Australian Rainfall & Runoff

Revision Projects

PROJECT 6

Loss Models for Catchment Simulation – Urban Catchments

STAGE 2 REPORT

P6/S2/016C

FEBRUARY 2014

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

STAGE 2 REPORT

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Project Project 6: Loss Models For Catchment Simulation – Urban Losses	**ARR Report Number** P6/S2/016C
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FOREWORD

ARR Revision Process

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

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

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

However, many of the practices recommended in the 1987 edition of ARR now are becoming outdated, and no longer represent the accepted views of professionals, both in terms of technique and approach to water management.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

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

The update will be completed in three stages. Twenty one revision projects have been identified and will be undertaken with the aim of filling knowledge gaps. Of these 21 projects, ten projects commenced in Stage 1 and an additional 9 projects commenced in Stage 2. The remaining 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

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

Mark Babister
Chair Technical Committee for
ARR Research Projects

Assoc Prof James Ball
ARR Editor

ARR REVISION PROJECTS

The 21 ARR revision projects are listed below :

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

ARR Technical Committee:

Chair: Mark Babister, WMAwater
Members: Associate Professor James Ball, Editor ARR, UTS
Professor George Kuczera, University of Newcastle
Professor Martin Lambert, Chair NCWE, University of Adelaide
Dr Rory Nathan, SKM
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- Sahani Pathiraja (Cardno)
- Lisa Pomeroy (Cardno)
- Associate Professor James Ball (ARR Project Manager)
- Mark Babister (ARR Technical Committee)

Note: # provided their time as in kind.

This report was independently reviewed by:

- Michael Boyd

BACKGROUND

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

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

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

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

- **Phase 4** – Analysis of Data for Catchments across Australia (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 3**.

EXECUTIVE SUMMARY

Runoff from urban catchments is a function of both the impervious and pervious areas and the complex interactions between them. While the majority of Australia's population lives within urban areas, and hence are primarily affected by urban runoff, very little is understood of this complex impervious and pervious interaction. This is in no small part confounded by limited long term rainfall and flow gauging in urban catchments, making analysis of alternative models difficult to validate.

As a part of the broader Australian Rainfall and Runoff update, this report seeks to review urban hydrology in Australia. The particular aim of this particular project is the:

- Assessment of Effective Impervious Areas; and
- Review of urban loss models and analysis of their suitability.

Effective Impervious Area

Estimating the catchment imperviousness is an important step in urban rainfall runoff modelling, particularly given the sensitivity of simulated runoff to this parameter in many models (Alley et al., 1983). Traditionally, the Total Impervious Area (TIA) is used with the assumption that, neglecting depression losses, this area contributes fully to generating runoff. This is in spite of research dating back to the 1970s identifying the importance of the Effective Impervious Area (EIA) over the TIA (refer Cherkaver,1975; Beard et al.,1979).

Use of the TIA which includes impervious areas with no direct connection to the drainage network can result in the overestimation of urban runoff volumes and peak flows. Although definitions vary, the EIA is generally considered to be representative of the area of the catchment that generates a rapid runoff response in rainfall events. The EIA therefore provides a more realistic measure of the impervious area that generates runoff at the catchment outlet.

Three key methods have been adopted and reviewed in this report:

- Estimation of EIA through regression analysis of rainfall and runoff data;
- Estimation of EIA using GIS methods;
- Estimation of EIA using available guidance documents.

These methods have been applied to 8 urban catchments across Australia.

The regression analysis has identified that the EIA is typically 55 to 65% of the TIA, although there are some exceptions to this. A summary of this is provided in the Table i below.

Based on a sensitivity analysis of some of the key assumptions in the methodology, the estimates of EIA are expected to fall within a +/- 5% to 10% range. Some of the key assumptions include:

- The use of point rainfall and the assumption of uniformly distributed rainfall;
- The recording period of the data used in the regression;
- Criteria used to isolate storm events.

It is noted that the range of EIA estimated in this report is marginally higher than the Draft NSW MUSIC modelling guidelines.

The GIS method of identifying and estimating DCIA areas tended to overestimate the EIA from the regression analysis. As shown in Table i, the EIA from the regression analysis is about 70% (+/- 5%) of the DCIA from the GIS Analysis for most catchments. A majority of the DCIA areas determined from the GIS Analysis are roads and rooves, meaning that in general, the EIA from the regression analysis equates to about 70% (+/-5%) of all roads and rooves. However, it is noted that this general rule does not apply to all catchments. For example, Giralang (ACT) has a higher EIA/DCIA ratio of around 85%, although this is likely due to the higher degree of connected surfaces (as discussed in Goyen (2000) and also as evidenced by the higher EIA(regression)/TIA ratio of around 78%).

Table i. Summary of EIA Results*

Catchment	Urban TIA Fraction#	EIA/TIA	DCIA (GIS)/ TIA	EIA (Reg.) /DCIA(GIS)
Albany Drain (WA)	35%	59%	83%	71%
McArthur Park (NT)	45%	66%	93%	70%
Giralang (ACT)	46%	74 to 80%	95%	82%
Parra Hills Drain (SA)	55%	56%	87%	64%
Kinkora Road (VIC)	66%	59%	87%	68%
Powells Creek (NSW)	68%	59 – 63%	81%	75%

#The Urban TIA fraction is defined as the percentage of impervious area in the urban area and was based on the desktop GIS method.
**Note that Ithaca (QLD) and Argyle St (Tas) are not included in this table due primarily to large pervious (bushland) areas in these catchments, which influences the results. Further details are provided in Section* 6.

Urban Loss Models

The interaction of the pervious area with the impervious area in urban catchments results in a complication to hydrological analysis. To date, the most common loss models adopted for urban hydrology are the initial - continuing loss models. Two key models have been reviewed in this report:

- Initial loss – constant continuing loss model;
- Initial loss – proportional continuing loss model;

These loss models have been applied to historical storm events identified for five of the catchments from the EIA analysis. These catchments were selected based on the magnitude of storm events (particularly in relation to pervious runoff events) and the quality of the data. It is noted that two of the assessed catchments (McArthur Park (NT) and Argyle Street (TAS) are not well suited for the analysis, and so the results from these should be interpreted with caution.

The catchments have been conceptually divided into two distinct sub-areas:

- Directly Connected Impervious Area (DCIA), which results in a direct runoff following the exhaustion of any impervious area initial losses;
- Indirectly Connected Impervious Area + Pervious Areas, otherwise referred to in this report as the “Other Area”. Given the complexities of the interactions of these two areas, they have been conceptually lumped together such that appropriate loss values can be

determined for the overall combined area. Should more information or better catchment data become available, it may be possible to characterise these areas separately.

The analysis for determining the Other Area losses is primarily based on a storm volumetric methodology. From a broad perspective, the following is undertaken:

1) The initial loss on the Other Area is estimated by the point at which the cumulative volume of runoff exceeds the cumulative volume of runoff estimated from the EIA. This represents the assumed point at which the Other Area starts to contribute to the runoff;
2) The Other Area continuing loss is estimated by an analysis of the overall volume of the storm, and fitting the different models to the volume of runoff estimated from the Other Area.

Storm events were selected based on a number of factors, include the amount of runoff from the Other Area, the duration of the rainfall as well as a number of other checks such as the rainfall volume versus the gauged flow volume.

Other Area Initial Loss Estimates

Initial loss estimates tend to vary across the catchments, and also between the different storm events identified. Figure i shows a box plot of the five catchments and the estimated initial losses.

The initial loss is likely to be a function of the antecedent conditions and the overall duration of the storm event that was identified. Therefore, it is difficult to provide a single "estimator" of the initial loss that can then be applied to design rainfalls. A correlation analysis was undertaken with a number of key parameters. In most cases there was little to no correlation, although there was some correlation between the peak 1 hour rainfall intensity prior to the Other Area runoff, and the initial loss, where initial loss increases with peak 1 hour rainfall intensity. This correlation is largely due to the empirical nature of the initial loss-continuing loss model, where the estimates are heavily reliant on the storm characteristics.

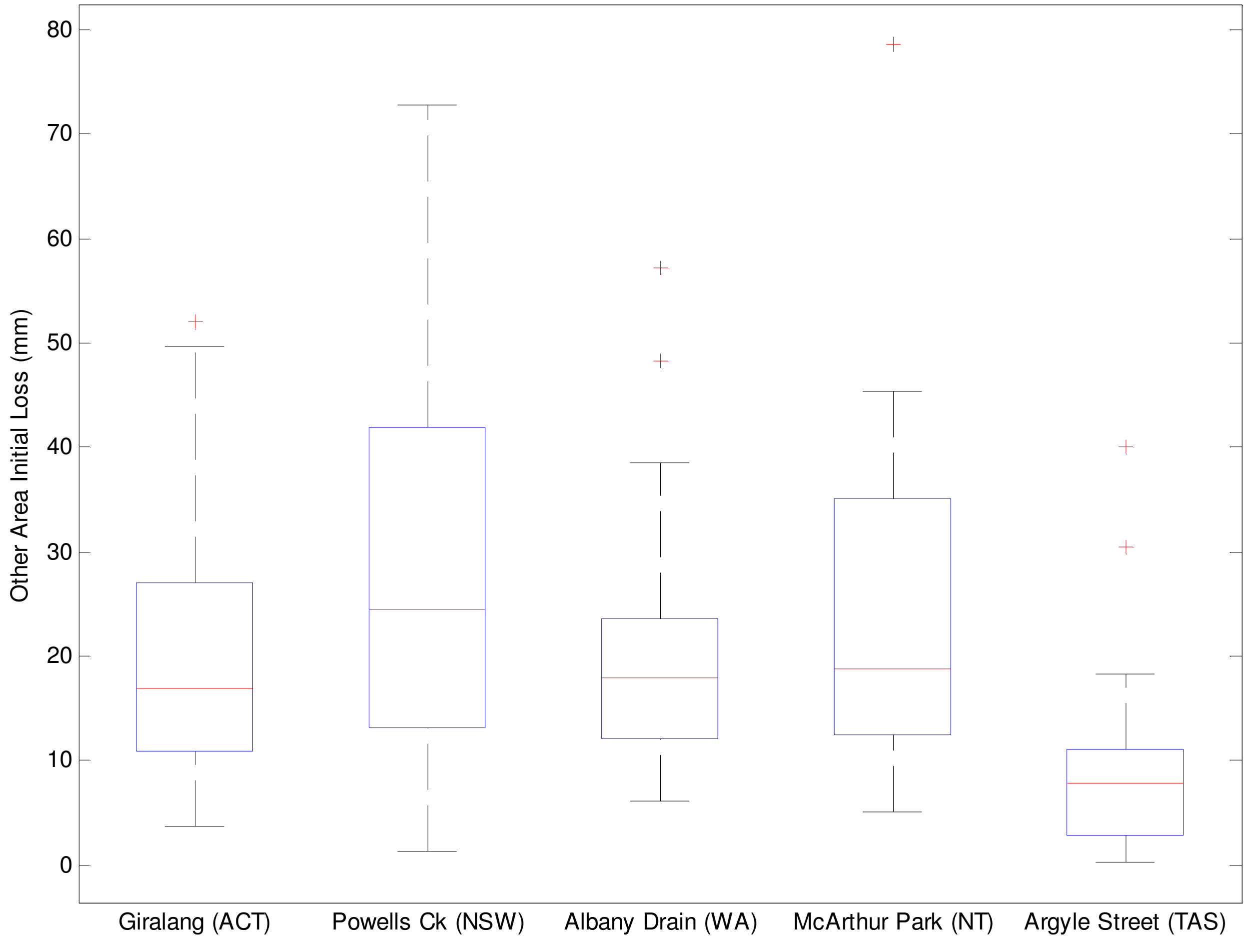


Figure i. Other Area Initial Loss Estimates

Other Area Constant Continuing Losses

A constant continuing loss model was applied to the events that were identified for the five catchments, and used in conjunction with the initial loss estimate determined above. Continuing losses were optimised both for individual storm events, as well as globally across all the storm events identified. The results of this analysis are provided in Figure ii. For Giralang and Powells Creek, the median continuing loss value estimated is in the order of 2.5mm/hr, while Albany Drain and McArthur Park are higher at 3.8mm/hr and 5.1mm/hr respectively. For Albany Drain, this higher value may be a function of the soil types in Western Australia, whilst McArthur Park is likely to be influenced the presence of a large detention basin which drains a majority of the catchment. The estimates for both McArthur Park and Argyle Street should be interpreted with caution, as these catchment are not suited to the analysis (for reasons discussed in Section 8.1).

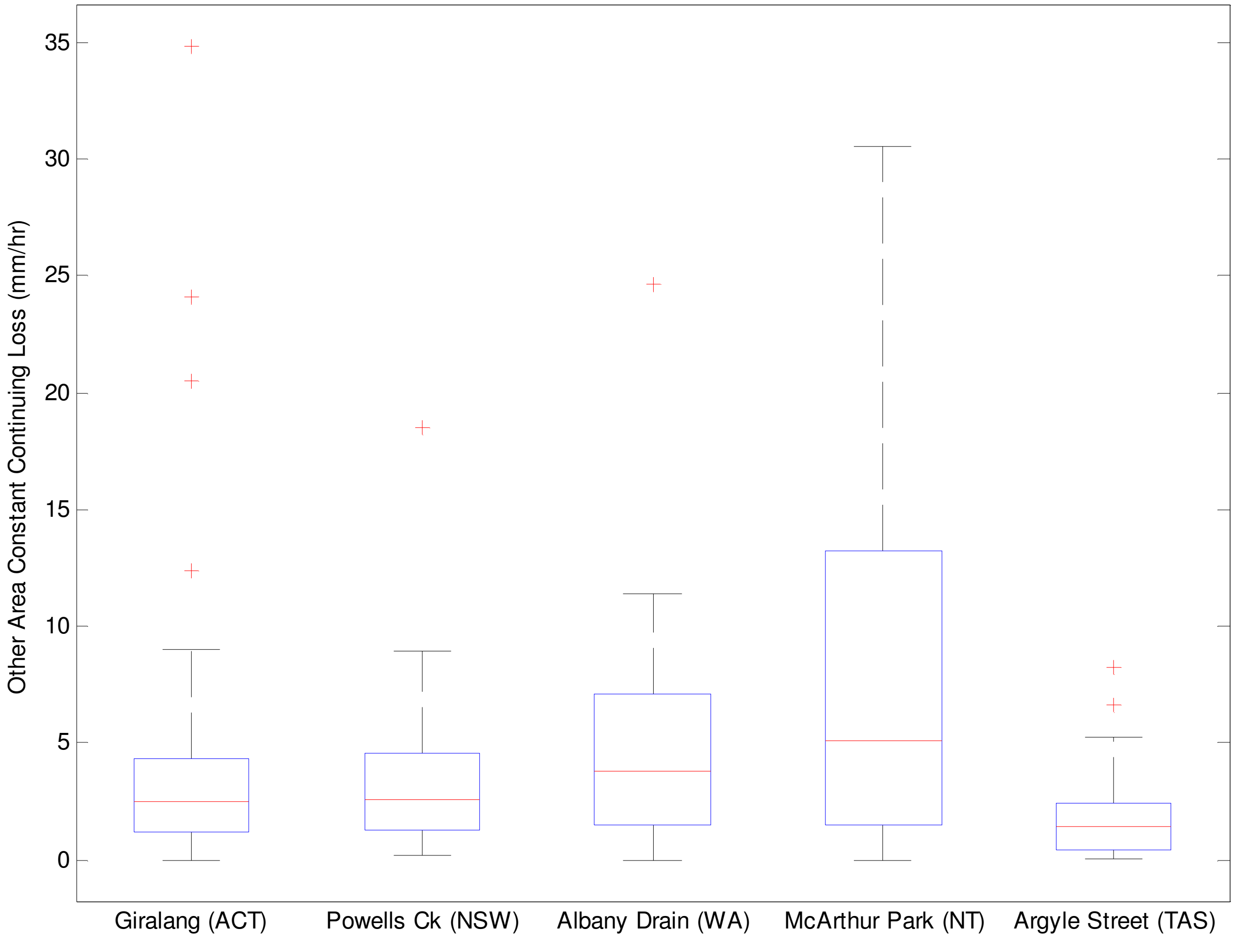


Figure ii. Other Area Constant Continuing Loss

Other Area Proportional Continuing Loss

Proportional Continuing losses were also estimated in a similar manner to the constant continung loss, the results of which are summarised in Figure iii. The range of proportional loss values estimated is quite large. As with the constant continuing loss, the losses for Albany Drain (WA) are generally higher, which is likely to be representative of the soil types in Western Australia. Care should be adopted when interpreting the results for McArthur Park and Argyle Street (for reasons discussed in Section 8.1).

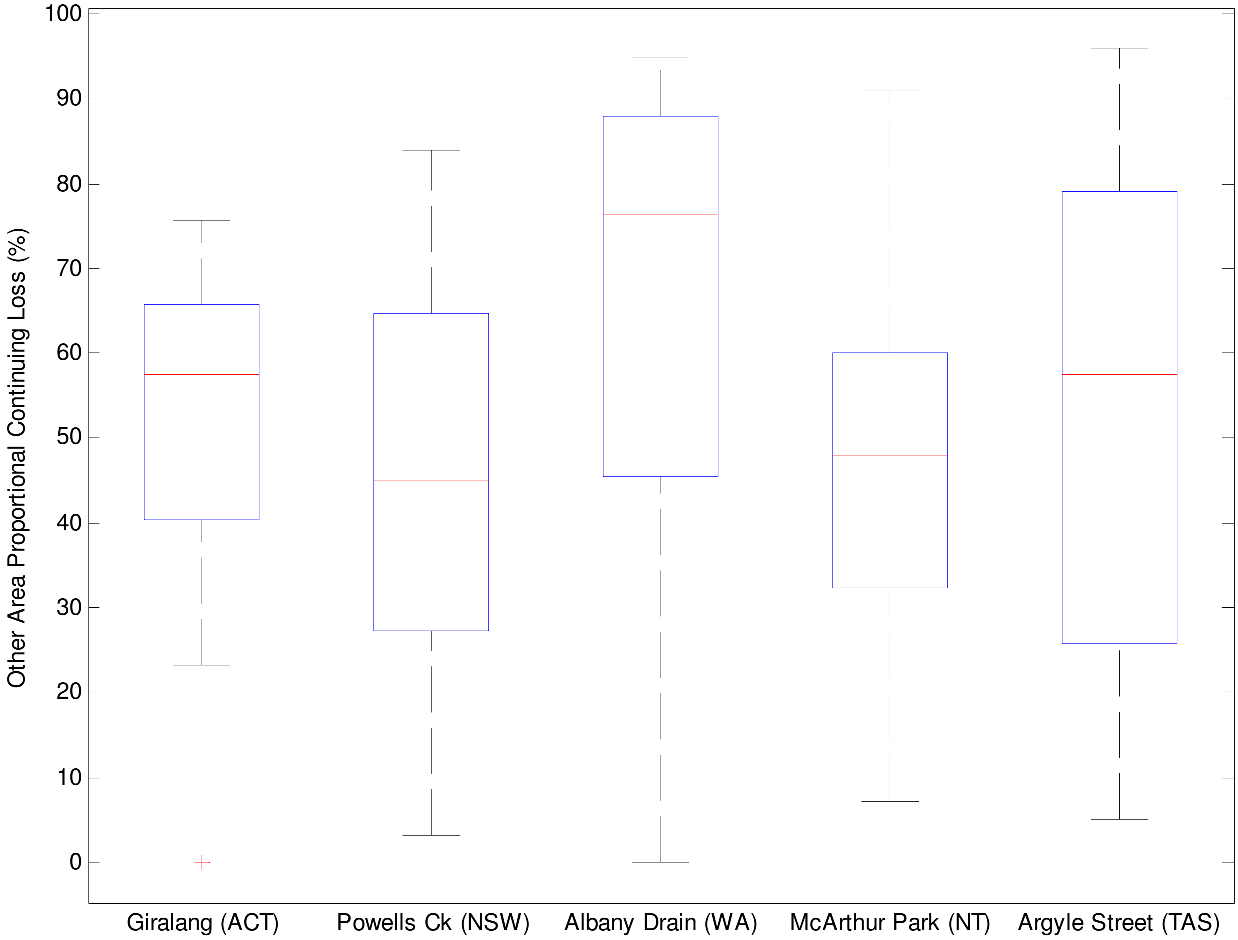


Figure iii. Other Area Proportional Continuing Loss Rates

Summary of Continuing Loss Models

Both of the loss models provide a range of potential solutions. In undertaking an analysis of globally optimised parameters, which effectively measures the ability for a single parameter to fit all the storms identified, the Proportional Loss model was found to fit better for Giralang (ACT) and Albany Drain (WA), but not as well for Powells Creek (NSW) (refer Table ii). The performance of both loss models are fairly similar for both McArthur Park (NT) and Argyle Street (TAS), although the results from these catchments should not be relied upon. At this stage, there is insufficient information to determine whether any particular model provides a better representation.

Table ii. Median Continuing Loss Estimates from optimising globally over all historical storms

	Median Error (Global Optimisation)	
Catchment	**Constant Continuing Loss**	**Proportional Continuing Loss**
Giralang (ACT)	39.3%	20.1%
Powells Creek (NSW)	13.7%	23.8%
Albany Drain (WA)	64.3%	53.2%
McArthur Park (NT)	29.4%	27.2%
Argyle Street (TAS)	33.0%	33.3%

A correlation analysis was undertaken on a number of parameters. The constant continuing loss for Giralang exhibits a strong correlation with the peak 1 hour rainfall intensity following the commencement of the Other Area runoff. However, this same behaviour is not observed for the other catchments. This correlation is largely due to the empirical nature of the initial loss-continuing loss model, where the estimates are heavily reliant on the storm characteristics.

TABLE OF CONTENTS

Abbreviations

ARI	Average Recurrence Interval
CL_{OA}	Constant Continuing Loss on the Other Area
DCIA	Directly Connected Impervious Area
EIA	Effective Impervious Area
GIS	Geographic Information System
ha	hectares
ICIA	Indirectly Connected Impervious Area
IL_{EIA}	Initial Loss on the EIA
IFD	Intensity – Frequency – Duration
IL_{OA}	Initial Loss on the Other Area
ILCL	Initial Loss Continuing Loss
ILPL	Initial Loss Proportional Loss
km^2	Square kilometres
m	metres
m^3/s	Cubic metres per second
mm	millimetres
OA	Other Area (Total Catchment Area excluding DCIA, assuming DCIA = EIA determined from Section 6)
PA	Pervious Area
PL_{OA}	Proportional Continuing Loss on the Other Area
TA	Total Catchment Area
TIA	Total Impervious Area
UA	Urban Area

1. Introduction

Estimating the catchment imperviousness is an important step in urban rainfall runoff modelling, particularly given the sensitivity of simulated runoff to this parameter in many models (Alley et al., 1983). Traditionally, the Total Impervious Area (TIA) is used with the assumption that, neglecting depression losses, this area contributes fully to generating runoff. This is in spite of research dating back to the 1970s identifying the importance of the Effective Impervious Area (EIA) over the TIA (refer Cherkaver,1975; Beard et al.,1979).

Use of the TIA which includes impervious areas with no direct connection to the drainage network can result in the overestimation of urban runoff volumes and peak flows. Although definitions vary, the EIA is generally considered to be representative of the area of the catchment that generates a rapid runoff response in rainfall events. It incorporates the impervious area with a hydraulic connection to the drainage network (herein referred to as Directly Connected Impervious Area (DCIA)), plus a contribution comprising discharges from an impervious area onto a pervious area (herein referred to as Indirectly Connected Impervious Area (ICIA)) which rapidly saturates and acts in a similar manner to an impervious area. The EIA therefore provides a more realistic measure of the impervious area that generates runoff at the catchment outlet.

In the absence of runoff data to estimate the connected impervious area in a rainfall-runoff model, practitioners most commonly rely on using the TIA or correlations between the TIA and EIA for different land use types (Lee and Heaney, 2003; Brabec et al., 2002). Although the potential for significant inaccuracies in using such approaches has been identified (see Han & Burian, 2009; Fletcher & Deletic, 2008), they persist because of the lack of an accepted procedure for estimating effective imperviousness with insufficient data for calibration. Given that there are very few urban catchments in Australia with gauge data, the option of calibrating impervious area runoff in models are generally limited.

1.1. Objectives

Given the limitations of current methodologies and estimation techniques, the aim of this project is to provide greater guidance on:

1) the estimation of Effective Impervious Areas (EIA) for urban catchments throughout Australia;
2) appropriate loss models for urban runoff modelling.

1.2. Approach

In order to achieve the objectives, the analysis in this report has been undertaken on gauged urban catchments, across all states and territories in Australia, to ensure that it is as representative as possible. Where possible, these gauged catchments are representative of different land-uses, climatic zones and soil types, to ensure that any guidance or conclusions from this assessment can be broadly applied.

It is noted that the key limitation in any analysis of this kind is the availability of long term, quality gauged (both rainfall and flow) small scale urban catchments. This resulted in only a small sub-set of catchments (one in each state or territory) that was analysed as a part of this study. For improvements in urban hydrological modelling, greater data is required for catchments, both in terms of quality and consistency (in terms of length of recording).

The various tasks that were undertaken for the estimation of effective imperviousness are outlined as follows:

(i) Identify urban catchments suitable for the study
- review previous studies and determine suitable data sets
- preliminary data check for data quality and reasonable length

(ii) Collate streamflow, rainfall and land use information
- request land use information and streamflow data from state agencies (if not available from other ARR Projects)
- request pluviograph and daily rainfall from ARR Project Manager
- preliminary data check to confirm data supplied is as requested
- detailed checks and formatting (quality codes, missing data, formatting)

(iii) Effective Impervious Area Analysis
   a. Review methods of estimating impervious areas
      i. review literature
      ii. make recommendations on methods
   b. Review and Compare different methods (using data from task 2)
      i. estimate effective impervious areas
      ii. compare with estimated impervious areas
      iii. make recommendations on methods
   c. Compare methods to effective impervious areas calculated from the analysis of rainfall and streamflow data for each catchment

(iv) Loss Model Analysis
   a. Review loss models adopted for urban catchments
   b. Review and compare different loss models
      i. Estimate losses based on historical storms
      ii. Make recommendations on models
   c. Compare outcomes across the different catchments

2. Literature Review

2.1. Estimation of Effective Impervious Area

There are several methods for estimating EIA in both the literature and hydrologic practice. They vary in accuracy, difficulty, data requirements and cost. They can be broadly classified into the following categories:

1) Empirical equations & guideline values based on land use or other predictors
2) Calibration of a rainfall runoff model
3) Direct analysis of rainfall and streamflow records.
4) GIS based estimates/Field survey

2.1.1. Australian State Based Guidelines

The concept of effective impervious area has received little attention in various urban drainage guidelines and modelling software manuals. For example, the Queensland Urban Drainage Manual (2007) recognises the impact of both DCIA and ICIA on runoff, but provides no details on how to estimate these quantities. One source of guidance are the various state-based MUSIC modelling guidelines, which rely generally on land use (or some other surrogate measure) to estimate the EIA (which is generally assumed to equal to the DCIA). For instance, the *(Draft) MUSIC Modelling Guidelines for NSW (2010)* provides default values of the EIA (as a fraction of the TIA) for different land use types, where the catchments are greater than 10 Ha. For catchments less than 1 Ha, the guidelines recommend adopting a map based approach to estimate the directly connected impervious areas, which is then taken to be the EIA. A similar land-use based approach was adopted in earlier manuals for other states, such as the *Guidelines for Pollutant Export Modelling in Brisbane Version 7 (2003).* Table 2-1 and Table 2-2 provide extracts of EIA to TIA ratios from these guidelines.

Table 2-1 Default EIA parameters as a fraction of the Total Impervious Area (TIA) from the Draft MUSIC Modelling Guidelines for NSW (2010).

Land Use Type	EIA Factor
Residential	0.55 x TIA
Commercial	0.80 x TIA
Rural residential	0.05 x SCA
Industrial	0.90 x TIA
Agricultural / grazing	0.00 x SCA
Native/plantation forest	0.00 x SCA

SCA = Subcatchment/surface area, TIA = Total Impervious Area, EIA = Effective impervious area

Table 2-2 Impervious area parameters for use in MUSIC as recommended in the Guidelines for Pollutant Export Modelling in Brisbane Version 7 (2003)

	Urban Residential	Commercial	Industrial	Rural Residential	Forested
Effective Impervious Area as a % of the Total Impervious Area	31	50	76	55	0

A slight variation on this approach is detailed in the Gold Coast City Council MUSIC Modelling Guidelines (2006). Instead of directly providing estimates of effective impervious, the Annual Volumetric Runoff Coefficient (AVRC) is provided for various land uses, which have been determined by Brisbane City Council "based on extensive streamflow records across the city" (GCCMMG, 2006). This is then used to determine the annual volume of runoff, which forms an objective function for calibration of the imperviousness parameters. However, a recent review by BMT WBM found that the data used to determine the AVRCs, as well as the EIA to TIA ratios given in the Guidelines for Pollutant Export Modelling in Brisbane Version 7 (2003) was poor quality, and in some cases with runoff coefficients greater than 1. As a result, the Water by Design MUSIC Modelling Guidelines (2010) for Queensland recommend using total impervious area for the effective impervious area.

The DRAINS hydrologic model considers the degree of connectedness of impervious surfaces in estimating runoff. It recognises three different surface types in most urban catchments for use with the ILSAX hydrology model, namely:

1) Paved areas (impervious areas directly connected to the pipe system, or DCIA);
2) Supplementary areas (impervious areas not directly connected to the drainage system, or ICIA); and
3) Grassed areas (pervious areas).

The DRAINS manual provides some guidance on the estimation of DCIA and ICIA (or Supplementary Areas), based on the findings of Dayaratne (2000). Dayaratne (2000) obtained relationships with housing density from modelling storms on 16 gauged residential catchments in four Victorian municipalities:

$$\text{DCIA/TA (\%)} = -0.85\text{hhd}^2 + 23.38\ \text{hhd} - 101.19 \quad (R^2 = 0.90) \tag{2.1}$$

$$\text{ICIA/TA (\%)} = -0.04\ \text{hhd}^2 + 1.13\ \text{hhd} - 3.79\ (R^2 = 0.91) \tag{2.2}$$

Where hhd = number of houses per hectare.

A potential issue with the available guidance is that in most cases, details on the locations and data used to derive the EIA method is not readily available and the validity of the method cannot be easily assessed. Furthermore, use of these ratios on basins outside of those used to derive them does not consider the impact of basin-specific stormwater connections and variations in land cover.

Quantifying DCIA and ICIA has also received little attention by the various manuals and guidelines, with the exception of the DRAINS model manual. Generally, the effective impervious area is assumed to be simply the DCIA, as is the case in MUSIC.

2.1.2. Model Calibration/Analysis of Rainfall and Streamflow Records

The availability of reasonable quality streamflow records of sufficient length can eliminate the need for hydrologists to rely on guideline values or empirical relationships. Such data allows calibration of the EIA parameter in a rainfall runoff model (Dotto et al., 2008; Ball & Rankin, 2010), or to determine the EIA by statistical analysis of rainfall and runoff data. The latter simply involves calculating the gradient of the regression between runoff and rainfall, subject to excluding events with runoff from pervious areas (see for instance Boyd, Bufill & Knee, 1993; Chiew & McMahon, 1999).

Figure 2-1 (taken from Boyd, Bufill& Knee, 1993) shows a subset of results from their analysis of 26 urban catchments in 12 countries. There is a high linear association between rainfall and impervious runoff, implying that the effective imperviousness is fairly constant with storm size. However, the EIA estimates are sensitive to how “impervious+pervious” events are defined, which seems to vary in the literature. These “impervious+pervious” events are removed from the regression analysis, as the focus is on the EIA runoff. In the case of Boyd, Bufill & Knee (1993), “impervious+pervious” events were defined as those points lying more than 1mm from the regression line, although it is not clear if this has any physical or theoretical basis. Ball and Rankin (2010) excluded events which had a large volume of rainfall on the basis that these were more likely to render pervious runoff. Ultimately it seems as though such events are defined in order to optimise the regression fit.

Some studies have taken a slight variation on this approach by plotting the impervious rainfall-runoff relationship as a series of straight line segments of increasing gradient with storm size (Miller, 1978; Calomino & Veltri, 1984). This would indicate that the effective impervious area increases as storm size increases, which could potentially be a result of increasing contribution from the indirectly connected impervious area.

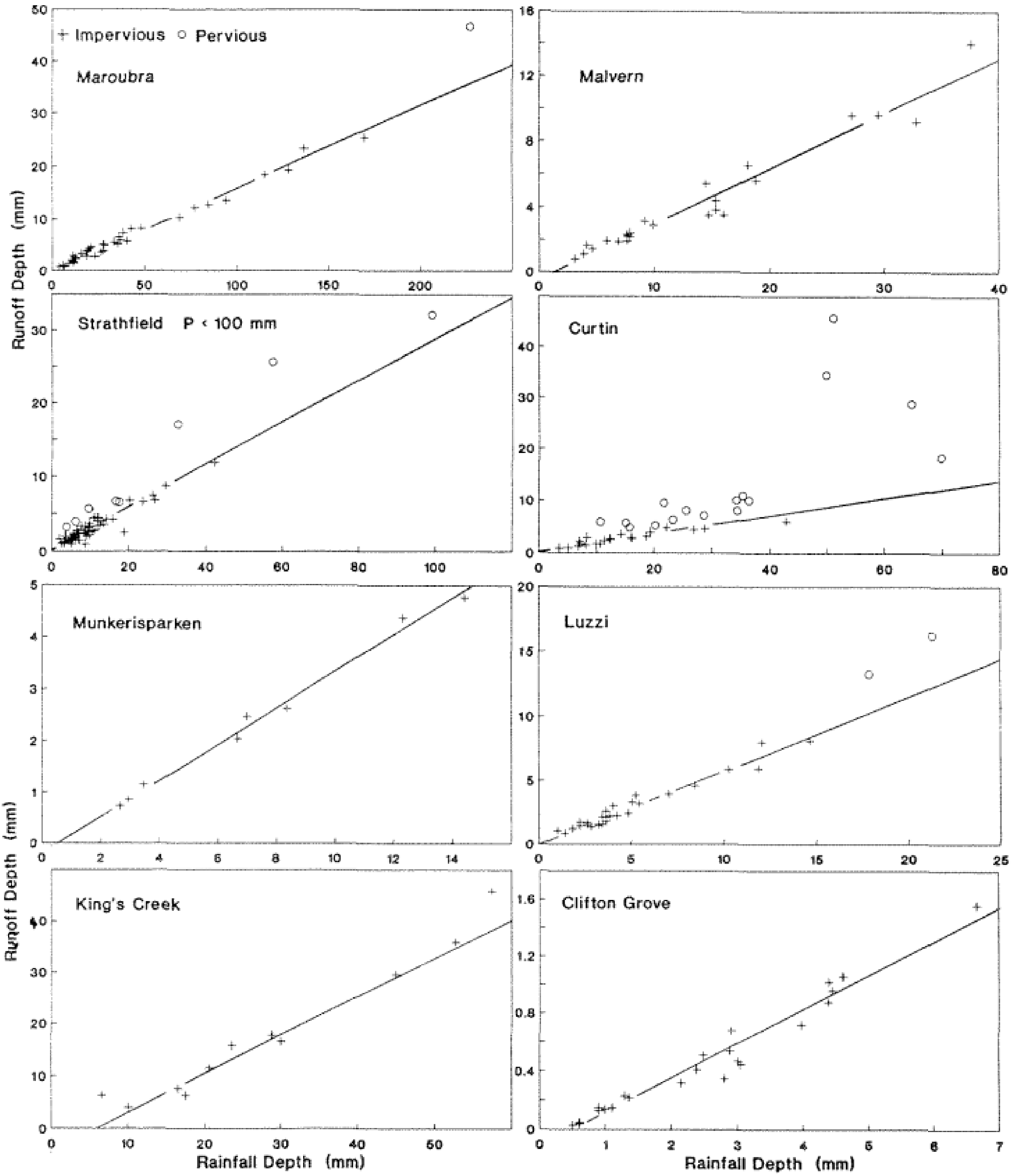


Figure 2-1 Rainfall vs Streamflow Depths For A Select Group Of Catchments (Boyd, Bufill& Knee, 1993)

This approach was adopted in a study by Lee and Heaney (2002), in which the total runoff was assumed to be composed of DCIA runoff (determined by the DCIA portion found from maps) and "Other Area" Runoff. Figure 2-2 shows that the regression line is then composed of two straight line segments. Under this representation, storm events of rainfall depth less than the breakpoint (point at which the gradient of the regression line changes) result in DCIA runoff only. Larger storm events have an additional contribution from the remaining impervious area and potentially also pervious areas.

This approach is more suitable in cases where the DCIA is much less than the TIA or a poor fit to the data is obtained in a standard linear regression. However, it does not take into account other predictors which can influence the runoff coefficient for an event, namely antecedent moisture conditions, rainfall intensity and duration. This is potentially one of the reasons why Boyd, Bufill& Knee (1993) concluded from their analysis of 26 urban basins that the separation of EIA into DCIA and ICIA by a similar approach was “not warranted.”

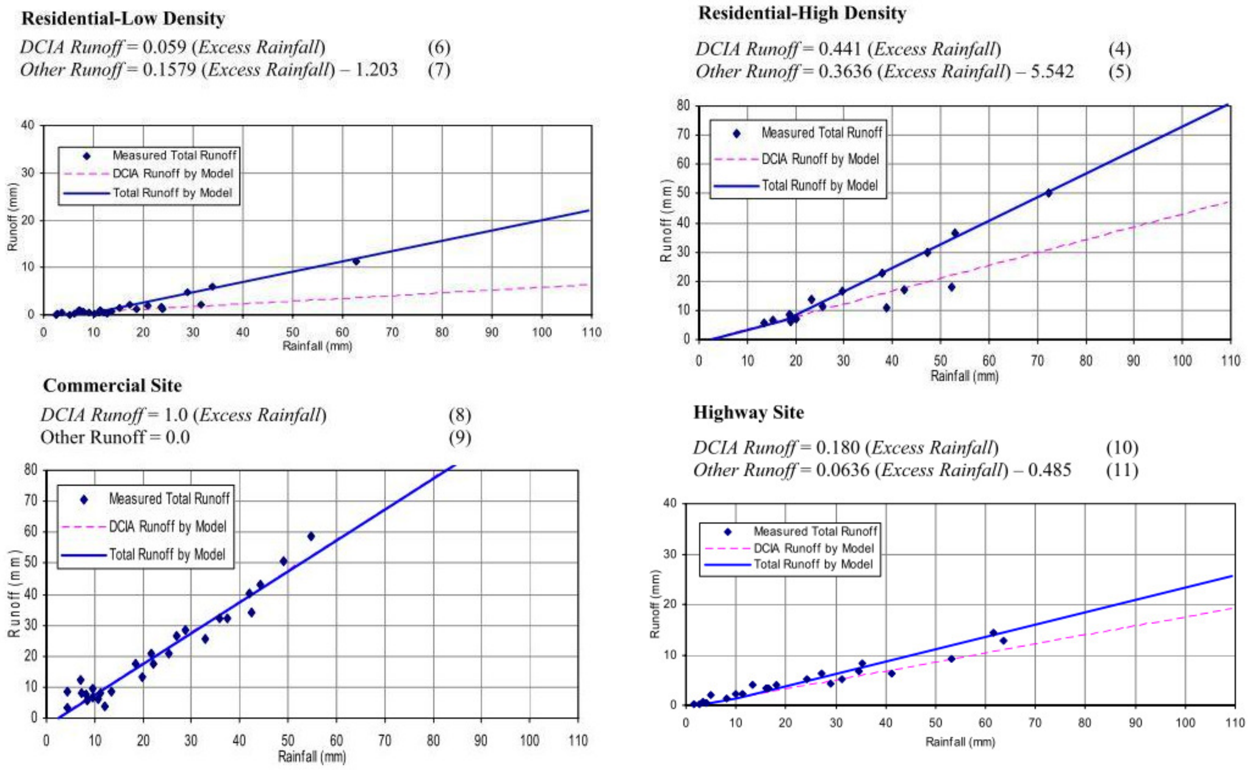


Figure 2-2 Rainfall – Runoff Relationship For Four Sites (Lee and Heaney, 2002)

Although the regression approach serves as a relatively simple method to determine EIA, it can be unsuitable if there is significant scatter in the plotted values of runoff and rainfall or the data is of poor quality. Furthermore, there are few gauged urban catchments in Australia where this approach can be undertaken.

2.1.3. GIS Based methods/Field Survey

Aerial photographs are commonly used to estimate the total impervious area in a catchment, typically through visual analysis. This may be accompanied by field survey, which is generally regarded as a relatively accurate but costly and time consuming approach (Han & Burian, 2009, Brabec et al., 2002; Lee & Heaney, 2003). Due to recent advances in GIS technology, there has been a shift in the literature from analysis of rainfall and runoff to map based methods. They focus on land cover characterisation techniques to identify impervious areas, with the use of digital elevation models and drainage system plans to identify areas which have a direct connection to the drainage system (see for instance Botsford, Hill & Booth, 2003; Han & Burian, 2009; Janke & Wilson, 2011). Roso, Boyd & Chisolm (2006) investigated a number of different GIS based methods using human and computer based estimation:

- Land use zoning based with typical impervious cover percentages for various land uses;
- Computer based surface recognition methods based on satellite imagery (eg. machine learning algorithms to recognise patterns and textures of different surface types); and

- Using intensity of laser pulse returns from LiDAR data to characterise impervious surfaces.

They found that the seven human and computer based methods used to estimate impervious cover tended to under or overestimate the actual total impervious area (measured by accurate manual digitisation of the entire catchment) by about 10 – 20%.

Some issues with GIS based methods include impervious areas hidden by tree canopy cover (Han & Burian, 2009) as well as a degree of subjectivity in assigning impervious areas as directly connected. For instance, Janke & Wilson (2011) found that assuming alleys were 100% directly connected led to overestimates of the EIA, because they were in poor condition with sparse vegetation cover that disconnected a portion of the alley from the drained area. Furthermore, there seems to be little research into using GIS tools to estimate ICIA, which is evidently a component of the EIA that has received little attention in the literature.

2.2. Loss Models for Urban Catchments

Rainfall losses occur due to infiltration into the soil layer, interception by leaf and canopy cover, evaporation and depression storage (Mansell & Rollet, 2009; Rahman, Weinmann & Mein, 2002; Tularam & Ilahee, 2007; Walsh, 1991). Each component is dependent on topography, soil classification, vegetation cover and climate. Furthermore, losses resulting from these components generally exhibit temporal and spatial variability during storm events.

These losses are typically accounted for in Rainfall – Runoff Modelling through lumped loss models. Such loss models ignore the spatial variability (within the sub-catchment scale) of the various loss components and adopt spatially averaged values (Al-Smadi, 1998, Tularam & Ilahee, 2007). The physical processes contributing to loss are typically modelled by separating into initial losses (depression, infiltration prior to saturation and interception storage) and continuing losses (mainly infiltration).

In Australia, there is little guidance in relation to the most appropriate values to use for design losses (Pilgrim & Robinson, 1988; Walsh, 1991; Rahman, Weinmann, & Mein, 2002; Tularam & Ilahee, 2007). Most practitioners adopt the guidance that is provided in the current revision of Australian Rainfall and Runoff. However, the extent of this guidance, and its applicability to urban based catchments, is generally limited.

The models discussed below rely on the concept of initial loss coupled with a continuing loss. These types of loss models are the most common models adopted for urban environments.

2.2.1. Initial Loss - Continuing loss models

The most common method of estimating losses in hydrologic modelling in Australia is the initial – continuing loss model (Rahman, Weinmann & Mein, 2002; Tularam & Ilahee, 2007; Institution of Engineers Australia, 1987; Ilahee M., 2005; Ilahee & Imteaz, 2009). Figure 2-3 illustrates three common initial – continuing loss models.

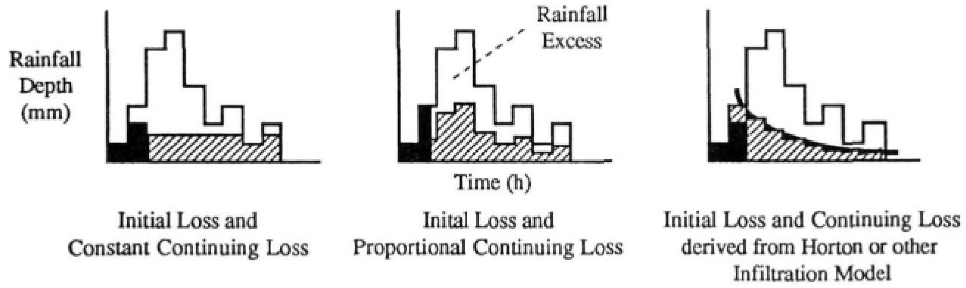


Figure 2-3 Commonly used loss models as described by O'Loughlin et al. (1996).

Initial-continuing loss models have been adopted for many Australian catchments, yet no single model has been demonstrated to be uniformly superior across all catchments. Initial losses occur early on in the storm prior to surface runoff occurring. It is assumed to be composed of interception losses, depression storage and infiltration before the soil surface is saturated. Commonly used continuing loss models are illustrated in Figure 2-3, and defined as constant, proportional or derived from a physically based infiltration model.

However, from many studies undertaken using the model, it has been concluded that it is inadequate for approximating temporal patterns of storm losses (Hill & Mein, 1996; Ilahee, 2005). However, the initial-continuing loss model is believed to have an acceptable approximation of storm losses in relation to temporal patterns (Ilahee, 2005; El-Kafageea & Rahman, 2011).

Under the current guidelines, design losses have been derived from complete storm events and used in conjunction with temporal patterns derived from storm bursts embedded within larger storms. Studies undertaken by Hill & Mein (1996) and Tularam & Ilahee (2007) have indicated that the use of design losses as recommended by Australian Rainfall and Runoff (ARR) (Institution of Engineers Australia, 1987) have resulted in an overestimation of design peak flows in comparison to flood frequency analyses. Such studies have concluded that the design losses recommended in the ARR are too low.

In a study undertaken by Rahman, Weinmann, & Mein (2002), the initial loss values obtained presented great variability across the ten selected Australian catchments. It was concluded that this variability was a reflection of moisture conditions for each catchment prior to storm commencement. Despite applying a Monte Carlo simulation to three catchments, the results obtained confirmed that assumptions made by previous authors regarding the use of representative design loss values and associated biased estimates extended to these catchments. The authors also state that the use of a stochastic model to estimate initial losses avoided the need to select a representative value, but the over-simplified approach has inherent problems of its own in relation to model parameters selected. In addition, continuing losses which have previously assumed to be constant for all rainfall events were found to provide overestimates of the total losses. This overestimation has been attributed to the models simplicity (Rahman, Weinmann, & Mein, 2002).

2.2.2. Constant Continuing Loss

The constant continuing loss is the average loss rate throughout the remainder of the rainfall event after initial losses has been satisfied. ARR recommends that constant loss rates are most applicable to large storm events where a significant proportion of rainfall becomes runoff (El-Kafagee & Rahman, 2011; Institution of Engineers Australia, 1987).

2.2.3. Proportional loss rate model

Proportional loss models assume a fixed proportion or percentage of the rainfall is lost at each time step. This means that losses throughout the event may vary depending on the temporal pattern of rainfall. As a result, proportional loss models may give more physically realistic losses than a constant loss rate. Proportional loss models are beginning to gain acceptance and through evaluation, the model is being likened conceptually to saturated overland flow (Hill & Mein, 1996). In addition, the model performs well in locations where runoff occurs in a particular area of the catchment (Ilahee, 2005).

2.2.4. Physically based infiltration loss models

Horton's equation has been used and modified over the years to provide an estimate of losses due to infiltration into pervious surfaces. It is based on a diminishing continual loss as described in Equation 2.3 (O'Loughlin, et al., 1996).

$$f_{p=}f_c + (f_0 - f_c)e^{-kt} \qquad (2.3)$$

Where: f_p = Infiltration capacity at time t(mm/h)

f_o = Initial infiltration capacity (mm/h) at time t=0

f_c = Final infiltration capacity (mm/h)

t = time

k = exponential decay constant

However, the model is limited by its suitability to small catchments only (Rahman, et al., 2002). The reason for this is that the final infiltration capacity (f_c) and the exponential decay constant (k) are dependent on soil type and degree of vegetative cover, making these parameters difficult to estimate.

2.2.5. Australian Representative Basins Programme (ARBP)

The programme was initiated with the aim to classify and select hydrologically diverse basins at a significant scale for resource development (Fleming, P., 1974; Mein, R., McMahon, T., 1982). Furthermore, the programme sought to increase understanding of the hydrological processes in each basin.

The ARBP is a process model structured to best represent the actual passage of water over and through the catchment as illustrated in Figure 2-4. It is based on Chapman's work (1968 & 1970), which originally sought to optimise certain parameters, whilst measuring others. However, developers Boyd, *et al.* began optimising all parameters as it was believed that measurements were difficult, uncertain, costly and impractical (Mein & McMahon,1982).

The model uses a deterministic mathematical model intended to represent the physical processes and relationships between rainfall and runoff for the catchment. It operates in a continuous mode, considering both rainfall events and initial estimations of soil moisture conditions for each wetting event. This is done by simulating soil moisture depletion by evaporation between rainfall events (Fleming, 1974). It is expected that the parameters used would be related to the physical catchment characteristics, therefore making the model applicable to any Australian gauged or ungauged catchment.

