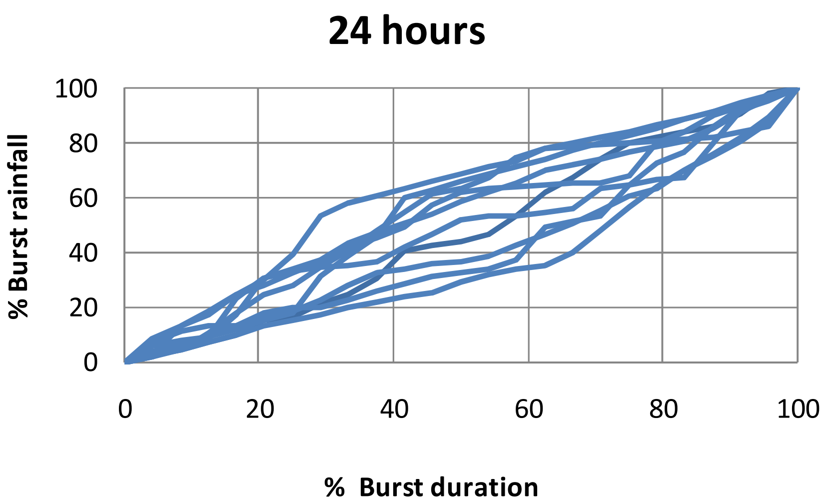




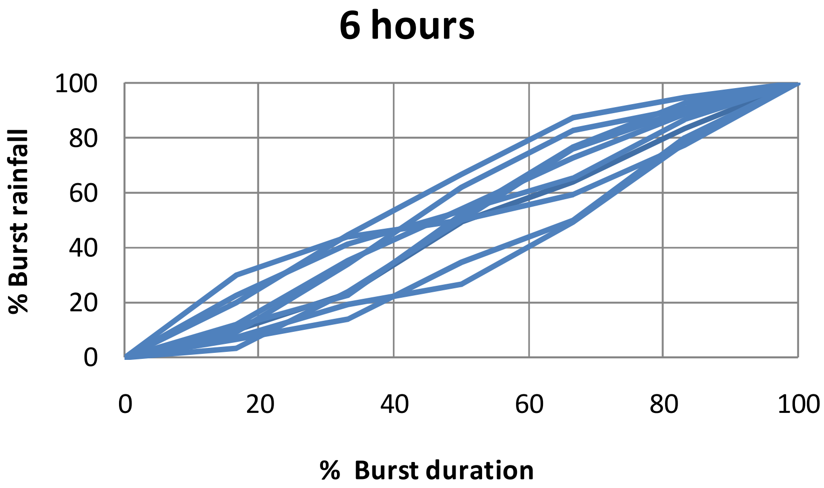
141009 North Maroochy River @ Eumundi

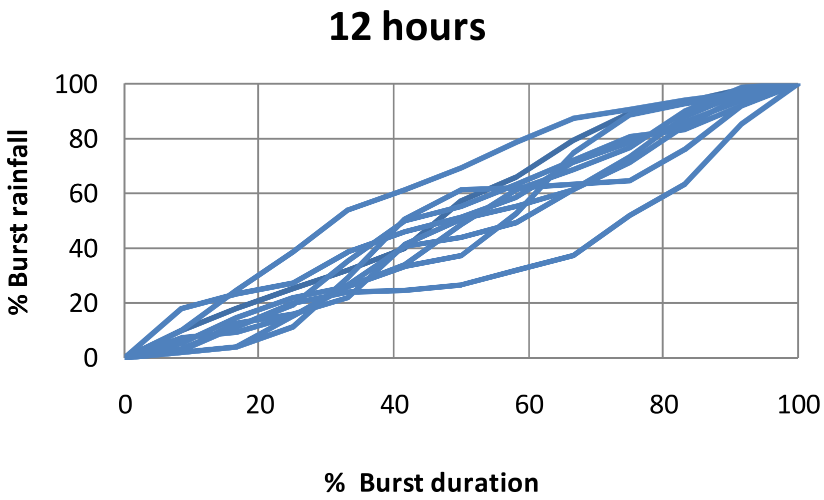


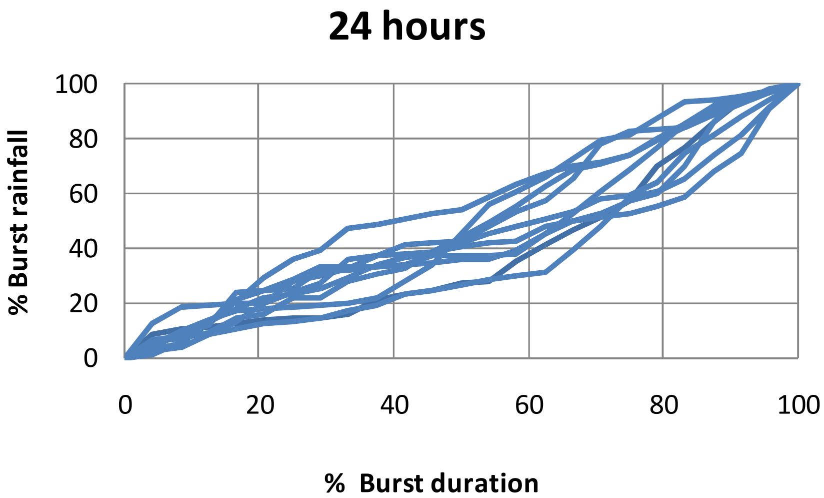




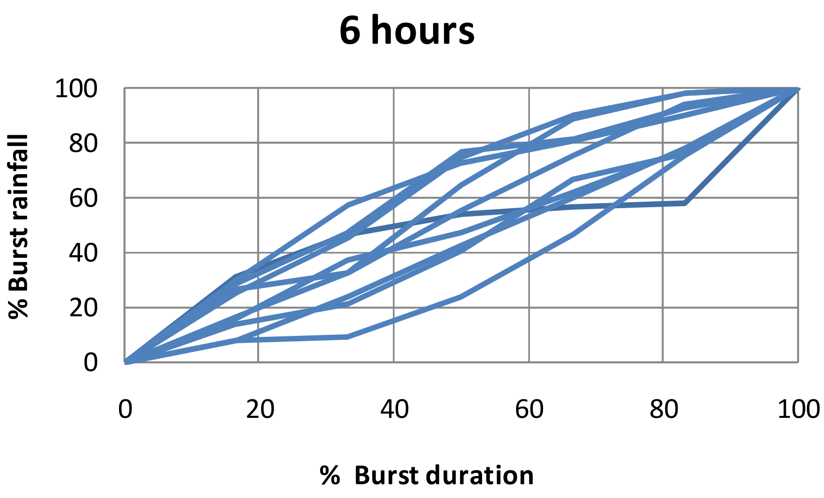
A5040523 Sixth Creek @ Castambul

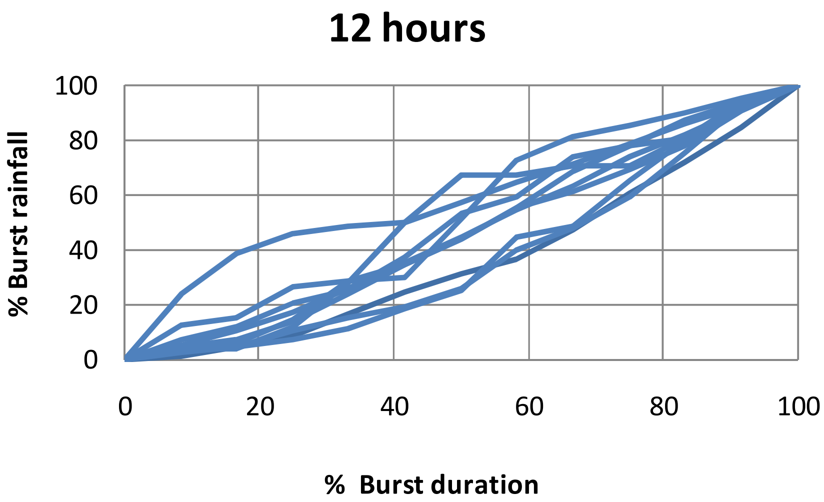


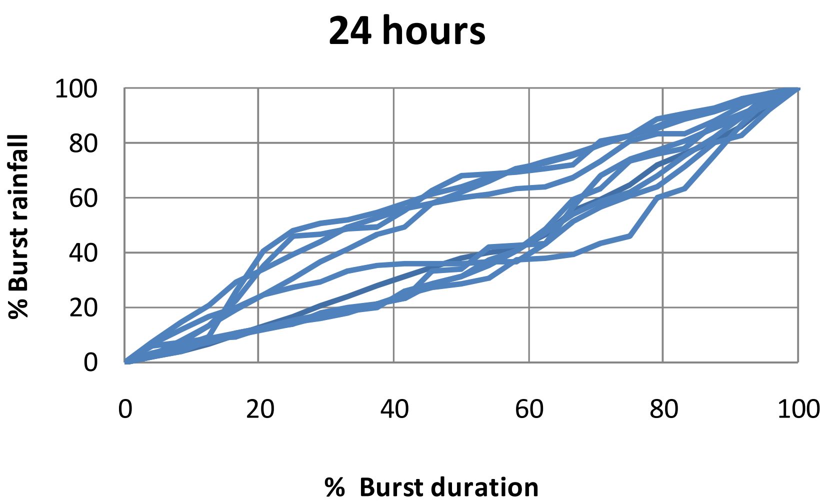