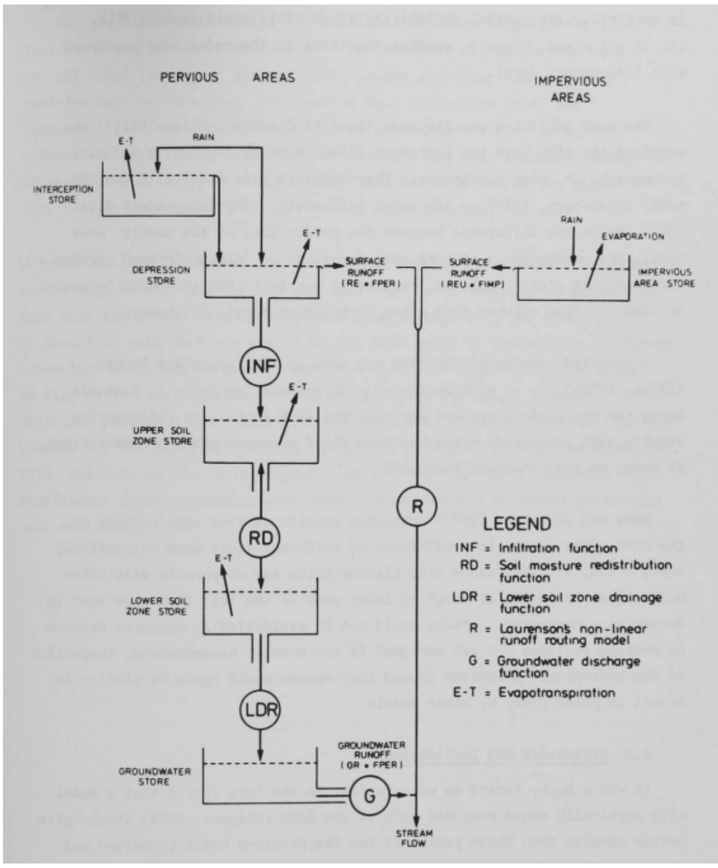


Figure 2-4 The model structure of the Australian Representative Basins model based on the work of Chapman (1968). Diagram obtained from Black and Aitken (1977) and Mein & McMahon (1982).

Despite being developed, the optimised parameters have not exhibited uniqueness. Mein and McMahon (1982) however do not believe that this particular model produces outcomes any different to other process models developed for the same purpose.

2.3. Embedded Design Storm method

Past studies have focused on quantifying the underestimation of peak discharge obtained using ARR design burst procedures and the need for an embedded design storm approach. As outlined by Rigby, et al (2003), the embedded design storm method is designed to recreate a design storm which contains a rainfall burst that has duration critical to the specific catchment (Rigby, et al., 2003). In addition to this, it is required that the recreated design storm have an appropriate intensity and pattern for the selected ARI.

The embedded design storm method is the current approach being adopted by Australian Rainfall and Runoff, as a part of the overall update. The utilisation of this approach will effectively introduce additional antecedent rainfall prior to the main rainfall burst (when compared with the current ARR rainfall approach). This will have an impact on the assumed initial losses under each of the loss model approaches.

2.4. Probabilistic Representation of Losses

In the application of a four parameter Beta distribution by Rahman, Weinmann and Mein (2002) for a Victorian catchment, the upper and lower limits, mean and standard deviation of the observed loss vales are utilised in the application to the initial losses of the site. By doing so, it was observed that the relationships between the loss data parameters were well preserved. A deviation from the input statistics was observed to be less than 10% across the 10 Victorian catchments when compared to the observed initial loss data.

Other methods used to observe the variability of event initial losses include Gamma, Exponential, Truncate Normal and Log-Normal distributions (where the log transformation occurs before fitting the data to the distribution). However, very little literature explores the applicability of such methods.

3. Defining Effective Impervious Area

Impervious surfaces within an urban catchment can be categorised into the following:

- Directly Connected Impervious Areas (DCIA) – these surfaces have a direct hydraulic connection to the drainage network. Examples include roads with kerb and gutter drainage (see Figure 3-1) and roofs connected to the stormwater drainage network. These surfaces often generate runoff even in frequent, low rainfall depth events.
- Indirectly Connected Impervious Areas (ICIA) –these surfaces generate runoff which flows over pervious area before reaching the drainage network. Examples include footpaths with nature strips (as shown in Figure 3-1) and some driveways. In addition to the depression losses on the impervious surface, the runoff from these surfaces experience further losses on the pervious surfaces. They are not likely to generate runoff that enters the drainage network in low rainfall depth events unless the pervious areas are saturated prior to the high intensity short duration storm.

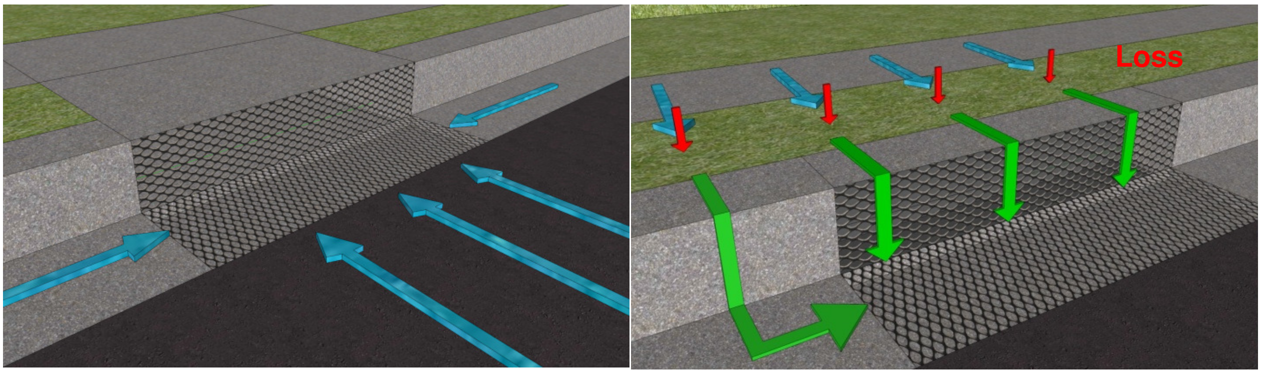


Figure 3-1 Example of a Directly Connected Impervious Surface (Left) and an Indirectly Connected Impervious Surface (Right).

As noted in Section 2, there is some inconsistency in both the literature and guideline documents as to whether any indirectly connected portions should be included in the effective imperviousness. Often the DCIA is deemed a suitable measure, as recommended in the various state based MUSIC Modelling Guidelines. However, some hydrologic model platforms (namely DRAINS, which relies on the ILSAX hydrology model) consider runoff behaviour from DCIA and ICIA areas separately.

4. Catchment Selection

The selection of catchments for the analysis was based on the data provided by Bowen Hicks of WMAwater, together with the information presented in Hicks et al. (2009). This study identified 20 urban gauged catchments based on a number of criteria:

- Area less than 20 km2 (smaller areas preferable, in the order of 1 km2);
- Continuous records greater than 10 years in length;
- Fairly urbanised (greater than 50%);
- Acceptable gauge rating (max gauged flow: max recorded flow); and
- Stationary upstream urbanisation.

These criteria were considered compatible for the assessments in this project, and therefore have been adopted for this study with some minor adjustments:

- Area less than 5km2 (500 ha), so that spatial variability in rainfall has less of an impact on the analysis (due to the use of point rainfall data);
- Record lengths of at least 10 years;
- High quality measurements (more than 70% of the record classed as reasonable or high quality based on descriptors provided by the data collector);
- Fairly urbanised (% urbanisation by area greater than 50%), although variation in % urbanisation is desirable across catchments;
- Variation in effective runoff modifiers across catchments (eg. age of catchment, roof drainage methods, type of urbanisation etc.);
- 1 – 2 catchments for each state.

It is noted that in a number of states, there are only a minimal number of gauged catchments and therefore some flexibility was undertaken in the catchment selection process. For instance, no preference was identified for the Northern Territory and Tasmania due to the lack of information on the catchments identified in Hicks et al. (2009).

The set of candidate catchments were ranked for each state based on the above criteria (see Appendix A). In assessing the suitability of these catchments, the following was carried out at in the initial stage:

- Percent urbanisation and age were determined qualitatively using Google Maps and an estimated extent of the catchment (since no catchment delineations were available);
- Where available, data quality was analysed based on descriptors provided by the data collector which consider the quality of measurement and correction methods.

4.1. Rainfall and Streamflow Data

The catchments chosen for this study based on the selection procedure described above are shown in Table 4-1 and Figure 4-1. The top priority catchment was selected for all catchments except for Queensland due to data acquisition issues.

Pluviograph rainfall and continuous streamflow records were obtained from a number of sources as indicated in Table 4-1. Given the size of the selected catchments, the use of point rainfall was generally considered sufficient and so multiple gauges were not sourced for determining catchment averaged rainfall. However, for Powells Creek (NSW), Giralang (ACT) and Ithaca Creek (QLD), a sensitivity analysis was undertaken as data from multiple rain gauges within the catchment were available (see Section 6.1.2).

As indicated in Table 4-1, most catchments have data records with few missing values (generally ranging from 0 – 10%). Information on data quality was available for some records, generally in the form of HYDSTRA quality codes. Table 4-1 shows that in most cases, a large proportion of the data is of high quality. The impacts of poor quality data on the analysis were minimised by excluding selected events which had poor quality readings (See Section 5.1.2 for further details).

Table 4-1 Rainfall and Streamflow Metadata

				Rainfall Data			Streamflow Data		
State	**Catchment Name**	**Data Source**	**Period of Record**	**Station No.***	**Missing Values**	**Data Quality**	**Station No.**	**Missing Values**	**Data Quality**
ACT	Giralang	Goyen (2000)	1993 – 1995	570987/570991	0%^	N/A	410763	0%^	N/A
		ALS Global	1973 – 2012	570987/ 570990/570991/ 570992	0%^	N/A			
NSW	Powells Creek	James Ball	1981 – 1993	566004	0%	79% Code 10† 16% Code 255† 5% Various†	213304	0%	82% Code 10†# 15% Code 16† 3% Various†
			1981 – 1996	566005	0%	61% Code 10† 19% Code 1† 8% Code 255† 12% Various†			
NT	McArthur Park	Department of Lands and Planning	1983 – 2004	G8150233	1%	91% Good 1% Satisfactory 8% Poor	G8150233	1%	N/A
QLD	Ithaca Creek	Department of Environment & Resource Management	1998 – 2011	143028A	0%^	N/A	143028A	0%^	N/A
		Bureau of Meteorology	1972 – 1978	040533	10%	N/A			
SA	Parra Hills Drain	Department of Water (SA)	1992 – 1999	A5040567	1%	97% Fair 2% Fair (Estimated) 1% Poor	A5040546	11%	97% Good 3% WL below recordable range
TAS	Argyle Street	Mark Babister	1984 – 1994	094029	8%	N/A	354	2%	100% Code 33†
VIC	Kinkora Road	Melbourne Water	1977 – 2012	229636A	1%	72% Good 27% Very Good 1% Poor	229636A	6%	68% Good 32% Very Good 1% Poor
WA	Albany Drain	Department of Water (WA)	1983 – 1993	509268	1%	100% Very Good	602006	1%	100% Very Good

**For locations of the rain gauges, refer to Appendix B (catchment mapping figures).*

^Data supplied at an irregular time interval, #Quality refers to stage and does not take into account the accuracy of the rating curve, †Meaning of Quality Code to be confirmed.

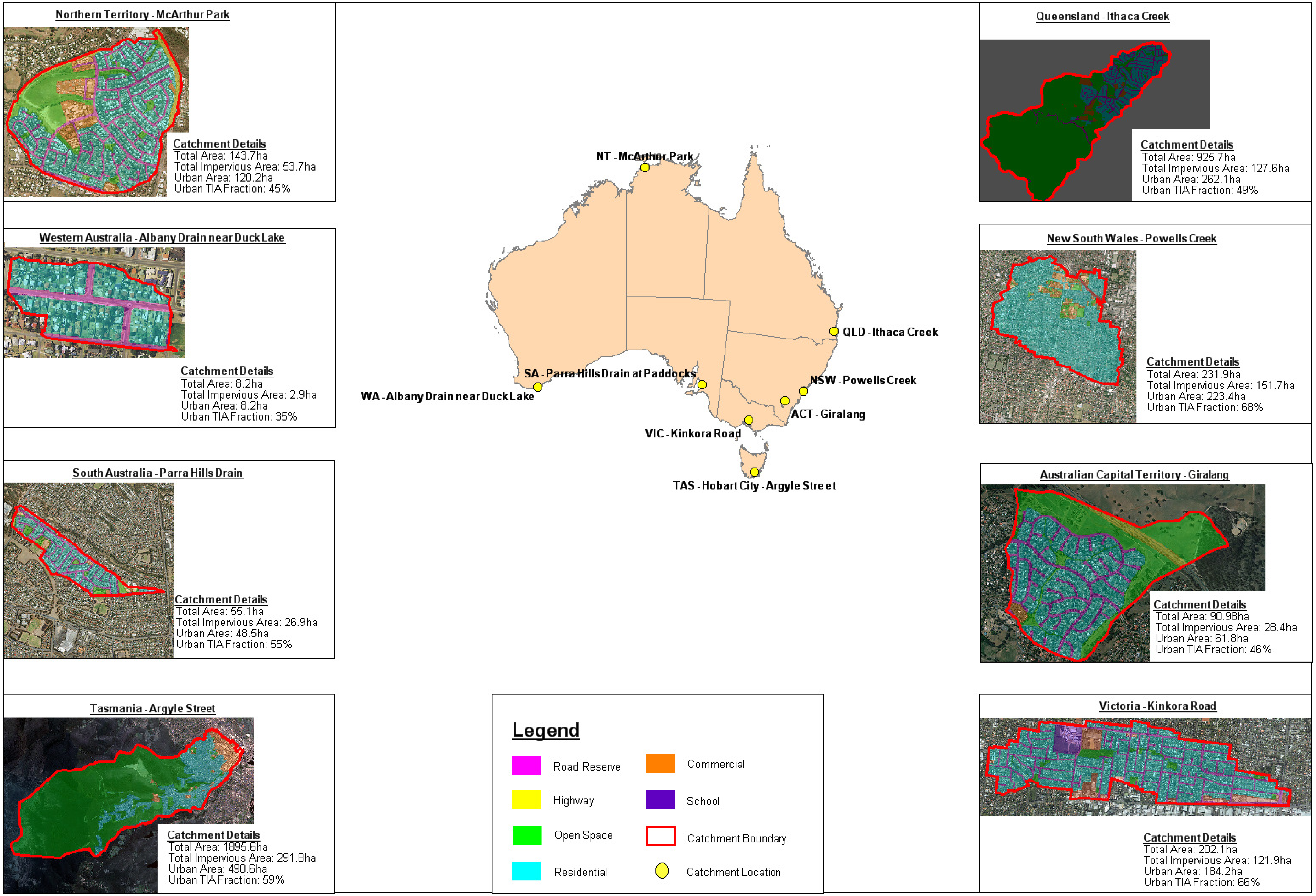


Figure 4-1 Location of catchments examined in this study

4.2. GIS data

The following GIS information was sourced for the purposes of determining catchment imperviousness through a visual desktop analysis:

- Cadastre;
- Aerial Photography;
- Contours/Digital Terrain model (DTM);
- Pit and Pipe Data/Watercourse Data;

This data was sourced from a range of local and state government departments, as shown in Table 4-2.

Table 4-2 Summary of data for the GIS method

State	Catchment	Requested Data	Authority/Data Source
ACT	Giralang	Aerial Photographs, Aerial Laser Survey (ALS), Cadastre	Cardno Spatial Databases
		Cadastre, 2m Contours	Cardno Spatial Databases
NSW	Powells Creek	Aerial Photographs, ALS	Sydney Metropolitan Catchment Management Authority (CMA)
		Cadastre, 2m Contours	Cardno Spatial Databases
		Pit and Pipe Data	Strathfield City Council
NT	McArthur Park	Pit and Pipe Data	Palmerston City Council
		Contours, Aerial Photographs, Digital Terrain Model (DTM), Cadastre	Department of Lands and Planning (NT)
QLD	Ithaca Creek	Aerial Photographs, 1m Contours, Cadastre, Stormwater Catchments	Brisbane City Council
SA	Parra Hills Drain	Digital Terrain Model (DTM), Cadastre	Salisbury City Council
TAS	Argyle Street	Cadastre, 1m Contours, Stormwater Catchments	Hobart City Council
		Aerial Photographs	Department of Primary Industries, Parks, Water and Environment (TAS)
VIC	Kinkora Road	Aerial Photographs, LiDAR Digital Terrain Model (DTM)	Melbourne Water
		Cadastre, Contours	Cardno Spatial Databases
WA	Albany Drain	Cadastre, Aerial Photographs, Digital Terrain Model (DTM)	Landgate WA

5. Analysis of Effective Impervious Area

A range of established methods for estimating effective imperviousness were discussed in Section 2.1. From these, it was determined that the analysis of rainfall and streamflow data as well as the desktop GIS analysis would be the most suitable for determining effective imperviousness for a number of catchments across Australia. Details of the methodology adopted are discussed in the remainder of this section.

5.1. Analysis of Rainfall and Streamflow data

The methodology for determining EIA based on rainfall and streamflow is outlined in Figure 5-1. This method is a variation on the approach undertaken by Boyd, Bufill & Knee (1993) for estimating effective imperviousness in gauged catchments. The methodology shown below was undertaken for each of the selected catchments detailed in Section 4.

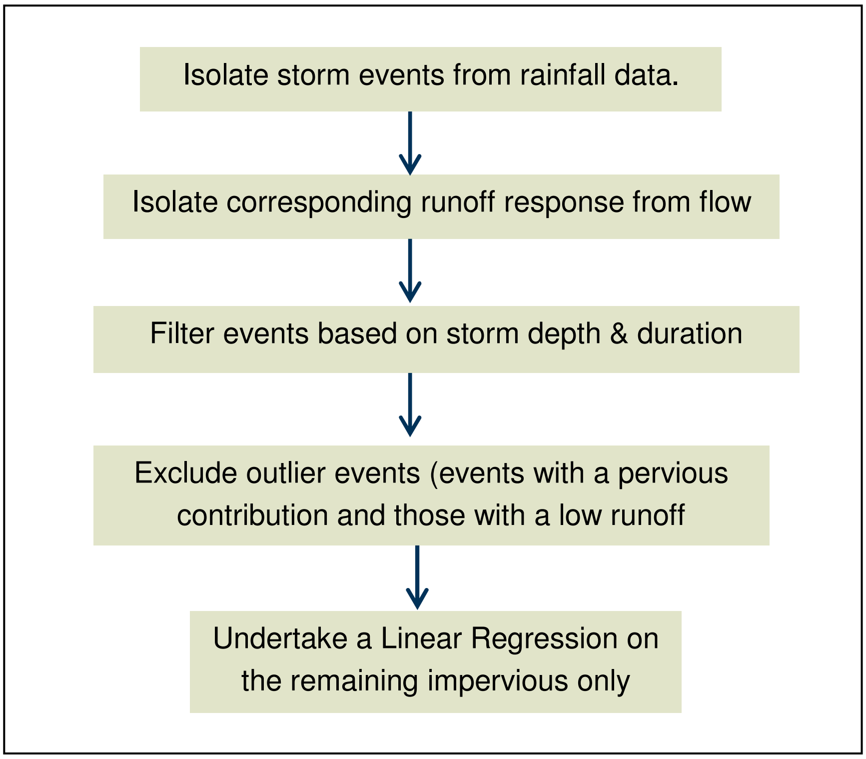


Figure 5-1 Methodology for estimating EIA using rainfall and streamflow data

5.1.1. Identification of Events

The first step of the analysis was to isolate rainfall events and the associated runoff responses within the continuous data. Storm events were extracted using the concept of inter-event time, where a specified period of time in which no rainfall is recorded separates two sequential rainfall events(see for example Lloyd 1990; Aryal, Furumai et al. 2007; Taboada-Castro et al. 2012). For the purposes of this analysis, the start of a storm event was defined as the time at which there is no rainfall in the preceding two hours. The end of the event was defined as the time at which rainfall ceased and there was no rainfall in the following hour.

Corresponding runoff events were selected primarily by examination of the variations in recorded flows. Under conditions where baseflows were present, the end of runoff was determined as the earliest time at which the recorded flow fell beneath a nominal baseflow value, determined from a review of rainfall hyetographs and runoff hydrographs. If the assessed end time overlapped with a following rainfall event, the end of runoff was taken to be the latest time before the start of the next rainfall event.

5.1.2. Filtering of Identified Events

In order to exclude the impacts of evaporation and other loss factors on runoff volume, storm events of duration less than 10 hours were sought. Events with low rainfall depths (<2mm) were excluded from the analysis, as these are within the measurement accuracy of the gauges. Events were also discarded if the runoff response started more than 30 minutes after the commencement of rainfall. This time was deemed sufficient for surface runoff from the urbanised areas to be conveyed to the catchment outlet for all the study catchments.

Due to the presence of baseflows in many of the catchments, the direct runoff volume was used instead of the total runoff volume. Baseflow extraction was undertaken by assuming a constant baseflow throughout the event, determined to be the flow rate just before the start of runoff. Lastly, any events for which the total runoff depth exceeded the total rainfall depth were excluded, as this suggested a spatial variation in rainfall across the catchment which was not reflected in the rainfall readings. This also ensures that any errors in the data or the event selection process are not included in the analysis. Events with poor quality readings were also excluded. A summary of the criterion adopted for selecting and filtering events is given in Table 5-1.

Table 5-1 Criteria adopted in identifying and filtering events

	Parameter	Value Adopted	Units
Storm Selection	Minimum cumulative depth of storm	2	mm
	Maximum duration of storm	10	hours
	Storm selected if no rainfall in previous	2	hours
	End of storm is when there is no rainfall for the next	1	hour
Runoff Selection	Constant baseflow	(0-0.02)*	m^3/s
	Latest start time of runoff response	0.5	Hours after end of rainfall

**values adopted vary between catchments but are in this range.*

5.1.3. Outlier Events

Before undertaking the regression, it was necessary to filter events that may have a pervious runoff contribution. If events with a pervious contribution were included in the analysis, the slope of the regression line could increase and estimates of the EIA could potentially exceed the TIA. Therefore, the selected events were categorised into “impervious” and “impervious+pervious” events, based on the following equations:

$$impervious\ if\ \mathrm{Q} < \frac{\mathrm{TIA}}{\mathrm{TA}} * (\mathrm{P} - \mathrm{IL}) \tag{5.1}$$

$$impervious + pervious\ if\ \mathrm{Q} \geq \frac{\mathrm{TIA}}{\mathrm{TA}} * (\mathrm{P} - \mathrm{IL}) \tag{5.2}$$

Where Q = runoff depth (mm)
P = rainfall depth (mm)
TIA = Total Impervious Area (ha) determined from Desktop GIS Analysis
TA = Total Area (ha)
IL = Initial Loss on impervious surfaces (mm)

A nominal initial loss of 1mm on impervious surfaces was assumed in Equations 5.1 and 5.2.

Additionally, events with a significantly low runoff coefficient were deemed outliers and excluded from the regression analysis. Such events may be a result of errors in the rainfall and/or streamflow data, spatial variability in rainfall or limitations in the event selection method. For the purposes of the analysis, such outliers were defined as any events with an effective runoff coefficient less than 5% of the Urban Area (UA), as given by Equation 5.3:

$$\mathrm{Q} < 0.05 \frac{\mathrm{UA}}{\mathrm{TA}} * (\mathrm{P} - \mathrm{IL}) \tag{5.3}$$

5.1.4. Linear Regression

An ordinary least squares (OLS) regression analysis was then undertaken on the events satisfying the conditions described in Sections 5.1.2 and 5.1.3. The regression line is given by Equation 5.4:

$$\mathrm{Q} = \frac{\mathrm{EIA}}{\mathrm{TA}} * (\mathrm{P} - \mathrm{IL}) \tag{5.4}$$

The slope of the regression line gives a reasonable estimate for the expected EIA if rainfall and runoff are linearly correlated and the residuals are normally distributed with mean zero and constant variance. This was ensured for all catchments through visual examination of rainfall vs runoff scatterplots and residual plots.

An estimate of the average depth of initial loss across the catchment is given as the point where the regression line intercepts the rainfall depth axis.

5.2. Desktop GIS Analysis

This method relies on the use of GIS information such as aerial photographs, drainage maps, cadastre and where available elevation information to estimate both the TIA and both the DCIA and ICIA.

Catchment delineation was first undertaken on all the study catchments using contours and Digital Terrain models (where available). Due to the availability of catchment shapes for Ithaca Creek (QLD) and Argyle Street (TAS), this step was not necessary for these catchments.

The catchment was then divided into surface types using aerial photographs. Due to the size of the catchments examined, the catchment was first divided into general land-use categories (residential, commercial, road reserve, highway, open space and other) using both cadastre and aerial photographs. A representative sample area for each land use was analysed in detail to determine the proportion of surface types indicated in Table 5-2.

The breakdown for each sample area was then applied uniformly to the remainder of the land use in the catchment. Figure 5-2 provides a representative example for the Giralang catchment, with detailed classification for all study catchments provided in Appendix B. Note that the Albany Drain Catchment (WA) was of a reasonable size that allowed surface types to be mapped directly, without the need for approximation based on land use.

The DCIA was estimated to be the sum of the area of all roofs, roads and driveways in the catchment. This is likely to provide an upper bound estimate of the DCIA, in that catchments without inter-allotment drainage are not likely to have all roofs and driveways directly connected. As an example, Boyd & Bufill (1993) indicated that roofs were not directly connected in the Powells Creek catchment.

Table 5-2 Catchment Surface Type and Classification

Surface Type	Description	Classification
Roof	Any roof surface that would be likely to be guttered and therefore directly connected to a stormwater drainage network.	DCIA
Road	Any road with a sealed surface with stormwater to flow directly into road drainage.	DCIA
Driveway	Any driveway with a sealed surface, in which it is assumed that stormwater would flow down the driveway and into road drainage.	DCIA
Hardstand	Includes areas such as paved backyard areas, footpaths adjacent to nature strips and tennis courts which are sealed impervious surfaces but are unlikely to be directly connected to any drainage network and would likely either stagnate stormwater or flow onto pervious surfaces.	ICIA
Partial Driveway	Sealed driveways with vegetated strips in between tyre tracks, flow unlikely to reach road drainage without flowing over a pervious area	ICIA
Shed	Backyard sheds that are unlikely to have guttering that is directly connected to the stormwater drainage network.	ICIA
Pool/Pool Hardstand	A swimming pool or paced area surrounding a pool which would likely flow into the pool. Rainwater likely to be retained in the pool and never contribute to stormwater flows.	Pervious
Pervious	Any surface that has either exposed soil or vegetation, including railway lines	Pervious

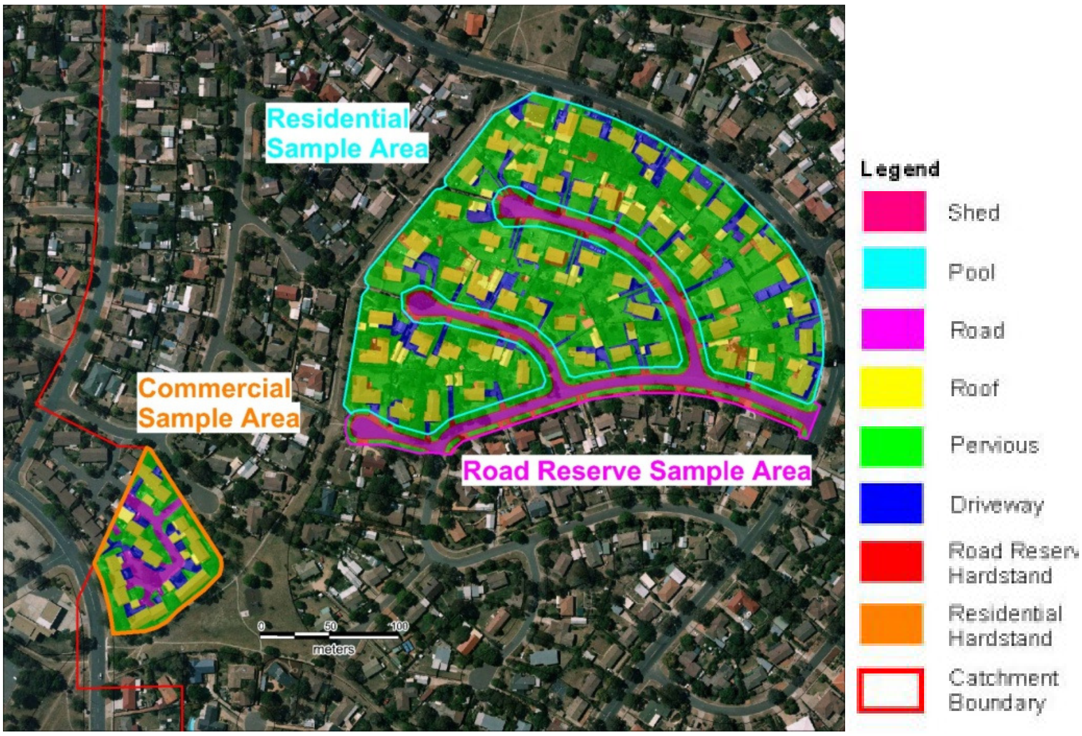


Figure 5-2 Example Sample Area Analysis for Residential and Commercial Land Use for the Giralang Catchment (ACT).

5.3. Land use based guidelines

As discussed in Section 2.1.1, there is a lack of guidance in modelling and drainage manuals for estimating effective imperviousness in Australian catchments. It was noted that the MUSIC modelling guidelines are a notable exception, although the documents are state based with only New South Wales and Queensland providing guidance on how to estimate effective imperviousness. The *Draft NSW MUSIC Modelling Guidelines (2010)* provide a land used based methodology for determining the fraction of the total impervious area that is effective. In contrast, the *Water by Design MUSIC Modelling Guidelines (2010)* (developed for South East Queensland, although applicable across Australia) recommend using the TIA as an estimate for the EIA.

Given the lack of guidance for other states, the methodology provided in the *Draft NSW MUSIC Modelling Guidelines (2010)* was adopted to obtain estimates of EIA for all the study catchments. The land use breakdown undertaken for the Desktop GIS Analysis was utilised in applying the land use based EIA factors.

6. Effective Impervious Area Estimates

Estimates of EIA were determined for the study catchments using each of the methods described in Section 5. The results are summarised in

Table 6-1, Table 6-2 and Figure 6-1, and indicate that the EIA estimated by the regression analysis of rainfall and streamflow is generally about 55% - 65% of the TIA.

Given the variation in catchment size, location, urban density and land use across the study catchments, this range is fairly narrow. However, it is noted that this indicative range is based only on eight catchments, and further study across a larger pool of catchments (particularly with lower urban TIA fractions) may be required to determine its validity.

The key exception to the analysis is Giralang (ACT), where the EIA/TIA ratio is around 75 to 80%. This catchment generally has a greater degree of connected surfaces (as discussed in Goyen, 2000). This is expected to result in a higher proportion of the impervious runoff being directly connected to the drainage system.

It is noted that the estimates for McArthur Park (NT) are not reliable as the flow gauge captures surface flows only, meaning that piped low flows are not accounted for. This may explain the higher initial losses of about 5 mm for this catchment, compared with 1-3 mm for the other study catchments.

Table 6-2 also shows that the estimates based on the Draft NSW MUSIC Modelling Guidelines (2010) are fairly consistent with the results from the regression of rainfall and streamflow. The estimates are generally between 55% - 60% of the TIA compared with 55% - 65% based on the regression. This is likely because the study catchments are predominantly residential, and the MUSIC guidelines recommend an EIA factor of 55% of the TIA for a residential land use.

The results indicate that estimates from the desktop GIS analysis tend to be greater than the effective imperviousness resulting from the regression method. The DCIA estimated from the desktop GIS analysis overestimates the regression estimate by about 40% – 50% (except for the Powells Creek and Giralang catchments). This is most likely due to the fact that the method is subjective and reliant on judgement to determine the degree of connectedness of impervious surfaces. For instance, one would commonly assume all roofs in a catchment are directly connected to a drainage network, although this may not be the case in the absence of inter allotment drainage. Furthermore, the method does not take into account inefficiencies in the drainage system which can reduce the volume of runoff at the catchment outlet such as blocked drains and roof gutters.

Lastly, Figure 6-2 demonstrates that there is a fairly strong linear association between the various catchment surface variables (EIA from regression, DCIA, Urban Area (UA), Total Impervious Area from GIS Analysis). Note that Ithaca Creek (QLD) has been excluded from the data set due to the questionable reliability of the rainfall and streamflow data. Key results from these correlations are:

- The EIA based on regression is approximately 60% of the TIA;
- The EIA based on regression is approximately 35% of the UA;
- The EIA based on regression is approximately 70% of the DCIA from the GIS method;

However, it is noted that these relationships are based only on eight catchments, and further study across a larger pool of catchments is needed to determine the strength and form of these relationships, with particular focus on outlier catchments.

Table 6-1 Details of Study Catchments

State	Catchment Name	Total Area (TA)* (ha)	Total Impervious Area (TIA)* (ha)	Urban Area (UA)^ (ha)	Urban TIA fraction#
ACT	Giralang	91.0	28.4	61.8	46%
NSW	Powells Creek	232	152	223	68%
NT	McArthur Park	144	53.7	120	45%
QLD	Ithaca Creek	926	128	262	49%
SA	Parra Hills Drain	55.1	26.9	48.5	55%
TAS	Argyle Street	1900	292	491	59%
VIC	Kinkora Road	202	122	184	66%
WA	Albany Drain	8.20	2.90	8.20	35%

**Determined using the desktop GIS method*

^The Urban Area is classified as the total developed area excluding large open space

#The Urban TIA fraction is defined as the percentage of impervious area in the urban area and was based on the desktop GIS method.

Table 6-2 Summary of Effective Impervious Estimates

	Regression of Rainfall and Streamflow						DRAFT NSW MUSIC guidelines	Desktop GIS Method		
Catchment	**Rain Gauge**	**Data Period**	**EIA (ha)**	**EIA/TIA#**	**Initial Loss (mm)**	**R^2**	**EIA/TIA#**	**DCIA (ha)**	**DCIA/TIA#**	**EIA(regression) /DCIA (GIS)**
Giralang (ACT)	570987	1993 – 1995	21.5	**76%**	1.3	0.95	55%	26.9	95%	82%
		1973 – 2012	21.0	**74%**	1.4	0.93				
	570991	1993 – 1995	22.4	**79%**	1.3	0.96				
		1973 – 2012	22.7	**80%**	1.5	0.92				
	570990	1976 – 2011	21.5	**76%**	1.5	0.90				
	570992	1973 – 2012	22.7	**80%**	1.6	0.94				
Powells Creek (NSW)	566004	1981 – 1993	95.1	**63%**	2.6	0.85	58%	122.8	81%	75%
	566005	1981 – 1996	89.8^	**59%**	2.9	0.85				
McArthur Park (NT)	G8150233	1983 – 2004	35.3	**66%**	5.0*	0.71	57%	50.2	93%	70%
Ithaca Creek (QLD)	143028A	1998 – 2011	70.4	**55%$^{\alpha}$**	2.8	0.85	58%	120.9	95%	58%
Parra Hills Drain (SA)	A5040567	1992 – 1999	15.0	**56%**	1.0	0.90	55%	23.5	87%	64%
Argyle Street (TAS)	094029	1984 – 1994	182.4	**63%**	0.9	0.77	60%	270.0	93%	68%
Kinkora Road (VIC)	229636A	1977 – 2012	72.3	**60%**	2.5	0.86	55%	105.9	87%	68%
Albany Drain (WA)	509268	1983 – 1993	1.7	**60%**	1.4	0.90	55%	2.4	83%	71%

^note that the EIA estimate decreases if a single influential data point is included (when included, EIA = 75.2 ha or 50% TIA).

**The gauging station for this site does not capture piped low flows*

 # The TIA (Total Impervious Area) has been determined from the Desktop GIS Analysis.

$^{\alpha}$ Both rainfall and flow data for this catchment is unreliable and by consequence, the EIA estimate.

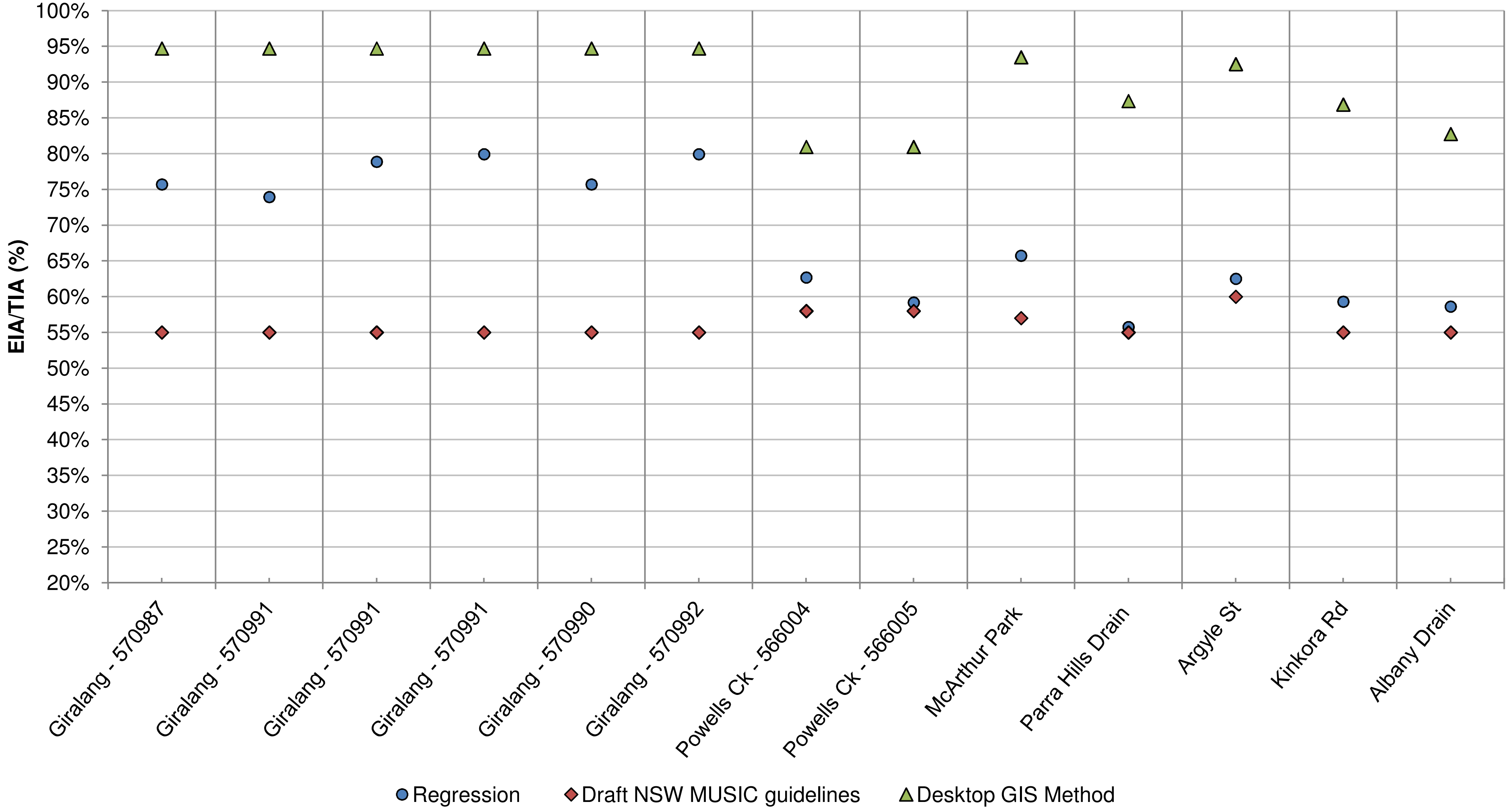
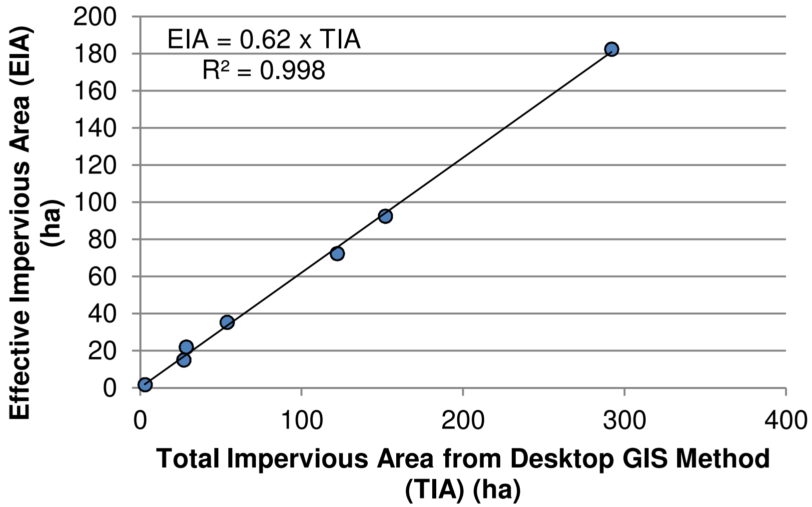
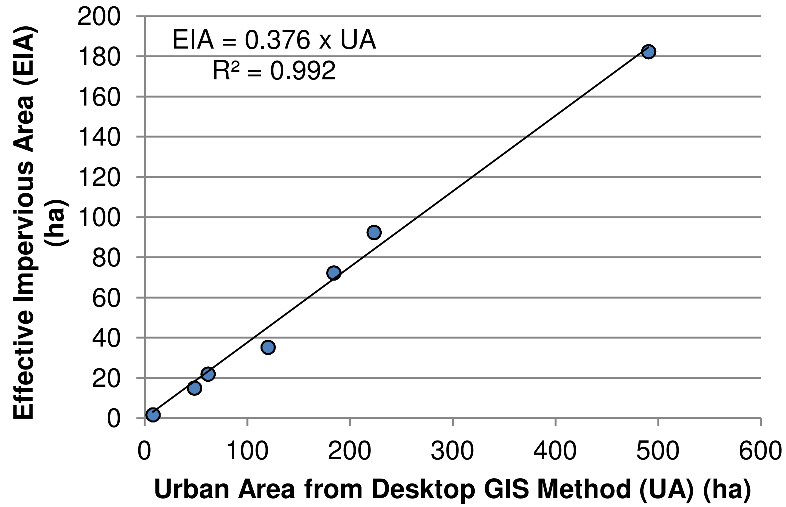
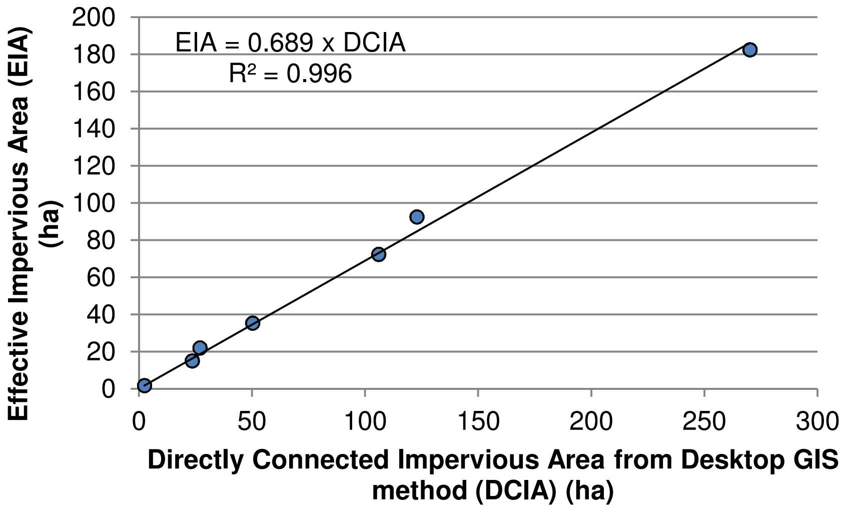
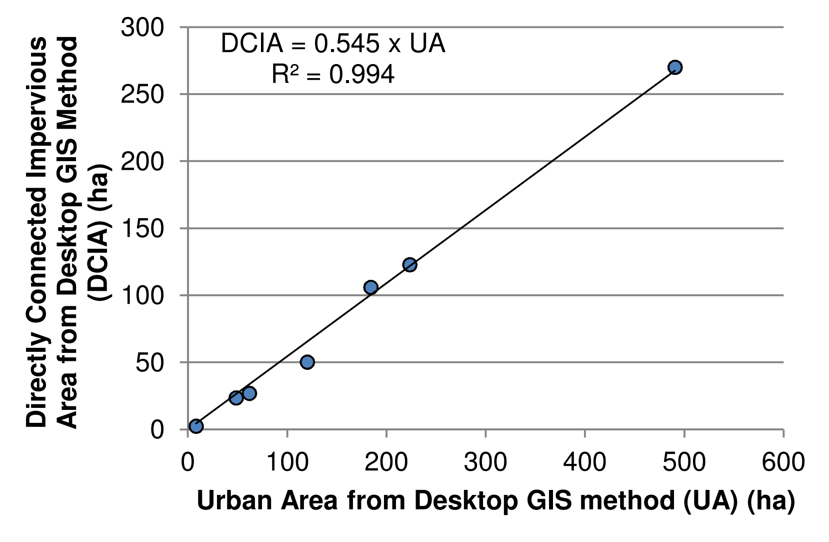


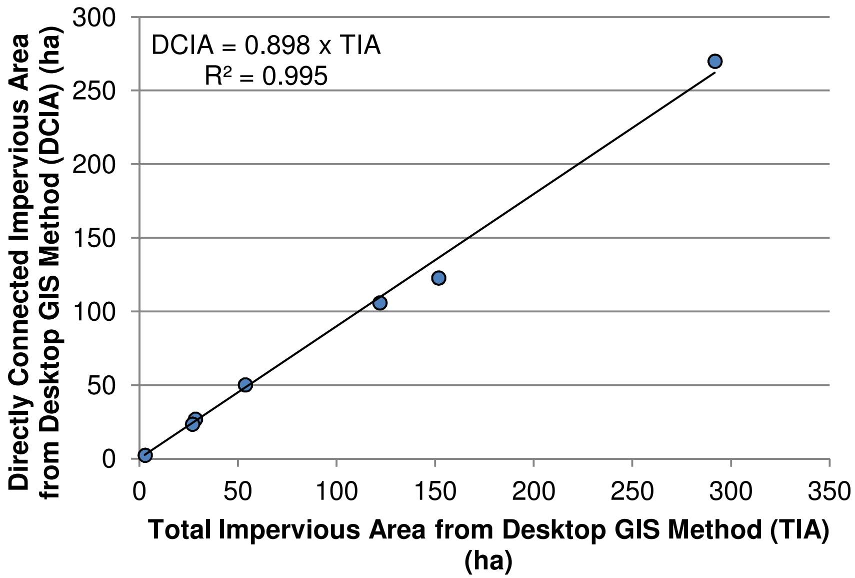
Figure 6-1 Summary of Effective Impervious Estimates using Regression Analysis, Desktop GIS Method and based on the Draft NSW MUSIC Modelling Guidelines (2010)


EIA = 0.62 x TIA
R² = 0.998
Effective Impervious Area (EIA) (ha)
Total Impervious Area from Desktop GIS Method (TIA) (ha)
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400


EIA = 0.376 x UA
R² = 0.992
Effective Impervious Area (EIA) (ha)
Urban Area from Desktop GIS Method (UA) (ha)
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600


EIA = 0.689 x DCIA
R² = 0.996
Effective Impervious Area (EIA) (ha)
Directly Connected Impervious Area from Desktop GIS method (DCIA) (ha)
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300


DCIA = 0.545 x UA
R² = 0.994
Directly Connected Impervious Area from Desktop GIS Method (DCIA) (ha)
Urban Area from Desktop GIS method (UA) (ha)
0
50
100
150
200
250
300
0
100
200
300
400
500
600



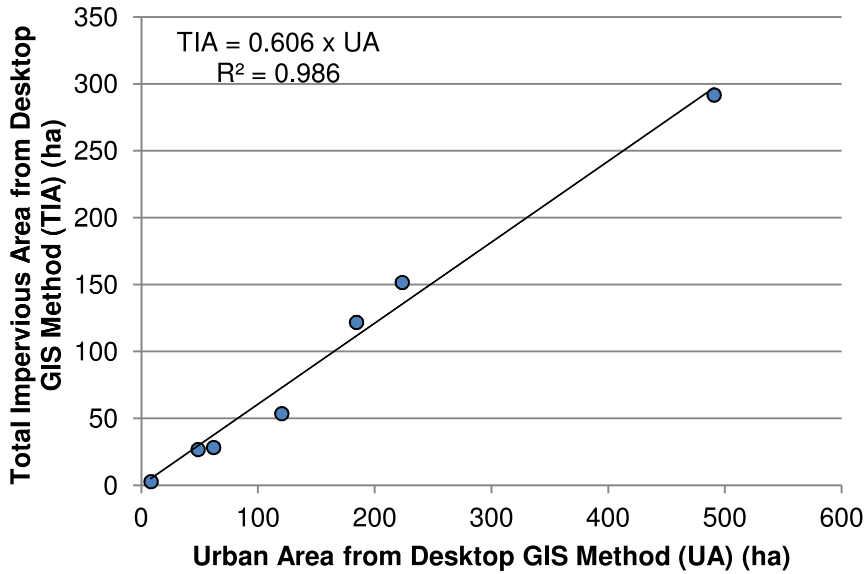


Figure 6-2 Relationships between Various Catchment Surface Variables

6.1. Implications of assumptions for Regression Analysis

6.1.1. Regression Performance

The linear regression provides a reasonable fit to the data in most cases (see Appendix C). The coefficient of determination is generally greater than 0.8, and the assumption of a linear relationship between rainfall and runoff depth is sound.

There are several low rainfall depth events (< 5mm total) with a pervious runoff contribution in some catchments. Upon examination of these events, it was found that there are a number of reasons which may cause this:

- Saturated antecedent soil moisture conditions coupled with a highly intense rainfall burst. For example, an event in the Giralang catchment was isolated with only 4mm of rainfall but 2mm depth of runoff. The runoff coefficient in this case is approximately 50%, which is significantly more than the total impervious fraction of 28%. This event was relatively intense (average of 13 mm/hr over 18 minutes) and there had been a rain event in the preceding 5 hours with 21mm of total rainfall.
- Limitations in the methodology for isolating events. The assumption of a 1mm initial loss on the impervious surface may be too high, particularly if the impervious surfaces had been pre-wetted from a recent rain event.
- Errors in the rainfall and/or streamflow data.

The impacts of any errors or limitations in the event selection process are minimised, as events with a pervious contribution are excluded from the regression analysis.

It is also noted that in almost all catchments, there is an underrepresentation of high rainfall depth events (> 20 mm). This means that the coefficient estimates of the regression is likely to be biased towards low rainfall depth events.