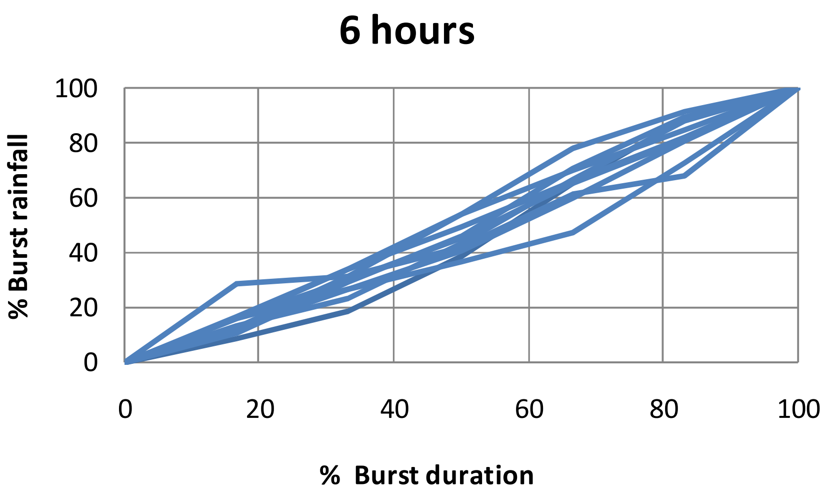
422321 Spring Creek @ Killarney

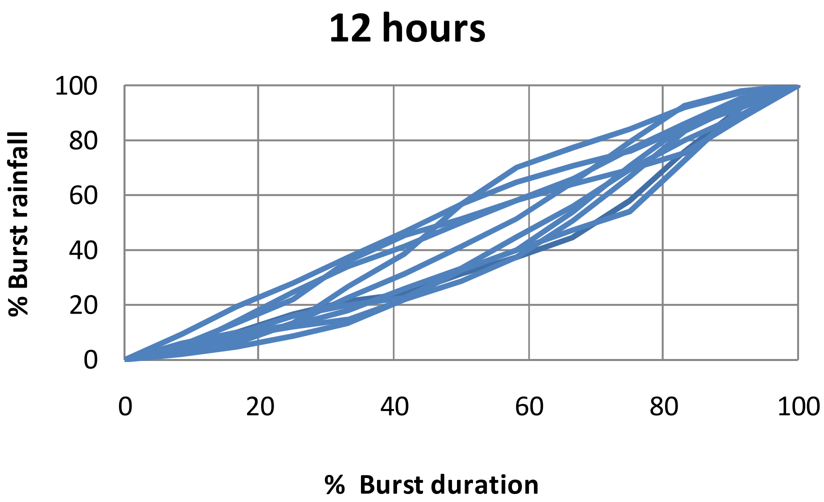


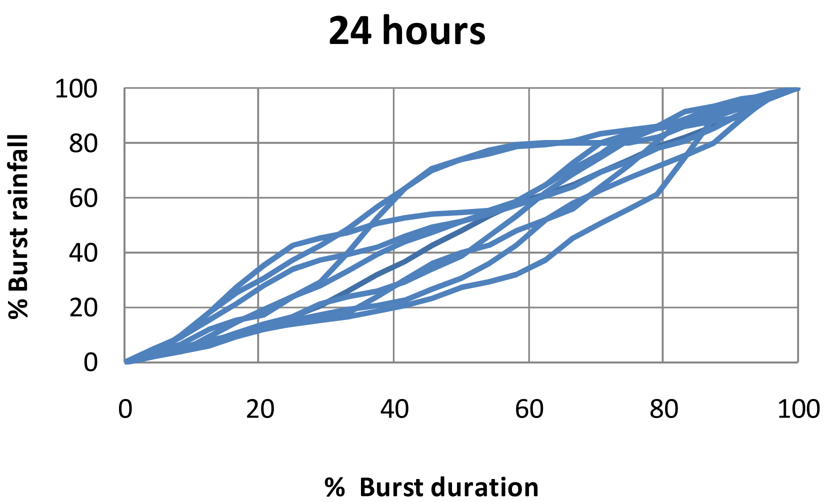




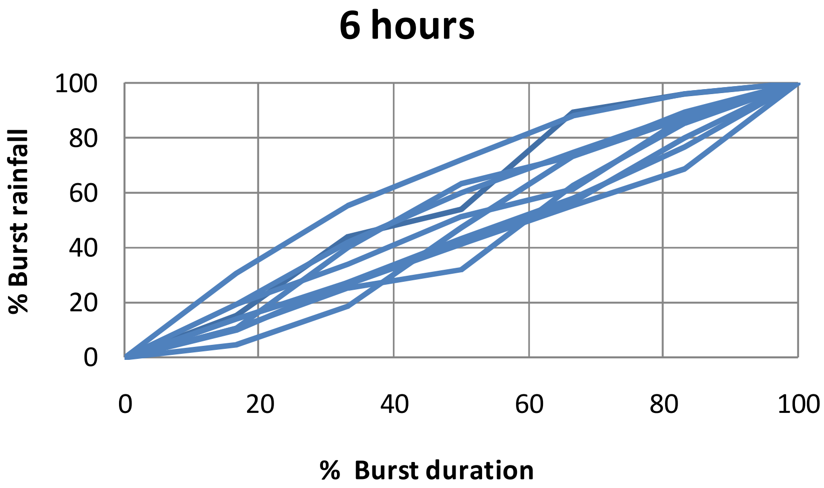
2219 Swan River upstream Harding Falls

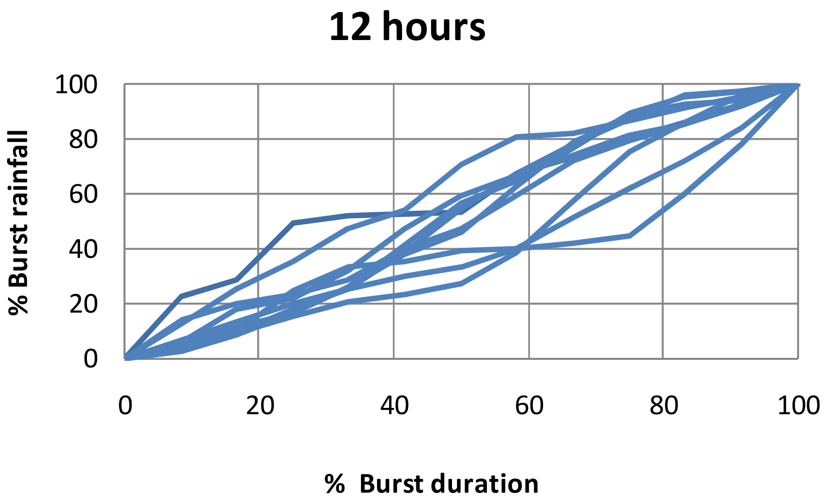


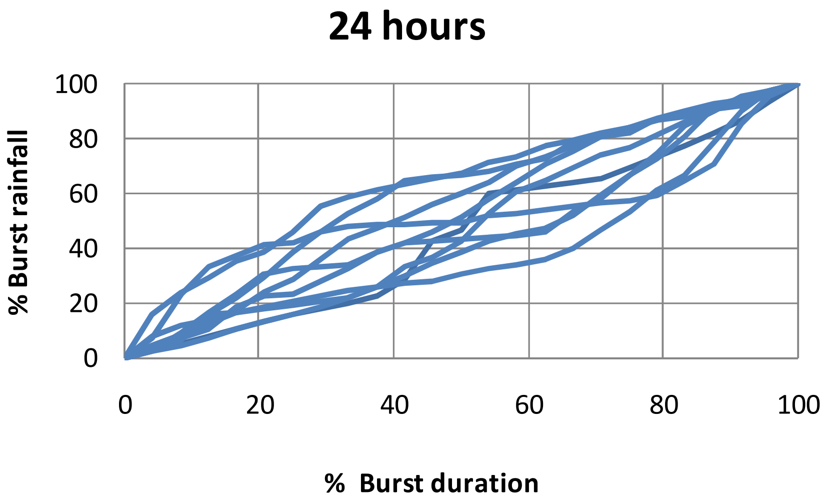




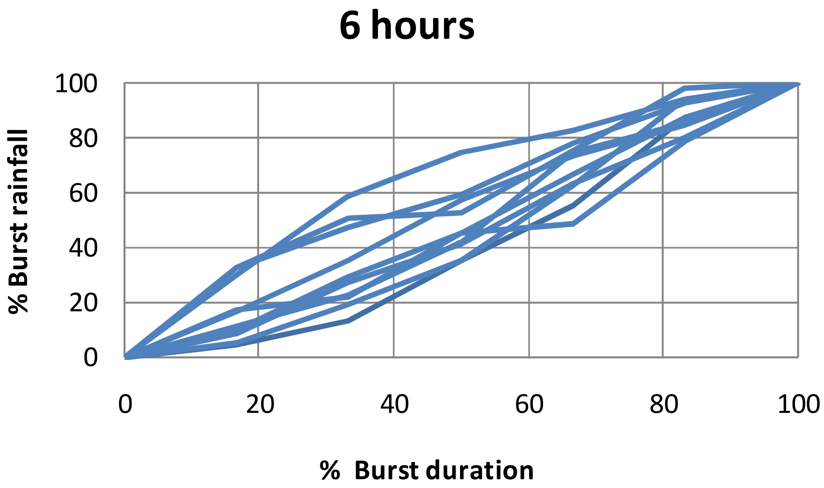
228217 Toomuc Creek @ Pakenham

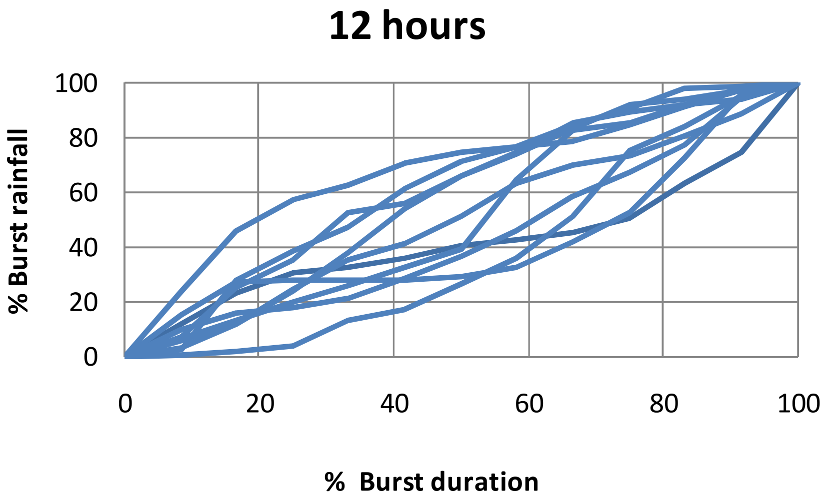


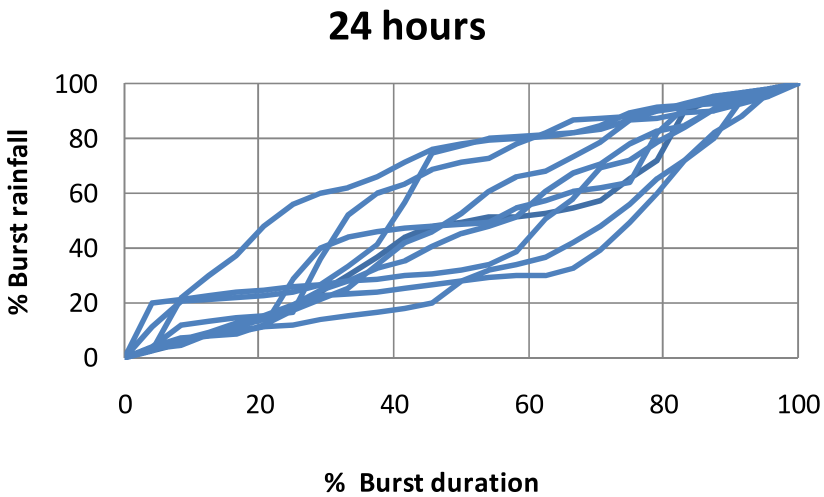




603190 Yates Flat Creek @ Woonanup







Appendix L Design flood estimates

Dirk Brook @ Kentish Farm

Adopted Losses

		IL/CL		IL/RoC		SWMOD	
		IL=6, CL=8.8, k_c=14		IL=5, RoC=0.12, k_c=12		IMC=80, CF=5.4, k_c=12	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	5.6	4.3	18	5.1	18	2.6	18