In addition to this, the lack of data at high rainfall depths gives rise to influential data points which can have a significant impact on the slope of the regression line (ie. the estimate of effective imperviousness). For example, Figure 6-3 shows the impact of an influential data point on the regression fit for Powells Creek. This data point with (Rainfall depth, Runoff depth) = (107.6mm, 16.24mm) was isolated from the rain gauge 566005 data set, but was not present in the rain gauge 566004 set. When this data point was included in the regression analysis, the EIA estimate was 72.5 ha, approximately 15% lower (when expressed as a fraction of the TIA) than the estimate from gauge 566004.

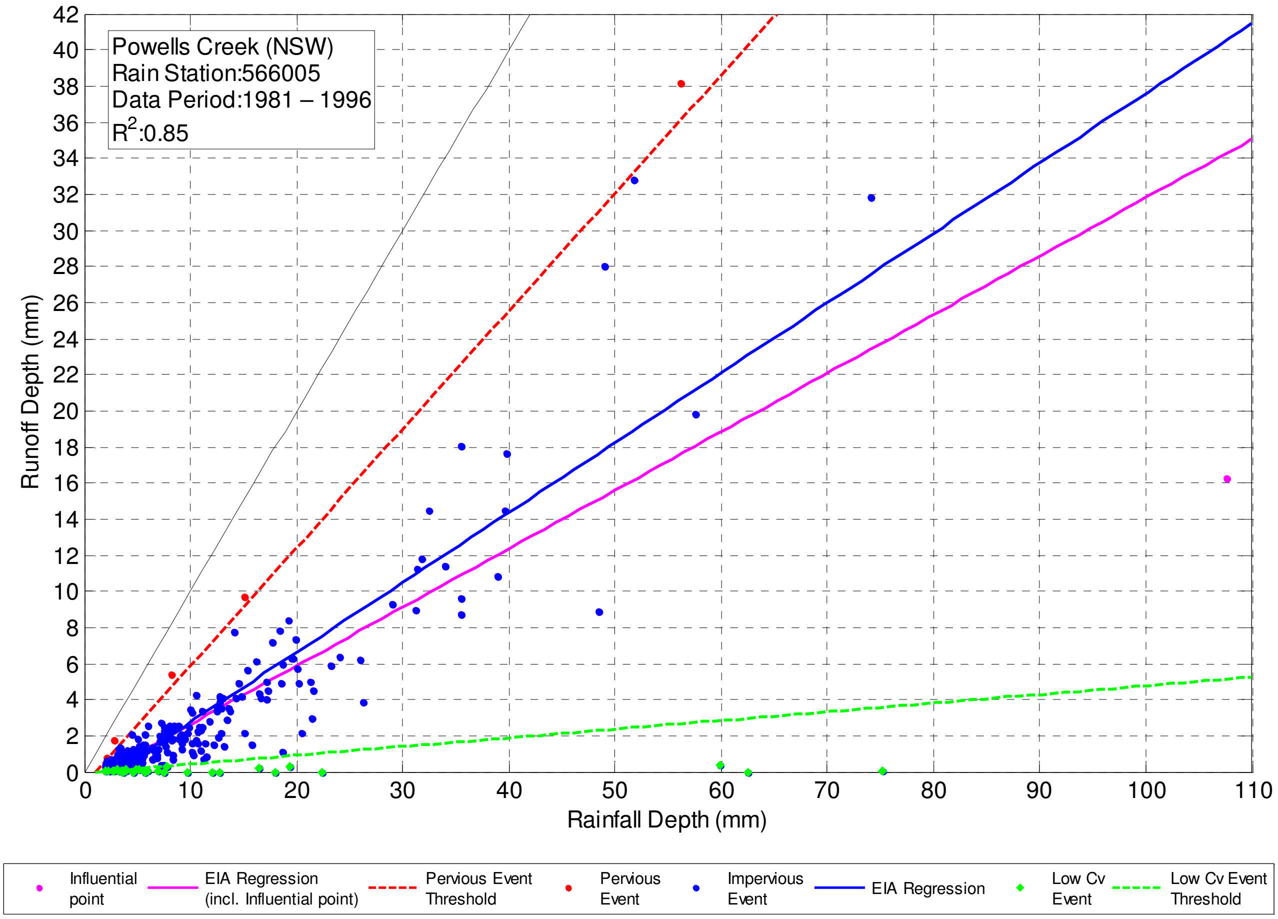


Figure 6-3 Impact of an influential data point on the regression analysis for the Powells Creek Catchment

6.1.2. Spatial Variation in Rainfall

As discussed in Section 5.1, point rainfall data was used with the assumption of negligible spatial variation in rainfall. Where data from multiple rain gauges within the catchment were available, the implications of this assumption were examined by repeating the regression analysis using the different sets of rainfall data from different rainfall gauges. This was possible for the Giralang and Powells Creek catchments, where rainfall data spanning the same recording period was available from a number of gauges. Table 6-2 shows that the variation in the EIA (as a fraction of the TIA) is generally within the range of ± 5% for both catchments.

6.1.3. Impact of recording period

There is potential for the recording period of the rainfall or streamflow data to affect the EIA estimate, particularly if there is significant non-stationarity in catchment urbanisation and drainage. To determine if the effective imperviousness of the study catchments changes with time, the regression was undertaken on events from discrete time periods of roughly 10 years. This was undertaken for the Giralang and Kinkora Road catchments as they both had a relatively lengthy continuous data set. It is noted that this only provides an indication of possible variation in EIA estimates with time, and will not reflect changes in stormwater management (for instance increased on site detention, water sensitive urban design) that have occurred outside the recording period.

Table 6-3 shows that the variation in the EIA as a fraction of the TIA is around 10% when data from different recording periods is used. The results do not seem to indicate a consistent trend in the effective imperviousness with time, which is further reinforced by the scatter in Figure 6-4. The variation is most likely attributed to the presence of influential data points, particularly at higher rainfall depths.

Table 6-3 Effective Impervious Area Estimates for different recording periods

Catchment	Rain Gauge	Data Period	EIA (ha)	EIA/TIA	Initial Loss (mm)	R^2
Giralang (ACT)	570987	1973 – 1980	19.8	**70%**	1.7	0.90
		1980 – 1990	19.9	**70%**	1.2	0.90
		1990 – 2000	22.1	**78%**	1.4	0.94
		2000 – 2012	21.0	**74%**	1.4	0.95
Kinkora Road (VIC)	229636A	1977 – 1990	74.7	**62%**	2.3	0.87
		1990 – 2000	66.0	**54%**	2.6	0.85
		2000 – 2012	80.7	**66%**	2.8	0.85

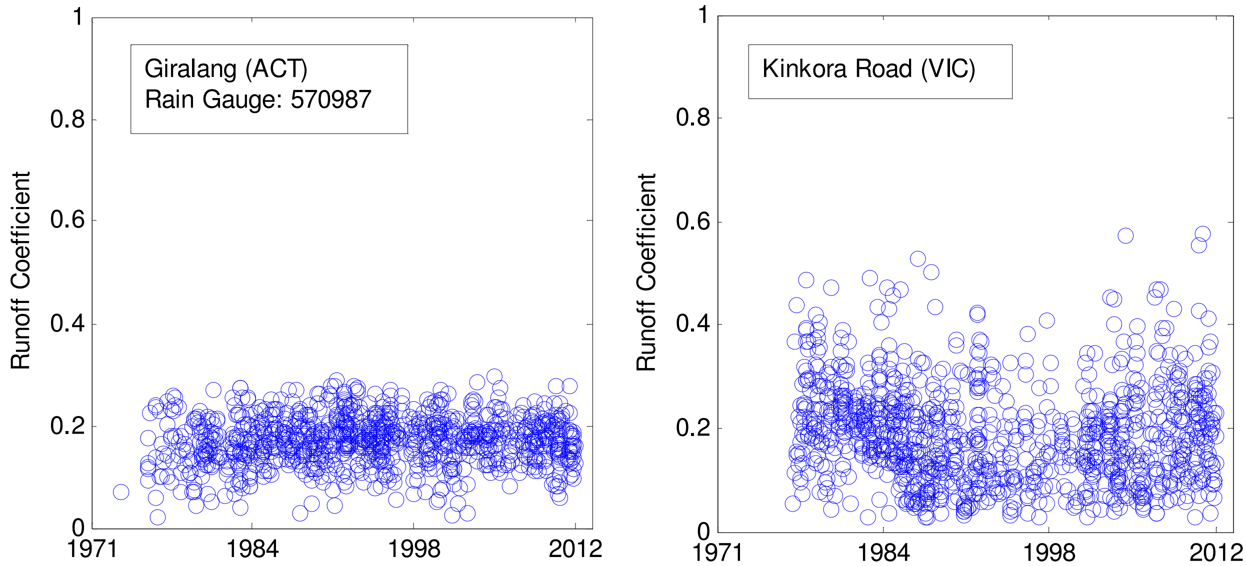


Figure 6-4 Variation of Runoff Coefficient with the recording period of the rainfall & streamflow data

6.1.4. Impact of Event Selection Criterion

The EIA estimates provided in Table 6-2 were derived based on a set of criterion for isolating and filtering events (see Section 5.1). In order to examine the sensitivity of the EIA estimates to the event selection parameters, the analysis was repeated by altering the main parameters of interest:

- Start of the storm event;
- End of the storm event ; and
- Maximum duration of the storm event.

The scenarios examined are shown in Table 6-4.

Table 6-4 Event selection parameters for different scenarios examined in the sensitivity analysis

Scenario	Start of Storm (hours prior with no rainfall)	End of Storm (hours following with no rainfall)	Maximum Duration of Storm
Base Case	**2**	**1**	**10**
Shorter duration bursts ↓	**1**	**1**	**1**
	2	**2**	**3**
	6	**6**	**5**
Longer duration, more isolated storms.	**6**	**6**	**15**

Table 6-5 shows the range of EIA estimates obtained when the above criteria are used to discretise and select storm events. In general, the variation in the EIA as a fraction of TIA is around 10%, and it was not possible to identify a trend between effective impervious estimates and the criteria used to isolate storms. The wider band of variability for Argyle Street (TAS) is attributed to the presence of consistent baseflows and a large pervious area upstream of the urbanised area.

Table 6-5 Range of EIA estimates from varying the event selection criteria

Catchment	Rain Gauge	Data Period	EIA (ha)	EIA/TIA
Giralang (ACT)	570987	1993 – 1995	19.1-23.3	**67% - 82%**
		1973 – 2012	19.8-21.3	**70% - 75%**
Powells Creek (NSW)	566005	1981 – 1996	72.5-80.3	**50% - 53%**
McArthur Park (NT)	G8150233	1983 – 2004	33.4-38.4	**62% - 72%**
Ithaca Creek (QLD)	143028A	1998 – 2011	72.8-92.1	**57% - 72%**
Parra Hills Drain (SA)	A5040567	1992 – 1999	12.6-16.5	**47% - 61%**
Argyle Street (TAS)	094029	1984 – 1994	119.5 – 194.3	**41% - 67%**
Kinkora Road (VIC)	229636A	1977 – 2012	59.2-72.1	**49% - 59%**
Albany Drain (WA)	509268	1983 – 1993	1.8-1.9	**62% - 66%**

6.1.5. Conclusions

A range of sensitivity tests were undertaken to examine the impacts of the assumptions made in the regression of rainfall and streamflow. It has been shown that the variability in the effective impervious estimates, when expressed as a fraction of the TIA is around 5% - 10% due to factors such as:

- The use of point rainfall and the assumption of uniformly distributed rainfall;
- The recording period of the data used in the regression;
- Criteria used to isolate storm events.

6.2. Detailed Desktop GIS Analysis

Table 6-6 provides a detailed summary of the results of the Desktop GIS Analysis using the method outlined in Section 5.2.

6.2.1. Key Challenges

There were a number of key challenges in this assessment:

- The location of the stream gauge was taken from the data provided by the various gauge owners, in the case of Powells Creek (NSW), McArthur Park (NT), and Albany Drain (WA) the gauge location was verified by identifying the gauge on aerial photography. The remaining gauge locations were estimated based on available information which could have a significant effect on catchment delineation and total area calculation.

- In lieu of aerial survey data, catchment delineation is reliant on contour data which raises issues of data resolution with 1 metre contours used for Parra Hills Drain (SA) and Ithaca Creek (QLD). Though the other catchments used more accurate DTM as a basis, delineation of the catchment area was still done on a desktop basis and is therefore subject to some level of error.

- Catchment delineation is particularly difficult in urbanised areas, such as the study areas, as stormwater flow is more impacted by stormwater drainage networks than natural topography. For example, house roofs may be connected to large capacity rainwater tanks, the impact of detention basins are not noted in this methodology, and portions of the catchment may be diverted away from the stream gauge. The use of council pit & pipe data for Powells Creek (NSW), McArthur Park (NT), Parra Hills (SA), and Albany Drain (WA) allowed a better estimate of catchment area based on the drainage network. It should be noted that Albany Drain (WA) incorporates a large detention basin that may influence the results.

- The errors associated with selecting a representative sample area for each land-use were reduced by choosing areas that best represented the entire land-use for the catchment. This was not an issue for Albany Drain (WA) where the entire catchment was divided into surface types.

- There are inherent errors associated with manually tracing impervious area boundaries using GIS software caused by aerial photography resolution, tree coverage, and human error. The impact of these errors was limited by choosing large sample areas so that the overall significance of these errors is minimised.

- All catchments used aerial photography that was taken in the last decade, despite the stream gauge data spanning the last 20-30 years. Any development that has occurred between the stream gauge data recording and the taking of the aerial photography will result in some potential errors.

Table 6-6 Detailed Summary of Desktop GIS Analysis

			Area (hectares)							
	Land Use	**Type**	**ACT**	**NSW**	**NT**	**QLD**	**SA**	**TAS**	**VIC**	**WA**
Directly Connected Impervious Area (DCIA)	Residential	Roof	11.3	54.9	21.0	51.8	10.0	81.8	53.9	0.9
		Driveway	5.8	27.9	6.6	6.4	2.2	16.5	21.6	0.4
		Garage	-	-	-	-	-	-	-	0.2
		Road	-	21.3	-	-	-	81.8	13.9	-
	Commercial	Roof	0.2	-	4.3	-	1.2	90.0	-	-
		Internal Road	0.1	-	3.0	-	1.5		-	-
	Highway	Road	0.7	-	2.5	-	0.5	-	-	-
		Hardstand	0.3							
	Road Reserve	Road	5.6	-	11.1	42.5	8.2	-	-	0.9
		Driveway	2.9	-	1.7	5.4	-	-	-	-
	Other^	Roof	-	-	-	10.8		-	6.9	-
		Road	-	-	-	-	-	-	9.2	-
		Hardstand#	-	18.6	-	4.0			0.4	
	TOTAL ESTIMATED DCIA:		**26.9**	**122.8**	**50.2**	**121.0**	**23.5**	**270.0**	**105.9**	**2.4**
Indirectly Connected Impervious Area (ICIA)	Residential	Hardstand	1.4	15.3	3.0	1.7	1.1	15.9	7.6	0.4
		Partial Driveway	-	-	-	3.3	-	-	-	-
		Shed	-	3.3	-	-	2.3	5.9	-	0.1
		Pool Hardstand	-	4.2					0.4	
	Commercial	Hardstand	0.1	-	0.5	-	-	-	-	-
	Highway	Hardstand	-	-	-	-	-	-	-	-
	Road Reserve	Partial Driveway	-	-	-	1.6	-	-	-	-
		Hardstand	-	6.6	-	-	0.0	-	8.0	-
	TOTAL ESTIMATED ICIA:		**1.5**	**29.4**	**3.5**	**6.7**	**3.4**	**21.8**	**16.0**	**0.5**
Pervious	Residential	Pervious	27.7	67.1	43.5	96.2	15.3	188.8	57.6	4.1
	Road Reserve	Pervious	6.4		11.8	23.3	6.2		5.5	0.9
	Commercial	Pervious	0.3	12.6	6.8	-	-	10.0	-	-
	Highway	Pervious	1.6		3.6	-	0.1	-	-	-
	Open Space	Pervious	26.7		23.5	663.6	6.6	1405.0	-	-
	Other	Pervious	-		0.8	15.0	-	-	17.0	0.2
	TOTAL PERVIOUS AREA:		**62.6**	**79.7**	**90.0**	**798.1**	**28.1**	**1603.8**	**80.1**	**5.2***
TOTAL AREA:			91.0	231.9	143.7	925.7	55.1	1895.6	202.1	8.2

** includes other roof which is roof area that looks to be directed to another discharge point and not the one of interest.*
^ Combined Commercial, Industrial, Special Use, Grassed Space and Public Space.
 # Includes internal roads and roof areas in commercial, industrial and special land use areas.

6.3. Land Use Based Guidelines (MUSIC Modelling Manuals)

As discussed in Section 5.3, the Land Use based EIA factors given in the Draft MUSIC Modelling Guidelines for NSW (2010) (see Table 6-7) were used to determine EIA estimates for all the study catchments.
Table 6-8 outlines the calculations and resulting estimates for each of the catchments.

Table 6-7 Default EIA parameters as a fraction of the Total Impervious Area (TIA) from the Draft MUSIC Modelling Guidelines for NSW (2010).

Land Use Type	EIA Factor
Residential	0.55 x TIA
Commercial	0.80 x TIA
Rural residential	0.05 x SCA
Industrial	0.90 x TIA
Agricultural / grazing	0.00 x SCA
Native/plantation forest	0.00 x SCA

SCA = Subcatchment/surface area, TIA = Total Impervious Area, EIA = Effective impervious area

Table 6-8 Summary of EIA as a fraction of TIA based on the Draft MUSIC Modelling guidelines for NSW.

State	Catchment	Land Use with Impervious Area		Total Areas with Imperviousness* (ha)	Weighted EIA factor (EIA/TIA)
		Residential (ha)	Commercial (ha)		
ACT	Giralang	61.1	0.7	61.8	=0.55*(61.1/61.8) + 0.8*(0.7/61.8) = **0.55**
NSW	Powells Creek	200.6	31.2	231.9	=0.55*(200.6/231.9) + 0.8*(31.2/231.9) = **0.58**
NT	McArthur Park	105.6	14.6	120.2	=0.55*(105.6/120.2) + 0.8*(14.6/120.2) = **0.57**
QLD	Ithaca Creek	232.3	29.8	262.1	=0.55*(232.3/262.1) + 0.8*(29.8/262.1) = **0.58**
SA	Parra Hills Drain	48.5	0	48.5	=0.55*(48.5/48.5) = **0.55**
TAS	Argyle Street	390.6	100.0	490.6	=0.55*(390.6/490.6) + 0.8*(100/490.6) = **0.60**
VIC	Kinkora Road	184.2	0	184.2	=0.55*(185.3/185.3) = **0.55**
WA	Albany Drain	8.2	0	8.2	=0.55*(8.2/8.2) = **0.55**

**Total size of land uses with impervious areas (forest, agricultural etc. not included).*

6.4. Summary

The analysis on EIA using the regression analysis has demonstrated that, in general, the EIA is around
55% – 65% of the TIA. A summary is provided in Table 6-9, with results in order of lowest density to highest density, as measured by the TIA fraction of the urban area. Due to the challenges with both the Ithaca Creek (QLD) and Argyle Street (TAS) catchments, both of these have been excluded from this table for simplicity.

As noted in the preceding sections, the GIS analysis, which attempted to estimate the DCIA, tended to be greater than the EIA when compared with the regression analysis. Table 6-9 and Figure 6-2 show that the EIA from the regression analysis is about 70% of the DCIA (+/- 5%) for most catchments. A majority of the DCIA areas determined from the GIS Analysis are roads and rooves, meaning that in general, the EIA from the regression analysis equates to about 70% (+/- 5%) of all roads and roof areas in the catchment. However, it is noted that this general rule does not apply to all catchments. For example, Giralang (ACT) has a higher EIA/DCIA ratio of around 80%, although this is likely due to the higher degree of connected surfaces (as discussed in Goyen (2000) and also as evidenced by the higher EIA/TIA ratio of around 78%).

Table 6-9 Summary of EIA results

Catchment	Urban TIA Fraction#	EIA/TIA	DCIA (GIS)/ TIA	EIA (Reg.) /DCIA(GIS)
Albany Drain (WA)	35%	59%	83%	71%
McArthur Park (NT)	45%	66%	93%	70%
Giralang (ACT)	46%	74 to 80%	95%	82%
Parra Hills Drain (SA)	55%	56%	87%	64%
Kinkora Road (VIC)	66%	59%	87%	68%
Powells Creek (NSW)	68%	59 – 63%	81%	75%

#The Urban TIA fraction is defined as the percentage of impervious area in the urban area and was based on the desktop GIS method.

7. Loss Models for Urban Catchments

7.1. Overview of Approach

There are a number of potential approaches for derivation of losses for catchments. Two approaches were considered in this study:

- Analysis of flow gauges and use of hydrological models;
- Volumetric analysis of historical storm events.

These two methodologies are discussed briefly in the following sections.

7.1.1. Flow Gauge Analysis & Hydrological Models

The first option considered for the assessment was the use of a flood frequency analysis of flow gauge data along with a comparison of this data to design flows obtained from a calibrated hydrological model. The general process can be outlined as follows:

1) Undertake flood frequency analysis of flow gauge data;
2) Calibrate hydrological model to historical events;
3) Apply design rainfall events to hydrological model and determine peak flows;
4) Compare peak flows from hydrology and gauge and adjust losses accordingly – repeat to step 3 as appropriate

This approach has a number of key advantages:

- Optimised losses from the approach ensure AEP neutrality;
- The methodology is based on peak flows, which are generally the focus of hydrology;
- The methodology incorporates the lag within the catchment, which is not possible under the second methodology.

However, the key disadvantages are:

- It assumes that the gauge record is sufficiently long and with sufficient large events to derive an appropriate flood frequency curve, which is generally not the case for the majority of the catchments. This introduces a significant source of error into the analysis;
- It requires a thoroughly calibrated hydrological model, which was not available for the majority of the catchments. While one can be calibrated, this also introduces additional sources of error through assumptions in lagging throughout the catchment, which can affect the losses assumed;
- It assumes that the design rainfall events are representative for the catchment.

7.1.2. Volumetric Analysis of Historical Storms

The second option looks at an analysis of historical rainfall events, comparing the volume of rainfall from these events with the volume of runoff from the gauge. The key advantages of this analysis include:

- No hydrological model is required, which removes a potential source of error through assumptions on timing;
- Historical events may provide a more realistic representation of the catchment behaviour, as opposed to inferring information from design rainfall;
- It does not require long gauging records to determine an appropriate flood frequency analysis.

However, the key limitations of this methodology include:

- The analysis focuses on a volumetric assessment, rather than on peak flows. The assumption being that losses are representative of volumetric loss in the catchment alone, and do not incorporate other adjustment factors;
- The analysis is based on historical events only. It is envisaged that the estimated losses would be applied to design storms in a future study.

Overall, this methodology was adopted for the analysis given the key constraints of the first option. However, it is important to understand the limitations of this analysis.

7.2. Losses derived from Historical Storms

The analysis is focused on rainfall excess loss models. As noted in Section 2.2, such loss models have considerable popularity amongst hydrologists and modellers. However, they are empirical in nature, and will give rise to parameters which vary depending on the characteristics of the storm used to derive them. Therefore, a number of historical storms were extracted from the available data for the study catchments (as described in Section 4), so as to examine the variability between loss estimates. Specifically, the following loss models were examined:

- Initial loss – constant continuing loss (ILCL)
- Initial Loss – proportional continuing loss (ILPL)

Traditionally, loss parameters for initial loss continuing loss models are defined separately for impervious and pervious surfaces. A slightly different approach was taken in this analysis, utilising the concept of effective imperviousness outlined in Section 5. Loss estimates were derived for:

- DCIA – the losses on these surfaces would be similar to losses on the traditional impervious surface. It has been assumed that the EIA estimates determined in Section 6 are equal to the DCIA.
- Other Areas – this is a combination of all pervious surfaces and indirectly connected impervious surfaces.

The “other area” incorporates the combination of the pervious and indirectly connected impervious surfaces. This assumes that these two areas are effectively acting together, with the effective losses of this area some representation of this interaction. One would expect that a higher proportion of impervious surfaces within the “other area” would give rise to lower loss values compared to a catchment with a higher proportion of pervious areas in the “other area.”

The alternative would be to separate out the “other area” into an ICIA and a pervious area that is connected to the ICIA. Under this approach, two sets of losses would be applied, with the loss on the connected pervious area potentially being a function of the ICIA runoff. While this has not been assessed in this analysis, the losses estimated in this report could be utilised to establish such a model.

7.2.1. Pervious Area

It is noted that this simplified breakdown does not take into account pervious areas that are not connected to an impervious area in any way (such as large parks, rural areas, forests etc. Out of the catchments that have been analysed, the following have relatively large pervious areas:

- Ithaca (QLD);
- Giralang (NSW);
- Argyle Street (TAS); and
- McArthur Park (NT), which has a large detention basin just upstream of the flow gauge.

It is noted that of these, both Argyle Street and Ithaca Creek are not suited to the analysis, based on the discussion in Section 8.1.

The proportion of pervious only area in Giralang is approximately 36%, while for McArthur Park it is about 25%. This has the potential to influence the losses estimated. However, it is noted that the majority of the runoff events identified have a relatively low proportion of runoff from the “other area”, and therefore the influence of this may be low. The influence of the pervious only area has been investigated in Section 9.6.

An overview of the study methodology is provided in Figure 7-1.

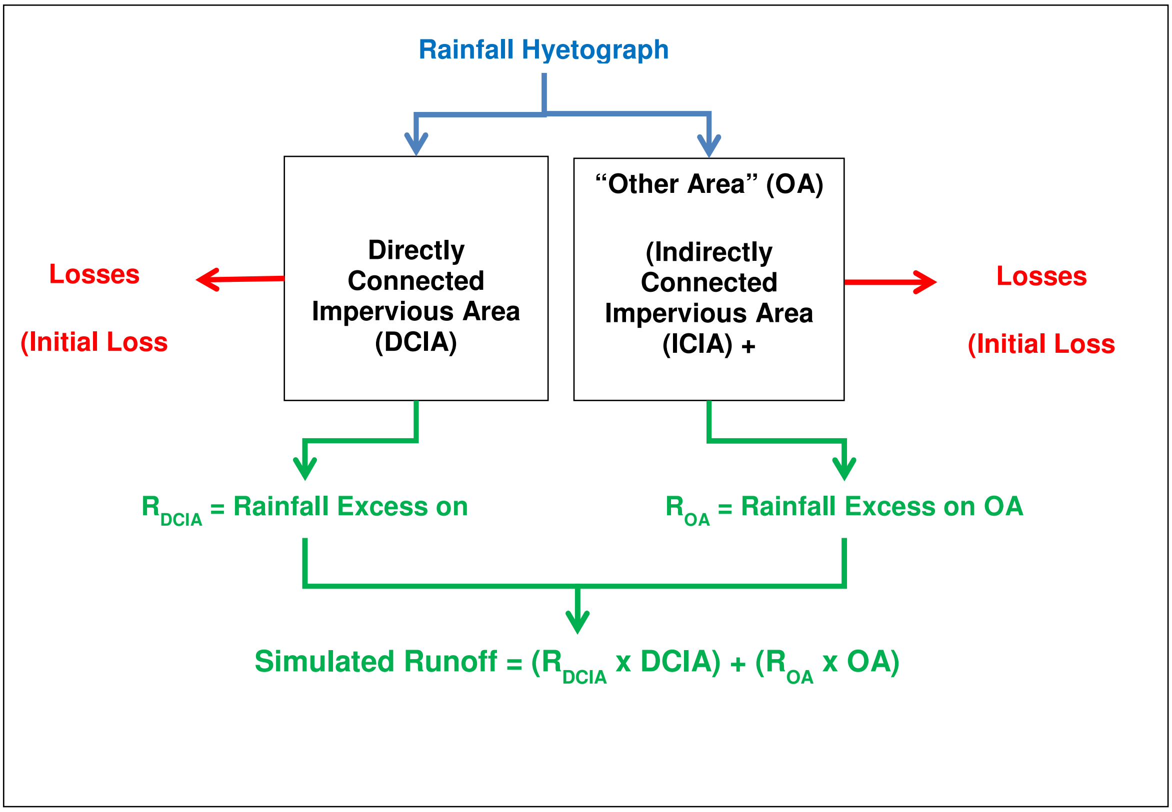


Figure 7-1 Methodology to determine losses based on volumetric analysis of historical storm events

7.2.2. Identification & Filtering of Events

Historical events were isolated from the data using a slightly modified version of the procedure outlined in Section 5.1.1. Since the aim of this analysis is to select events with sufficient pervious runoff (so that Other Area losses can be defined), the selection criteria (specifically maximum duration of storm and inter-event time) was altered to allow for the selection of longer duration storms (which may potentially have pervious runoff generating intense short duration bursts within them) rather than short duration bursts that generate only directly connected impervious runoff.

Additionally, events were selected only if they were deemed to have another area (ICIA + pervious) runoff contribution, as determined by Equation 7.1. A 10% allowance was provided in Equation 7.1, to allow for errors in the EIA estimation and to ensure that a reasonable proportion of the flow was represented by the other area (ICIA+pervious area). Note that it has been assumed here that the DCIA is equal to the EIA estimates obtained from Section 6.

Some of the catchments, as identified in Section 7.2.1, also incorporate a pervious area outside of the main urban area (for example, parks, rural areas, forest etc). Of the catchments examined so far, Giralang is the only catchment for which the schematisation shown in Figure 7-1 may not be suitable. Therefore, Equation 7.2 was used to determine if events were being selected with a contribution from the rural portion. The equation assumes zero continuing loss on the Other Area (ie. the UA – EIA term in Equation 7.2), and therefore only provides the minimum number of events with a contribution from the rural portion. This is because additional events may display runoff from the rural area when continuing losses from the other area are taken into account. The implications of this on the loss estimates are discussed in Section 9.6.

A summary of the parameters used for the identification of such events is shown in Table 7-1. Note that the maximum duration of the event was deliberately set quite high in the interest of identifying as many events as possible. A discussion of the variation of results with event duration is provided in Sections 9.1.1 and 9.2.1. Lastly, the direct runoff hydrograph was extracted by assuming a constant baseflow equal to the flow rate just before the start of runoff.

$$\text{Other Area event } if \ \mathrm{Q} \geq \frac{1.1 * \mathrm{EIA}}{\mathrm{TA}} * (\mathrm{P} - \mathrm{IL_{EIA}}) \tag{7.1}$$

$$\text{Pervious Only Contribution if } \forall_{\mathrm{obs}} > \ \mathrm{EIA} * 10 * (\mathrm{P} - \mathrm{IL_{EIA}}) + (\mathrm{UA} - \mathrm{EIA}) * 10 * (\mathrm{P} - \mathrm{IL_{OA}}) \tag{7.2}$$

Where Q = runoff depth (mm)
P = rainfall depth (mm)
EIA = Effective Impervious Area (ha), as determined from Section 6.
TA = Total Area (ha)
UA = Urban Area (ha)
IL_{EIA} = Initial Loss (mm) on the EIA, as determined from Section 6.
IL_{OA} = Initial Loss (mm) on the Other Area, as determined from Section 9.1.
$\forall_{obs}$ = Total runoff volume (m^3)

Table 7-1 Criteria adopted for identifying and filtering events for the losses analysis

	Parameter	Value Adopted	Units
Storm Selection	Minimum cumulative depth of storm	10	mm
	Maximum duration of storm	100	hours
	Storm selected if no rainfall in previous	5	hours
	End of storm is when there is no rainfall for the next	5	hour
Runoff Selection	Constant baseflow	(0-0.02)*	m^3/s
	Latest start time of runoff response	0.5	Hours after end of rainfall

**values adopted vary between catchments but are in this range.*

7.2.3. Estimation of Other Area Initial Loss

The regression analysis undertaken for the estimation of effective imperviousness provided a best – fit estimate of the initial loss on the EIA. This estimate was adopted for the historical storms selected in Section 7.2.2, together with zero continuing loss, which is reasonable for impervious surfaces. The remaining parameters to be estimated, for both the ILCL and ILPL loss models are thus:

- Other Area Initial Loss;
- Other Area Continuing Loss.

Preliminary calibration of these parameters to the selected storms indicated that there were several parameter combinations that would be suitable. An example of this is shown in Figure 7-2 for a storm event occurring in October 1976 in the Giralang catchment. Here the initial loss can vary between 0 and 25 mm depending on the continuing loss adopted. In order to reduce the parameter estimation uncertainty, an approach was devised to reduce the range of variability in the initial loss estimate (and by consequence, the continuing loss).This was a graphical analysis based on isolating the EIA runoff and Other Area runoff from the observed runoff hydrograph. A more detailed explanation of the methodology is provided below.

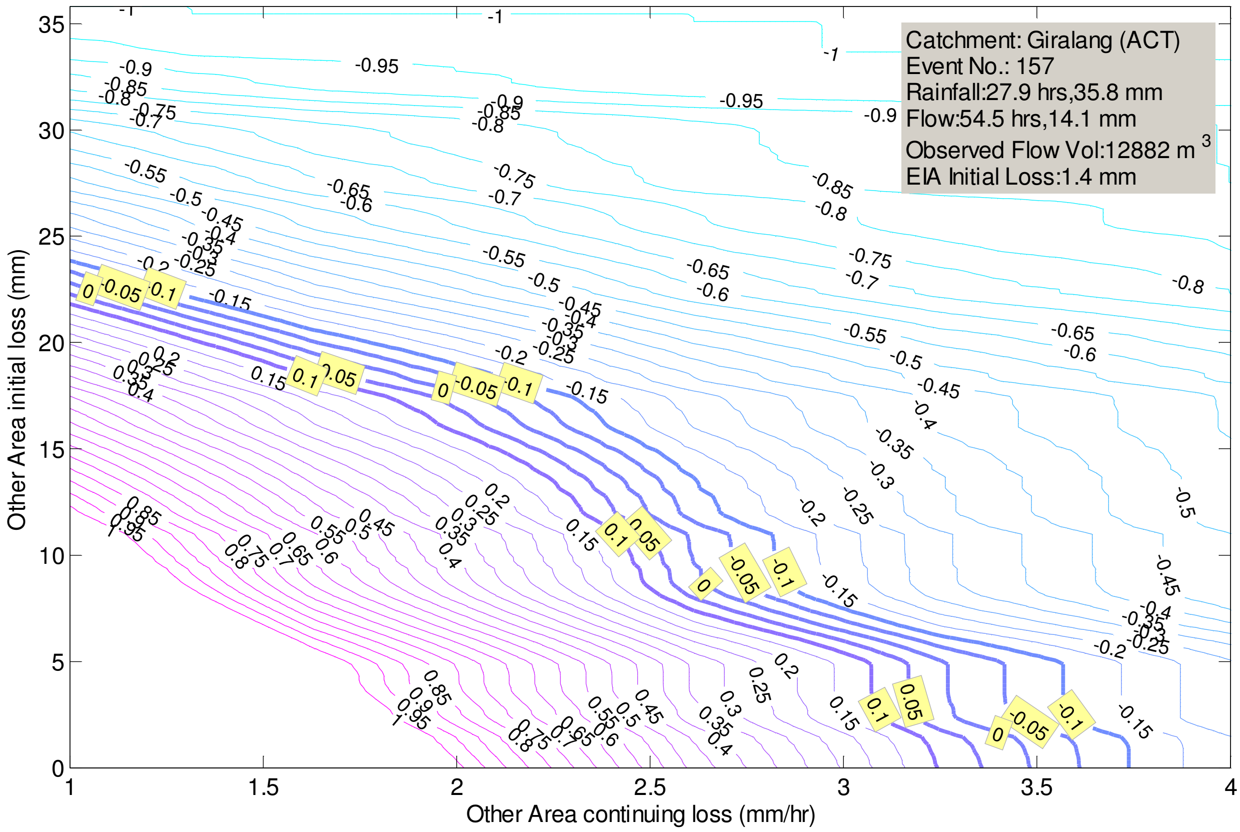


Figure 7-2 Error contours for different Initial Loss – Continuing Loss pairs for the Other Area. The Error is defined as (Simulated Runoff Volume – Observed Runoff Volume)/(Observed Runoff Volume – EIA Runoff Volume).

The Other Area runoff was determined by first estimating the time series of EIA runoff volume using Equation 7.3, assuming there is no spatial variation in rainfall.

$$\hat{r} = < r_1, r_2, \dots, r_n > \\ \text{where } r_i = \max(0, p_i - IL_{EIA}) \tag{7.3}$$

$$\hat{\forall}_{EIA} = EIA \text{ x } \hat{r} \tag{7.4}$$

Where $\hat{\forall}_{EIA} = < \forall_1, \forall_2, \dots, \forall_n >$ = Time series of cumulative volume of EIA runoff (in m^3)

$\hat{p} = < p_1, p_2, \dots, p_n >$ = Time series of cumulative rainfall depth (in m)

n = number of data points in rainfall time series.

IL_{EIA} = Best – fit estimate of initial loss on EIA, as given in Table 6-2 (in m)

EIA = Effective Impervious Area, as given in Table 6-2 (in m^2).

Catchment routing processes were approximated by simple translation of the cumulative volume time series ($\hat{\forall}_{\mathrm{EIA}}$). Specifically, the time series obtained from Equation 7.3 was shifted so that the start time coincided with the observed runoff hydrograph. This approach is reasonable so long as the catchment characteristics do not significantly affect the shape of the hydrograph, ie.:

- there are no major storages in the catchment (eg. detention and/or retarding basins);
- there is fairly uniform drainage density throughout the catchment for the effective impervious areas;
- fairly uniform slope throughout the catchment.

Figure 7-3 shows an example of the resulting cumulative runoff curves for the Giralang catchment. Runoff from the Other Area appears at the catchment outlet at approximately 3 am, the flow at the catchment outlet is entirely runoff from the EIA. The close correspondence between the observed runoff hydrograph and the calculated EIA runoff hydrograph until this time adds confidence to the EIA estimate given in Section 6.

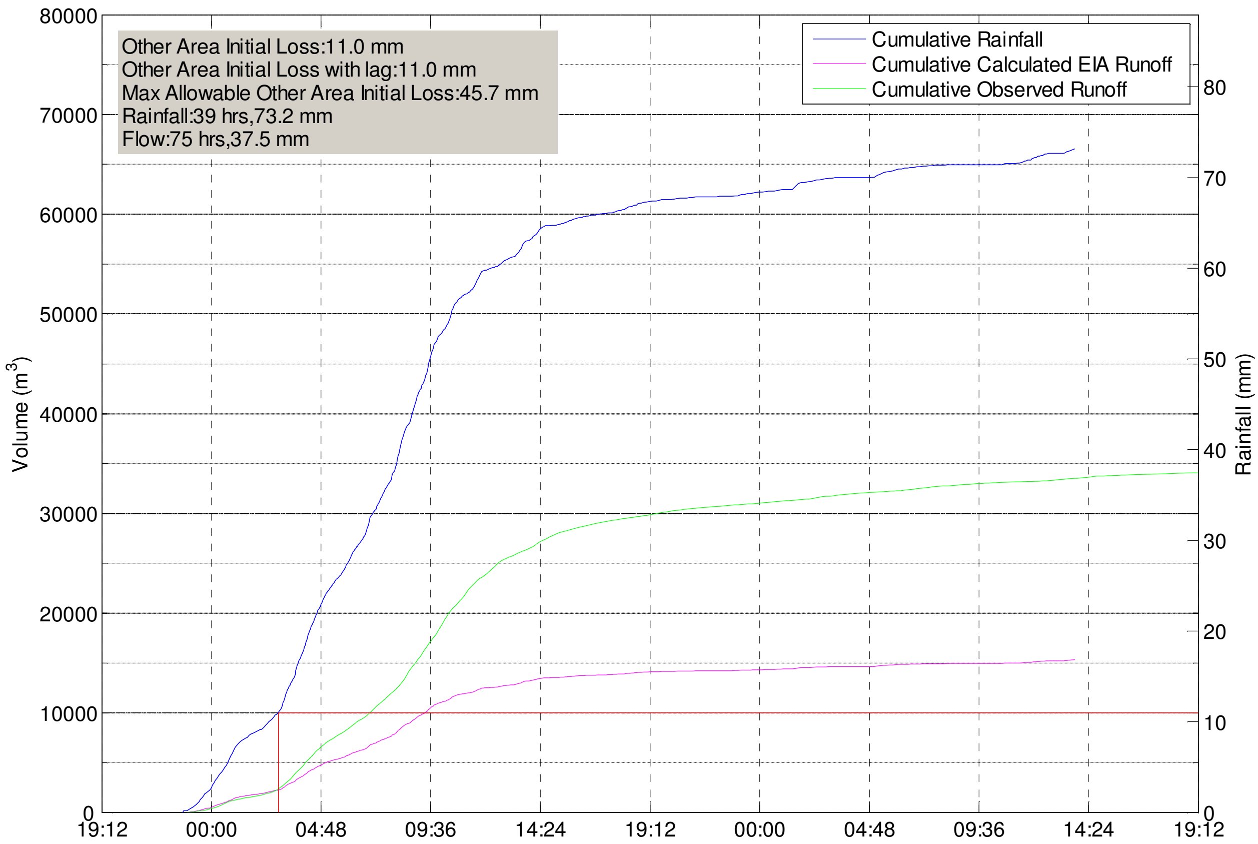


Figure 7-3 Example estimation of Other Area Initial Loss using cumulative volumes for an historical event in the Giralang Catchment.

The time where the observed runoff curve deviates above the EIA runoff curve was then used to estimate the other area initial loss, as shown in Equation 7.5. This estimate was accepted if it was less than the maximum allowable initial loss, which is the initial loss assuming zero continuing loss on the other area.

$$IL_{OA} = P_{t_d} \tag{7.5}$$

Where P_{t_d} = Cumulative rainfall depth at time t_d

$t_d = t_{OA} - l$

t_{OA} = time at which the cumulative observed runoff curve exceeds the cumulative calculated EIA runoff curve

l = hydrograph translation time (ie. Observed Runoff start time – Rainfall start time)

IL_{OA} = Initial Loss on Other Area

7.2.4. Estimation of Other Area Continuing Loss

Having determined a value of the other area initial loss, the continuing loss was estimated for each event as the optimum parameter which yields the lowest error, as defined in Equation 7.6.

$$\text{Error} = \frac{|\,Q_{\text{sim}} - Q_{\text{obs}}|}{Q_{\text{OA}}} = \frac{|\,Q_{\text{sim}} - Q_{\text{obs}}|}{Q_{\text{obs}} - Q_{\text{EIA}}} \tag{7.6}$$

Where Q_{EIA} = EIA runoff volume = (Total Rainfall Depth – IL_{EIA}) x EIA.

Q_{sim} = simulated runoff obtained from applying loss model to rainfall hyetograph

= Q_{EIA} + (Rainfall – Losses on Other Area) x OA

Q_{obs} = observed runoff volume

Q_{OA} = Other Area runoff volume = Q_{obs} – Q_{EIA}

7.2.5. Globally optimised Other Area Continuing Loss

It is noted that the methodology described above gives the optimal loss parameters for each individual historical event. This is advantageous in that it can be used to determine the potential variability in loss parameters, given that they are highly dependent on storm characteristics. In particular, the initial loss, which lumps together the contribution of interception, infiltration prior to saturation and depression storage is highly dependent on the catchment antecedent wetness state.

Therefore, it is expected that the initial loss can vary considerably between storms (for reasons discussed earlier). However, ideally it would be useful to have a continuing loss parameter that is able to be applied to a range of different storm events. To determine the suitability of doing this, a globally optimum continuing loss parameter which gives the best volumetric fit over all the identified events was estimated. For this, the initial losses derived for each event (as per Section 0) were used along with a single continuing loss parameter for all the events. The error (as defined in Equation 7.6) was determined for each of the events, and the continuing loss parameter which gave the minimum median error across all the events was taken as the optimum.

8. Identified Storm Events for Loss Models

8.1. Storm Event Selection

Storm events for the loss model testing were identified based on the methodology in Section 7.2.2. A summary of the storms identified are provided in Table 8-1.

Histograms were also prepared for each of the catchments, demonstrating the proportion of the volume of runoff represented by the other area (pervious & ICIA). These histograms are provided in Figure 8-1 to Figure 8-8.

While a number of events were identified in each catchment, a significant proportion of these events in most cases were less than 10mm. This is similar to the findings in Section 5.1, where this may be the result in errors in the gauge data, spatial variation in rainfall or intensity of the rainfall itself. These events were excluded from the analysis for the estimation of losses. Events were also excluded from the analysis due to the inability to locate a suitable Other Area Initial Loss using the graphical analysis. This was generally because this initial loss was greater than the maximum possible other area initial loss (ie. the initial loss assuming zero continuing loss on the other area).

One of the key challenges in the data set is the length of record and the number of significant events, in terms of other area runoff. Many of the catchments did not have many events that produced a significant volume of runoff when compared with the EIA runoff. It was determined that the following catchments were not suited to the analysis:

- Argyle Street (TAS), as identified previously, has a significant forested pervious area, which represents the majority of the catchment. Therefore, while there is a reasonable spread of storms identified, this catchment is not well suited to the analysis. Note also that this catchment is fairly large (1900 ha), which means that spatial variation in rainfall has the potential to impact on the estimated losses. Results from the analysis of this catchment have been provided nonetheless.

- Parra Hills (SA) – only a limited number of storms were identified. The number of storms was too small to provide any meaningful analysis of the losses.

- Kinkora Road (VIC) – further analysis of the data suggested some unusual behaviour, with periods of runoff with no rainfall and vice versa for the selected events. This catchment was therefore not included in any further analysis.

- Ithaca Creek (QLD) – this catchment, as identified previously, is similar to Argyle Street, and has a large forested area in the catchment that is connected to the drainage network. This is particularly problematic for this component of the analysis (as opposed to the EIA), as the runoff events analysed are larger and hence more influenced by the pervious area contribution. Similar to Kinkora Road (VIC), analysis of the rainfall and streamflow data showed several events with significant flows but no rainfall recorded at the gauge. This could potentially be because of spatial variation in rainfall, which is likely to be a considerable due to the size of the catchment (926 ha). Therefore, this catchment was not included in this analysis.

- McArthur Park (NT) – a large detention basin which drains a majority of the catchment is located just upstream of the flow gauge. Additionally, the flow gauge at the catchment outlet captures surface flows only, meaning that piped low flows are not accounted for. This may not be a significant issue for larger events in which surface flows dominate. These factors have the potential to influence:
  - the initial loss on the DCIA (obtained from Section 6), as the piped low flows are not captured by the flow gauge;
  - the Other Area initial loss, as the presence of the detention basin influences the timing of the flow hydrograph. The Other Area initial loss estimate is estimated based on the timing of the rainfall, estimated DCIA runoff and observed runoff; and
  - the Other Area continuing losses, due to the potential for infiltration within the basin as surface flows make their way to the catchment outlet via the basin.

Results from the analysis of this catchment have been provided nonetheless.