10	6.9	7.5	18	6.0	18	5.3	18
20	8.3	11.3	18	6.9	18	6.9	18
50	10.1	17.7	18	8.2	18	8.4	18
100	11.6	25.3	18	9.4	18	10.0	18

Zero Initial Losses

		IL/CL		IL/RoC		SWMOD	
		IL=34, CL=8.8, k_c=14		IL=0, RoC=0.12, k_c=12		IMC=95, CF=5.4, k_c=12	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	5.6	1.7	18	5.4	18	3.3	18
10	6.9	4.7	18	6.3	18	6.5	18
20	8.3	8.0	18	7.1	18	8.5	18
50	10.1	13.4	18	8.4	18	10.3	18
100	11.6	19.2	18	9.6	18	12.1	18

Finch Hatton Creek @ Dam Site

Adopted Losses

		IL/CL		IL/RoC		SWMOD	
		IL=15, CL=7, k_c=4		IL=15, RoC=0.57, k_c=4		IMC=80, CF=0.6, k_c=4	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	258	207.3	6	156.1	6	184.8	48
10	354	282.3	6	197.8	6	248.6	48
20	446	349.0	6	235.8	6	316.2	48
50	562	417.2	6	273.5	6	405.6	48
100	644	480.4	6	307.9	6	470.5	48

Zero Initial Losses

		IL/CL		IL/RoC		SWMOD	
		IL=0, CL=7 k_c=4		IL=0, RoC=0.57, k_c=4		IMC=564, CF=0.6, k_c=4	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	258	223.6	3	161.4	6	255.4	6
10	354	296.1	3	202.1	6	328.9	6
20	446	359.1	3	240.5	6	397.3	6
50	562	428.1	3	278.9	6	476.6	6
100	644	488.4	6	314.5	6	532.9	6

Jerrabomberra Creek @ Four Mile Creek

Adopted Losses

		IL/CL		IL/RoC		SWMOD	
		IL=8, CL=2.3, k_c=4		IL=8, RoC=0.59, k_c=4		IMC=12.1, CF=0.3, k_c=4	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	84.3	85.1	18	67.8	18	87.6	18
10	134	110.2	18	82.7	18	119.4	18
20	187	139.3	18	99.5	18	148.3	18
50	258	179.8	12	123.5	18	193.8	18
100	310	215.0	12	143.9	18	229.9	18

Zero Initial Losses

		IL/CL		IL/RoC		SWMOD	
		IL=0, CL=2.3, k_c=4		IL=0, RoC=0.59, k_c=4		IMC=185, CF=0.3, k_c=4	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	84.3	89.7	6	71.0	12	116.5	6
10	134	116.2	6	85.4	12	142.8	6
20	187	143.8	6	102.5	12	171.5	12
50	258	185.4	6	124.9	18	212.0	12
100	310	220.5	6	145.3	6	245.8	12

Manton River upstream Manton Dam

Adopted Losses

		IL/CL		IL/RoC		SWMOD	
		IL=11, CL=2.4, k_c=8		IL=10, RoC=0.67, k_c=7		IMC=25, CF=1.3, kc=7	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	66.2	81.3	18	70.0	18	60.9	48
10	90	105.3	18	86.3	18	85.3	48
20	114	129.2	18	102.7	18	113.4	48
50	146	161.5	18	126.4	18	155.5	48
100	171	190.8	18	146.8	18	187.9	48

Zero Initial Losses

		IL/CL*		IL/RoC*		SWMOD	
						IMC=110, CF=0.36, kc=7	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	66.2	-	-	-	-	101.8	6
10	90	-	-	-	-	124.3	6
20	114	-	-	-	-	151.8	3
50	146	-	-	-	-	187.5	3
100	171	-	-	-	-	219.4	3

*Not run because decreasing initial loss would not improve the match to flood frequency results

North Maroochy River @ Eumundi

Adopted Losses

		IL/CL		IL/RoC		SWMOD	
		IL=7, CL=2, k_c=20		IL=6, RoC=0.84, k_c=20		IMC=25, CF=0.68, k_c=20	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	115	122.4	18	120.5	18	124.7	18
10	153	162.4	18	152.6	18	163.8	18
20	189	197.0	18	181.9	18	200.5	18
50	233	242.2	18	219.8	18	246.5	18
100	265	285.8	18	256.4	18	289.1	18

Zero Initial Losses

		IL/CL*		IL/RoC*		SWMOD*	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	115	-	-	-	-	-	-
10	153	-	-	-	-	-	-
20	189	-	-	-	-	-	-
50	233	-	-	-	-	-	-
100	265	-	-	-	-	-	-

*Not run because decreasing initial loss would not improve the match to flood frequency results

Sixth Creek @ Castambul

Adopted Losses

		IL/CL		IL/RoC		SWMOD	
		IL=14, CL=2.5, k_c=6		IL=14, RoC=0.39, k_c=4		IMC=45, CF=0.95, kc=4	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	29.4	32.8	18	27.3	18	25.9	48
10	45.2	41.9	18	32.0	18	48.7	6
20	64.5	49.8	18	35.4	18	68.5	6
50	96.3	61.0	18	40.1	18	83.5	6
100	125.9	70.2	18	44.1	18	92.0	6

Zero Initial Losses

		IL/CL		IL/RoC		SWMOD*	
		IL=0, CL=2.5, k_c=6		IL=0, RoC=0.39, k_c=4		-	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	29.4	44.6	3	32.6	6	-	-
10	45.2	53.5	3	36.5	6	-	-
20	64.5	61.4	6	40.1	6	-	-
50	96.3	71.9	6	44.8	6	-	-
100	125.9	86.5	6	50.5	6	-	-

*Not run because decreasing initial loss would not improve the match to flood frequency results