Table 8-1 Summary Statistics for Identified Storms

Catchment	No. of Events satisfying Criteria in Section 7.2	No. of Events > 20% of Runoff Volume from Other Area
Giralang (ACT)	111	82
Albany Drain (WA)	85	36
Argyle Street (TAS)	74	70
McArthur Park (NT)	104	96
Kinkora Rd (Vic)	79	44
Parra Hills (SA)	8	4
Powells Creek (NSW)	29	22
Ithaca Creek (QLD)	68	60

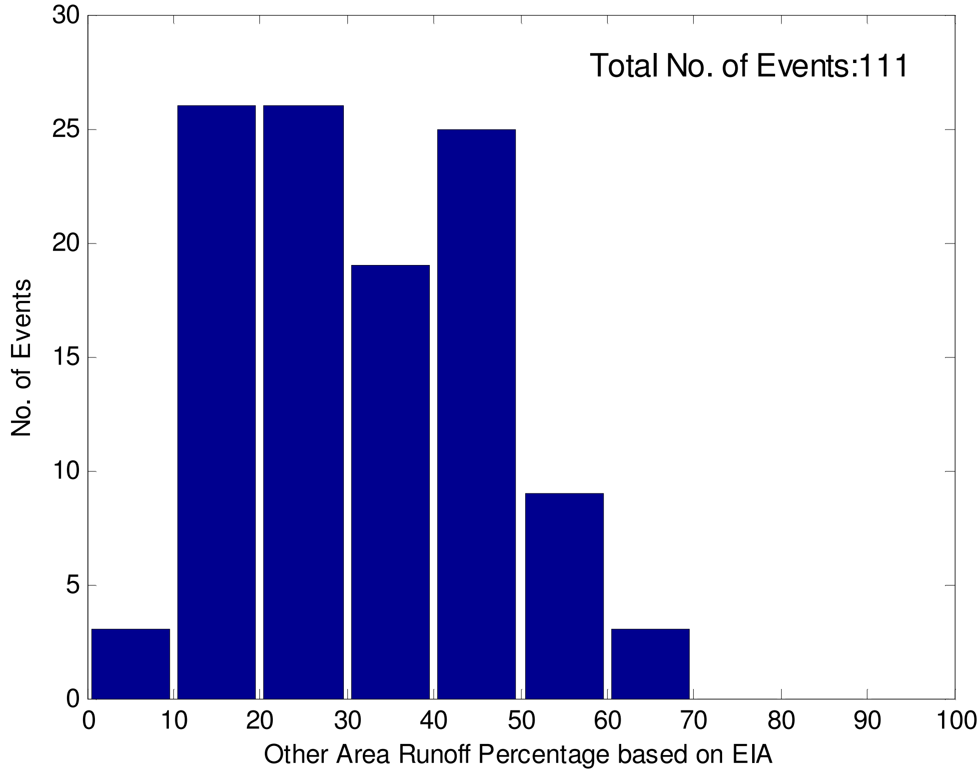


Figure 8-1. Giralang (ACT) - Histogram of Identified Storm Events – Volume of Runoff from Other Area relative to total runoff

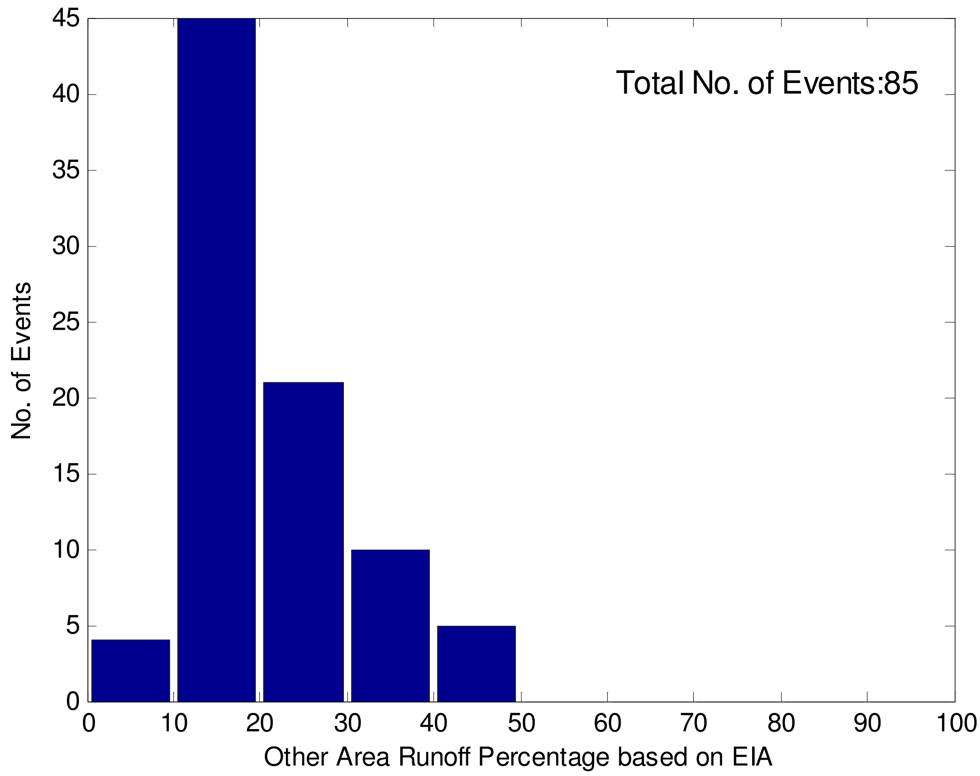


Figure 8-2. Albany Drain (WA) - Histogram of Identified Storm Events – Volume of Runoff from Other Area relative to total runoff

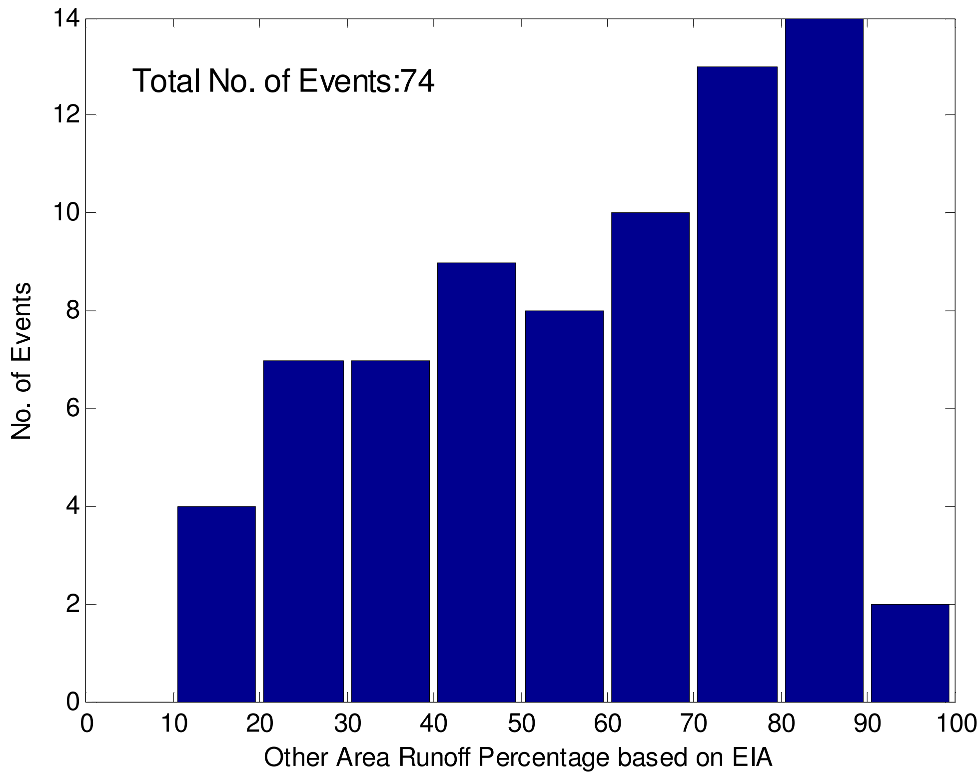


Figure 8-3. Argyle Street (TAS) - Histogram of Identified Storm Events – Volume of Runoff from Other Area relative to total runoff

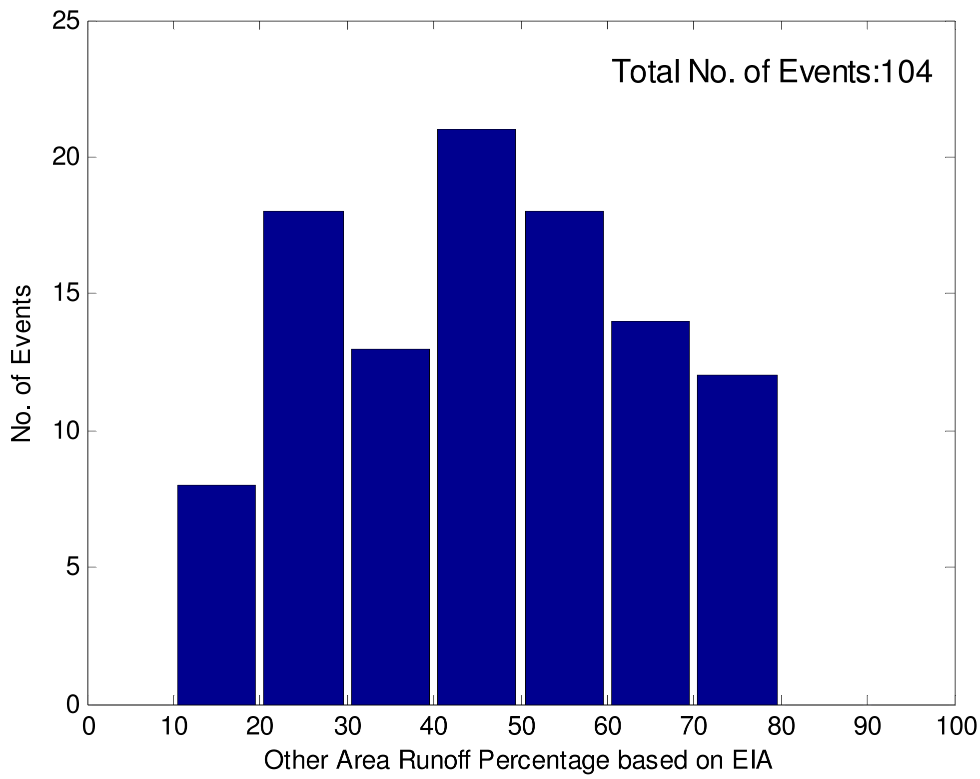


Figure 8-4. McArthur Park (NT) - Histogram of Identified Storm Events – Volume of Runoff from Other Area relative to total runoff

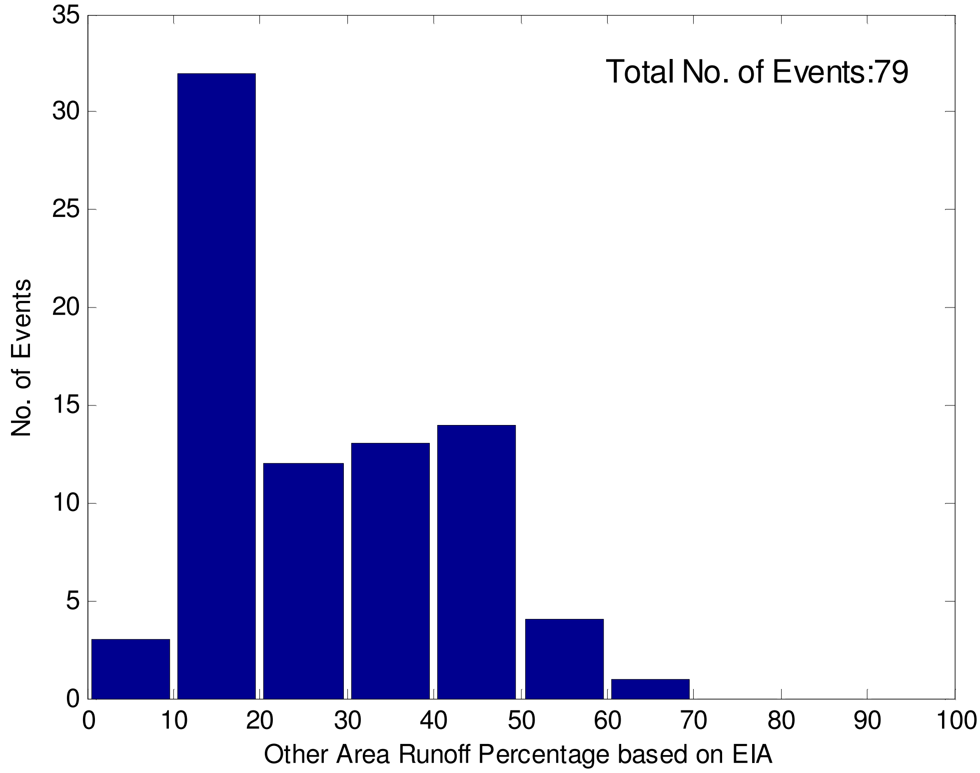


Figure 8-5. Kinkora Road (VIC) - Histogram of Identified Storm Events – Volume of Runoff from Other Area relative to total runoff

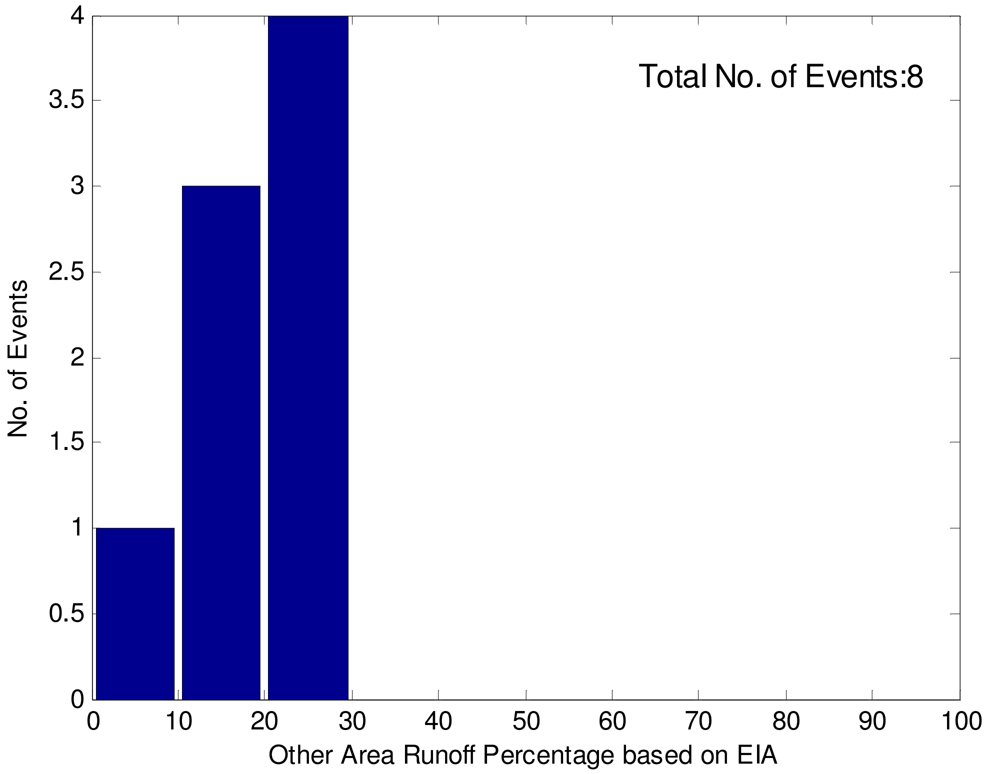


Figure 8-6. Parra Hills (SA) - Histogram of Identified Storm Events – Volume of Runoff from Other Area relative to total runoff

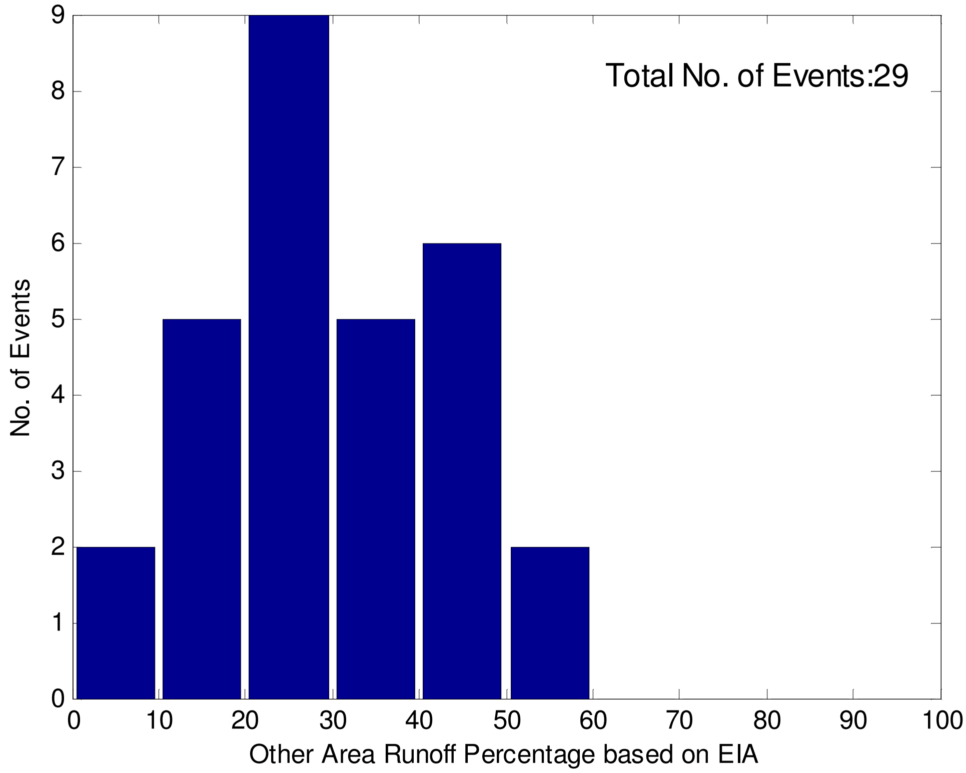


Figure 8-7. Powells Creek (NSW) - Histogram of Identified Storm Events – Volume of Runoff from Other Area relative to total runoff

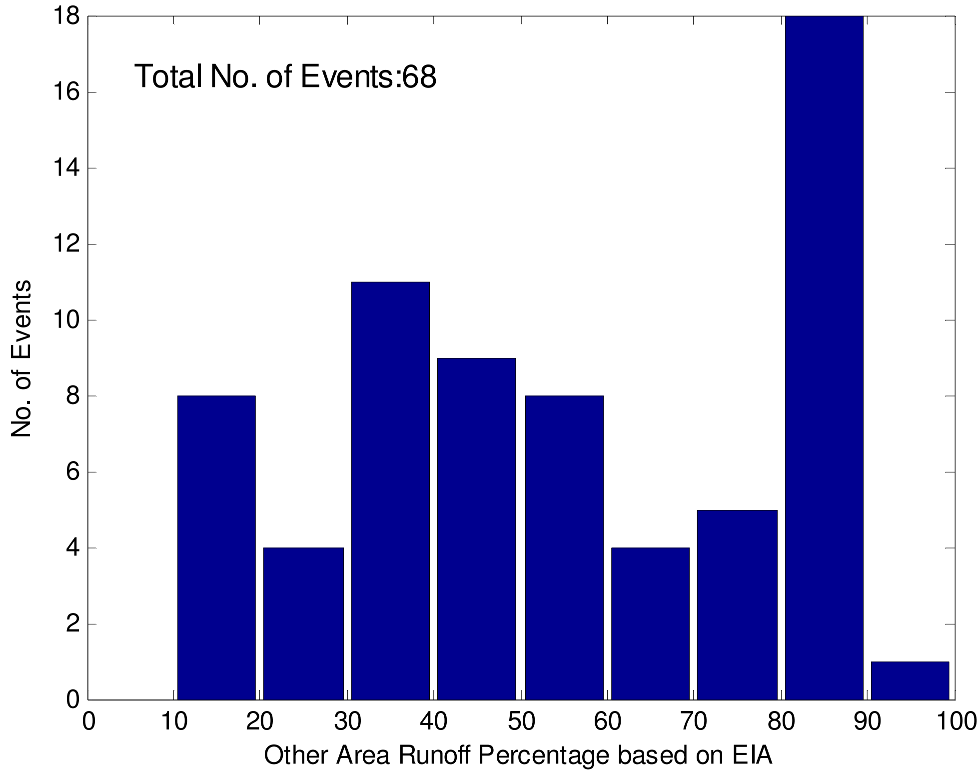


Figure 8-8. Ithaca Creek (QLD) - Histogram of Identified Storm Events – Volume of Runoff from Other Area relative to total runoff

8.1.1. Events Excluded

The filtering process discussed in Section 7.2.2 removed a number of events. Table 8-2 provides a summary of the number of events that were excluded at each of the steps in the filtering process. A review of the included and excluded flow events is provided in Section 8.3.

Table 8-2 Events Excluded

	Giralang (ACT)	Powells Creek (NSW)	Albany Drain (WA)	McArthur Park (NT)	Argyle St (TAS)
Number of events selected based on inter-event time (see Table 7-1) only	3591	1232	2207	2046	1144
Number of storms with rainfall depth < 10mm	2888	962	1958	1194	1004
Number of events longer than 100 hours	0	52	43	1	0
Number of storms where runoff started more than 30 minutes after the start of rainfall	1984	379	13	1678	99
Number of events where the flow volume exceeded the rainfall volume and/or the volume of the direct runoff is negative*	2274	736	924	1801	530
Remaining storms which satisfy all the criteria in Table 7-1	368	139	240	204	101
Number of storms satisfying the criteria in Table 7-1 with Other Area Runoff (based on Equation 7.1)	111	29	85	104	74
Final storms selected for further analysis, following a review of the flow behaviour and the ability to identify the Other Area Initial Loss. This included a manual review of the cumulative runoff volumes.	41	14	30	20	49

**negative direct runoff may result if the assumed constant baseflow is too high.*

8.2. Magnitude of Storm Events Identified – Rainfall Analysis

The approach provided in this report to identify losses is based on historical storm events. It is important to understand the magnitude, or relative frequency of these storm events, to understand over what conditions the loss estimates are relevant. This will be useful for any extrapolation of these loss estimates to less frequent design rainfall events.

An assessment was undertaken on the general magnitude of the storm events identified in the analysis. This was done by analysing the maximum 1 hour intensity over the period of the storm, where the 1 hour intensity is assumed to provide a rough reflection of the critical duration of each of the catchments. The results of this are provided in the histograms provided in Figure 8-9 to Figure 8-13.

An ARI of the storm events was also estimated from the rainfall data, based on the current IFDs from the current version of ARR for each of the catchments. Figure 8-14 shows the total number of storms that are 1 year ARI or greater based on the intensity. It is noted that Powells Creek had no storms selected based on the criteria greater than 1 year ARI, while the remaining catchments only had a small proportion of the storms identified with intensities greater than a 1 year ARI. Therefore, some caution needs to be adopted in interpreting the results of this analysis.

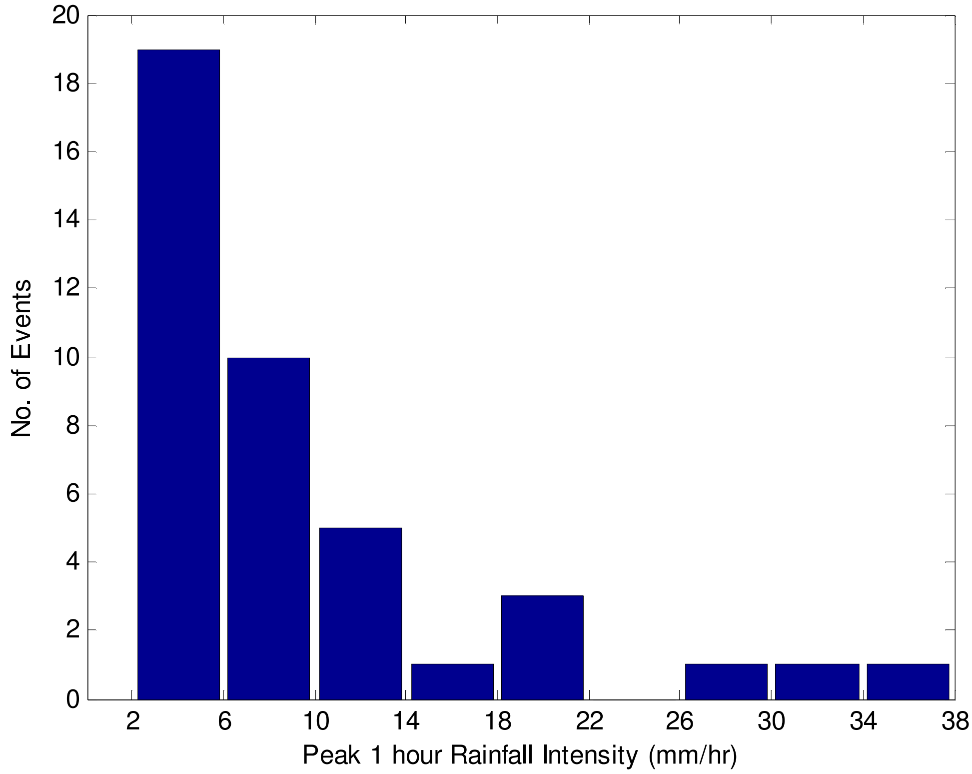


Figure 8-9. Giralang - 1 hour Rainfall Intensity Histogram

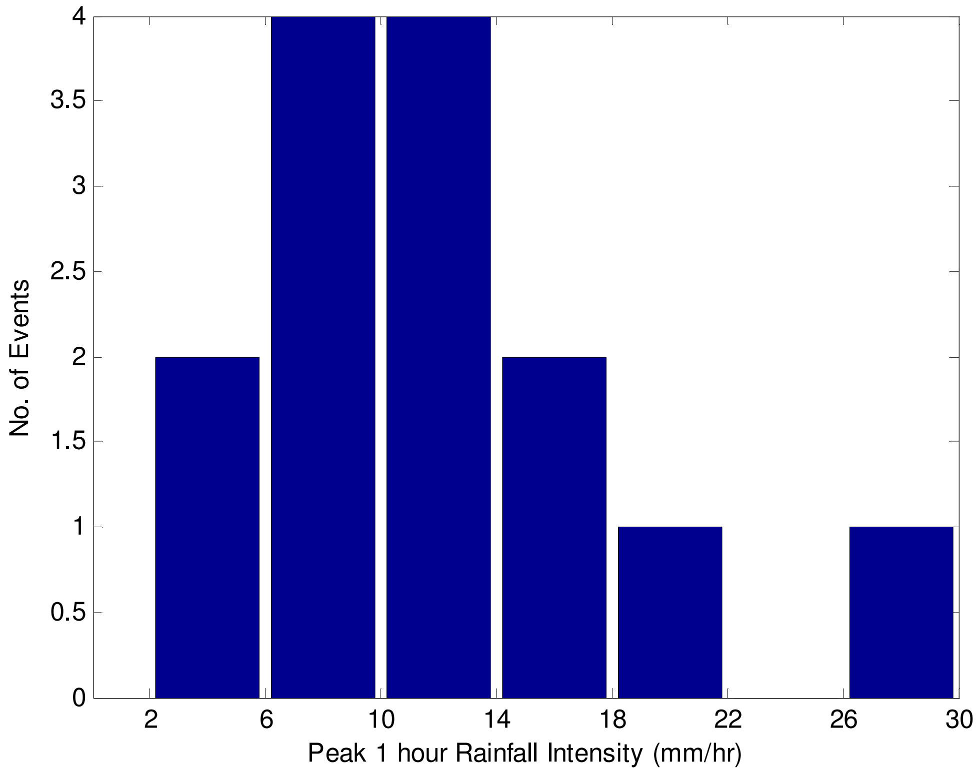


Figure 8-10. Powells Creek - 1 hour Rainfall Intensity Histogram

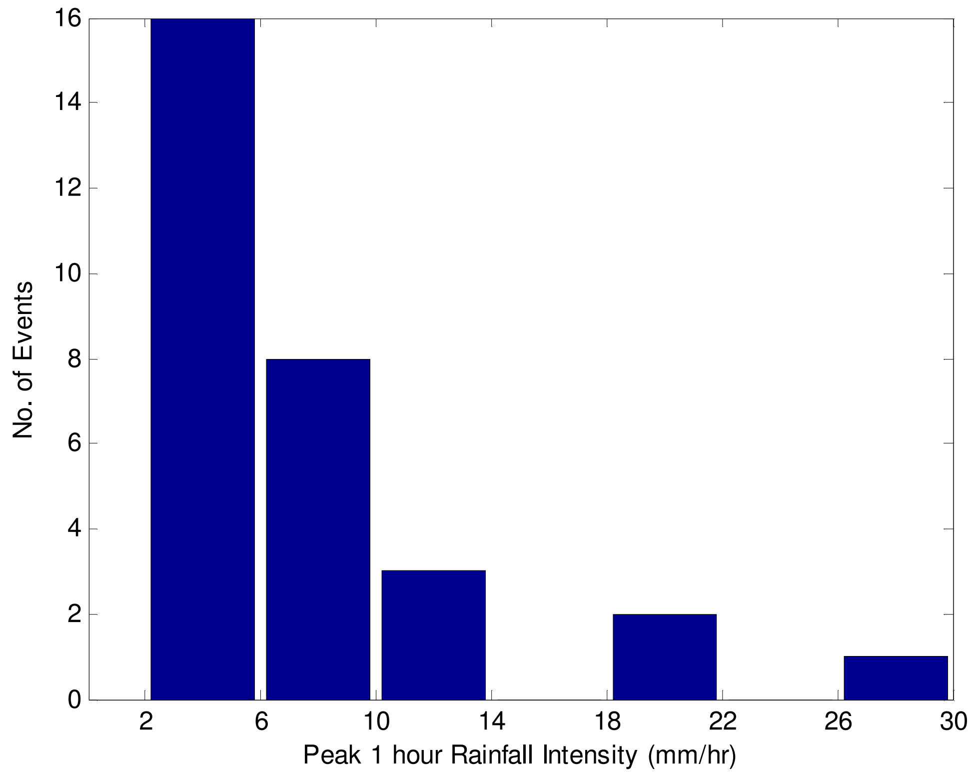


Figure 8-11. Albany Drain - 1 hour Rainfall Intensity Histogram

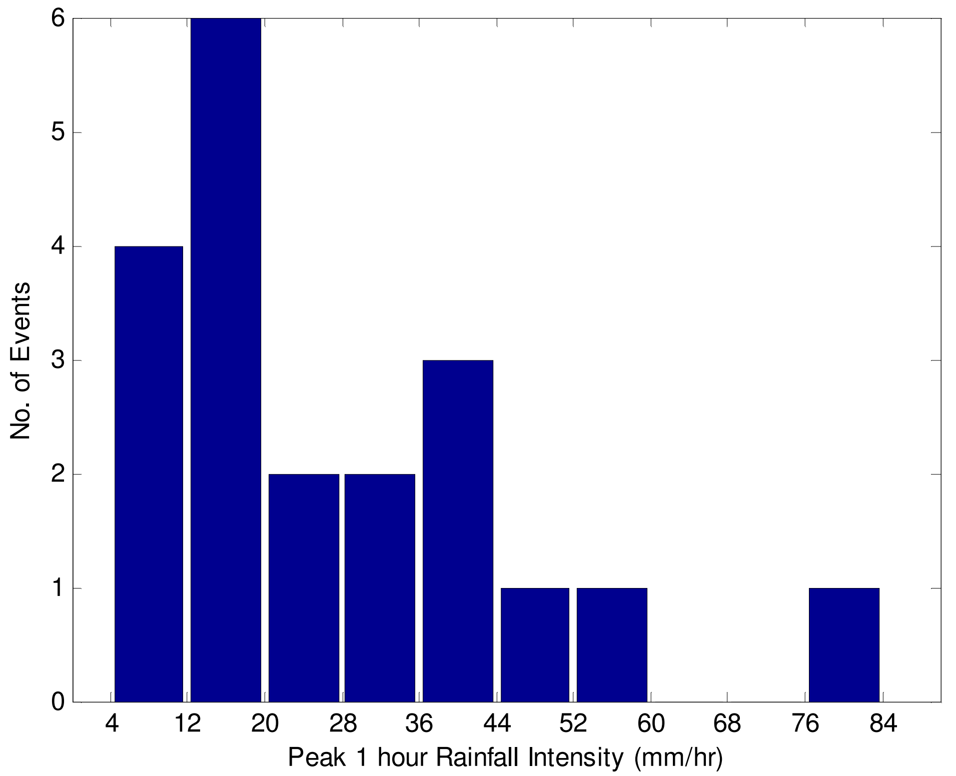


Figure 8-12. McArthur Park - 1 hour Rainfall Intensity Histogram

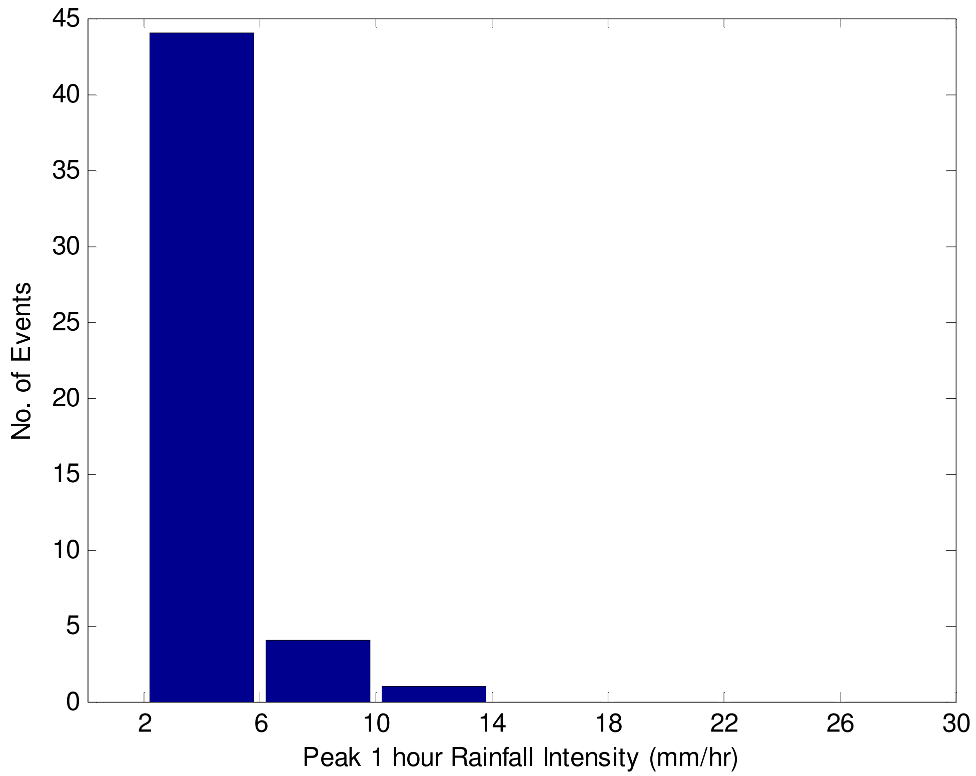


Figure 8-13. Argyle Street - 1 hour Rainfall Intensity Histogram

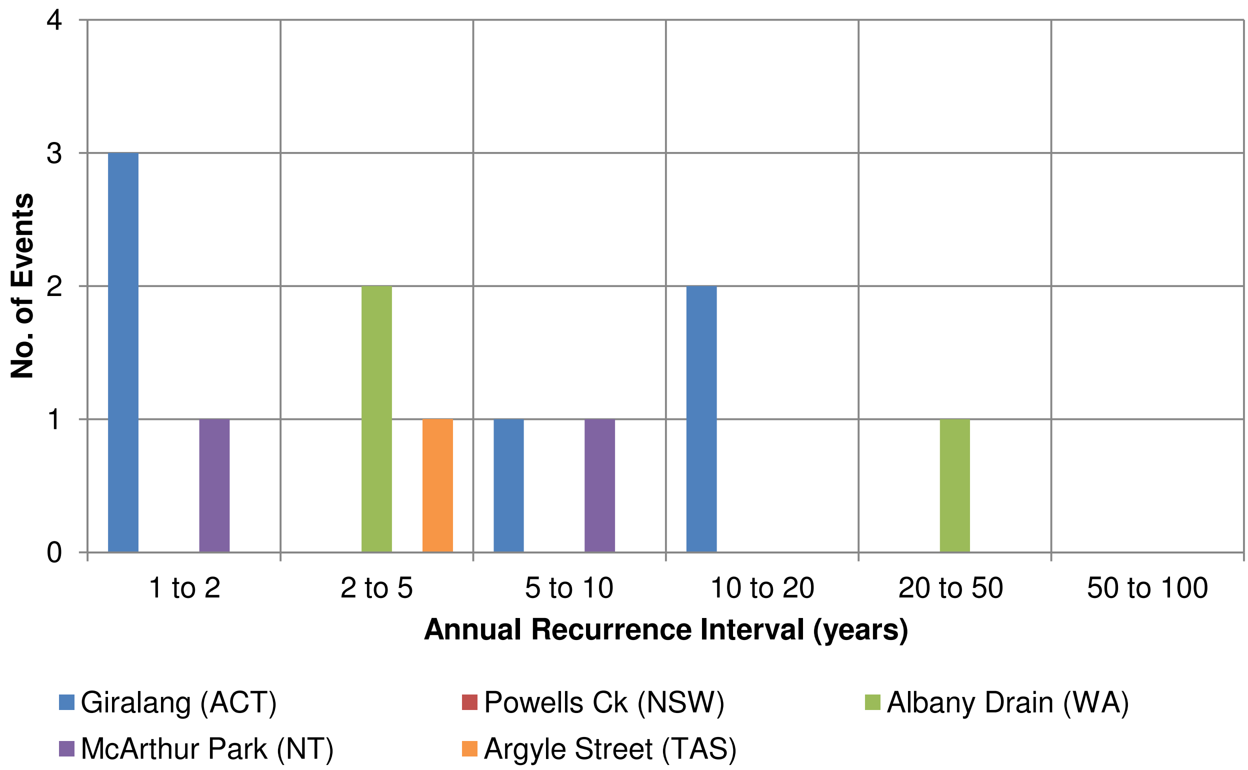


Figure 8-14 Identified Events versus Approximate IFD

8.3. Magnitude of Events – Flow Analysis

An alternative to analysing the rainfall data is to analyse the peak flows from the flow gauge. This provides a better representation of the magnitude of the events analysed, as the flow estimates include the effects of initial losses etc. throughout the catchment. Figure 8-15 to Figure 8-19 provides the time series of flows from the gauges. The following key information is provided in these figures:

- Events identified through the initial storm selection from Table 7-1 are shown in green;
- Events shortlisted for the loss analysis are identified in red, following the filtering identified in Section 7.2.2.

The key outcome of this analysis suggests that the filtering process has generally selected a good range across the data set of larger and smaller flow events. There are a number of events that have not been selected however, due to the criteria as identified in Table 8-2.

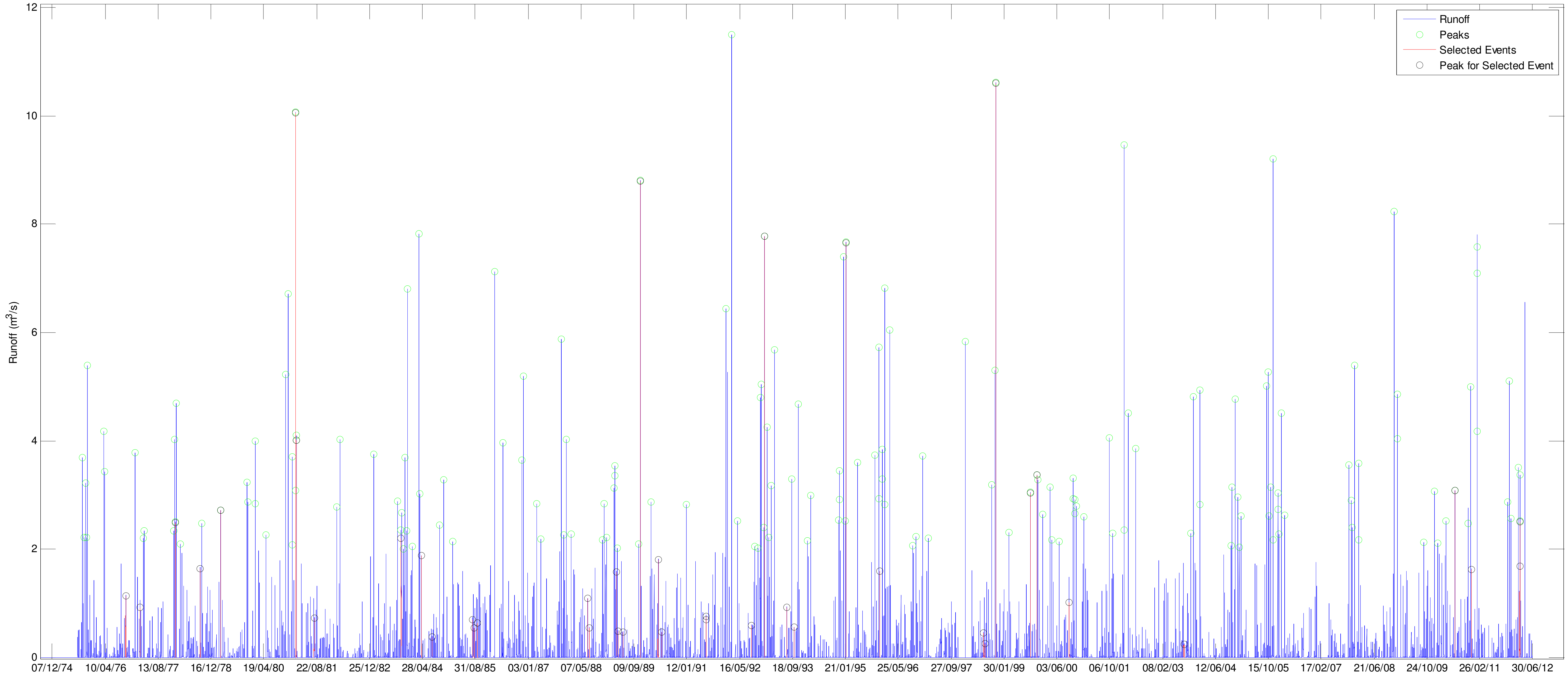


Figure 8-15. Giralang (ACT) - Summary of Flows and Events Selected

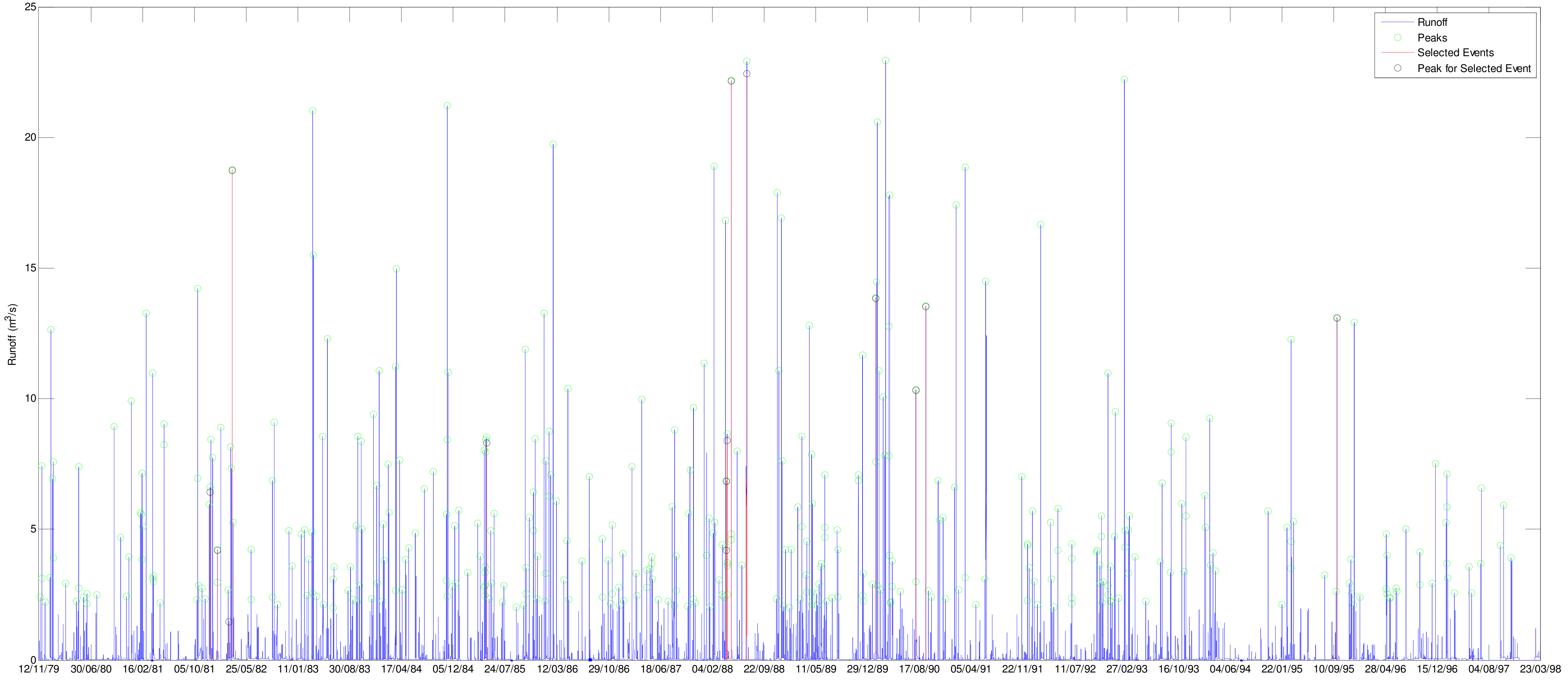


Figure 8-16. Powells Creek (NSW) - Summary of Flows and Events Selected

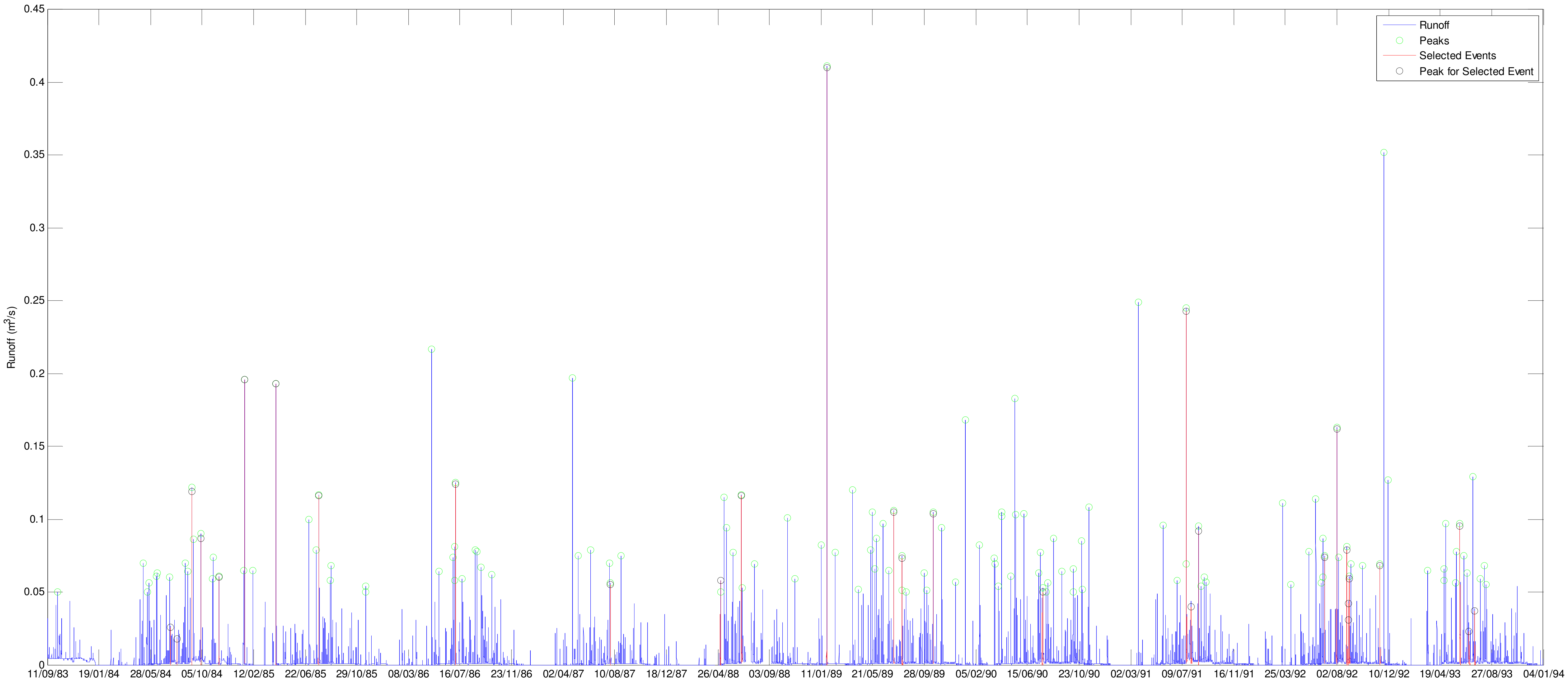


Figure 8-17. Albany Drain (WA) - Summary of Flows and Events Selected

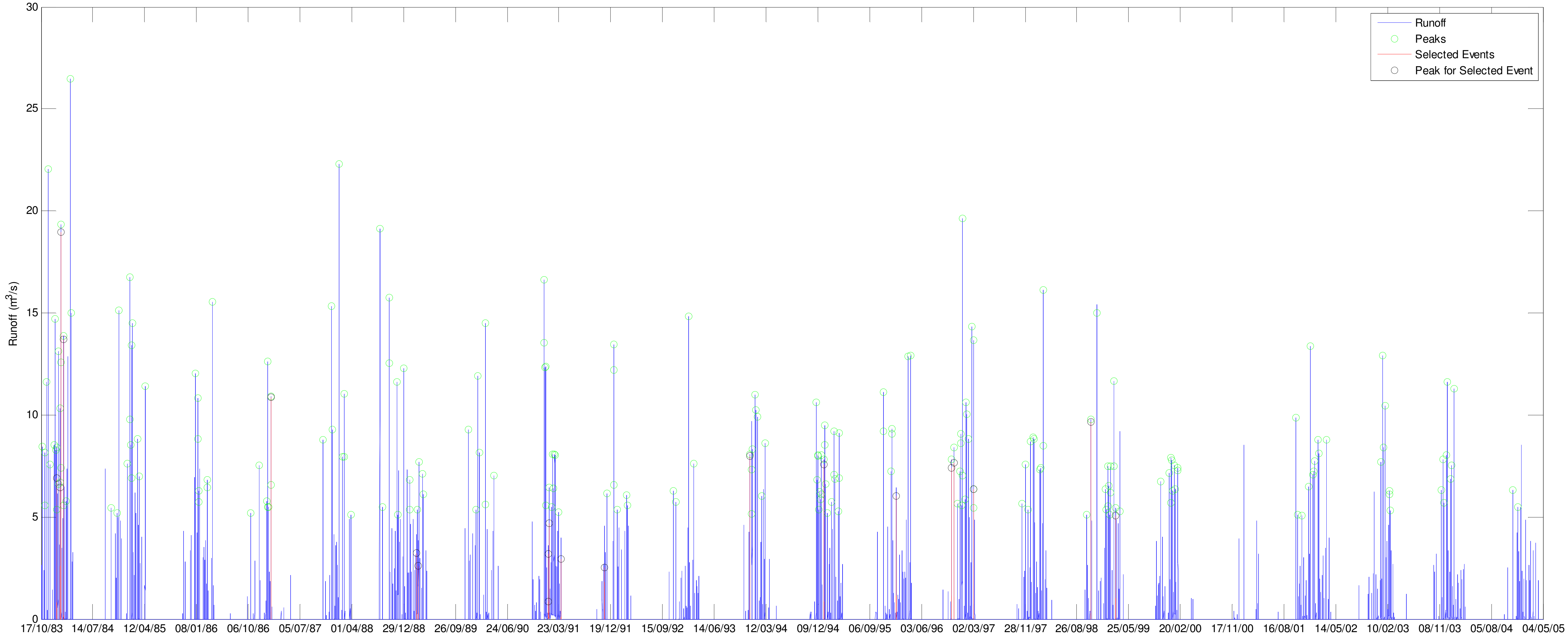


Figure 8-18. McArthur Park (NT) - Summary of Flows and Events Selected

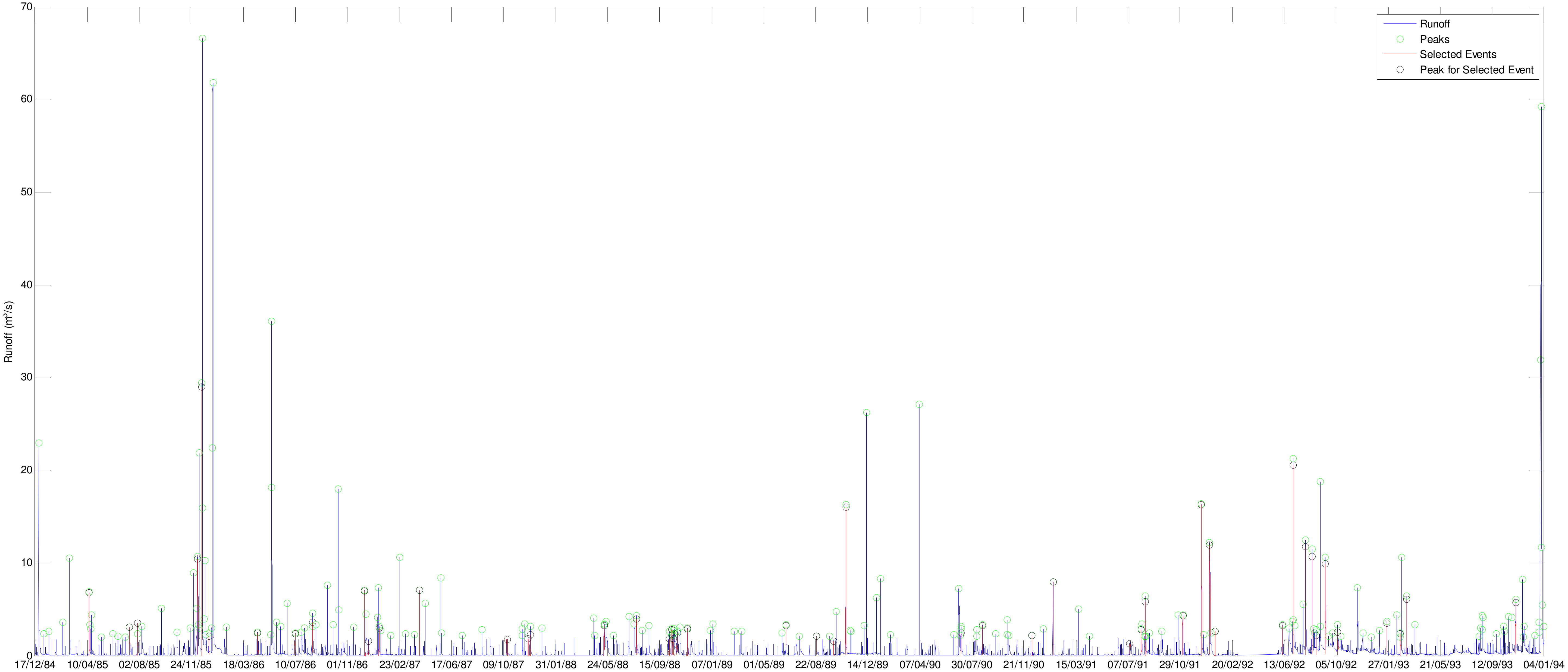


Figure 8-19. Argyle Street (TAS) - Summary of Flows and Events Selected

9. Other Area Loss Estimates

9.1. Initial Loss

Table 9-1 summarises the estimates of initial loss on the Other Area obtained across the study catchments using the method outlined in Section 0. Figure 9-1 provides a box plot of the initial losses derived from the analysis.

The initial loss estimates are generally in the range of 20 to 30mm, and would appear fairly consistent across most of the catchments. An exception to this is the Argyle Street (TAS) catchment, which gives estimates which are considerably lower than the others (approximately 50% lower). As noted in Section 8.1, this catchment is not well suited to the analysis, because of the size of the catchment and the presence of a large forested area. The lower initial loss estimates could be due to the impacts of spatially varying rainfall, and/or because baseflows, snowmelt or runoff from the upper reaches of the catchment (ie. forested area) from previous events are being mistakenly characterised as DCIA runoff. The estimates from this catchment are therefore not reliable.

Although the mean initial loss estimates across the catchments are generally similar, there is significant variation in the initial losses for different storms. This variation would be attributed to a number of factors, including the size of the rainfall event, antecedent rainfall, duration of the rainfall event etc. An analysis of the correlation of the initial loss with some of these parameters is provided in Section 9.1.2.

This variation represents a challenge in applying a suitable initial loss to design rainfall events, as opposed to historical rainfall events as have been analysed in this assessment. The actual initial loss adopted for design storm events may depend on the embedded storm method that is likely to be adopted for ARR, and the level of preceding rainfall prior to the main rainfall burst.

Powells Creek (NSW) shows the greatest variation in the estimates. Figure 9-1 suggests a wide spread of initial loss estimates for Powells Creek, with the majority of estimates between 15 and 45mm.

For Giralang and Albany Drain, there is a more clear distribution of initial loss estimates. For Giralang, around 65% of the estimates are within 10 to 30mm of initial loss. For Albany Drain, around 55% of the data set is within a 10 to 30mm range.

As noted in Section 0, in order to maximise the number of storm events identified, a longer duration filter was adopted. In the three catchments identified, the maximum storm duration extends from approximately 57 hours for Giralang (ACT) up to 75 hours for Albany Drain (WA) (a summary of the different durations is provided in Table 9-2. These durations would seem excessive, particularly when it would be expected that the three catchments have a critical duration of no more than 1 or 2 hours. However, it is noted that for the majority of these longer duration storm events, they are characterised by one or two storm bursts within a longer rainfall event. Without a way to adequately separate out these storm bursts without impacting on the estimate of the initial loss, the overall rainfall event was included.

These longer duration rainfall events may result in a higher initial loss estimate, particularly in situations where there may be longer periods of low rainfall, and evaporation and infiltration may result in increases. Therefore, a sensitivity analysis has been undertaken on the influence of the duration of the storm on the initial loss estimate. This is provided in Section 9.1.1.

Table 9-1 Summary Statistics for Initial Loss Estimates

Catchment	No. of Storms	Rainfall Depth Range (mm)	Rainfall Duration Range (hrs)	Mean OA Initial Loss (mm)	Median OA Initial Loss (mm)	Standard Deviation OA Initial Loss (mm)
Giralang (ACT)	41	12 to 130	1.4 to 56.9	20.4	17.0	11.9
Powells Creek (NSW)	14	14 to 394	11.8 to 63.4	27.8	24.5	19.4
Albany Drain (WA)	30	11 to 124	5.0 to 74.6	20.7	18.0	12.3
McArthur Park (NT)	20	14 to 109	1.3 to 29.8	24.2	18.9	17.8
Argyle Street (TAS)	49	10 to 51	5.8 to 43.8	8.5	7.9	7.3

Table 9-2 Distribution of event durations for storms used in the losses analysis

	No. of Events with duration:					
Catchment	**0 - 5hrs**	**5 – 10hrs**	**10 – 20 hrs**	**20 – 30 hrs**	**30 – 40 hrs**	**> 40 hrs**
Giralang (ACT)	2	9	8	10	7	5
PowellsCk (NSW)	0	0	4	4	3	3
Albany Drain (WA)	0	2	8	8	7	5
McArthur Park (NT)	10	5	3	2	0	0
Argyle Street (TAS)	0	7	19	11	10	2

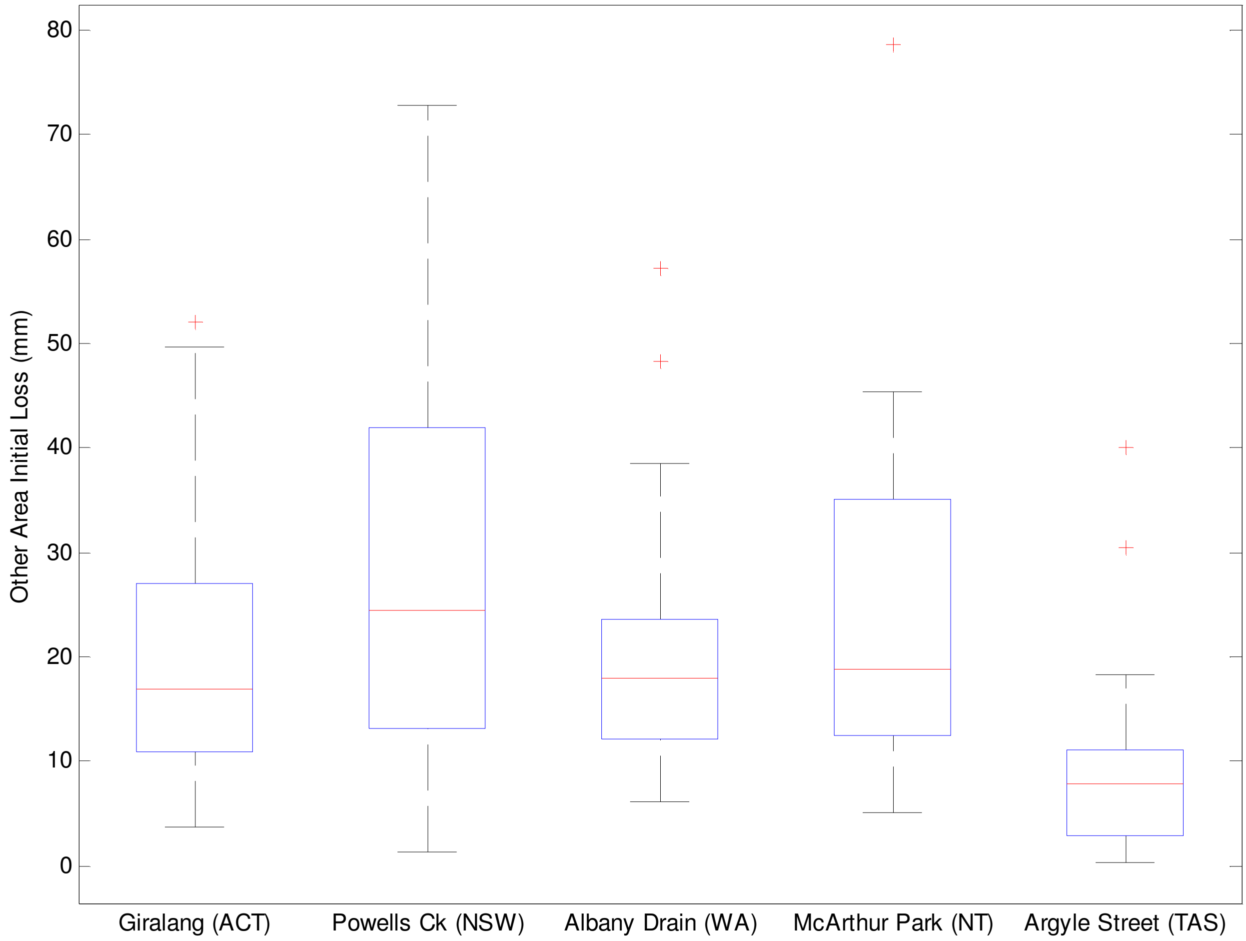


Figure 9-1 Boxplot of Other Area Initial Loss Estimates (Giralang: n = 41, PowellsCk: n = 14, Albany: n=30, McArthur Park: n = 20, Argyle Street: n = 49)

9.1.1. Sensitivity Analysis

In order to assess the impact of the duration of the storms identified on the initial loss, a sensitivity analysis was undertaken by varying the upper limit of the storm events chosen. Table 9-3 provides a summary of the results for storms less than 24 hours in duration. When compared with the results in Table 9-1, it is noted that the number of storms are nearly halved, which in itself would influence the overall results (with the exception of McArthur Park where there was only one storm with duration in excess of 24 hours). However, the general trend would appear to be a reduction in the initial loss estimated. As noted above, this may be the influence of a long duration of low rainfall prior to a rainfall burst, which would be influenced by a number of factors such as evaporation and infiltration.

Table 9-3 Summary Statistics for Initial Loss Estimates with a 24 hour duration restriction on storm events

Catchment	No. of Storms	Rainfall Depth Range (mm)	Mean OA Initial Loss (mm)	Median OA Initial Loss (mm)	Standard Deviation OA Initial Loss (mm)
Giralang (ACT)	19	12 to 76	18.6	16.6	9.7
Powells Creek (NSW)	8	14 to 95	17.1	17.5	9.5
Albany Drain (WA)	14	11 to 36	15.8	16.8	7.4
McArthur Park (NT)	19	14 to 89	24.4	18.8	18.3
Argyle Street	28	10 to 44	8.8	8.9	6.2

9.1.2. Correlation Analysis

Understanding the variation in initial loss, and whether this can be related to specific parameters, is important in being able to provide guidance for future application of urban loss models. A number of correlations were undertaken on the initial loss with other potential parameters and these results are provided in Appendix D. The results are summarised below:

- Antecedent rainfall - It generally might be expected that there would be a correlation between antecedent rainfall and the initial loss that is applied for the model. This is because antecedent rainfall is likely to soak or take up some of the initial loss prior to the storm event. It is clear from this scatter plots that there is no clear correlation between the two parameters. This may be in part a factor of the storm selection process that was adopted. It is also likely that the behaviour of the initial loss is more complex than simply being related to antecedent rainfall alone.

- Average rainfall intensity – there is no clear correlation between the other area initial loss and the average rainfall intensity prior to the commencement of Other Area runoff for most of the catchments.

- Largest 1 hour Rainfall Intensity – a correlation analysis was undertaken between the initial loss estimate and the largest 1 hour intensity of rainfall prior to the commencement of Other Area runoff. While there is only a loose correlation for Giralang, both Powells Creek and Albany Drain both show a higher correlation than between the average intensity of rainfall prior to other area runoff and the initial loss. Both McArthur Park and Argyle St display a weak positive relationship between initial losses and rainfall intensity prior to other area runoff. This applies to both the peak 1 hour rainfall intensity and average rainfall intensity, as unlike the other catchments, these storm events are generally characterised by a more uniform temporal pattern.

- Duration of Rainfall – due to the selection criteria adopted, it is possible that a number of the storms may have a long period of low level rainfall, which might result in a higher initial loss. It is clear that there is no distinct relationship between the two parameters. A similar result occurs when looking at the duration of rainfall prior to the commencement of runoff from the Other Area (refer Appendix D).

The overall outcome is that the only correlation appears to be between the largest 1 hour rainfall intensity prior to the other area runoff, and the initial loss. Note however that the Other Area Initial Loss is equal to the total depth of rainfall prior to the start of Other Area runoff. The correlation between the largest 1 hour rainfall intensity prior to other area runoff is a consequence of this, with the catchments showing this correlation having events with a majority of their rainfall prior to the start of other area runoff occurring in an approximately 1 hour period.

9.2. Constant Continuing Loss

As described in Section 7.2.4, the continuing loss was estimated based on the initial losses derived in Section 9.1. The results of this analysis are provided in Table 9-4, while box plots of the continuing loss estimates for each of the catchments are provided in Figure 9-2.

It is noted that there is a large difference between the median and mean value. It would be recommended that the median is adopted, as the mean is influenced by high individual values (refer to Figure 9-2).

The median values determined for both Giralang and Powells Creek are relatively similar, in the order of 2.5mm/hr. As identified in Table 9-5, the majority of the estimates for both of these catchments lie between 0 to 4mm/hr, with a large proportion in the 0 to 2mm/hr range. However, Albany Drain, which is in Western Australia, has a higher continuing loss which may be influenced by the soil types in that area. The estimates for McArthur Park are also higher, and also have the most variation of all the catchments. However, it is difficult to determine if these results represent any physical characteristics of the catchment, as there are several issues which make this catchment unsuitable for analysis (as noted in Section 8.1). Argyle Street (TAS) has considerably lower continuing loss estimates than the other catchments, a phenomenon that was also noted for the initial loss. The estimates from this catchment are not reliable, for reasons outlined in Section 9.1.

As with the initial loss, the continuing loss may be influenced by the length of storm that was chosen in the analysis. A sensitivity analysis on the influence of the storm duration on the analysis is provided in Section 9.2.1.

There are a few events identified where the continuing loss is very high (greater than 10mm/hr and up to 36mm/hr in the case of Giralang). A review of some of this data suggests that these estimators fit the cumulative volume of the storm reasonably well. However, these outliers may be the result of other factors such as spatially varying rainfall.

Table 9-4 also shows that the globally optimised parameters are slightly lower than the median parameters when optimising the events individually. However, Figure 9-3 shows that there are a range of parameters which give similar median error values for all of the catchments except Powells Creek (roughly 0.5 – 3.5 mm/hr for Giralang and 0 – 4 mm/hr for Albany).The median error when optimising globally is considerably greater than when optimising for each event individually. This is because the loss model provides a good fit (from a volumetric perspective) when different parameters can be selected for each event, but is more difficult to ensure lower error when a single loss value is adopted for different types of events.

Powells Creek has a low optimised value, with a relatively low median error. It is possible that Powells Creek other areas losses may be lower due to the higher imperviousness of this other area in Powells (compared with Giralang for example, which has a much higher pervious area). However, it is difficult to say this for certain based on the available data.

Table 9-4 Summary Statistics for Constant Continuing Loss Estimates

	Individual Event Optimisation				Global Optimisation	
Catchment	**Median CL_{OA} (mm/hr)**	**Mean CL_{OA} (mm/hr)**	**Standard Deviation CL_{OA} (mm/hr)**	**Median Error**	**Globally Optimised CL_{OA} (mm/hr)**	**Median Error**
Giralang (ACT)	2.5	4.6	6.9	0.8%	1.4	39.3%
Powells Creek (NSW)	2.6	4.1	4.8	0.5%	1.0	13.7%
Albany Drain (WA)	3.8	4.8	4.9	0.7%	2.3	64.3%
McArthur Park (NT)	5.1	8.0	8.4	0.8%	0.8	29.4%
Argyle Street (TAS)	1.4	1.8	1.8	0.4%	0.5	33.0%

Table 9-5 Summary Statistics for Constant Continuing Loss Estimates

	Percentage of Storms	
Catchment	**0-2 mm/hr**	**0- 4 mm/hr**
Giralang (ACT)	44%	73%
Powells Creek (NSW)	50%	71%
Albany Drain (WA)	33%	53%
McArthur Park (NT)	40%	50%
Argyle Street (TAS)	69%	88%

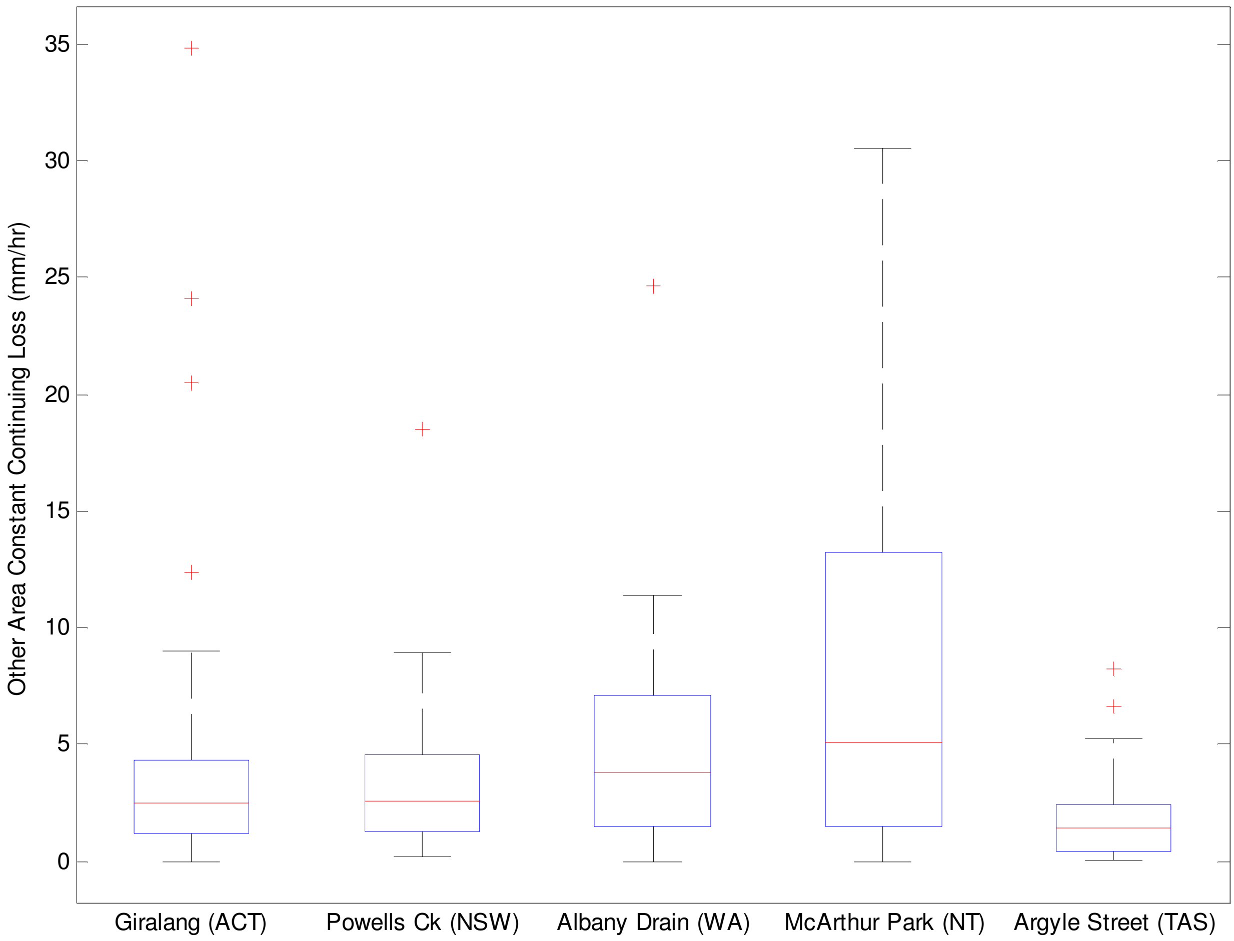


Figure 9-2 Boxplot of Other Area Constant Continuing Loss (Giralang: n = 41, Powells Ck: n = 14, Albany: n=30, McArthur Park: n = 20, Argyle Street: n = 49)

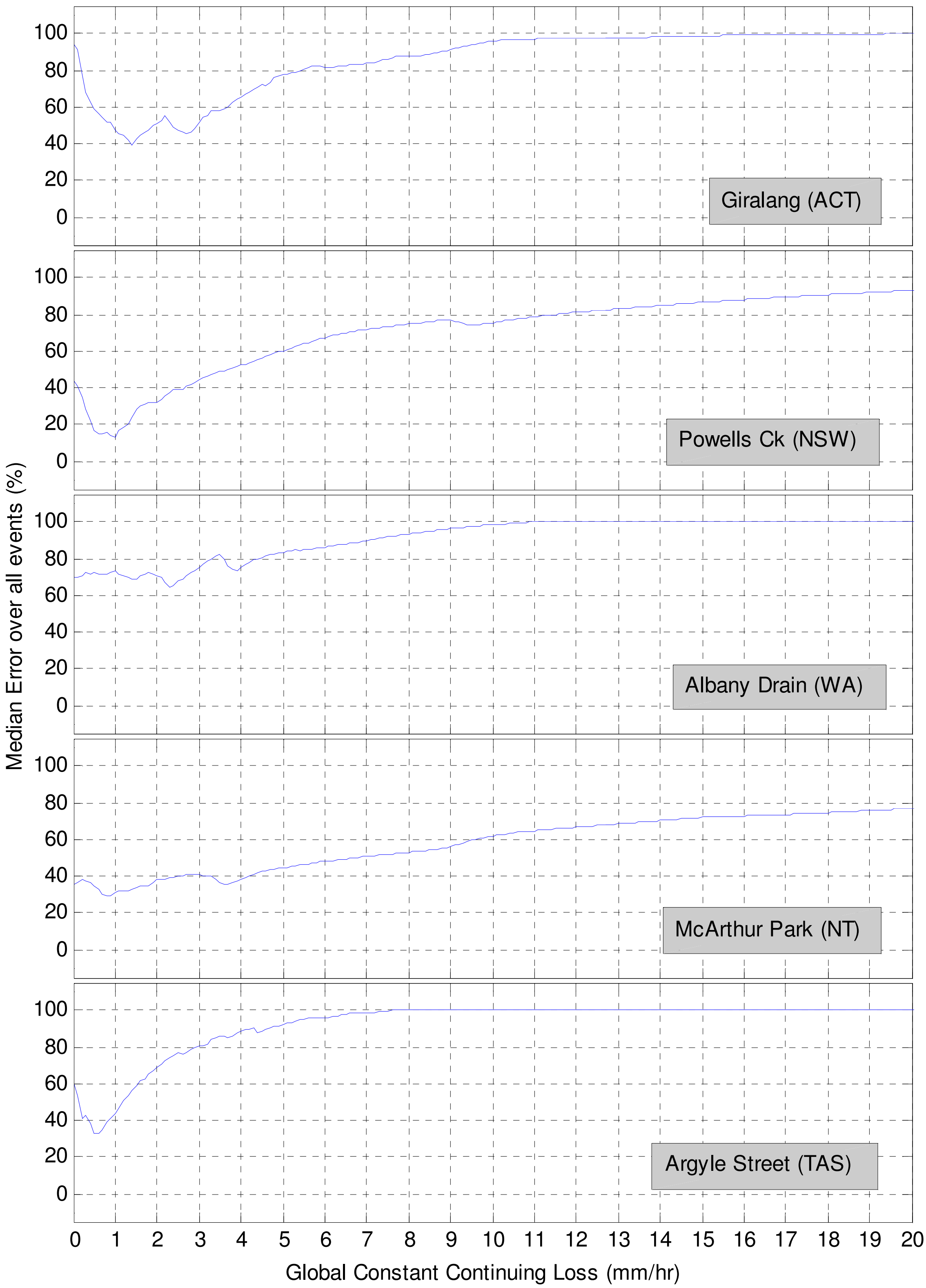


Figure 9-3 Median Error when optimising over all events for the range of Constant Continuing Loss Values

9.2.1. Sensitivity Analysis

Storm duration has the potential to influence the outcomes of the continuing loss estimates. For longer storm durations, there is the potential to have drier periods, which may result in some drying out of the soils and hence a potential increase in the continuing loss in the next burst of rainfall. Therefore, a sensitivity analysis was undertaken on the influence of reducing the storm filter to 24 hours. A summary of the results are provided in Table 9-6.

Both the estimates for Giralang and Powells Creek remain fairly consistent, and therefore may not be influenced significantly by the storm duration chosen.

Albany Drain (WA) reduces quite significantly, from 3.8mm/hr previously to 1.5mm/hr when the duration is shortened. This may be the influence of the soil types experienced in Western Australia, which are likely to be sandy soils and hence the infiltration is likely to be higher. The level of infiltration would likely be influenced more strongly by the storm duration, particularly if there are any drier periods during the overall storm duration.

McArthur Park (NT) also reduces considerably, from 5.1 mm/hr previously to 3.4 mm/hr when the duration is shortened. Similar to Albany Drain, the loss estimates are likely to be sensitive to the storm duration due to the potential for infiltration as catchment flows pass through the detention basin prior to reaching the gauge. Longer duration storms with dry periods within them have the potential to render higher continuing losses. This is because dry periods allow infiltration to occur in the basin at unsaturated antecedent moisture conditions for the following rainfall burst.

Table 9-6 Summary Statistics for Constant Continuing Loss Estimates with a 24 hour duration restriction on storm events

		Individual Event Optimisation			
Catchment	**No. of Storms**	**Median CL_{OA} (mm/hr)**	**Mean CL_{OA} (mm/hr)**	**Standard Deviation CL_{OA} (mm/hr)**	**Median Error**
Giralang (ACT)	19	2.2	5.4	6.8	0.6%
Powells Creek (NSW)	8	2.4	3.4	3.0	0.5%
Albany Drain (WA)	14	1.5	2.6	2.8	0.5%
McArthur Park (NT)	19	3.4	7.7	8.5	0.8%
Argyle Street (TAS)	28	1.6	2.0	2.0	0.5%

9.2.2. Relationship between Initial and Continuing Loss

The methodology adopted for estimating the losses first locks in an initial loss (as identified in Section 8.1) and then determines the appropriate continuing loss for the storm (either for individual storms, or globally over all storms). However, as noted previously, there are numerous potential solutions for the analysis.

The range of potential solutions for the analysis is presented in Figure 9-4 to Figure 9-8. In these figures, the individual lines correspond to initial and continuing loss solutions for specific events, where the mean error is 0. The red portion of the line lies within a +/-5mm range of the estimated initial loss from Section 8.1.

Unfortunately, this analysis demonstrates no clear pattern in the results. However, it does demonstrate the type of variability that is encountered.

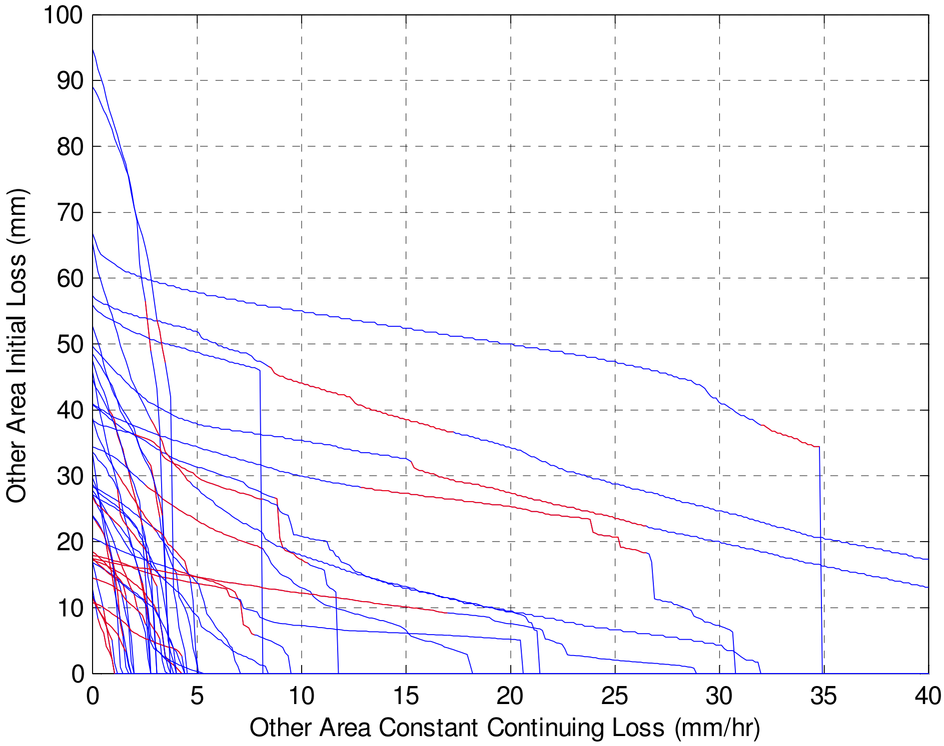


Figure 9-4. Contour Plot of Initial Loss & Constant Continuing Loss - Giralang (ACT)

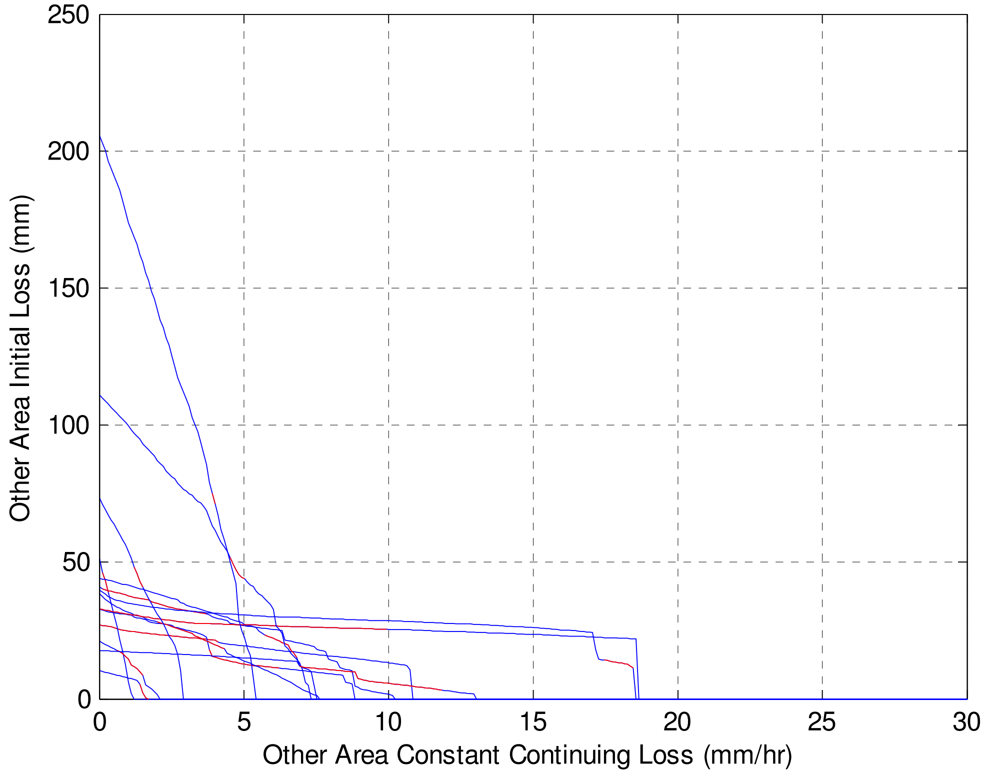


Figure 9-5. Contour Plot of Initial Loss & Constant Continuing Loss – PowellsCk (NSW)

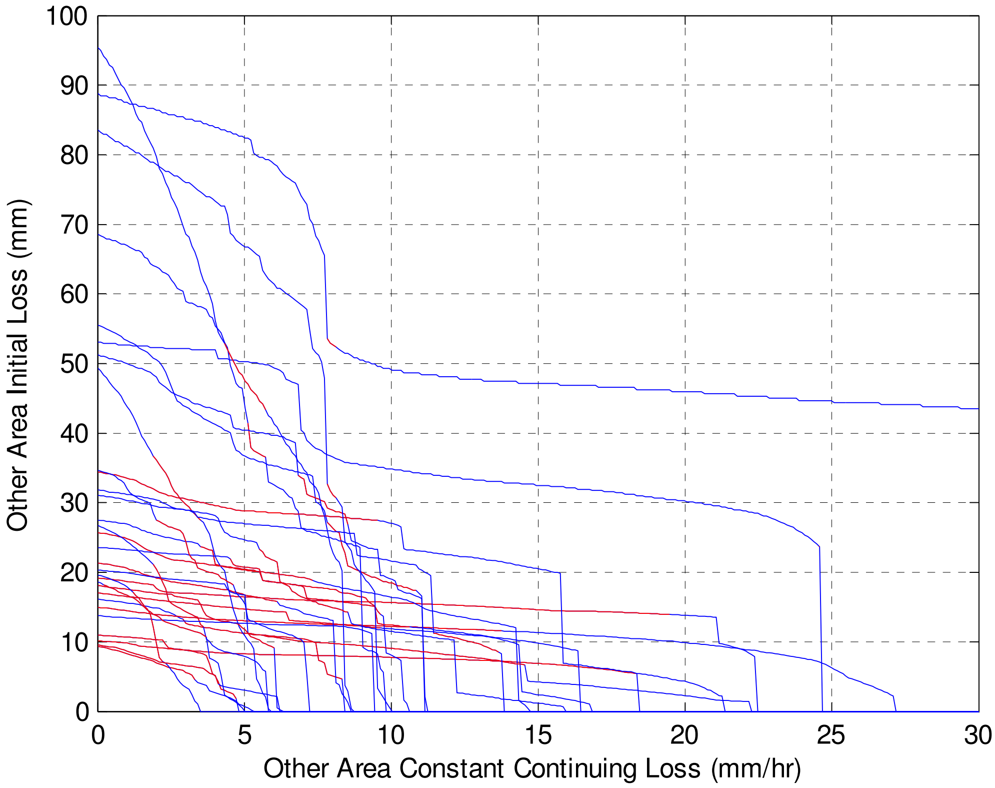


Figure 9-6. Contour Plot of Initial Loss & Constant Continuing Loss – Albany Drain (WA)

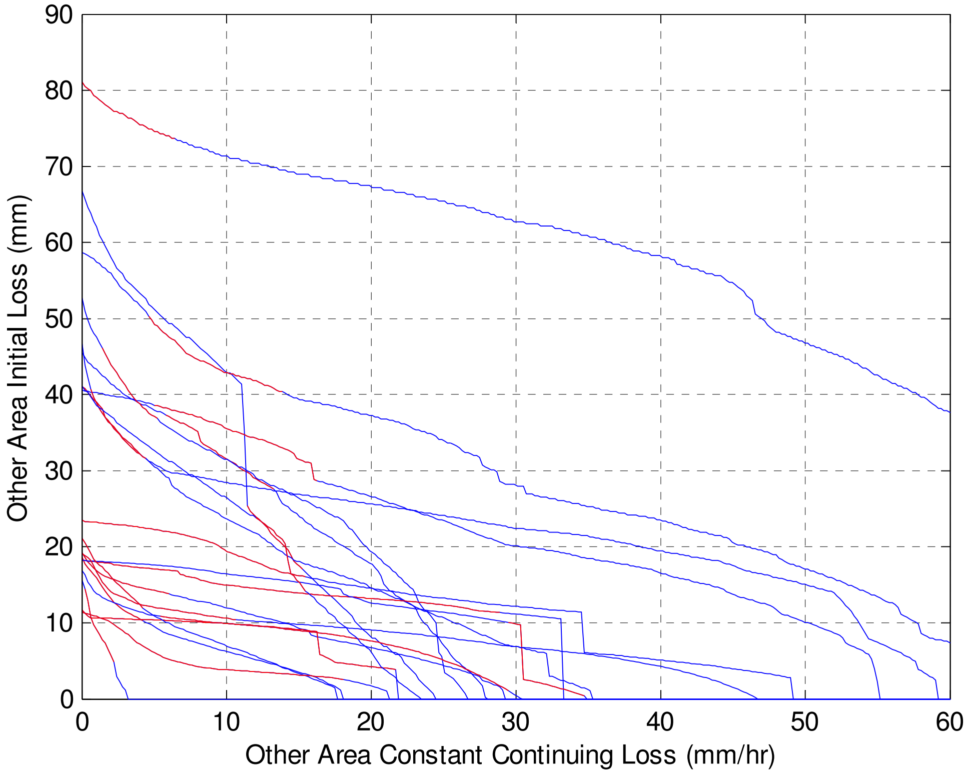


Figure 9-7 Contour Plot of Initial Loss & Constant Continuing Loss – McArthur Park (NT)

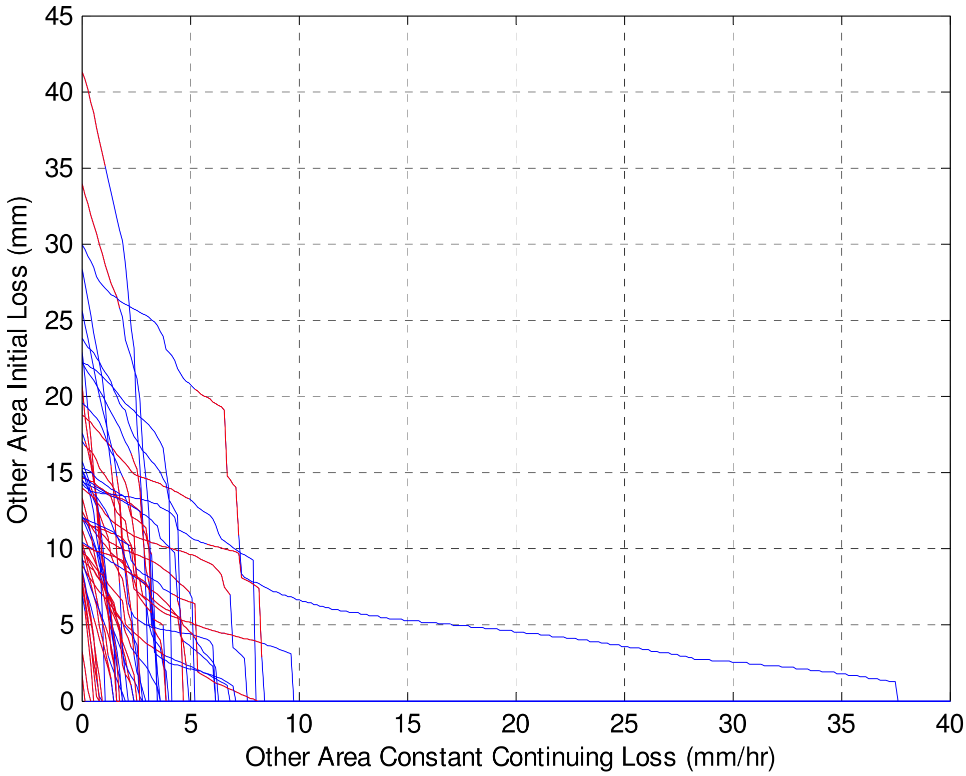


Figure 9-8 Contour Plot of Initial Loss & Constant Continuing Loss – Argyle Street (TAS)

9.3. Proportional Continuing Loss

As described in Section 7.2, the proportional loss was estimated based on the initial losses derived in Section 9.1. The results of this analysis are provided in Table 9-7 with boxplots of the continuing loss estimates for each of the catchments provided in Figure 9-9.

Albany Drain produces much higher estimates than Giralang or Powells Creek, as was noted with the constant continuing loss estimates. Again, this may be influenced by the sandy soils in Western Australia.

Care should be adopted when interpreting the results for McArthur Park and Argyle Street, for reasons discussed in Section 9.2.

The globally optimised estimates compare relatively well to the median estimates derived from optimising each event individually for Giralang. As with the constant continuing loss, Figure 9-10 shows that there are a range of parameters which will give similar values of the objective function (ie. the median error) in all catchments, particularly Albany Drain. It can also be seen that the median error from the global optimisation is considerably greater than in the individual event optimisation case, for reasons discussed in Section 9.2.

Table 9-7 Summary Statistics for Proportional Continuing Loss Estimates

	Individual Event Optimisation				Globally Optimisation	
Catchment	**Median PL_{OA}**	**Mean PL_{OA}**	**Standard Deviation PL_{OA}**	**Median Error**	**Globally Optimised PL_{OA}**	**Median Error**
Giralang (ACT)	57.5%	52.3%	18.1%	0.6%	52.5%	20.1%
Powells Creek (NSW)	45.0%	46.0%	24.8%	0.4%	24.2%	23.8%
Albany Drain (WA)	76.3%	64.7%	30.2%	0.9%	57.6%	53.2%
McArthur Park (NT)	48.0%	46.6%	21.7%	0.7%	25.3%	27.2%
Argyle Street (TAS)	57.6%	52.2%	28.1%	0.5%	28.2%	33.3%

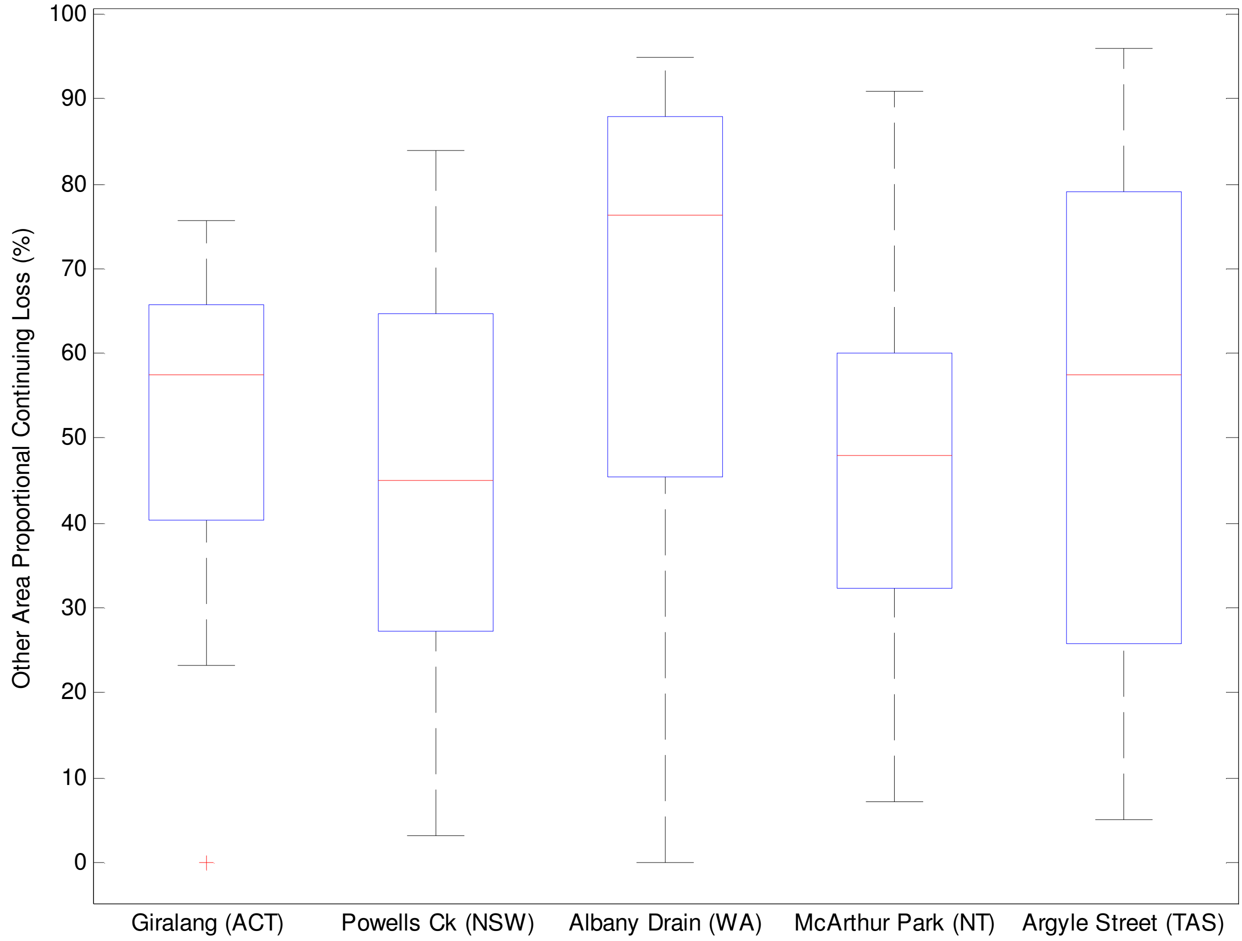


Figure 9-9 Boxplot Other Area Proportional Continuing Loss (Giralang: n = 41, Powells Ck: n = 14, Albany: n=30, McArthur Park: n = 20, Argyle Street: n = 49)

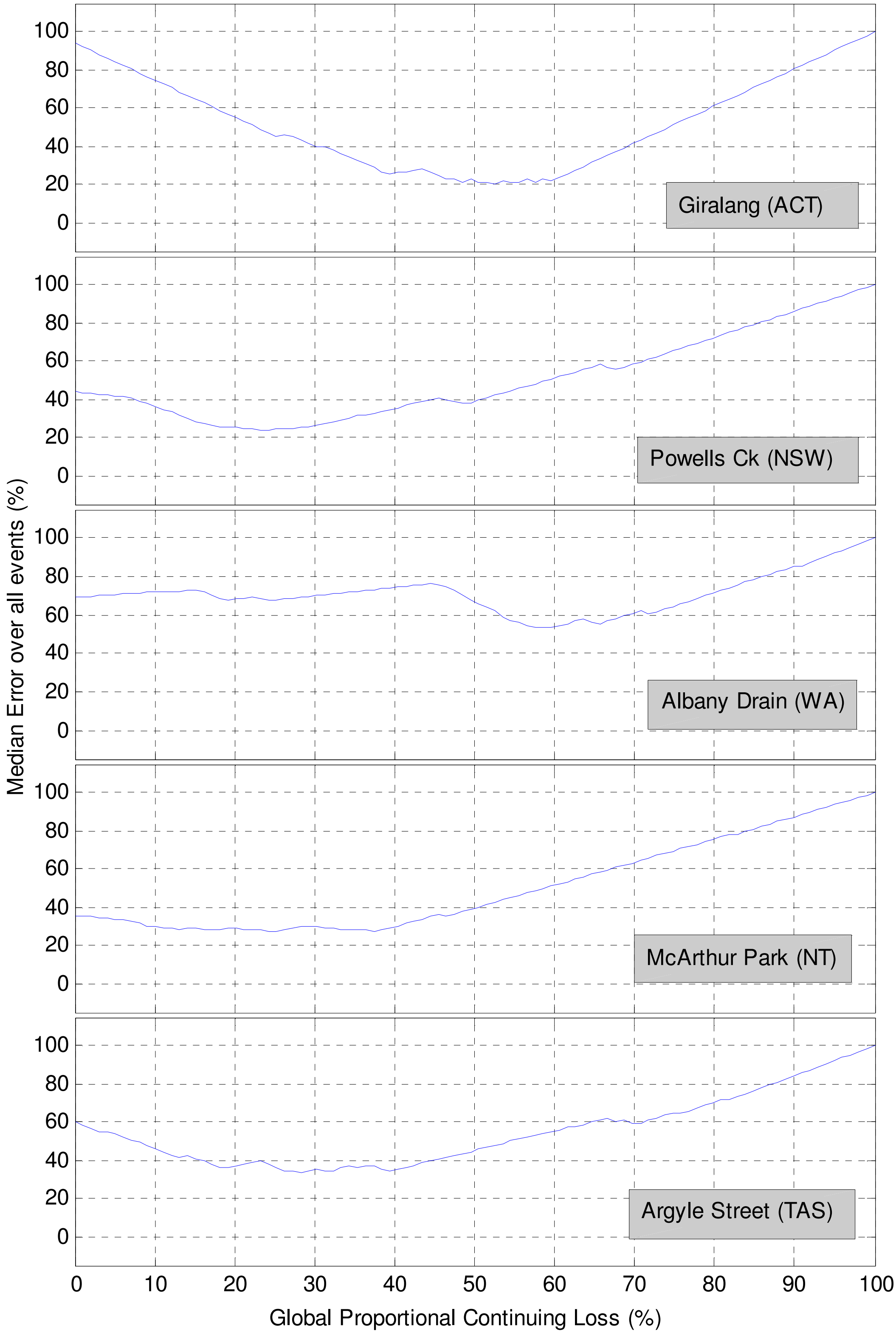


Figure 9-10 Median Error when optimising over all events for the range of Proportional Continuing Loss Values

9.3.1. Sensitivity Analysis

As with the constant continuing loss, a sensitivity analysis was undertaken on the influence of the longer storm durations on the estimates of the proportional loss. The outcomes of this analysis are provided in Table 9-8.

As with the constant continuing loss, there is a significant reduction in the proportional loss estimated. This may be a result of the factors identified in Section 9.2.1.