Spring Creek @ Killarney

Adopted Losses

		IL/CL		IL/RoC		SWMOD	
		IL=15, CL=5, k_c=6		IL=15, RoC=0.35, k_c=5		IMC=0, CF=2, k_c=5	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	40	22.1	6	19.8	12	24.9	48
10	70	35.0	6	25.6	12	34.1	48
20	108	52.1	6	32.8	12	47.0	48
50	171	79.9	6	42.9	12	64.6	48
100	229	102.6	12	51.2	12	81.6	48

Zero Initial Losses

		IL/CL		IL/RoC		SWMOD	
		IL=0, CL=5, k_c=6		IL=0, RoC=0.35, k_c=5		IMC=394, CF=2, k_c=5	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	40	33.8	6	24.0	6	67.1	6
10	70	48.7	6	29.8	6	82.3	6
20	108	66.4	6	36.4	6	101.3	6
50	171	95.1	6	46.6	6	130.4	6
100	229	116.3	6	54.5	6	154.8	6

Swan River upstream Harding Falls

Adopted Losses

		IL/CL		IL/RoC		SWMOD	
		IL=12, CL=1.2, k_c=10		IL=11, RoC=0.71, k_c=10		IMC=0, CF=0.36, kc=10	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	111	83.1	12	66.5	12	68.4	18
10	155	105.9	12	81.7	12	85.4	18
20	193	126.5	12	95.9	12	102.6	18
50	236	152.3	12	114.2	12	123.0	12
100	263	176.8	12	131.1	12	142.3	12

Zero Initial Losses

		IL/CL		IL/RoC		SWMOD	
		IL=0, CL=1.2, k_c=10		IL=0, RoC=0.7, k_c=10		IMC=373, CF=0.36, kc=10	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	111	89.5	12	69.7	12	94.9	12
10	155	111.3	12	84.4	12	117.6	12
20	193	131.8	12	98.4	12	138.3	12
50	236	156.3	12	115.8	12	164.8	12
100	263	180.2	12	132.5	12	186.4	12

Toomuc Creek @ Pakenham

Adopted Losses

		IL/CL		IL/RoC		SWMOD	
		IL=11, CL=2.1, k_c=12		IL=10, RoC=0.44, k_c=11		IMC=10.5, CF=0.89, k_c=11	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	22.2	19.4	18	18.0	18	18.9	48
10	28.7	29.2	12	22.6	18	25.7	48
20	33.7	43.4	18	29.0	18	35.6	48
50	38.8	67.8	12	38.6	18	53.8	48
100	41.7	85.5	12	46.5	18	69.2	48

Zero Initial Losses

		IL/CL*		IL/RoC		SWMOD*	
		-		IL=0, RoC=0.44, k_c=11		-	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	22.2	-	-	19.8	18	-	-
10	28.7	-	-	24.7	18	-	-
20	33.7	-	-	30.9	18	-	-
50	38.8	-	-	41.7	12	-	-
100	41.7	-	-	49.3	12	-	-

*Not run because decreasing initial loss would not improve the match to flood frequency results

Yates Flat Creek @ Woonanup

Adopted Losses

		IL/CL		IL/RoC		SWMOD	
		IL=15, CL=0.3, k_c=10		IL=11, RoC=0.86, k_c=9		IMC=25, CF=0.32, k_c=9	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	14	44.4	18	47.1	18	31.9	24
10	20	56.9	18	58.4	18	52.9	18
20	24.9	70.3	18	70.6	18	64.9	18
50	31.7	88.8	18	87.2	18	83.6	18
100	36.7	104.6	18	101.3	18	99.3	18

Zero Initial Losses

		IL/CL		IL/RoC		SWMOD	
		IL=72, CL=0.3, k_c=10		IL=50, RoC=0.86, k_c=9		IMC=0, CF=0.32, k_c=9	
AEP	**FFA Q_{peak} (m^3/s)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**	**Q_{peak} (m^3/s)**	**T_{crit} (hrs)**
5	14	4.6	48	18.9	48	9.7	48
10	20	21.8	48	34.1	24	17.9	48
20	24.9	37.1	24	45.5	24	28.2	48
50	31.7	54.9	48	61.9	18	45.1	48
100	36.7	69.5	48	75.3	18	60.4	48