Table 9-8 Summary Statistics for Proportional Continuing Loss Estimates with a 24 hour duration restriction on storm events

		Individual Event Optimisation			
Catchment	**No. of Storms**	**Median PL_{OA}**	**Mean PL_{OA}**	**Standard Deviation PL_{OA}**	**Median Error**
Giralang (ACT)	19	47.5%	45.5%	21.4%	0.6%
Powells Creek (NSW)	8	54.0%	50.8%	23.5%	0.5%
Albany Drain (WA)	14	45.0%	45.7%	33.6%	0.6%
McArthur Park (NT)	19	43.4%	46.3%	22.3%	0.9%
Argyle Street (TAS)	28	58.6%	54.1%	28.8%	0.5%

9.4. Correlation Analysis – Continuing Loss Models

A correlation analysis was undertaken on the continuing loss parameters that were estimated (for both constant and proportional) and some potential parameters that might influence them. The key parameters that were tested were the relationship with:

- Peak 1 hour rainfall intensity after the commencement of the Other Area Runoff;
- Average rainfall intensity after the commencement of the Other Area Runoff;
- The duration of the rainfall after the Other Area Runoff.

The results of this correlation analysis are provided in Appendix E.

Giralang (ACT) shows a strong correlation between the peak 1 hour rainfall after the start of Other Area runoff and the constant continuing loss that was estimated, with the continuing loss increasing with increasing rainfall intensity. This is because the events for Giralang are generally characterised by a single large burst in the period after the start of Other Area runoff, which controls the required constant continuing loss estimate to replicate the observed runoff volume. This same pattern, however, was not observed for the other catchments, and may only be weakly correlated for Albany Drain (WA).

None of the other correlation analyses, including the proportional loss, showed any strong correlations.

9.5. Loss Model Performance

Originally, it was intended that the performance of the constant continuing loss and proportional continuing loss could be assessed based on the results of optimising globally. This in effect tests the ability of a single continuing loss parameter to be able to fit to a range of different storm events.

Table 9-9 shows that for Giralang, there is a reduction in the median error of 20% when a proportional loss model is used. This could indicate that the proportional loss model provides better estimates of runoff volumes for the Giralang catchment if a single loss value was to be adopted regardless of the event. The difference in median error for the remaining catchments is less than 10%, which may not be enough to provide a definitive indication of which is the more superior loss model for these catchments. Overall, there is insufficient evidence at this stage to provide guidance on which loss model provides the most optimum outcome.

Table 9-9 Median Error from Global Optimisation for the Constant Continuing Loss and Proportional Continuing Loss

	Median Error (Global Optimisation)	
Catchment	**Constant Continuing Loss**	**Proportional Continuing Loss**
Giralang (ACT)	39.3%	20.1%
Powells Creek (NSW)	13.7%	23.8%
Albany Drain (WA)	64.3%	53.2%
McArthur Park (NT)	29.4%	27.2%
Argyle Street (TAS)	33.0%	33.3%

9.6. Pervious Only Runoff

As noted in Section 7.2.1, some of the catchments analysed have large pervious areas, which has the potential to influence the estimated losses. Out of the five catchments analysed, both Giralang (ACT) and Argyle Street (TAS) have relatively large pervious only/rural/forest areas separate to the urban area of the catchment. For Giralang, approximately 36% of its total area is covered by rural areas separate to the urban area, and 74% of the total catchment area for Argyle Street is covered by a forested area.

To investigate the potential impact of these previously only areas on the loss estimates, the events without a rural runoff contribution (according to Equation 9.1) were re-analysed with the following assumptions:

- The “Other Area” is equal to the indirectly connected impervious areas and associated pervious areas only; and
- The losses on the pervious only/rural/forest area are assumed to be greater than the total depth of rainfall (ie. there is no excess rainfall on the pervious only/rural/forest areas).

Equation 9.1 indicates that there are at least 10 out of the 41 events for Giralang and 39 out of 49 events for Argyle St which potentially have a pervious only contribution (there could also be more events, for reasons outlined in Section 7.2.1). Details of the events with a pervious runoff contribution are provided in Table 9-10 and Table 9-11.

$$\text{Pervious Only Contribution if } \forall_{\text{obs}} > \ \text{EIA} * 10 * (\text{P} - \text{IL}_{\text{EIA}}) + (\text{UA} - \text{EIA}) * 10 * (\text{P} - \ \text{IL}_{\text{OA}}) \quad (9.1)$$

Where Q = runoff depth (mm)
P = rainfall depth (mm)
EIA = Effective Impervious Area (ha), as determined from Section 6.
TA = Total Area (ha)
UA = Urban Area (ha)
IL_{EIA} = Initial Loss (mm) on the EIA, as determined from Section 6.
IL_{OA} = Initial Loss (mm) on the Other Area, as determined from Section 9.1.
$\forall_{\text{obs}}$ = Total runoff volume (m^3)

Table 9-10 Characteristics of Events With And Without A Rural Runoff Contribution – Giralang (ACT)

	Events with Rural Contribution*	Remaining Events
No. of Events	10	31
Rainfall Depth Range	16 mm to 91 mm	12 mm to 131^ mm
Median Rainfall Depth	25 mm	46 mm
Rainfall Duration Range	1.4 hrs to 39.0 hrs	4.1 hrs to 56.9 hrs
Median Rainfall Duration	14.9 hrs	27.8 hrs

**based on Equation 9.1*
^This is for a long duration event (56.9 hours).

Table 9-11 Characteristics of Events With And Without A Rural Runoff Contribution – Argyle St (TAS)

	Events with Rural Contribution*	Remaining Events
No. of Events	39	10
Rainfall Depth Range	10 mm to 51 mm	13 mm to 31.6 mm
Median Rainfall Depth	18 mm	17.2 mm
Rainfall Duration Range	5.8 hrs to 41.9 hrs	7.5 hrs to 43.8 hrs
Median Rainfall Duration	19.5 hrs	19.8 hrs

**based on Equation 9.1*

The continuing loss (both constant and proportional) were estimated for the "Remaining Events" outlined in Table 9-10 and Table 9-11, ie. those events which may not have a pervious runoff contribution (according to Equation 9.1). This was undertaken using the following methods:

- Approach 1: The "Other Area" consists of indirectly connected impervious areas and associated urban pervious areas, as well as pervious only/rural/forest areas.
- Approach 2: The "Other Area" consists of only the indirectly connected impervious areas and associated urban pervious areas. Any pervious only/rural/forest areas are assumed

to have no contribution to the runoff at the gauge (ie. the losses on these areas are greater than the total depth of rainfall).

Note that the Other Area initial losses are entirely dependent on the estimate of the EIA and the rainfall pattern. Therefore, inclusion of pervious only areas in the Other Area does not affect the estimate of the Other Area Initial Loss. However, the estimate of the size of the Other Area has the potential to impact on the continuing losses.

The results of this analysis for Giralang (ACT) and Argyle St (TAS) are summarised in Table 9-12 to Table 9-15. They indicate that exclusion of the rural area from the analysis for Giralang does not lead to significantly different loss estimates, with a difference in the median constant continuing loss of about 0.3mm/hr and difference of about 5% for the median proportional continuing loss. This is not the case for Argyle Street, where exclusion of the forested area leads to considerable changes in the continuing loss estimates (see Table 9-14 and Table 9-15). The forested area represents a significant proportion of the catchment (approximately 74%), therefore Approach 2 may not be suitable.

Table 9-12 Constant Continuing Loss Estimates Excluding Rural Area - Giralang (ACT)

		Individual Event Optimisation			
Scenario	**No. of Events**	**Median CL_{OA} (mm/hr)**	**Mean CL_{OA} (mm/hr)**	**Standard Deviation CL_{OA} (mm/hr)**	**Median Error**
Approach 1 (Rural Area included in "Other Area")	31	2.9	5.7	7.6	0.8%
Approach 2 (Rural Area excluded from "Other Area")	31	2.6	4.7	6.3	0.8%

CL_{OA} = Other Area Constant Continuing Loss

Table 9-13 Proportional Continuing Loss Estimates Excluding Rural Area - Giralang (ACT)

		Individual Event Optimisation			
Scenario	**No. of Events**	**Median PL_{OA}**	**Mean PL_{OA}**	**Standard Deviation PL_{OA}**	**Median Error**
Approach 1 (Rural Area included in "Other Area")	31	60.6%	60.6%	8.6%	0.7%
Approach 2 (Rural Area excluded from "Other Area")	31	55.5%	55.6%	9.8%	0.7%

PL_{OA} = Other Area Proportional Continuing Loss

Table 9-14 Constant Continuing Loss Estimates Excluding Rural Area – Argyle Street (TAS)

		Individual Event Optimisation			
Scenario	**No. of Events**	**Median CL_{OA} (mm/hr)**	**Mean CL_{OA} (mm/hr)**	**Standard Deviation CL_{OA} (mm/hr)**	**Median Error**
Approach 1 (Rural Area included in "Other Area")	10	4.3	4.3	2.0	0.6%
Approach 2 (Rural Area excluded from "Other Area")	10	1.8	2.1	1.3	0.6%

CL_{OA} = Other Area Constant Continuing Loss

Table 9-15 Proportional Continuing Loss Estimates Excluding Rural Area – Argyle Street (TAS)

		Individual Event Optimisation			
Scenario	**No. of Events**	**Median PL_{OA}**	**Mean PL_{OA}**	**Standard Deviation PL_{OA}**	**Median Error**
Approach 1 (Rural Area included in "Other Area")	10	89.5%	89.9%	3.3%	0.2%
Approach 2 (Rural Area excluded from "Other Area")	10	65.7%	63.3%	11.4%	0.8%

PL_{OA} = Other Area Proportional Continuing Loss

10. Key Data Gaps and Additional Analysis

Data Gap/ Additional Analysis	Description
Gauge Data	The largest limitation for this study has been the availability of long term, reliable flow gauge and associated rainfall gauge data. The absence of this data limits the amount of research that can be done in this area. Further investment in gauging would result in an overall improvement in the understanding of urban hydrology.
Application of Losses to Design Storms	The loss estimates detailed in this study have been derived from historical storms only. Further investigation to determine their suitability for design storms (in particular storm bursts compared to full storms) is required.
Number of Catchments Analysed	The analysis would benefit from application to a larger pool of catchments to determine the validity of the estimates and relationships determined. Eight catchments across each state were analysed for the Effective Imperviousness, and five catchments analysed for the derivation of loss estimates.
Suitability of Catchments Analysed	Both the Argyle Street (TAS) and Ithaca Creek (QLD) catchments were not ideal due to the large forested areas in these catchments. The flow gauge in the McArthur Park catchment was found to capture surface flows only, meaning that piped low flows were not accounted for. These factors mean the EIA and losses estimates for these catchments should be interpreted with caution.

11. Conclusions

As a part of the broader Australian Rainfall and Runoff update, this report seeks to review urban hydrology. The analysis of this report has focused on two specific areas related to urban hydrology:

- Assessment of Effective Impervious Areas;
- Review of urban loss models and analysis of their suitability.

Effective Impervious Area

Three key methods have been adopted and reviewed in this report for the estimation of EIA:

- Estimation of EIA through regression analysis of rainfall and runoff data;
- Estimation of EIA using GIS methods;
- Estimation of EIA using available guidance documents.

The regression analysis has identified that the EIA is typically 55% to 65% of the TIA, although there are some exceptions to this.

Based on a sensitivity analysis of some of the key assumptions, the estimates of EIA are expected to fall within a +/- 5% to 10% range. Some of the key assumptions include:

- The use of point rainfall and the assumption of uniformly distributed rainfall;
- The recording period of the data used in the regression;
- Criteria used to isolate storm events.

The GIS method of identifying and estimating DCIA areas tended to overestimate the EIA from the regression analysis. The EIA from the regression analysis is about 70% (+/-5%) of the DCIA from the GIS Analysis for most catchments (except Giralang, ACT). A majority of the DCIA areas determined from the GIS Analysis are roads and rooves, meaning that in general, the EIA from the regression analysis equates to about 70% (+/-5%) of all roads and rooves.

Loss Models for Urban Catchments

The interaction of the pervious area with the impervious area in urban catchments results in a complication to hydrological analysis. To date, the most common loss models adopted for urban hydrology are the initial- continuing loss models. Three key models have been reviewed in this report:

- Initial loss – constant continuing loss model;
- Initial loss – proportional continuing loss model;

These loss models have been applied to historical storm events identified for five of the catchments from the EIA analysis. These catchments were selected based on the magnitude of storm events (particularly in relation to pervious runoff events) and the quality of the data. It is noted that two of the assessed catchments (McArthur Park (NT) and Argyle Street (TAS) are not well suited for the analysis, and so the results from these should be interpreted with caution.

The catchments have been conceptually divided into two distinct sub-areas:

- Directly Connected Impervious Area (DCIA), which results in a direct runoff following the exhaustion of any initial losses;
- Indirectly Connected Impervious Area + Pervious Areas, otherwise referred to in this report as the “Other Area”. Given the complexities of the interactions of these two areas, they have been conceptually lumped together such that appropriate loss values can be determined for the overall combined area. Should more information become available, or better catchment data, it may be possible to further separate out this analysis.

The analysis has identified a range of both initial losses and continuing losses. Some correlation is observed between the initial loss estimates and the peak 1 hour rainfall intensity prior to the Other Area runoff. Similarly, the constant continuing loss for Giralang exhibits a relatively strong correlation with the peak 1 hour rainfall intensity following the commencement of the Other Area runoff. However, this same behaviour is not observed for the other two catchments. These correlations are largely due to the empirical nature of the initial loss-continuing loss model, where the estimates are heavily reliant on the storm characteristics.

Based on the data available, it is not possible to determine whether the proportional loss or the continuing loss model is superior.

12. References

Abbott. M. B. & Refsgaard, J. C. (1996). *Distributed Hydrological Modelling*, The Netherlands: Kluwer Academic Publishers, pp. 11-13.

Alley, W.M., & Jack E. Veenhuis (1983). Effective impervious area in urban runoff modeling. *Journal of Hydraulic Engineering,*109 (2), 313-19.

Al-Smadi, M. (1998). *Incorporating spatial and temporal variation of watershed reponse in a GIS-based hydrologic model*. (Unpublished Master of Science). Virginia Polytechnic Institute and State University, USA.

Aryal, R. K., H. Furumai, et al. (2007). The role of inter-event time definition and recovery of initial/depression loss for the accuracy in quantitative simulations of highway runoff. *Urban Water Journa*l, 4(1), 53-58.

Ball, J.E., & Rankin, K. (2010). The hydrological performance of a permeable pavement, *Urban Water Journal*, 7(2), 79-90.

Ball, J.E., & Zaman, S. (1994). Simulation of small events in an urban catchment. In *Water Down Under 94: Surface Hydrology and Water Resources Papers (pp. 353-358)*; Barton, ACT: Institution of Engineers, Australia.

Beard, L.R., and Shin Chang. (1979). Urbanization impact on streamflow, *Journal of the Hydraulics Division ASCE*, 105, 647-59.

BMT WBM & Sydney CMA (2010). Draft MUSIC Modelling Guidelines for NSW.

Botsford E., Hill, K., Booth, D.B. (2003). *A Rapid Land Cover Classification Method For Use in Urban Watershed Analysis* (Water Resources Series Technical Report No.173), University of Washington.

Boyd, M.J., Bufill, M.C., Knee, R.M. (1993). Pervious and impervious runoff in urban catchments, *Hydrological Sciences*, 38 (6), 463-478.

Brabec E., Schulte S., Richards, P.L. (2002). Impervious Surfaces and Water Quality: A review of current literature and its implications for watershed planning, *Journal of Planning Literature*, 16(4), 499 – 514.

Brisbane City Council (2003) Guidelines for Pollutant Export Modelling in Brisbane Version 7.

Calomino, F. &Veltri, P. (1984). Rainfall-runoff in a small urban basin: experimental results from Luzzi, in *Proceedings of the 3rd International Conference on Urban Storm Drainage, 4-8 June 1984 (pp.223-231)*, Sweden.

Cherkaver, D. S. (1975). The hydrologic response of small watersheds to suburban development: Observations and modeling in urbanization and water quality control, in Whiple Jr. (Eds), *Proceedings of the American Water Resources Association* (pp. 110-119), Herndon,VA.

Chiew, F.H.S, McMahon, T.A. (1999). Modelling Runoff and diffuse pollution loads in urban areas. *Water Science Technology*, 39(12), 241-248.

Dayaratne, S.T. (2000). Modelling of Urban Stormwater Drainage Systems Using ILSAX, PhD Thesis, School of the Built Environment, Victoria University of Technology, Melbourne.

Department of Environment and Resource Management (DERM) (2007) Queensland Urban Drainage Manual, Volume 1, Second Edition.

Dotto, C.B.S., Deletic, A., Fletcher, T.D. (2008). *Analysis of uncertainty in flow and water quality in a stormwater model*. Paper presented at the 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK.

El-Kafagee, M., & Rahman, A., (2011). A study on initial and continuing losses for design flood estimation in New South Wales. In Chan, F., Marinova, D. and Anderssen, R.S. (eds) *MODSIM2011, 19th International Congress on Modelling and Simulation, (*pp. 3782 – 3787), Perth, Australia.

Fayen, L., Vázquez, R., Christiaens, K., Sels, O., &Feyen, J.(2000). Application of a distributed physically-based hydrological model to a medium size catchment, *Hydrology and Earth System Sciences* 4 (1), 47-63.

Fleming, P. M., (1974). The Australian Representatives Basins Programme, *Journal of Hydrology*, 13(1), 21-31.

Fletcher, T., Deletic, A. (2008). *Data requirements for integrated urban water management*. (Urban Water Series – UNESCO IHP).

Gold Coast City Council (2006) MUSIC Modelling Guidelines.

Goyen, A. (2000) *Spatial and Temporal effects on urban rainfall/runoff modelling*. (Thesis submitted for fulfilment of Doctor of Philosophy). University of Technology, Sydney.

Han, W.S., Burian, S. (2009). Determining effective impervious are for urban hydrologic modelling, *Journal of Hydrologic Engineering*, 14(2), 111-120.

Hicks, B., Gray, S., Ball, J. (2009). A Critical Review of the Urban Rational Method, in *Proceedings of H2O 09: 32nd Hydrology and Water Resources Symposium, 30 November – 3 December 2009 (*pp. 1424 – 1433.), Newcastle, NSW.

Hill, P. I. & Mein, R. G., (1996). Incompatibilities between Storm Temporal Patterns and Losses for Design Flood Estimation, in *Hydrology and Water Resources Symposium 1996: Water and the Environment; Preprints of Papers* (pp. 445-451). Barton, ACT: Institution of Engineers Australia.

Ilahee, M., (2005). *Modelling losses in flood estimation*, (Masters Thesis, Queensland University of Technology: School of Urban Development).

Ilahee, M. and Imteaz, M. A. (2009). Improved continuing losses estimation using initial loss-continuing loss (IL-CL) model for medium sized rural catchments. *American Journal of Engineering and Applied Sciences*. 2(4), 796 – 803.

Janke, B., Wilson, N. (2011). *Development of techniques to quantify effective impervious cover* (Centre for Transportation Studies Research Report). University of Minnesota, USA.

Lee, J.G., Heaney, J.P. (2003). Estimation of Urban Imperviousness and its Impacts on Storm Water Systems, *Journal of Water Resources Planning and Management*, 129(5), 419 – 426.

Lee, J.G., Heaney, J.P. (2002), Directly Connected Impervious Areas as Major Sources of Urban Stormwater Quality Problems – Evidence from South Florida, in *Proceedings of the Seventh Biennial Stormwater Research & Water Quality Management* (pp.45-54), Tampa (FL).

Lloyd, C. R. (1990). The temporal distribution of Amazonian rainfall and its implications for forest interception. *Quarterly Journal of the Royal Meteorological Society,* 116 (496), 1487-1494.

Lui, A., (2011). *Influence of rainfall and catchment characteristics on urban stormwater quality* (PhD Thesis, Faculty of Built Environment and Engineering, Queensland University of Technology).

Mansell, M. & Rollet, F. (2009). The effect of surface texture on evaporation, infiltration and storage properties of paved surfaces, *Water science and technology*, 348 (3-4), 71-76.

Mein, R. G. & McMahon, T. A., (1982). *Review of the role of process modelling in the Australian Representative Basins Program*, (In Review of the Australian Representative Basin Program. Rep. Basin Ser. Rep. 4).

Miller, R.A. (1978), The hydraulically effective impervious area of an urban basin, Broward County Florida, in *Proceedings of the International symposium on Urban stormwater management* (pp. 259 – 261), Kentucky University, Lexington.

O'Loughlin, G., Huber, W., & Chocat, B., (1996). Rainfall-runoff processes and modelling, *Journal of Hydraulic Research*, 34 (6), 733-751.

Pilgrim, DH, (ed)., Australian Rainfall & Runoff - A Guide to Flood Estimation, Institution of Engineers, Australia, Barton, ACT, 1987.

Phillips, B. C., Lees, S. J. & Lynch, S. J., 1994. Embedded Design Storms - An Improved Procedure for Design Flood Level Estimation?. In *Water Down Under 94: Surface Hydrology and Water Resources Papers; Preprints of Papers*, (pp. 235- 240). Barton, ACT: Institution of Engineers Australia.

Rahman, A; Weinmann, PE and Mein, RG. (2000). The Probabilistic Nature of Initial Losses and Its Impacts on Design Flood Estimates. In *Hydro 2000: Interactive Hydrology; Proceedings*, (pp. 71-75). Barton, ACT.: Institution of Engineers Australia.

Rahman, A., Weinmann, E. & Mein , R. G., (2002). The Use of Probability-distributed Initial Losses in Design Flood Estimation, *Australian Journal of Water Resources*, 6 (1), 17-29.

Rigby, E. H. & Bannigan, D. J., 1996.The Embedded Design Storm Concept - A Critical Review. In *Hydrology and Water Resources Symposium 1996: Water and the Environment; Preprints of Papers*, (pp.453 – 459). Barton, ACT: Institution of Engineers Australia.

Rigby, T., Boyd, M., Roso, S. & VanDrie, R., (2003). Storms, Storm Bursts and Flood Estimation - A need for Review of the ARR Procedures. In Boyd, MJ., Ball, J.E., Babister M.K., Green J. (Eds.) 28th *International Hydrology and Water Resources Symposium: About Water; Symposium Proceedings* (pp. 17-24). Barton, ACT: Institution of Engineers Australia.

Rodríguez-Blanco, M. L., Taboada-Castro M.M., et al. (2012). Rainfall–runoff response and event-based runoff coefficients in a humid area (northwest Spain), *Hydrological Sciences Journal,* 57(3), 445-459.

Roso, S., Boyd, M. J. & Chisholm, L. A. (2006). *Assessment of spatial analysis techniques for estimating impervious cover*. Paper presented at 30th Hydrology & Water Resources Symposium: Past, Present & Future, Sandy Bay, Tasmania.

Roso, S. & Rigby, T., (2006). *The Impact of Embedded Design Storms on Flows within a Catchment*. Paper presented at 30th Hydrology & Water Resources Symposium: Past, Present & Future, Sandy Bay, Tasmania.

Tetley, D. J. and Ryan, C. J. (2009). Do Gridded Hydrologic Models Have a Place in Australia? In *H2009: 32nd Hydrology and Water Resources Symposium, Newcastle: Adapting to Change*, (pp. 1124 – 1137). Barton, ACT: Institution of Engineers Australia.

Tularam, G. A. & Ilahee, M., (2007). Initial loss estimates for tropical catchments of Australia. *Environmental Impact Assessment Review*, 27, 493-504.

Walsh, M. A., (1991). Initial losses for design flood estimation in New South Wales, vol. 1:Thesis (M.E.) University of New South Wales.

Water By Design, (2010). MUSIC Modelling Guidelines.

Appendix A – Catchment Selection

Table A-1 Catchment Prioritisation

State	Station #	Station Name	River	Area (km^2)	Data Available?	Record Length	% Good Quality	Priority	Justification/ Description of Catchment and data characteristics
ACT	410763	Giralang		0.9	N	36.1	N/A	1	Ideal size, highly residential urbanisation approx 90%, good length record, age = 70s, detailed assessment and modelling already available
ACT	410764	Gungahlin		1.1	N	18	N/A	2	Ideal size, residential urbanisation approx 85%, reasonable length record, age = 70s
ACT	410763	Giralang West		0.1	N	33	N/A	3	Smaller size, highly residential urbanisation approx 90%, moderate length record, age = 70s
ACT	410746	Phillip	Yarralumla Creek	4.8	N	39.1	N/A	4	Slightly larger sized, mixed residential and commercial urbanisation approx 70%, good record length
ACT	410753	Mawson	Yarralumla Creek	4.4	N	38.1	N/A	4	Similar to above
NSW	23	Strathfield (Powells Ck)	Powells Ck	2.3	N	47	N/A	1	Based on available criteria alone, of the two catchments, Powell's Ck has a longer record and is thus preferred.
NSW	213006	Bradbury Park	Fishers Ghost Ck	2.5	N	29.1	N/A	2	
NT	G8150231	Moil Catchment U	Moil Catchment U	0.4	N	25.1	N/A		No Preference
NT	G8150233	McArthur Park	Palmerston Catch	1.4	N	26.1	N/A		
QLD		Highland Park-Gold Coast	Highland Park-Gold Coast	2	N	10.63	N/A	1	Ideal size, highly residential urbanised approx 90%, reasonable length record, age = combination of 70s and 90s
QLD	143028A	Jason St	Ithaca Ck	10	N	37.1	N/A	2	Relatively large, with good length record
QLD	143022A	Interstate Railway	Stable Swamp Ck	19	N	11	N/A	3	Larger size, reasonable length record
SA	A5040546	PARA HILLS DRAIN at Paddocks Inlet		0.6	Q,R	14	81.46	1	Reasonable size, residential urbanisation approx 90% urbanisation by area, good quality record of reasonable length, age = 70s
SA	A5040581	MORPHETT ROAD PIPE at Transfer Station		ND	Q	12	92.80	2	Unknown size, highly commercial/industrial urbanisation approx 95%, good quality record of reasonable length, age = 80s/90s
SA	A5040578	FIRST CREEK Downstream Botanic Gardens	First Creek	21	Q	13	56.44	3	Larger size, mostly residential urbanisation approx 80% urbanisation by area, moderate quality record of reasonable length
SA	A5040579	THIRD CREEK at Forsyth Grove	Third Creek	17	Q	12	43.40	4	Larger size, mostly residential urbanisation approx 95%, moderate quality record of reasonable length, age = 70s
SA	A5040582	ADELAIDE TERRACE PIPE Downstream West St		ND	Q	13	95.04	4	Unknown size, mostly residential urbanisation approx 95% good quality record of reasonable length, age = 70s
SA	A5040529	TORRENS RIVER at Holbrooks Road	Torrens River	492	Q	31	90.13	N/A	Exclude, as catchment size is far too large
SA	A5040549	STURT RIVER Downstream Anzac Highway	Sturt River	116	Q,R	19	81.21	N/A	Exclude, as catchment size is far too large
SA	A5040583	BROWN HILL CREEK @ Adelaide Airport(Morphett Road)	Brown Hill Creek	64.2	Q	16	91.01	N/A	Exclude, as catchment size far too large
TAS		Gore St		16.3	Q	49.1			No Preference
TAS		Argyle St		19	Q	46.1			
VIC	230112A	Stony Ck at Spotswood	Stony Ck	ND	Q	10.79	81.70	1	Unknown size, good quality record of reasonable length, mostly residential urbanisation approx 95%, age = 70s
VIC	407257A	BACK CREEK @ BENDIGO QUARRY HILL	Back Ck	14	Q	12	100.00	2	Larger size, mix of residential and commercial urbanisation approx 95%, good quality record of reasonable length
VIC	228229A	MONBULK CREEK @ TECOMA	Monbulk Ck	19	Q	21.1	100.00		Exclude as it is sparsely urbanised (< 20% by area)
WA	602006	ALBANY URBAN DRAIN - DUCK LAKE		0.1	Q	11	98.56	1	Ideal size and good quality record of reasonable length, mostly residential urbanisation approx 80%, age = 60s
WA	616087	STH BELMONT MAIN DRAIN - ABERNETHY ROAD		11.3	Q	21	22.08	2	Larger size, highly urbanised approx 90% with mix of residential and industrial spaces, however record quality is poor
WA	602009	Robinson Road Drain Drop Structure		12.4	Q	14	92.33		Exclude as it is sparsely urbanised (< 20% by area)
WA	612015	Vindictive Drain, Harris Road		2	Q	20	97.63		Exclude as it is essentially rural catchment
WA	612048	Bear Drain, Bunbury		ND	Q	18	62.70		Exclude as it is essentially rural catchment
WA	613014	Samson North Drain, Somers Road		17.5	Q	29	78.90		Exclude as catchment size too large and is essentially a rural catchment
WA	613054	Mayfield Sub G Drain, Mayfield		9.7	Q	17	78.90		Exclude as it is essentially rural catchment
WA	614013	Peel Drain, Hope Valley		10.4	Q	25	81.76		Exclude as it is essentially rural catchment

ND = NO DATA, N=No, Q = FLOW, R = RAINFALL

Appendix B – Catchment Figures

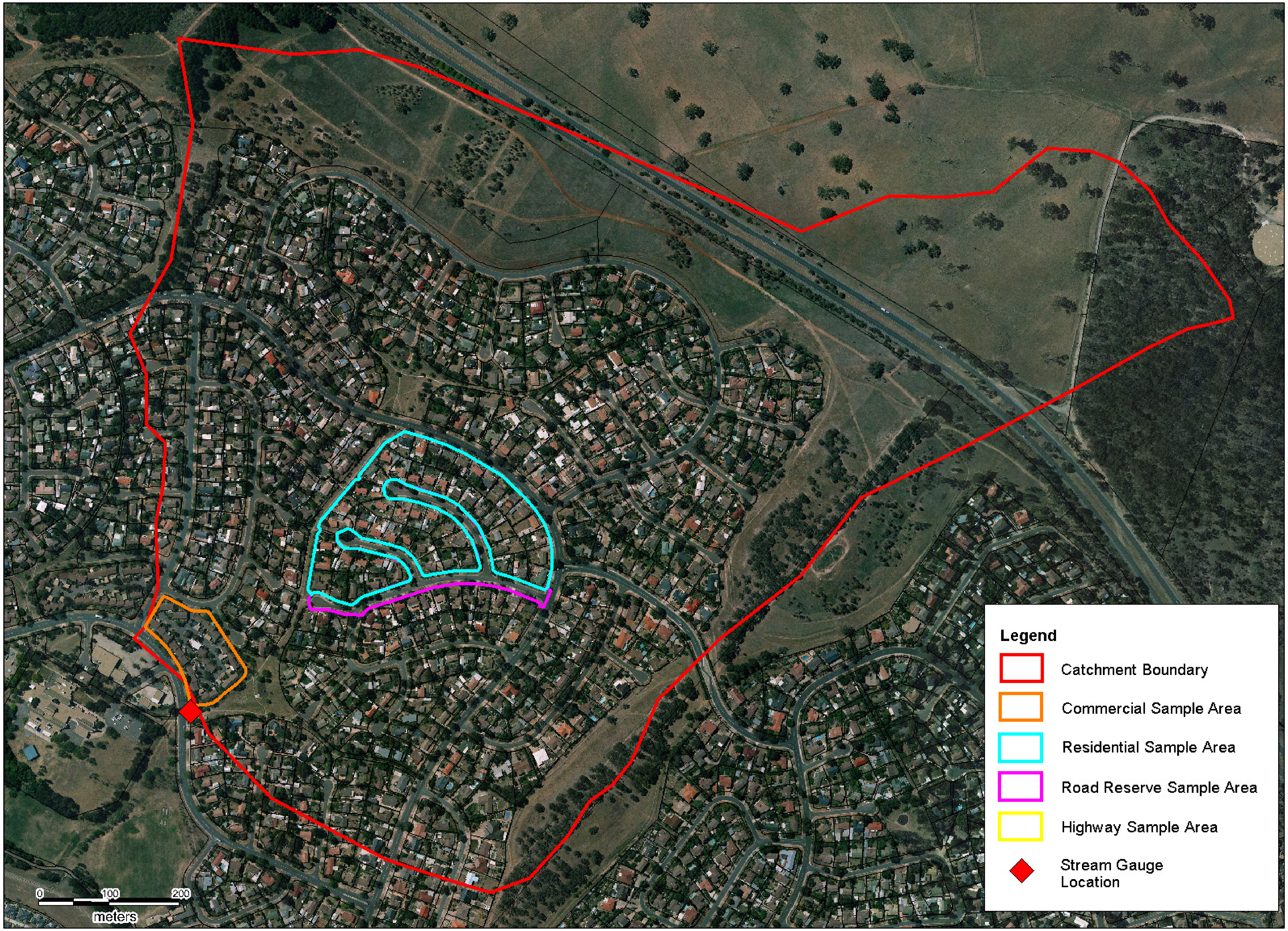


Figure B-1. Giralang, ACT, Catchment Summary

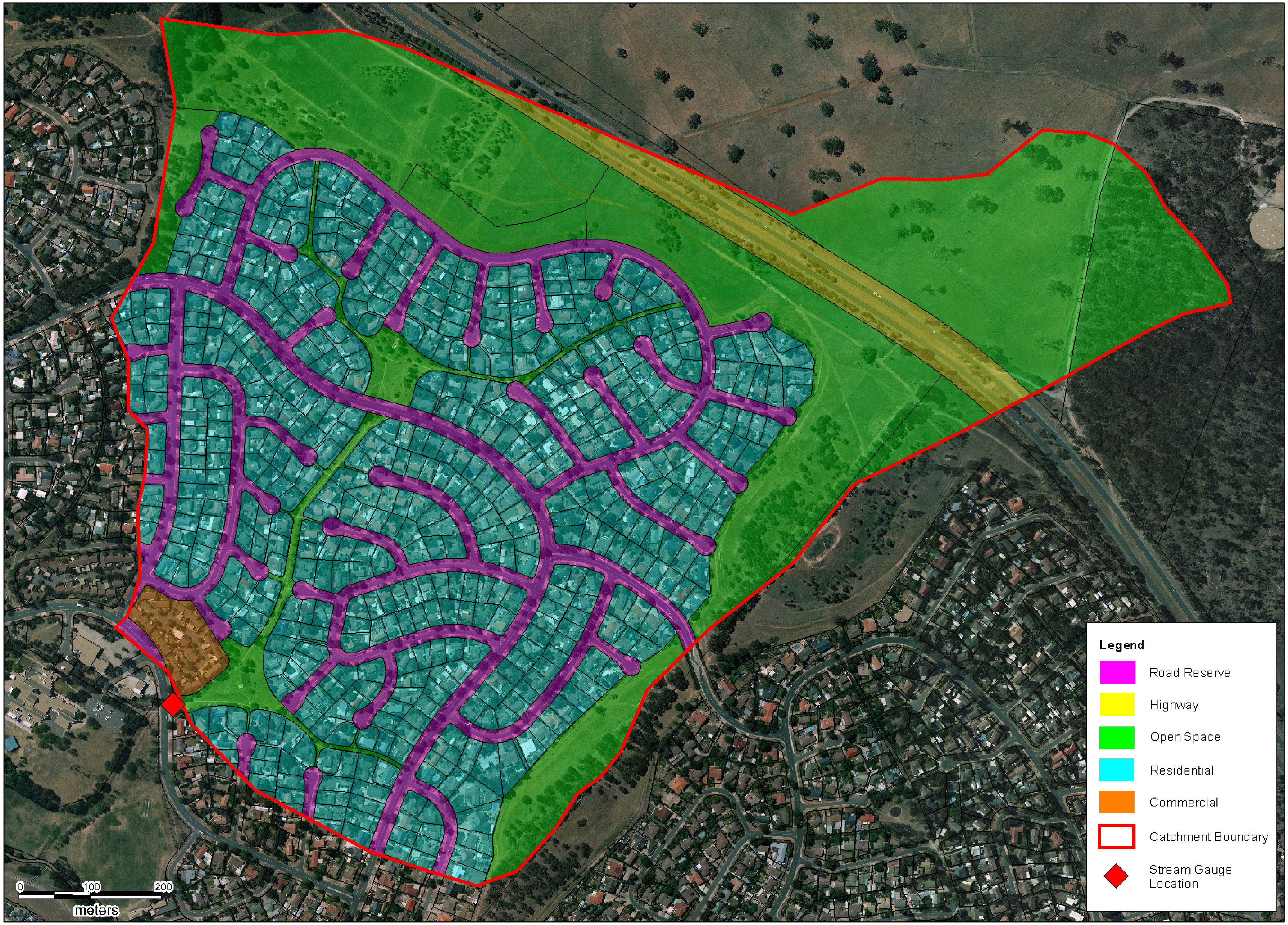


Figure B-2. Giralang, ACT, Land-Use

Figure B-3. Giralang, ACT, Sample Area Surface Types

Figure B-4. Powells Creek, NSW, Catchment Summary

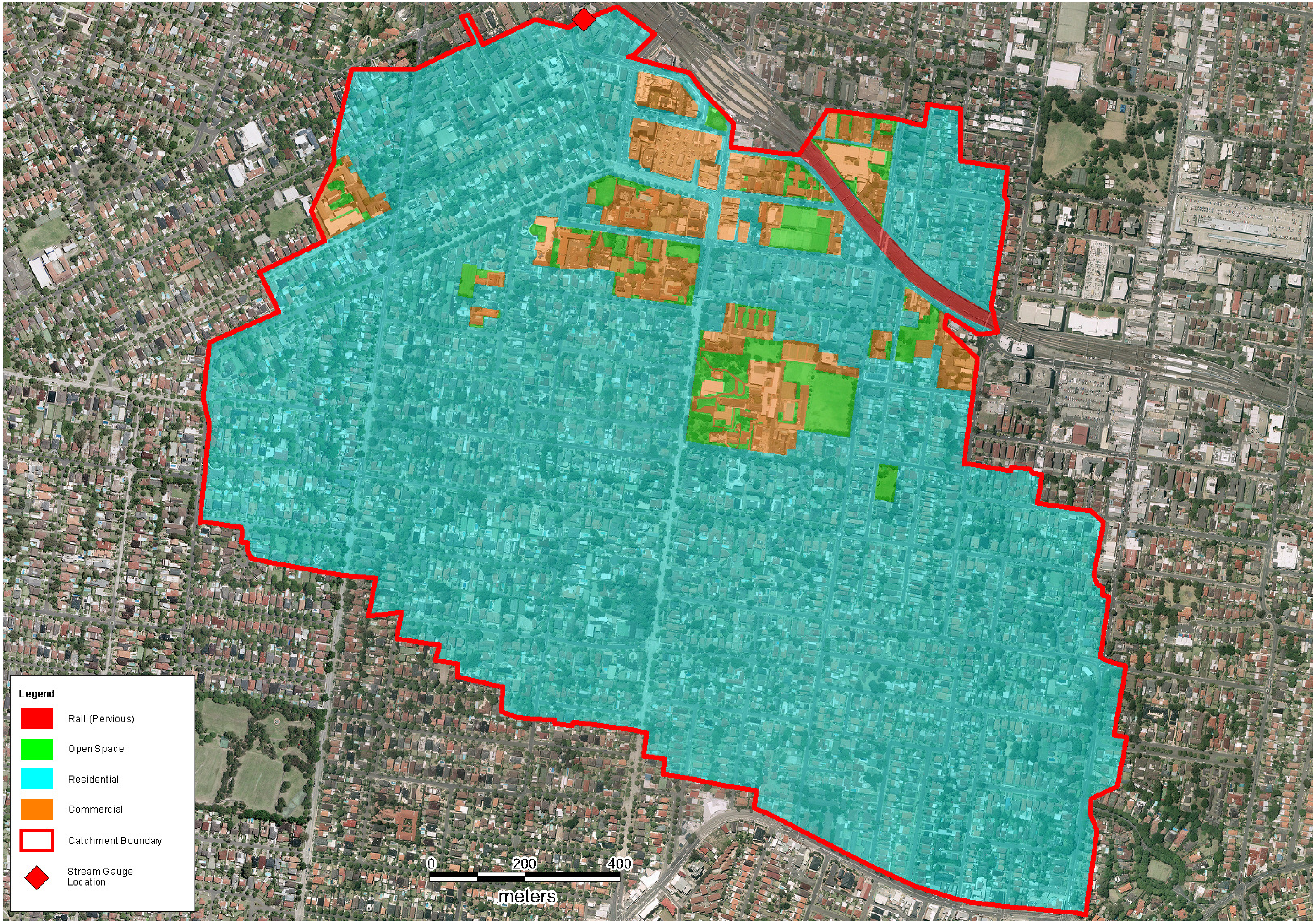


Figure B-5. Powells Creek, NSW, Land-Use

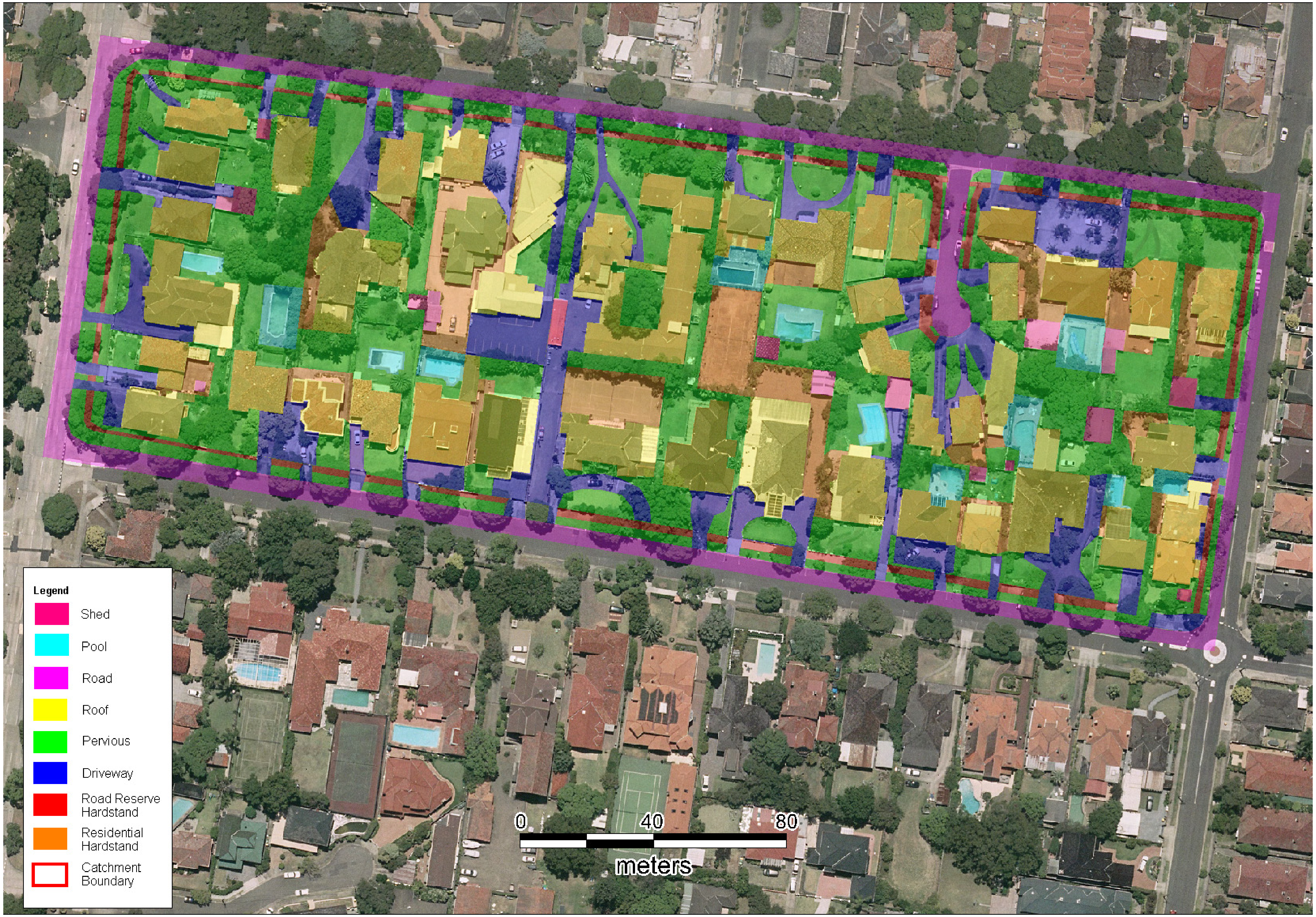


Figure B-6. Powells Creek, NSW, Residential Sample Area Surface Types

Figure B-7. McArthur Park, Palmerston, NT, Catchment Summary

Figure B-8. McArthur Park, Palmerston, NT, Land-Use

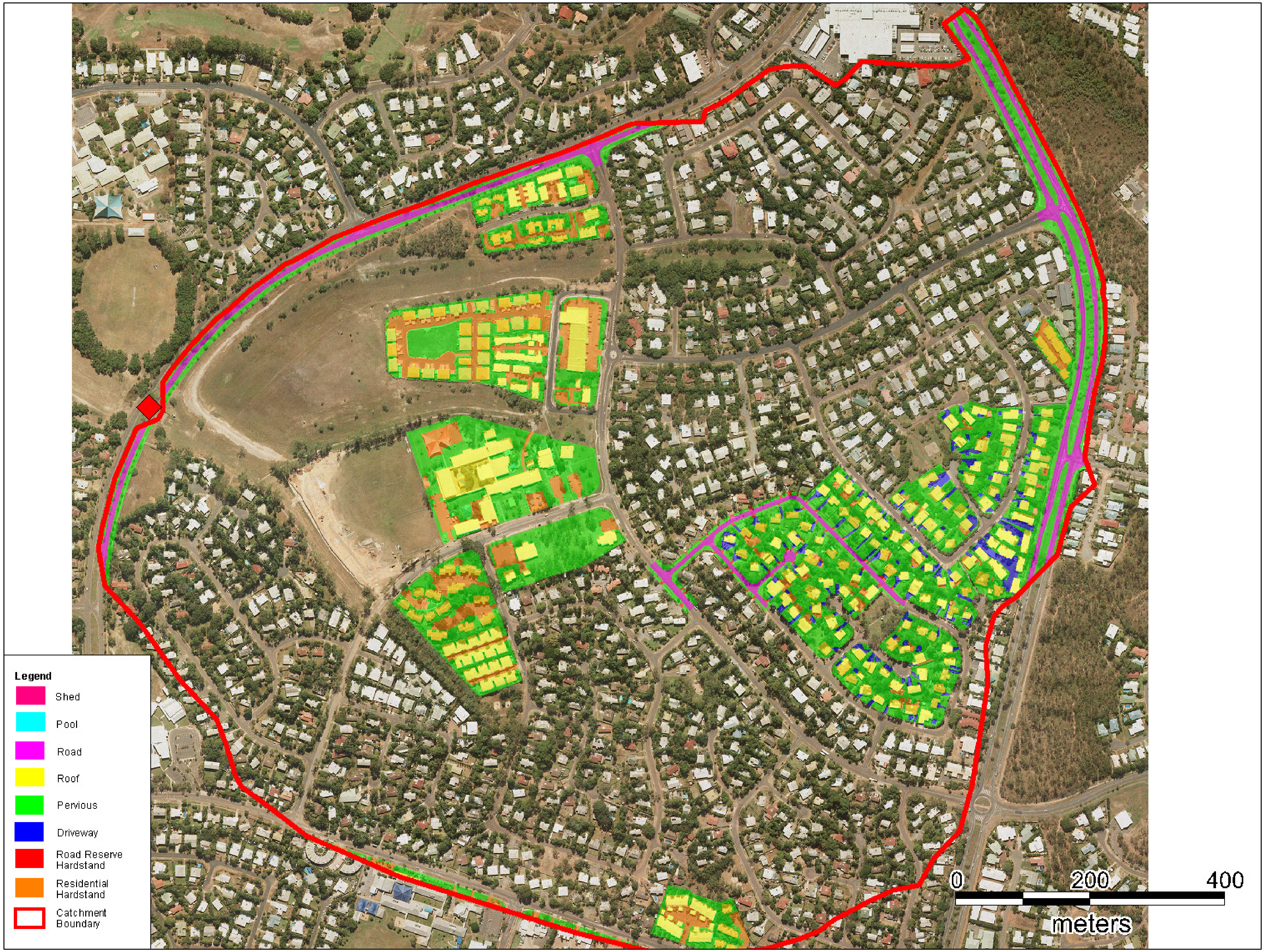


Figure B-9. McArthur Park, Palmerston, NT, Sample Area Surface Types

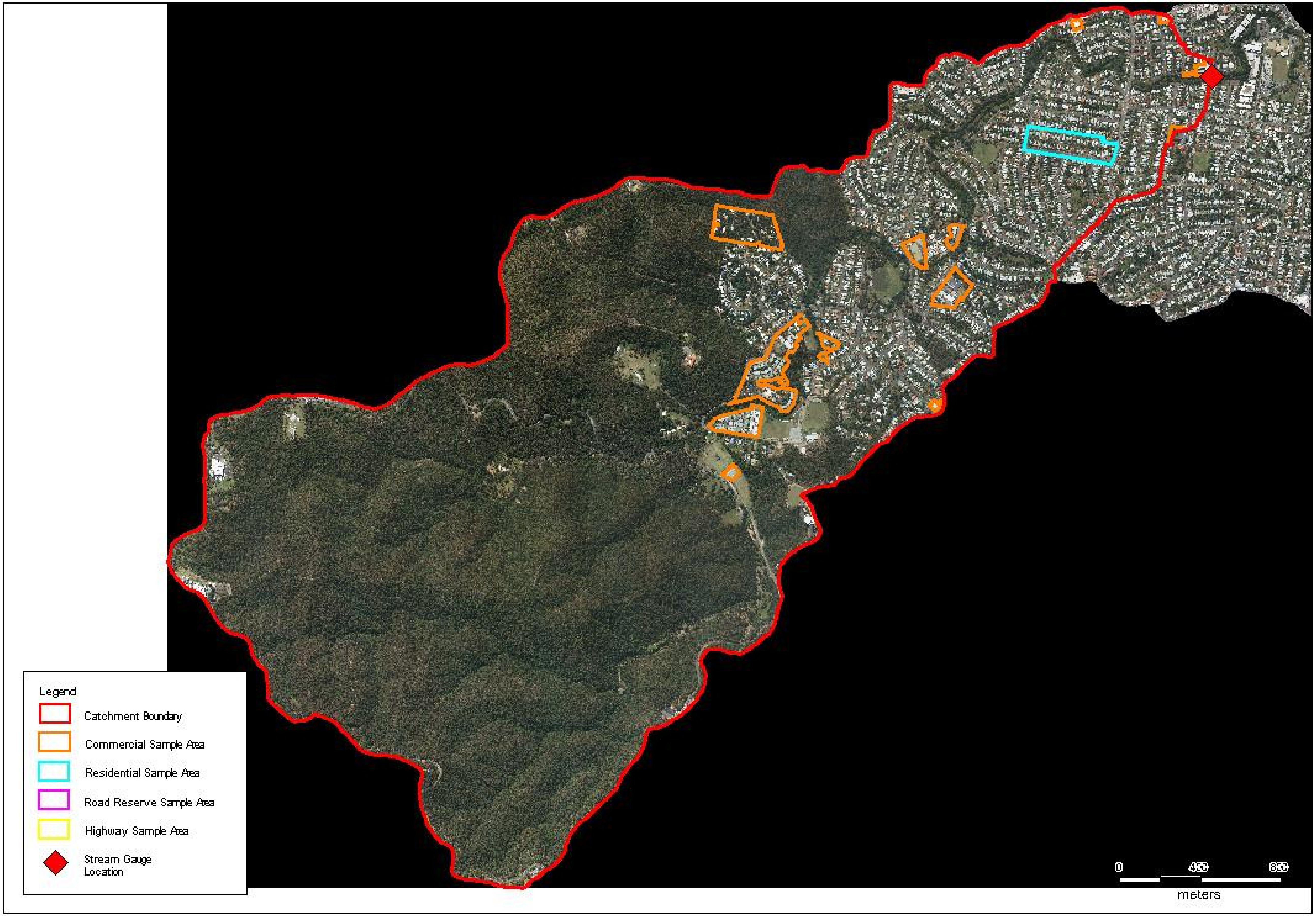


Figure B-10. Ithaca Creek, QLD, Catchment Summary

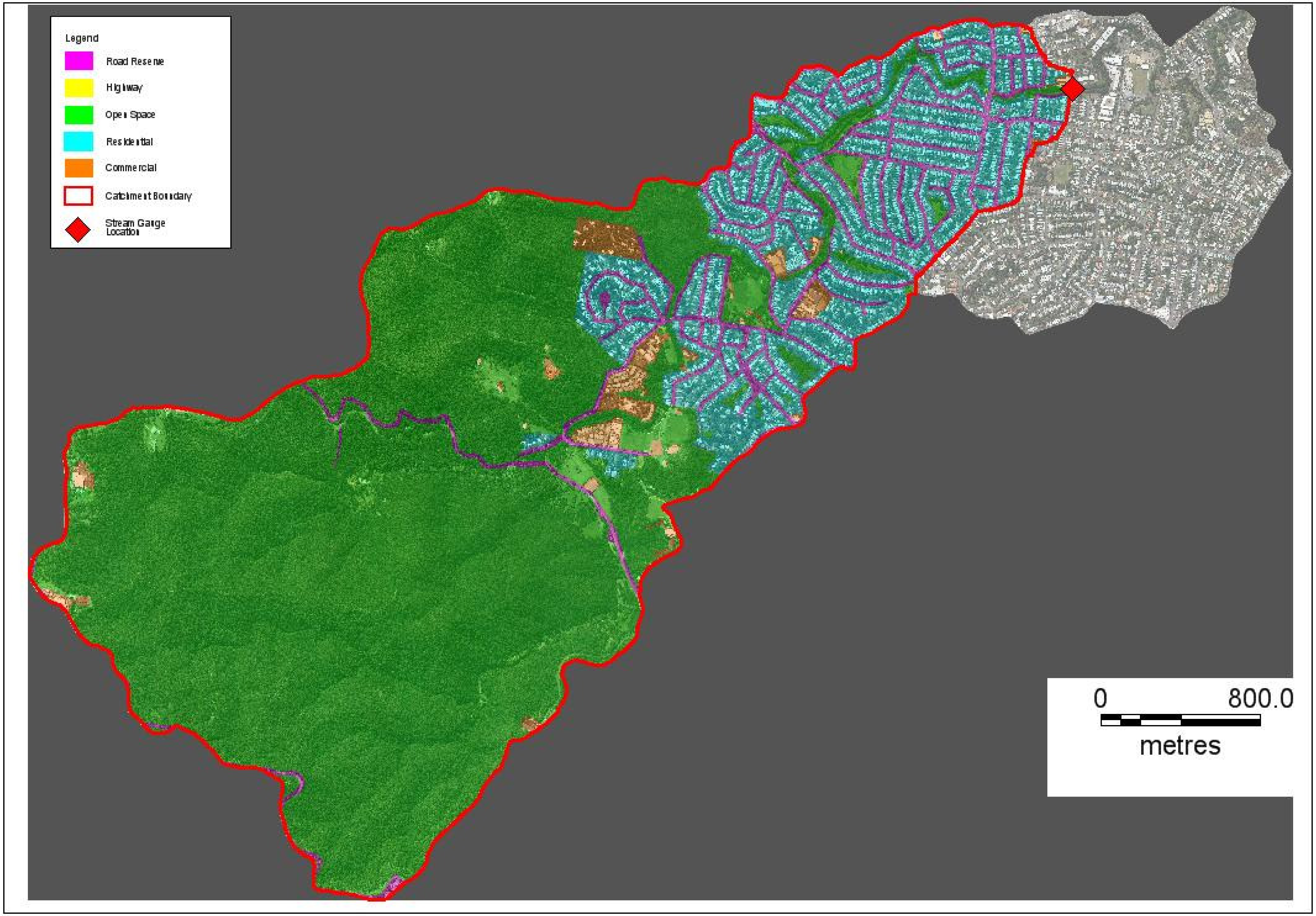


Figure B-11. Ithaca Creek, QLD, Land-Use

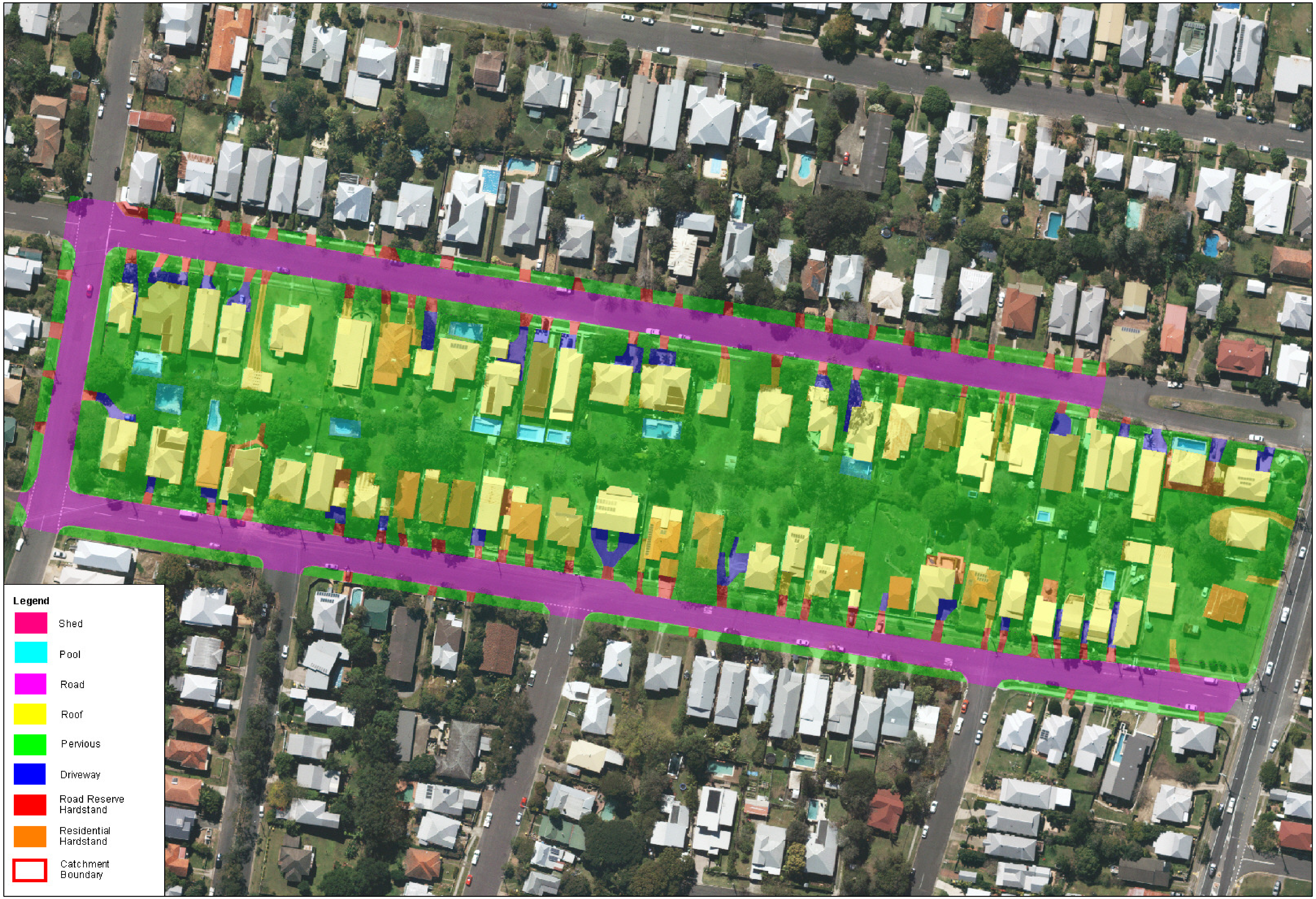


Figure B-12. Ithaca Creek, QLD, Sample Area Surface Types

Figure B-13. Parra Hills Drain at Paddocks Inlet, SA, Catchment Summary

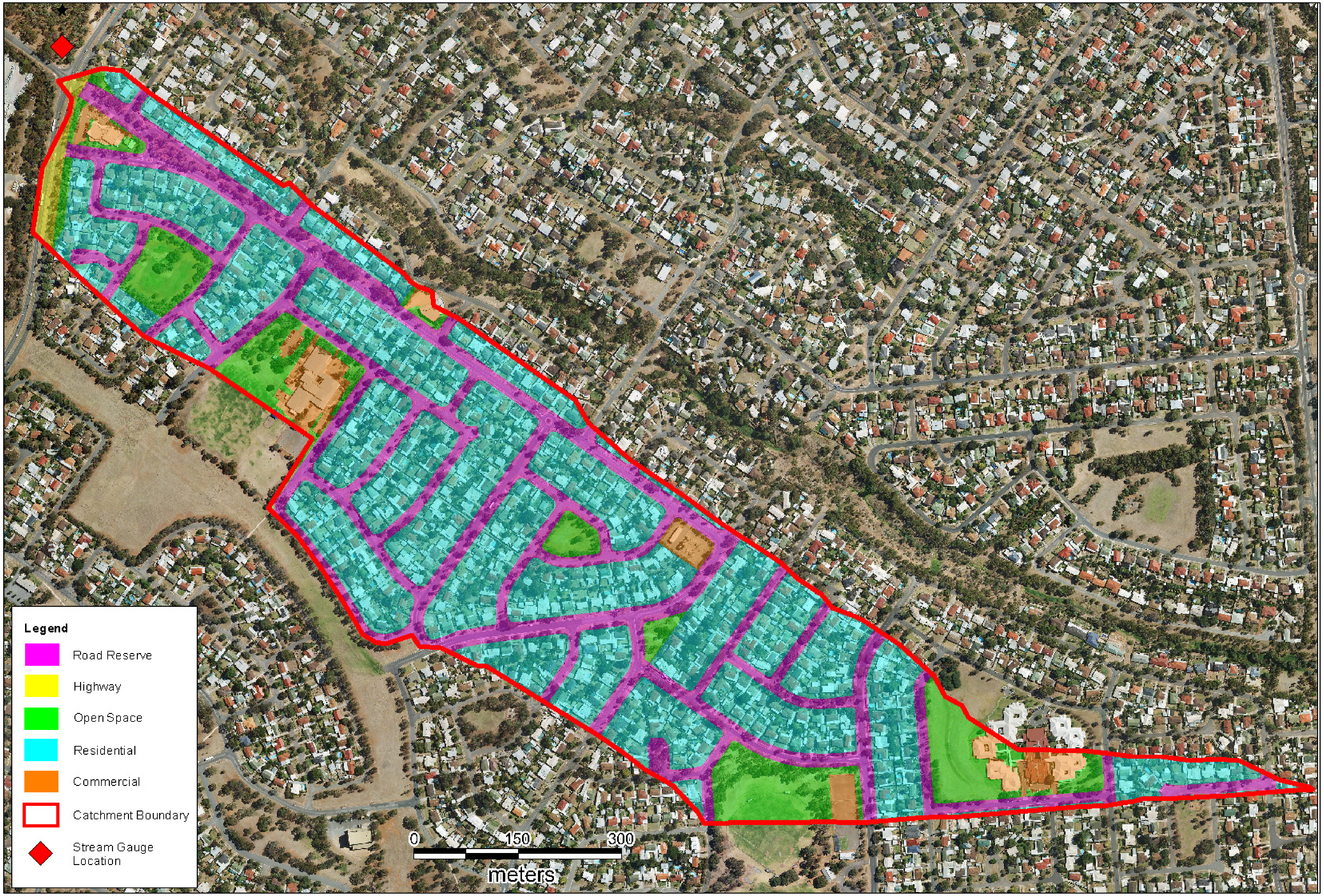


Figure B-14. Parra Hills Drain at Paddocks Inlet, SA, Land-Use

Figure B-15. Parra Hills Drain at Paddocks Inlet, SA, Sample Area

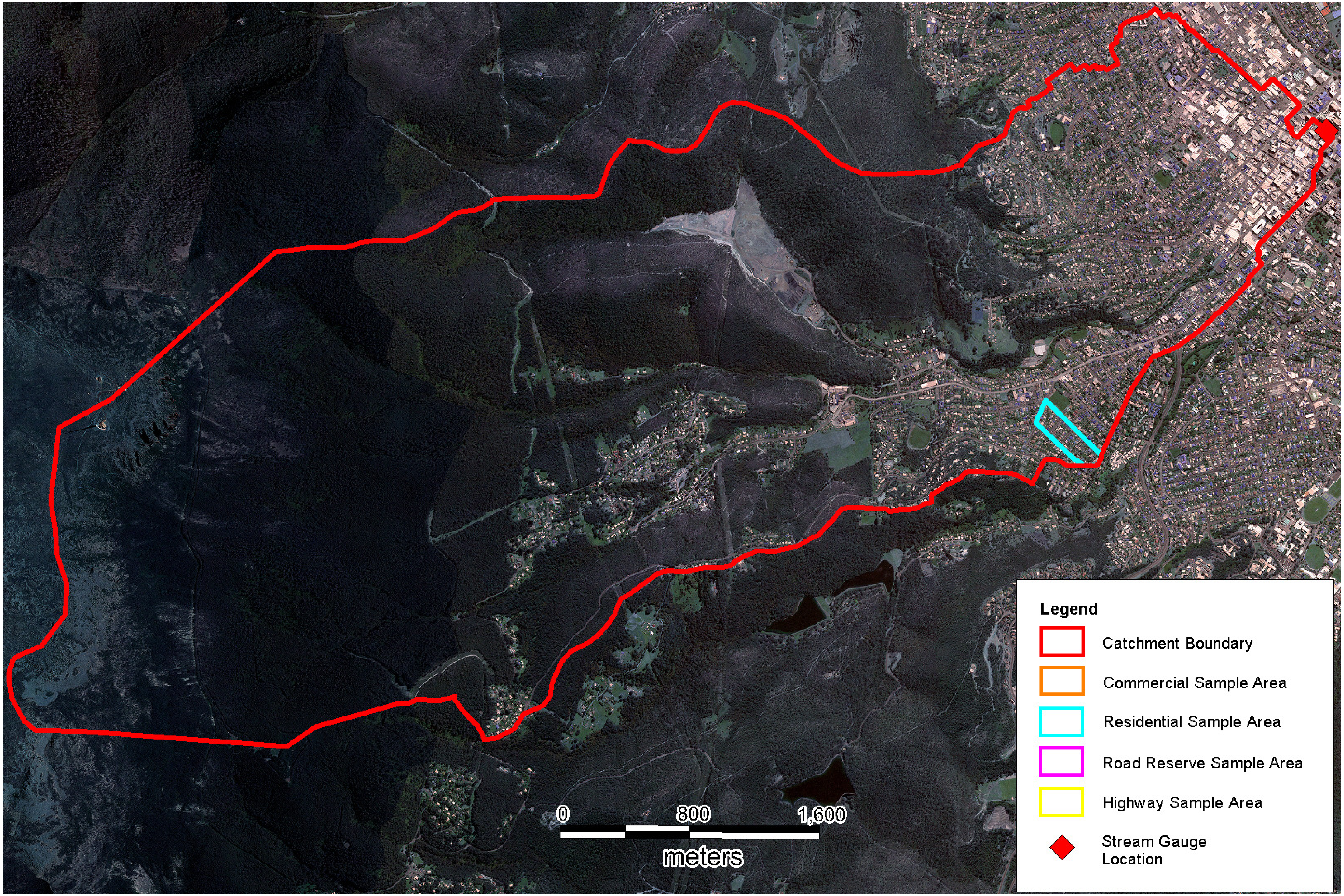


Figure B-16. Argyle Street, TAS, Catchment Summary

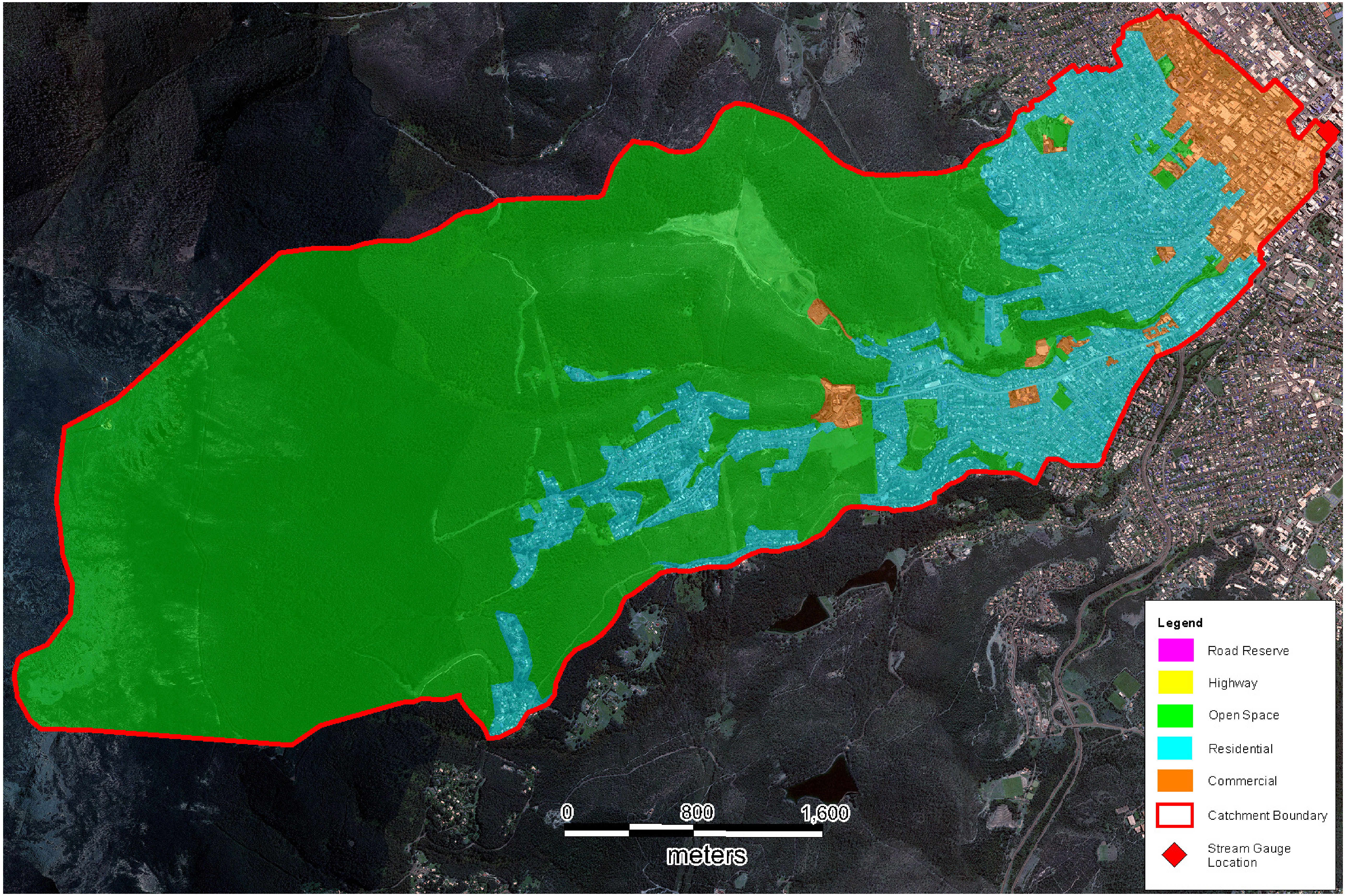


Figure B-17. Argyle Street, TAS, Land-Use

Figure B-18. Argyle Street, TAS, Sample Area

Figure B-19. Albany Drain at Duck Lake, WA, Catchment Summary

Figure B-20. Albany Drain at Duck Lake, WA, Surface Types

Figure B-21. Kinkora Rd, VIC, Land Use

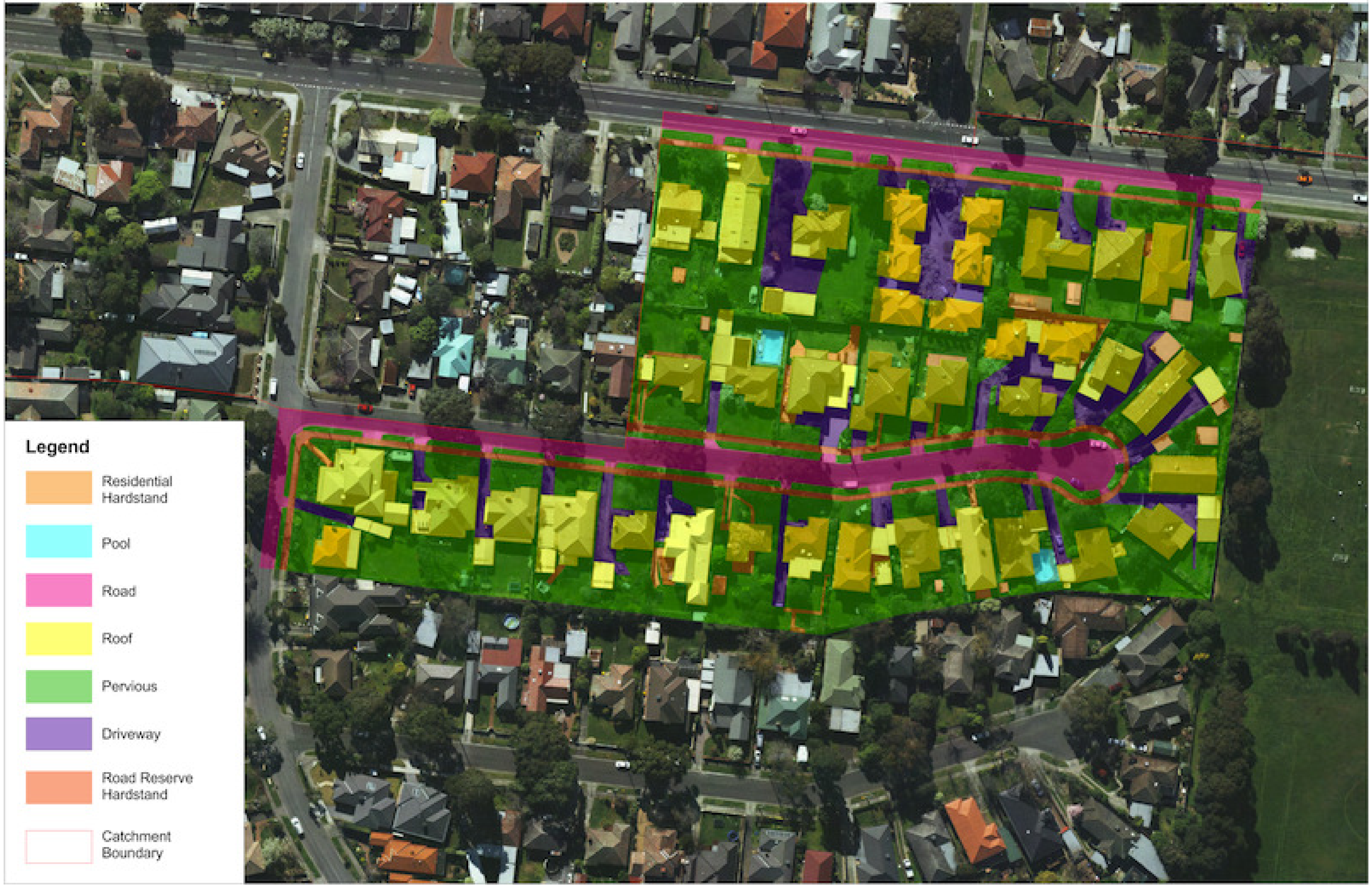


Figure B-22. Kinkora Rd, VIC, Sample Residential Area – Surface Types

Appendix C – Regression Analysis

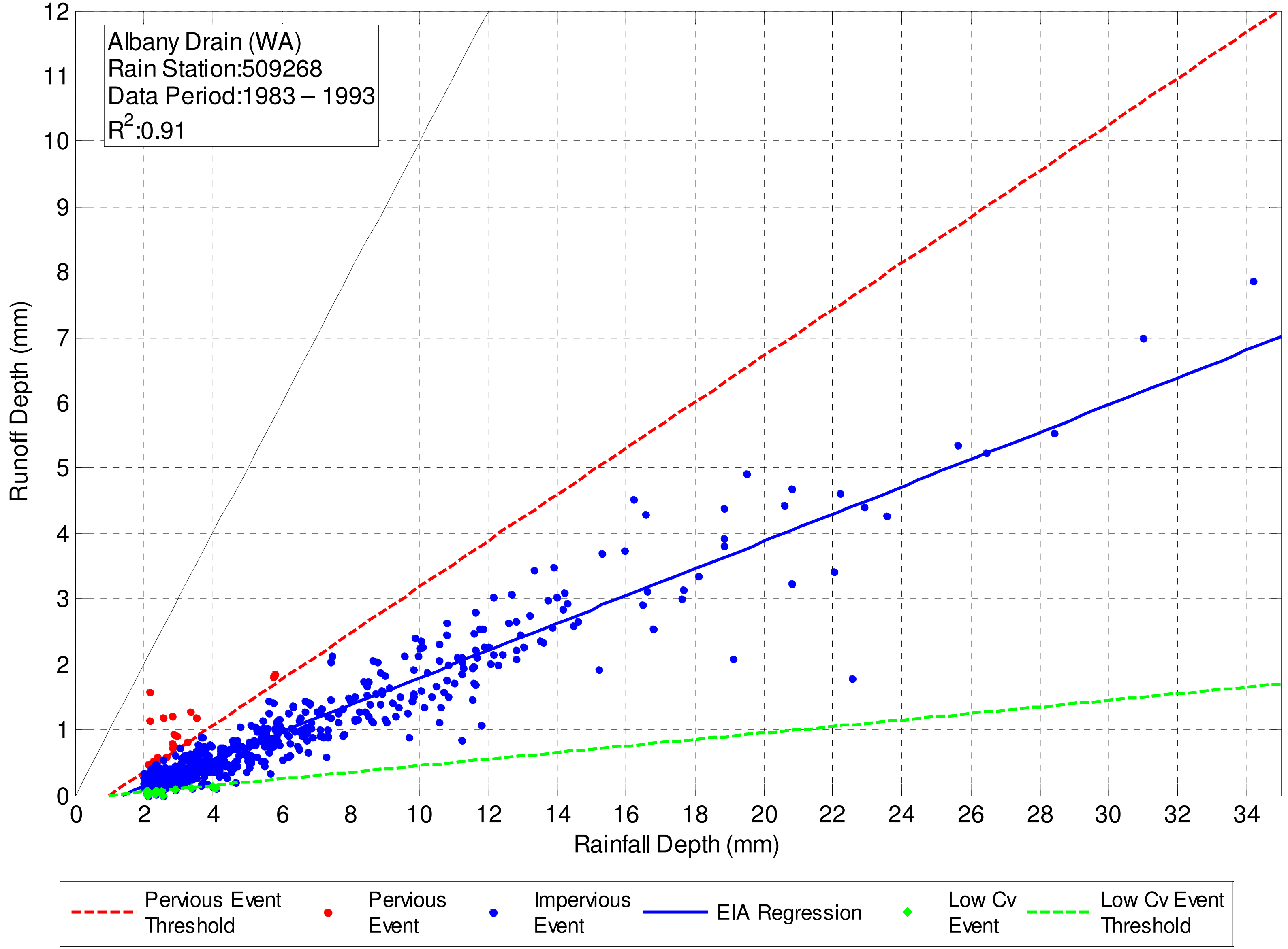


Figure C-1. Regression of Rainfall and Runoff – Albany Drain (WA)

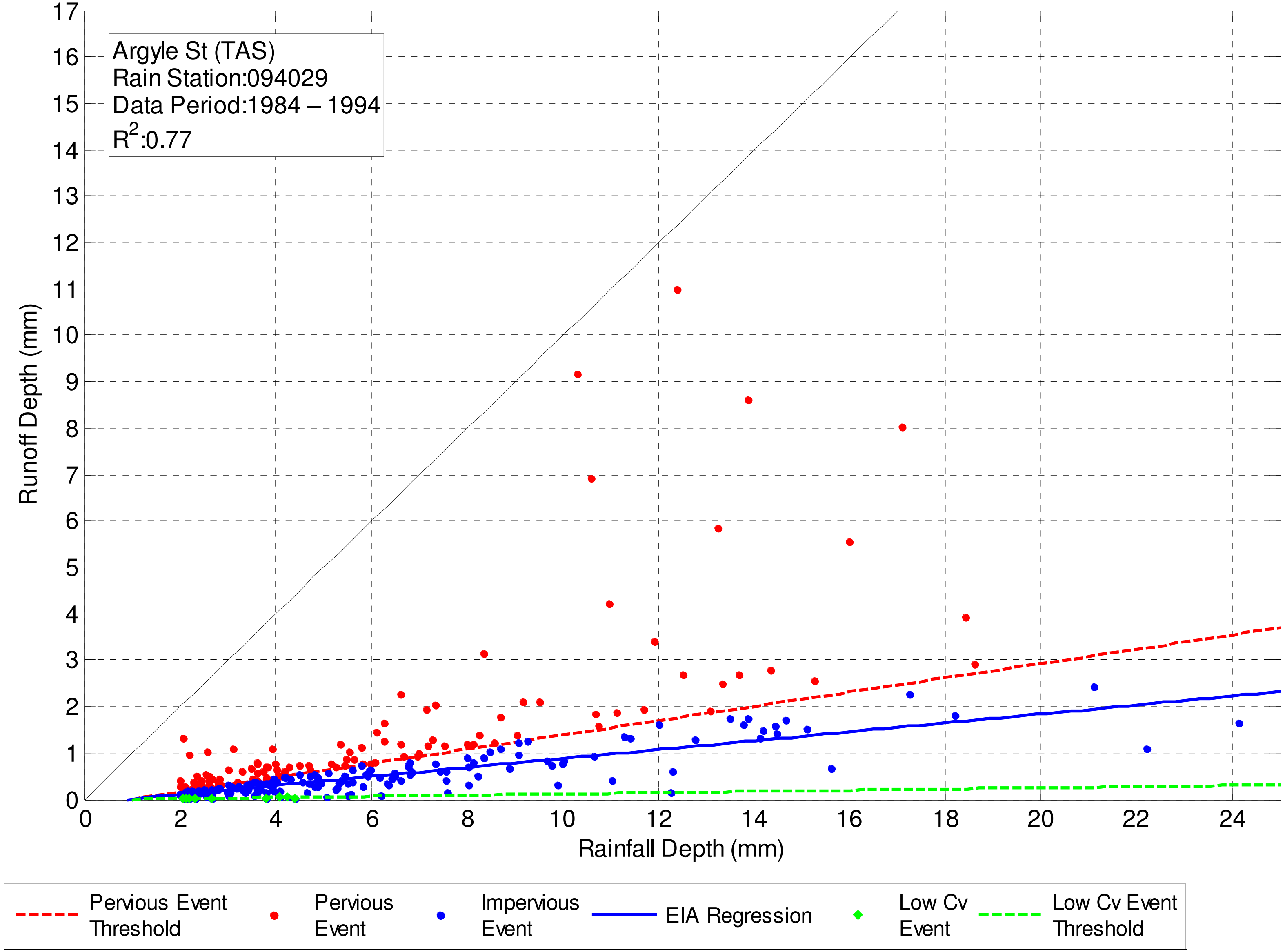


Figure C-2. Regression of Rainfall and Runoff – Argyle Street (TAS)

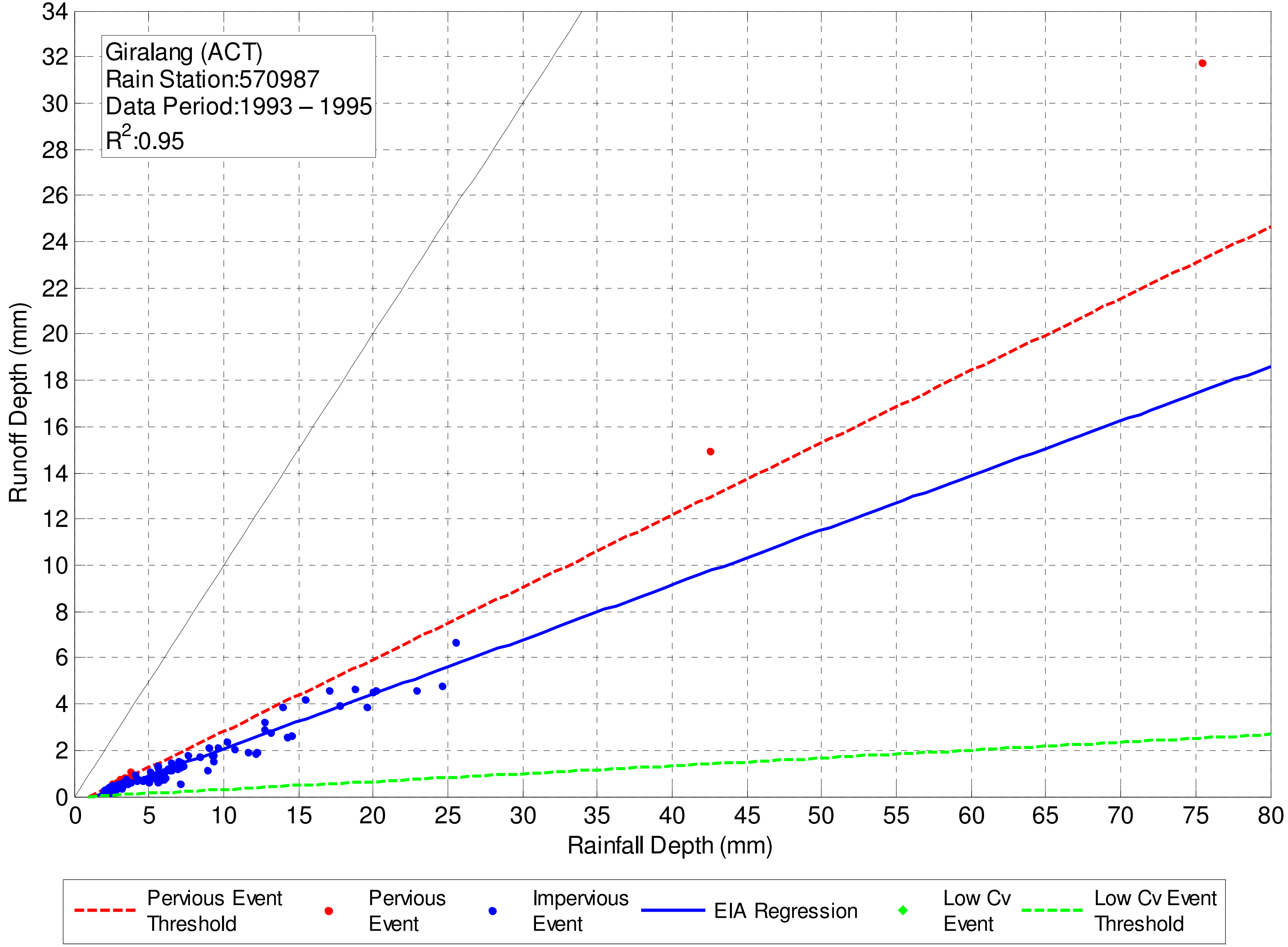


Figure C-3. Regression of Rainfall and Runoff – Giralang (ACT), Rain Gauge 570987, Data Period 1993 - 1995

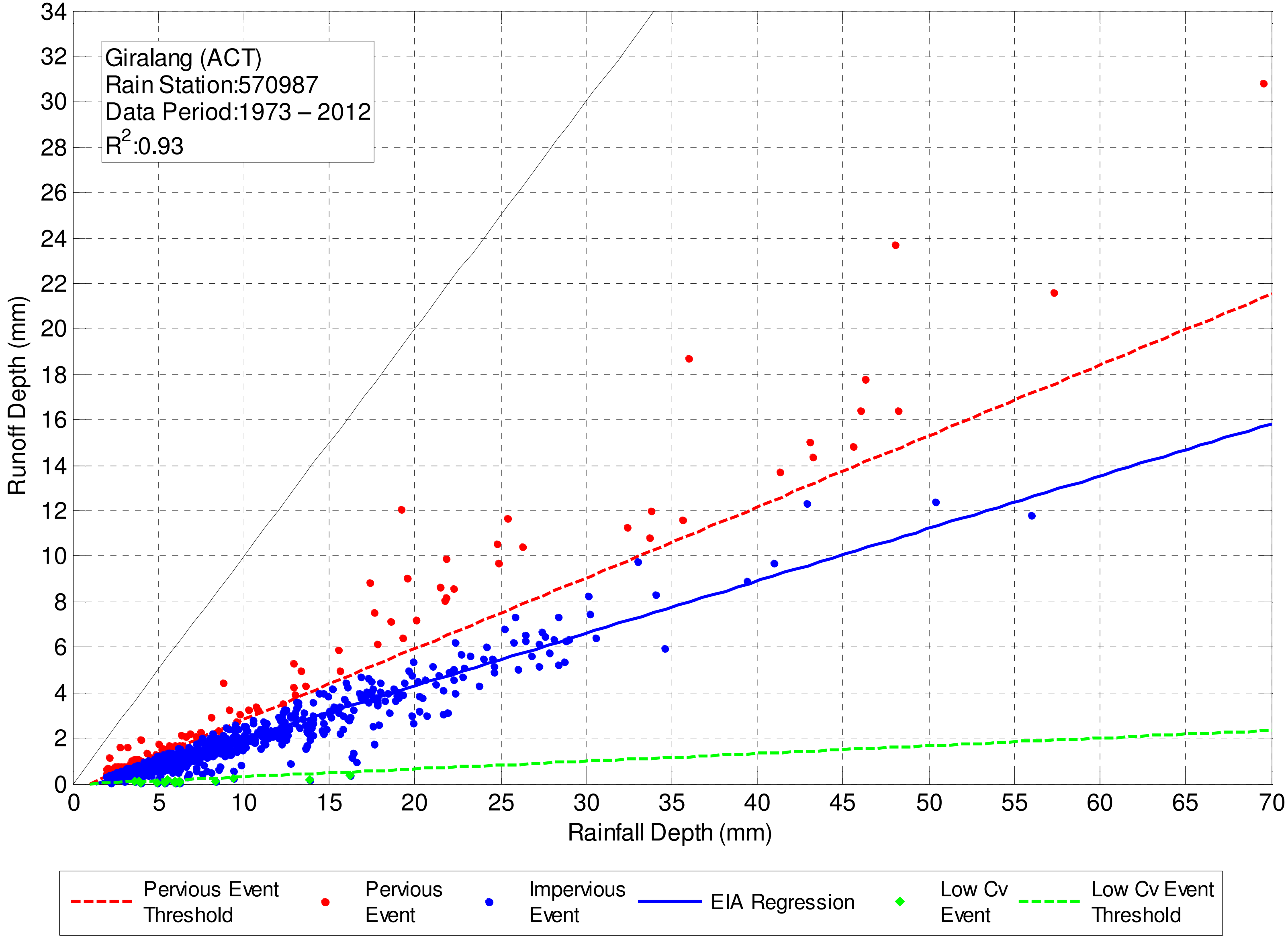


Figure C-4. Regression of Rainfall and Runoff – Giralang (ACT), Rain Gauge 570987, Data Period 1973 - 2012

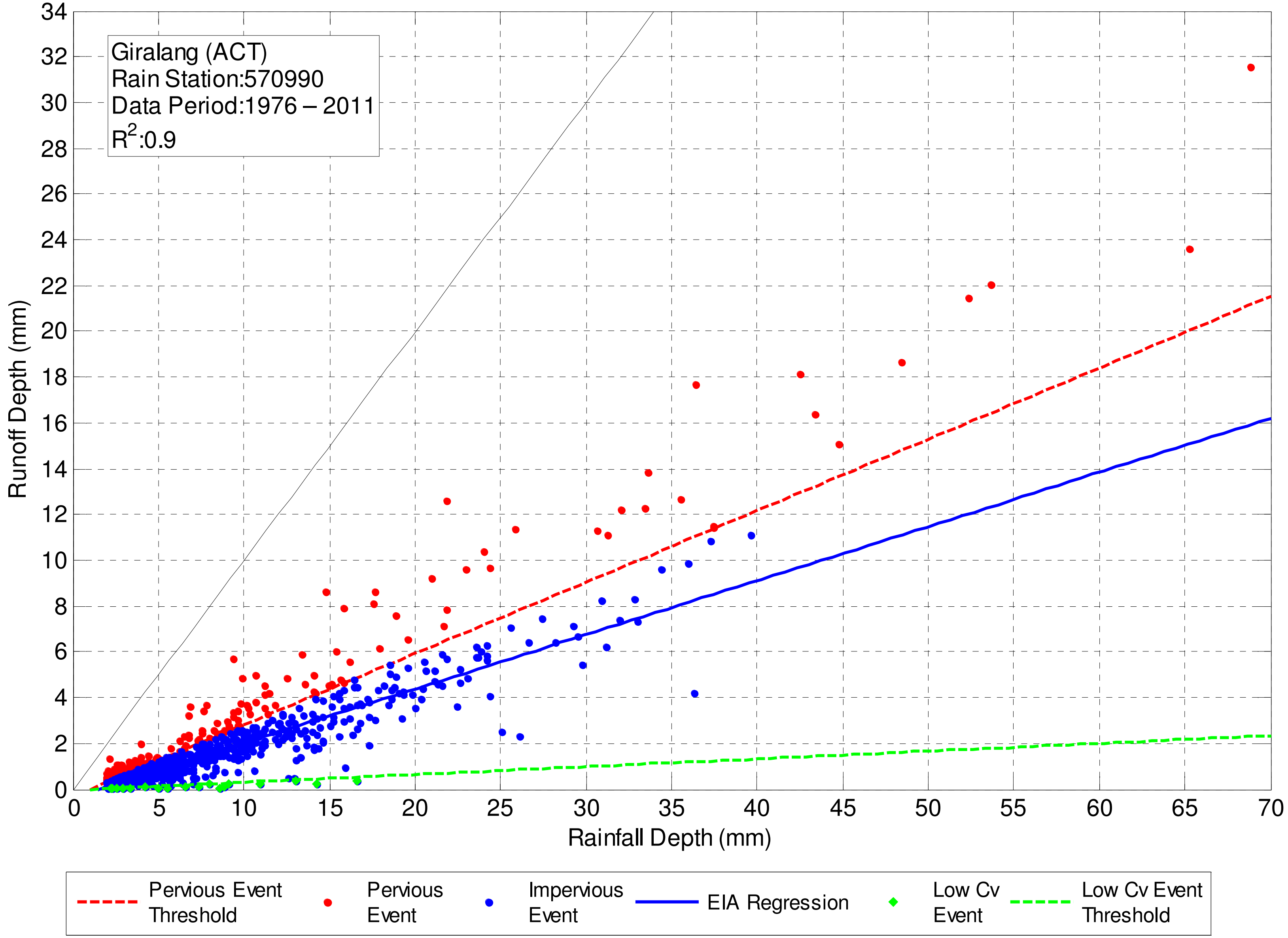


Figure C-5. Regression of Rainfall and Runoff – Giralang (ACT), Rain Gauge 570990, Data Period 1976 - 2011

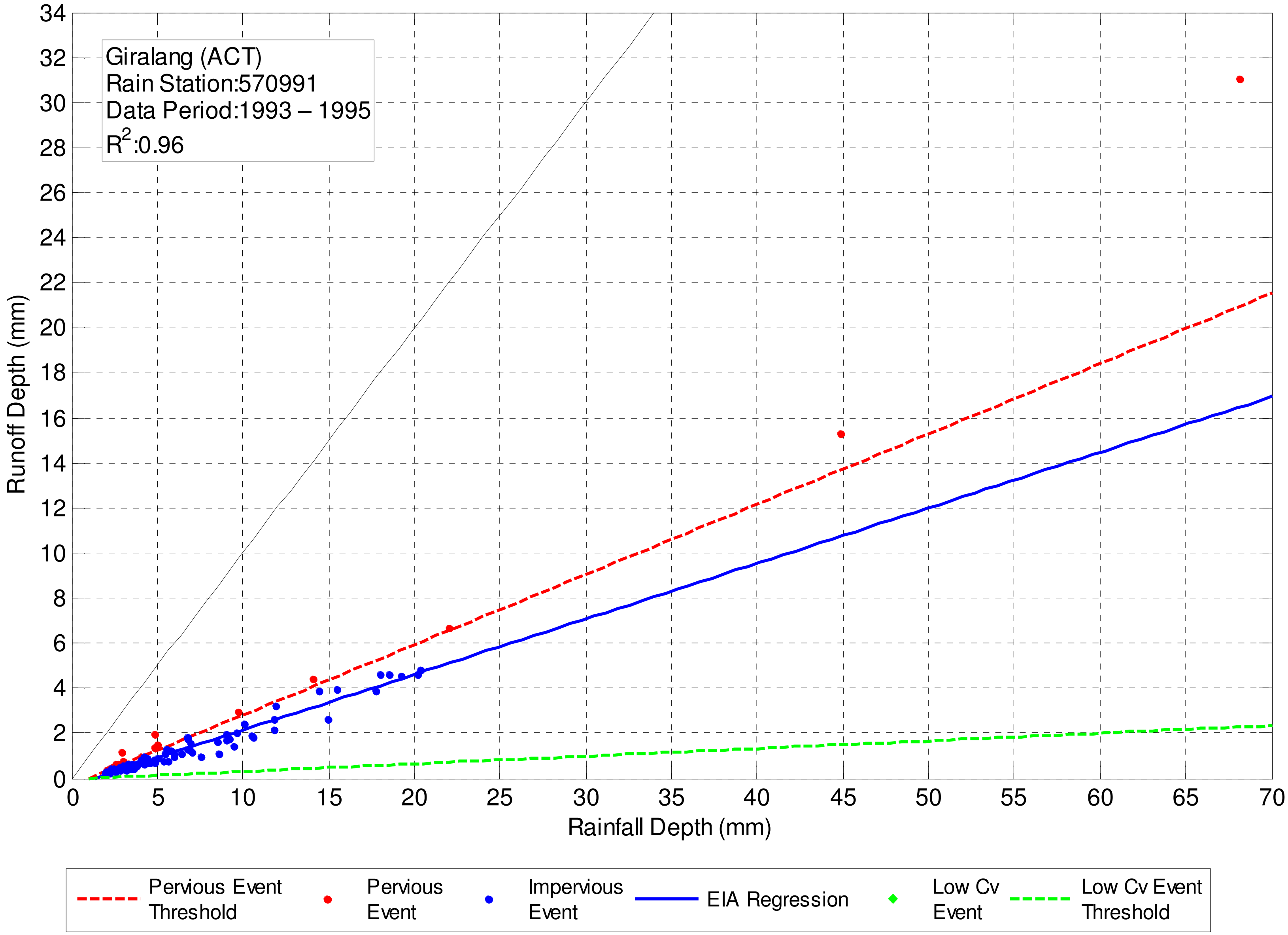


Figure C-6. Regression of Rainfall and Runoff – Giralang (ACT), Rain Gauge 570991, Data Period 1993 - 1995

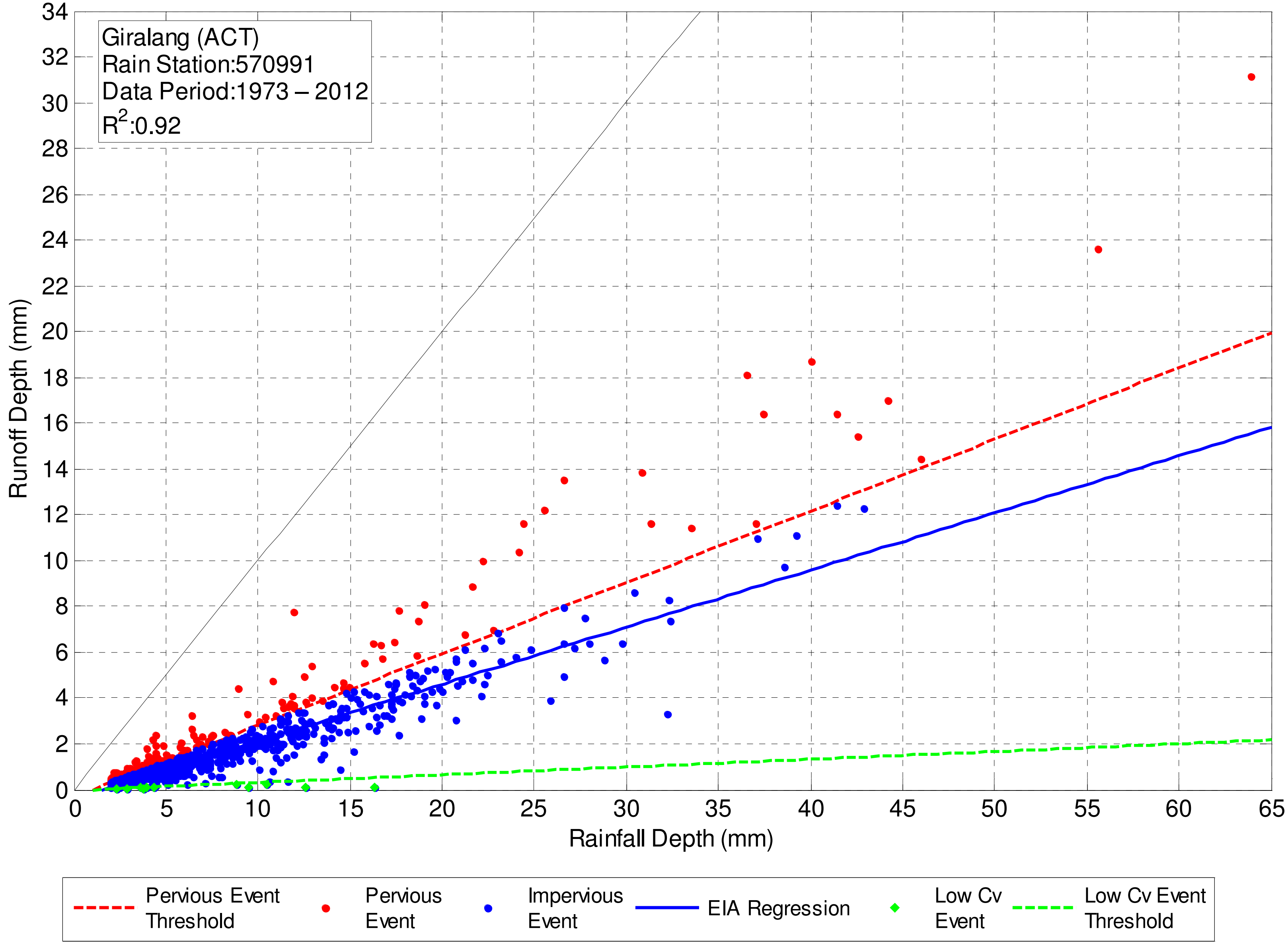


Figure C-7. Regression of Rainfall and Runoff – Giralang (ACT), Rain Gauge 570991, Data Period 1973 - 2012

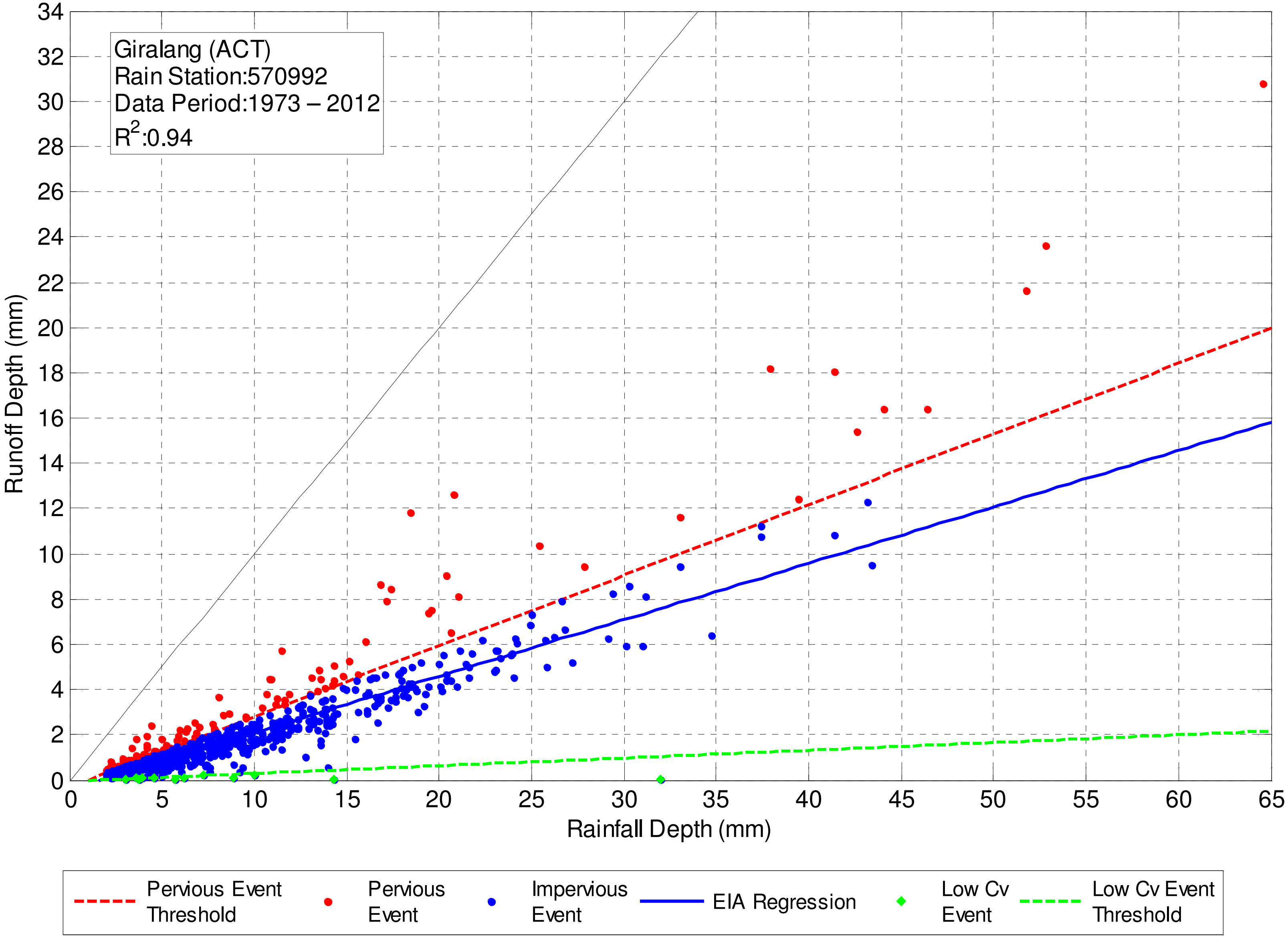


Figure C-8. Regression of Rainfall and Runoff – Giralang (ACT), Rain Gauge 570992, Data Period 1973 - 2012

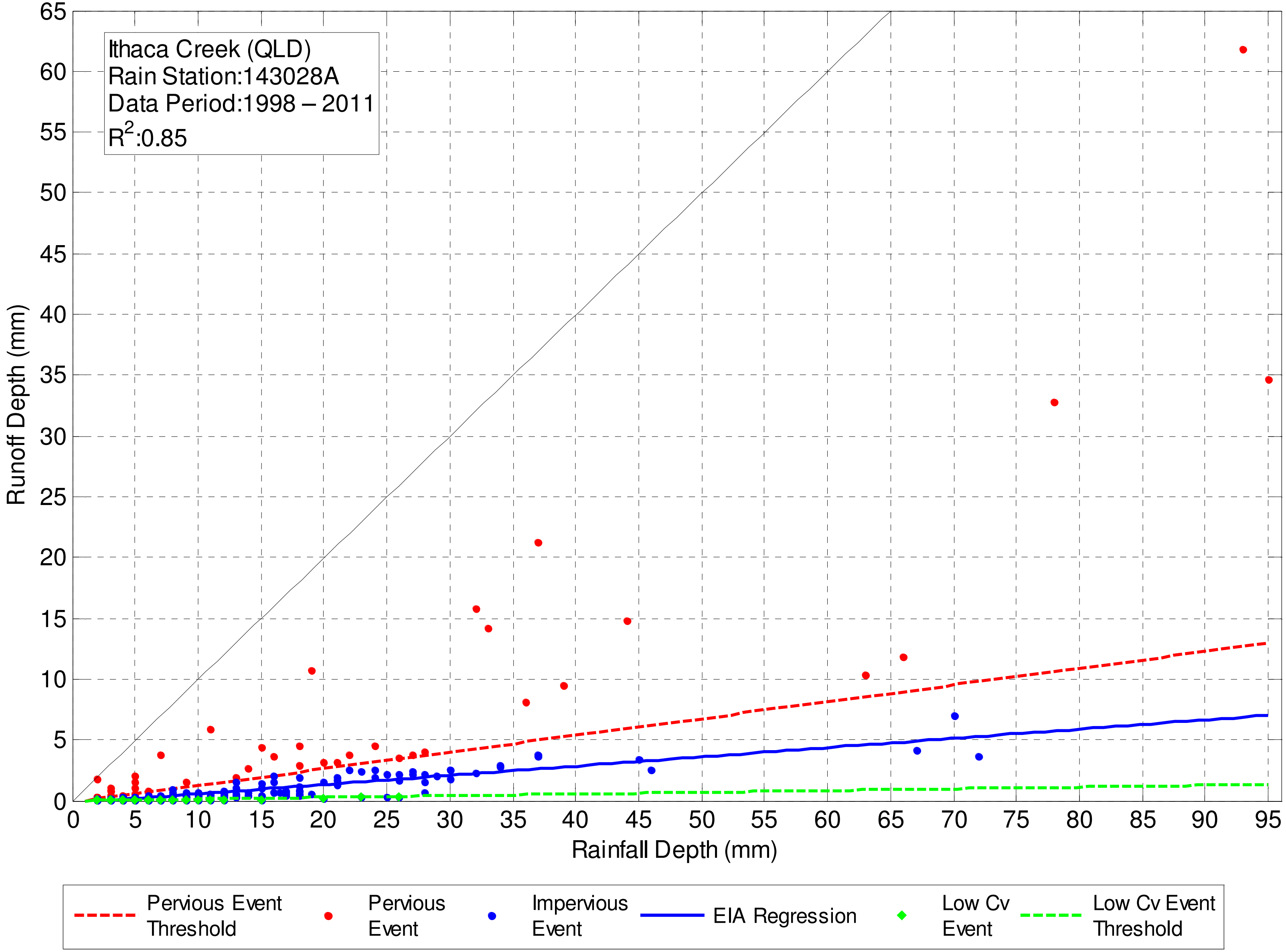


Figure C-9. Regression of Rainfall and Runoff – Ithaca Creek (QLD)

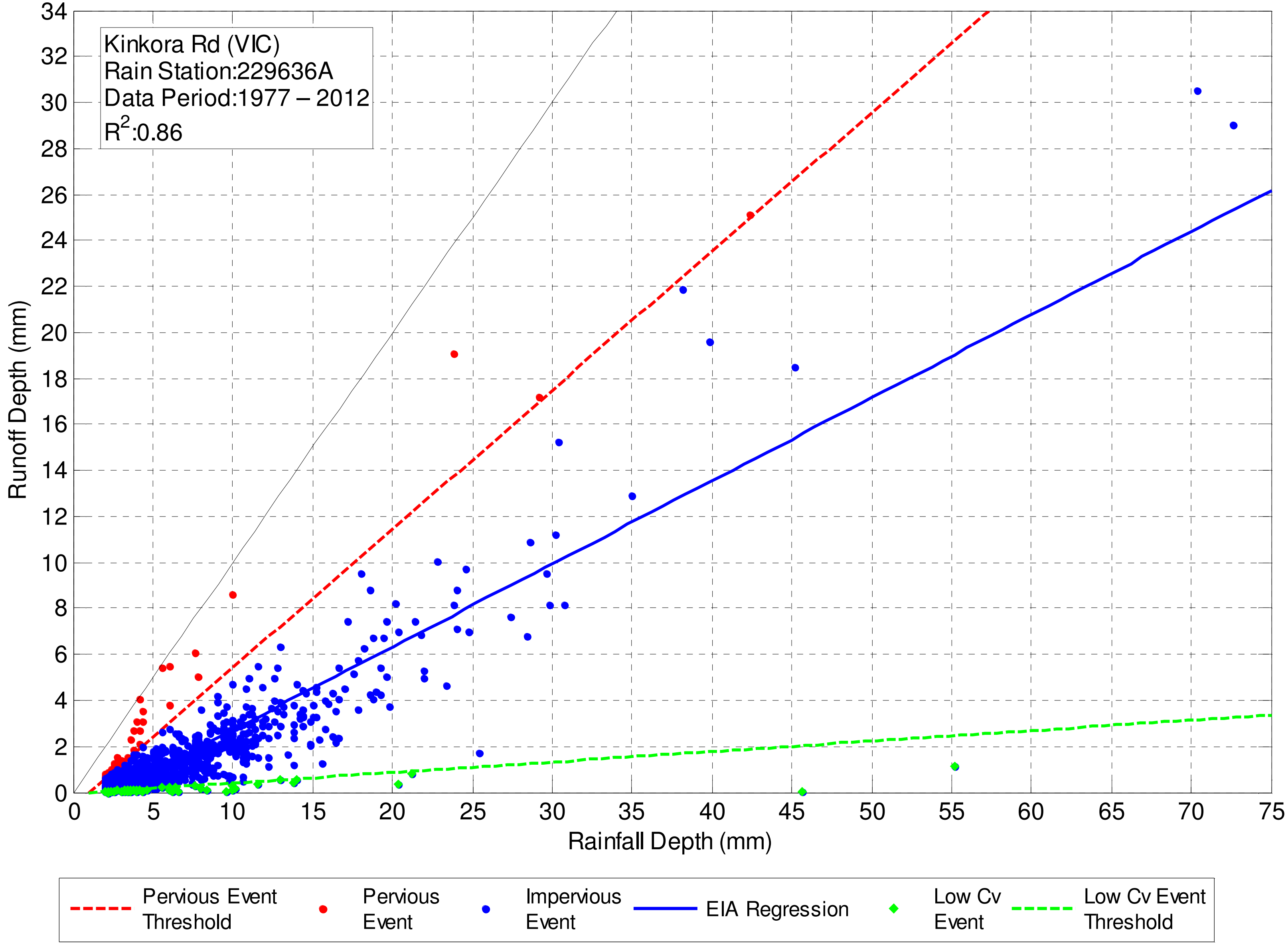


Figure C-10. Regression of Rainfall and Runoff – Kinkora Road (VIC)

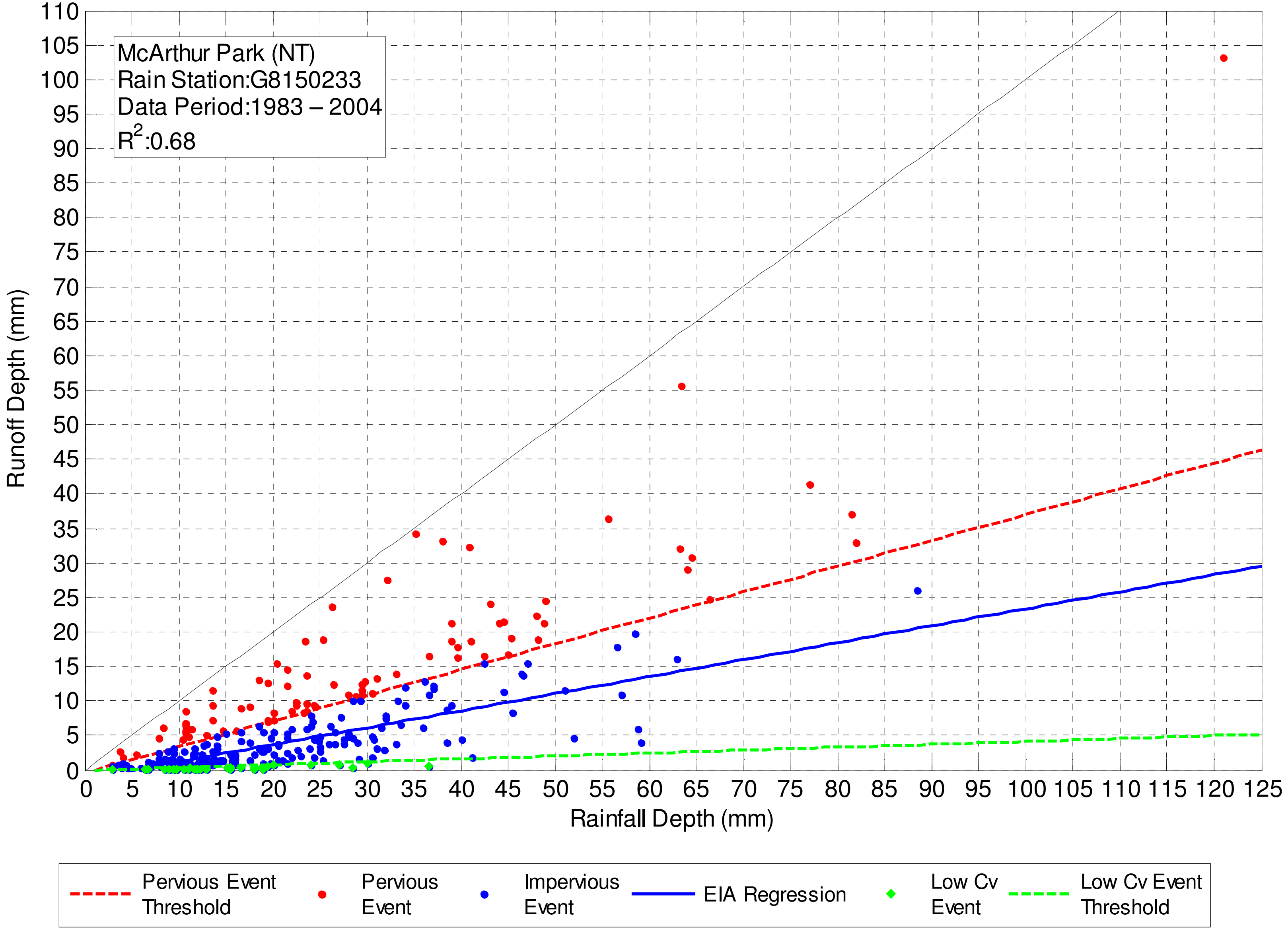


Figure C-11. Regression of Rainfall and Runoff – McArthur Park (NT)

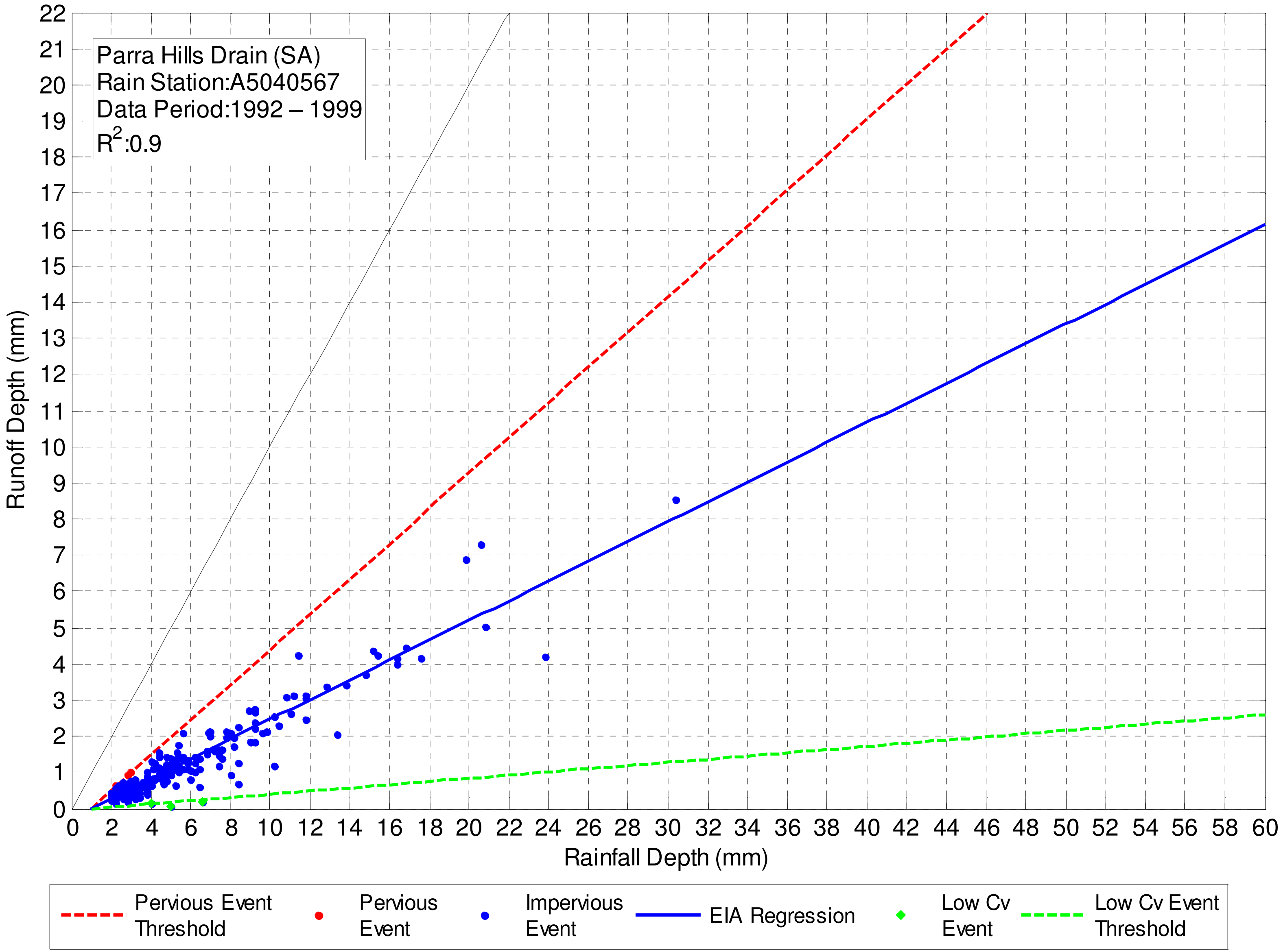


Figure C-12. Regression of Rainfall and Runoff – Para Hills Drain (SA)

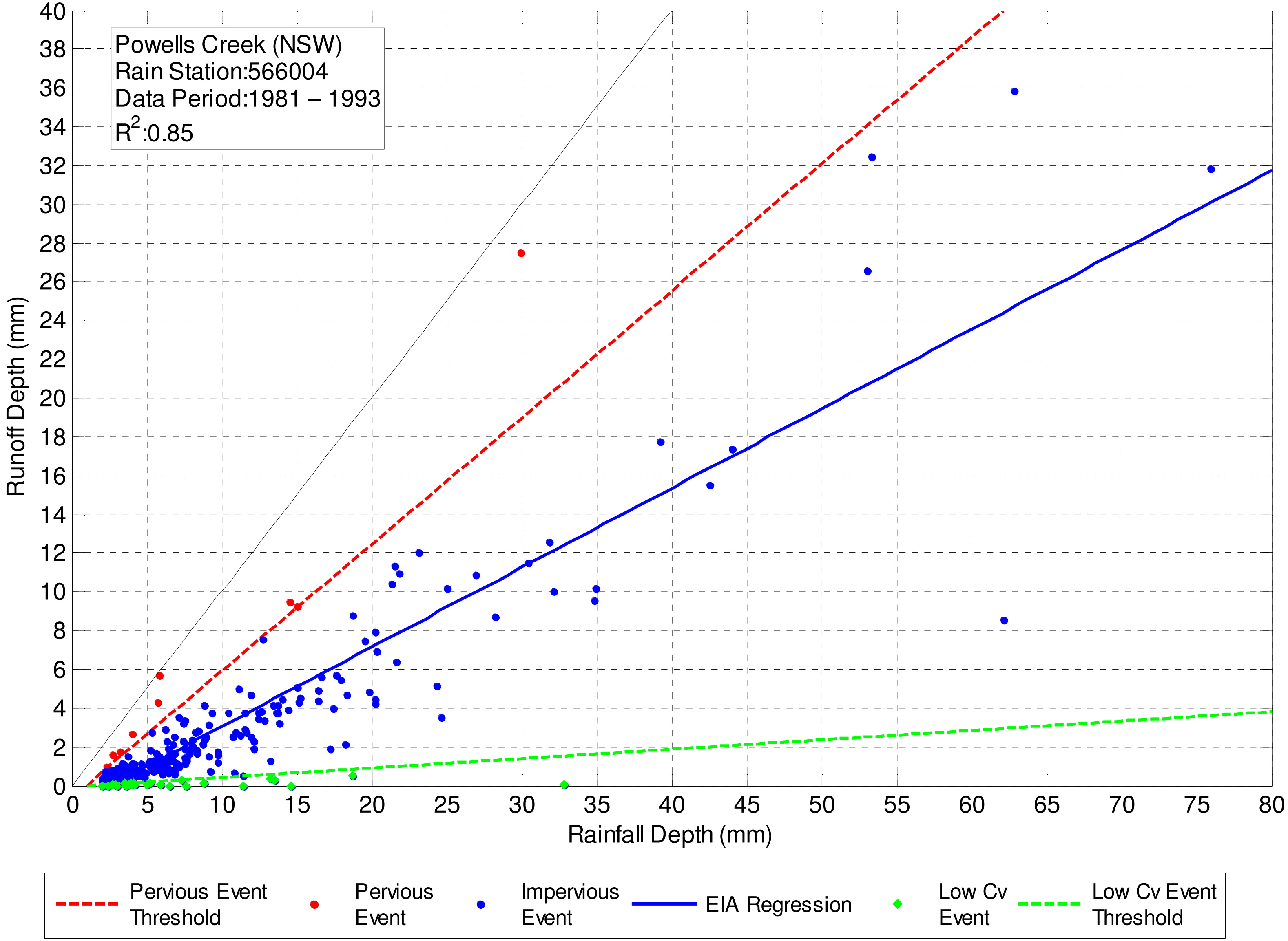


Figure C-13. Regression of Rainfall and Runoff – Powells Creek (NSW), Rain Gauge 566004

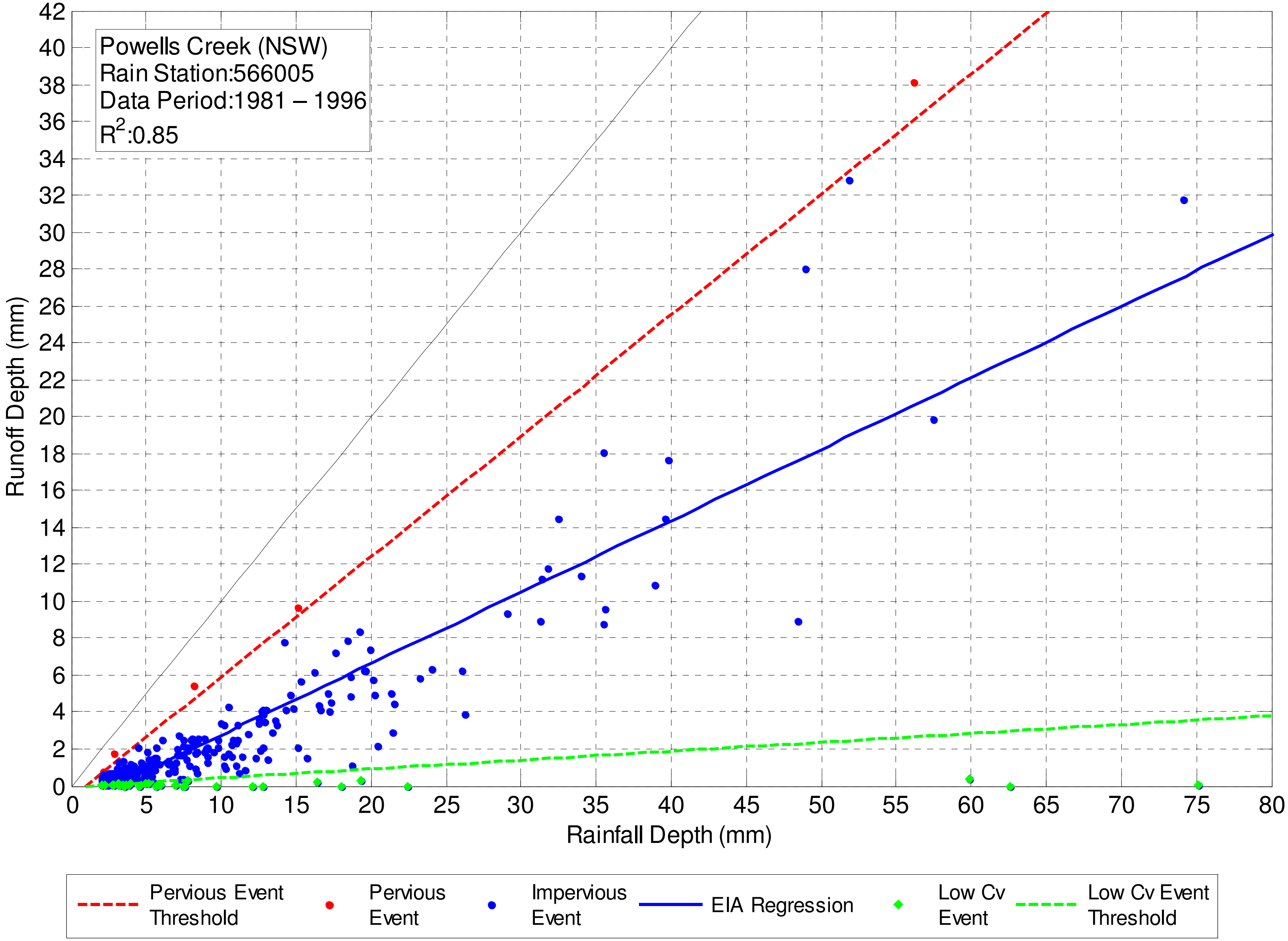


Figure C-14. Regression of Rainfall and Runoff – Powells Creek (NSW), Rain Gauge 566005

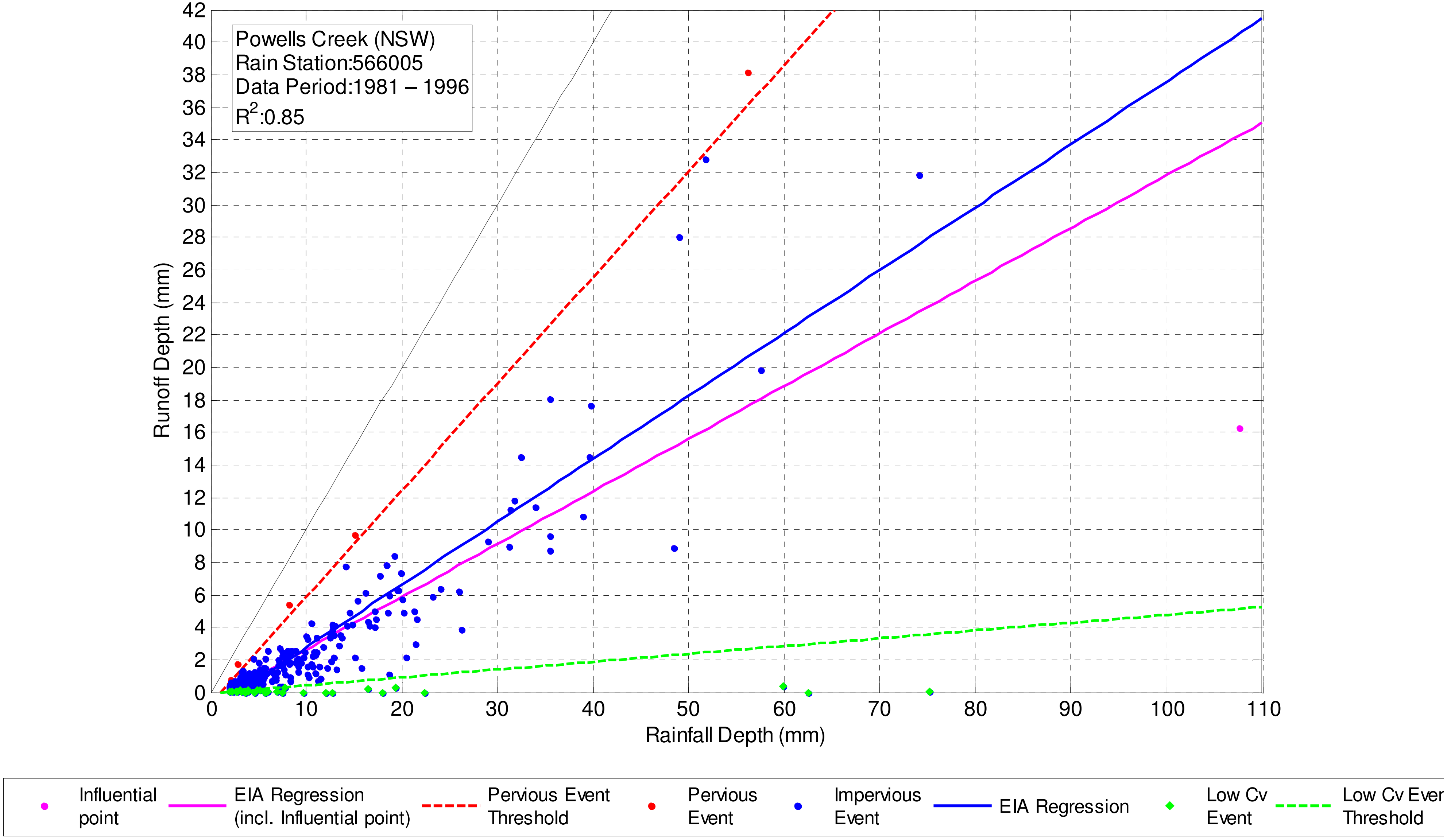
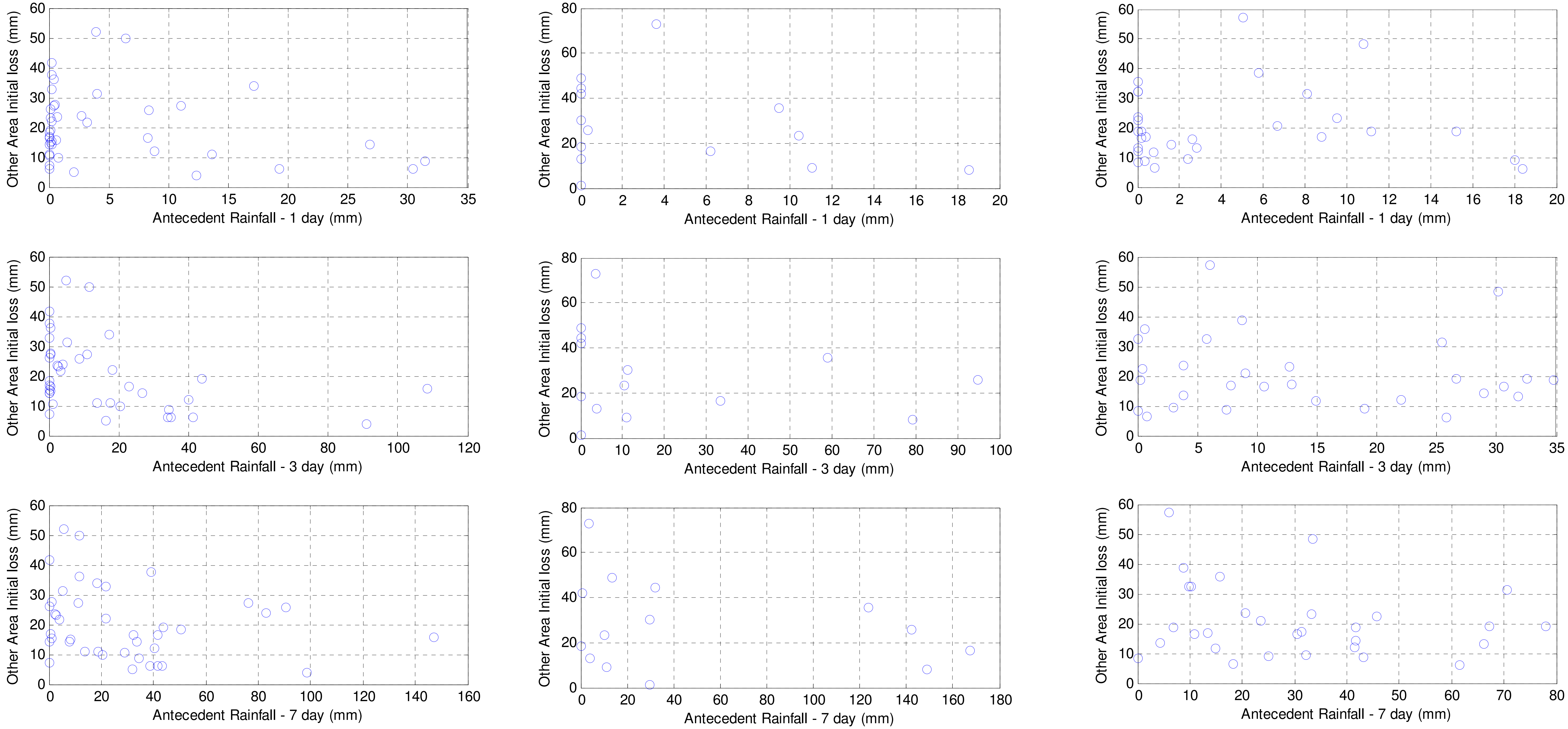


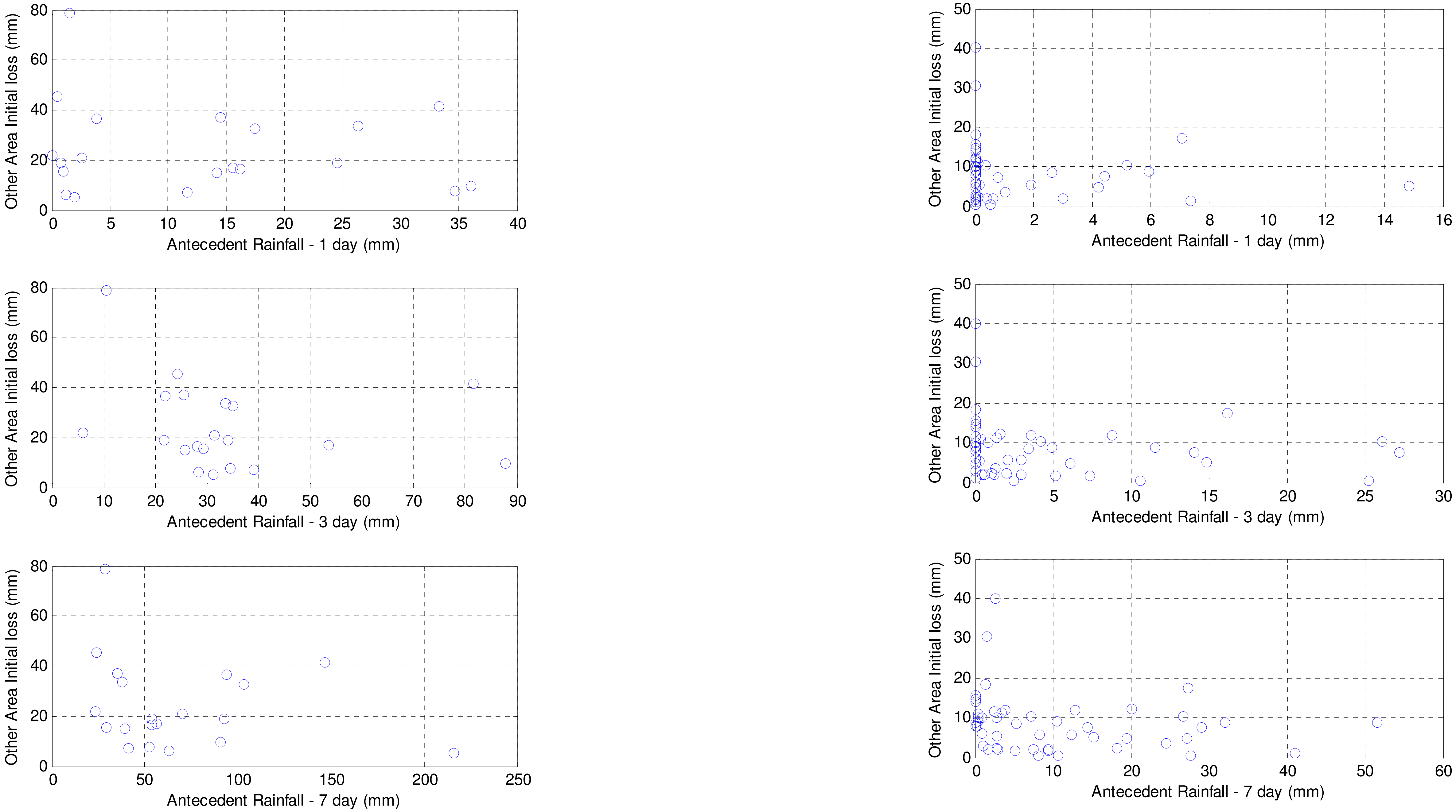
Figure C-15. Regression of Rainfall and Runoff – Powells Creek (NSW), Rain Gauge 566005, with influential data point

Appendix D – Other Area Initial Loss Correlation Analysis



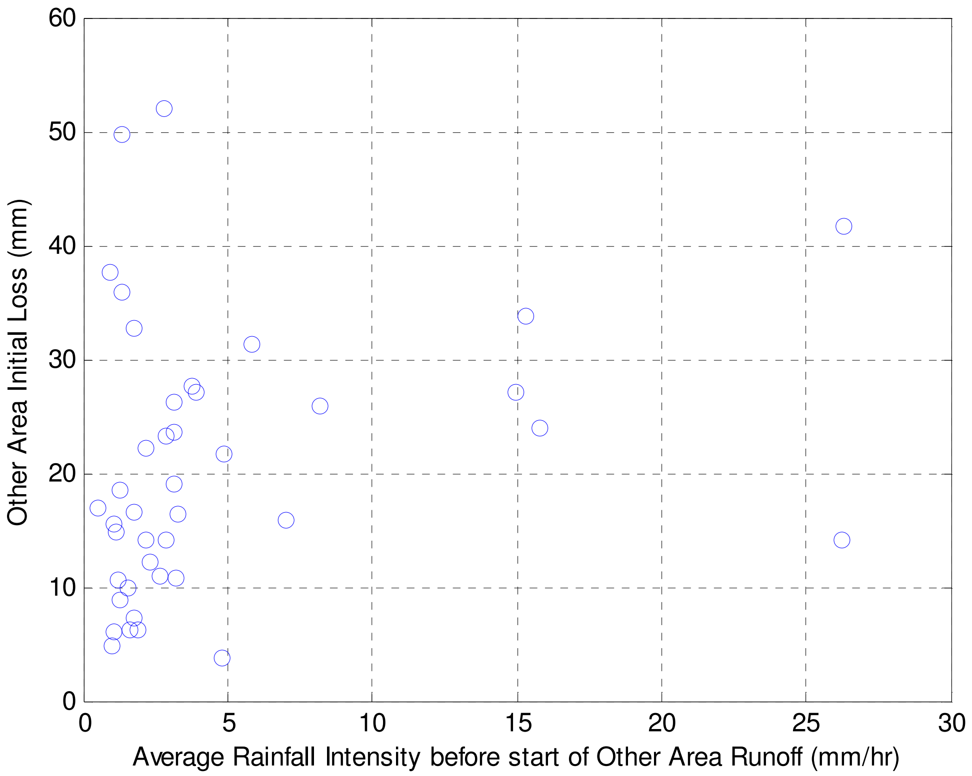
Giralang (ACT) **Powells Creek (NSW)** **Albany Drain (WA)**

Figure D-1. Correlation Analysis – Other Area Initial Loss vs Antecedent Rainfall

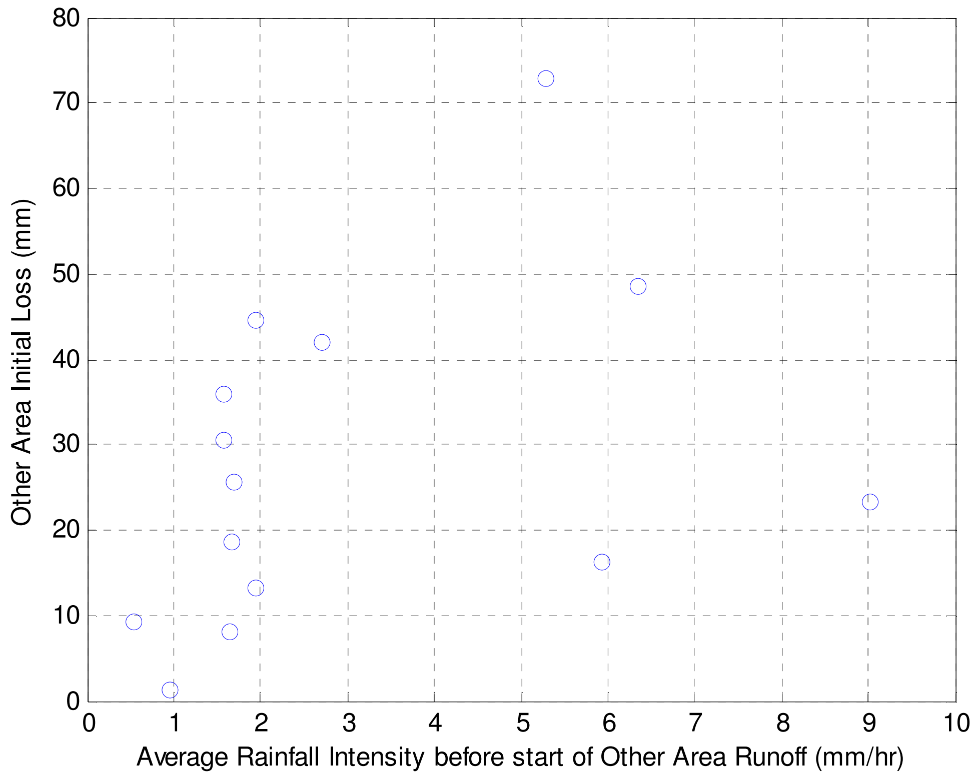


McArthur Park (NT) **Argyle Street (TAS)**

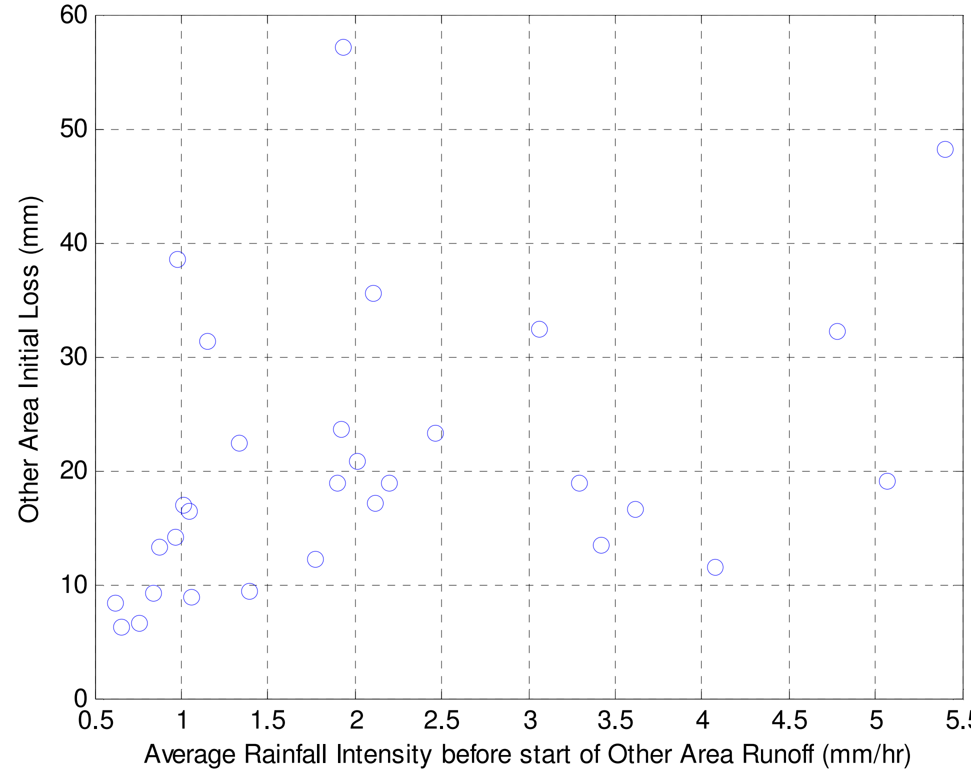
Figure D-2. Correlation Analysis – Other Area Initial Loss vs Antecedent Rainfall



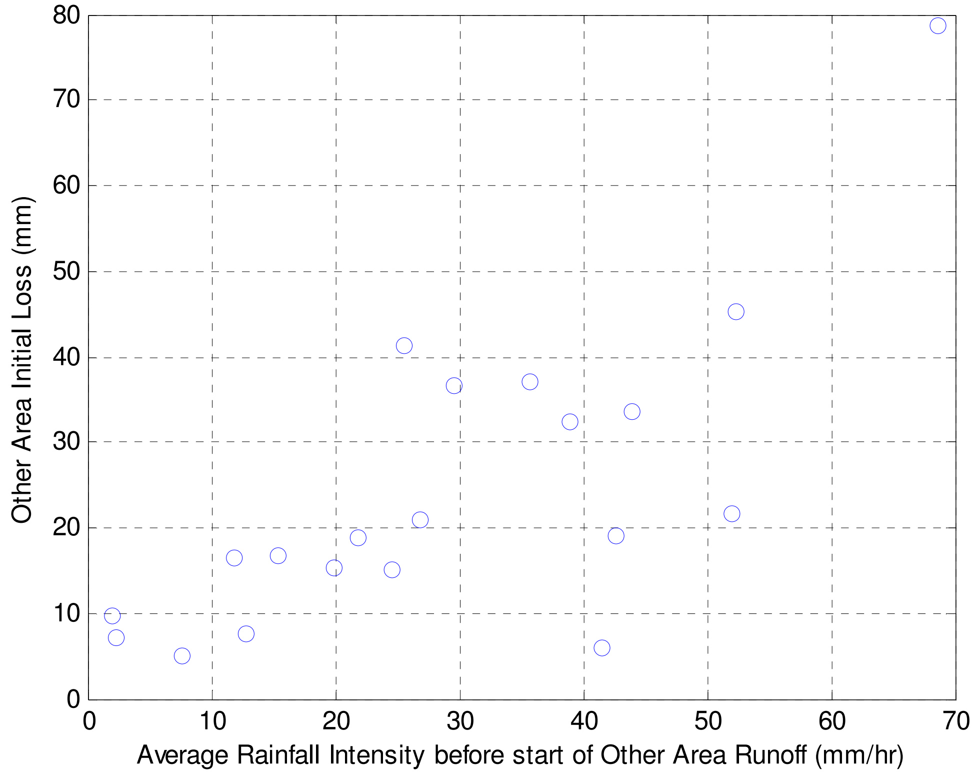
Giralang (ACT)



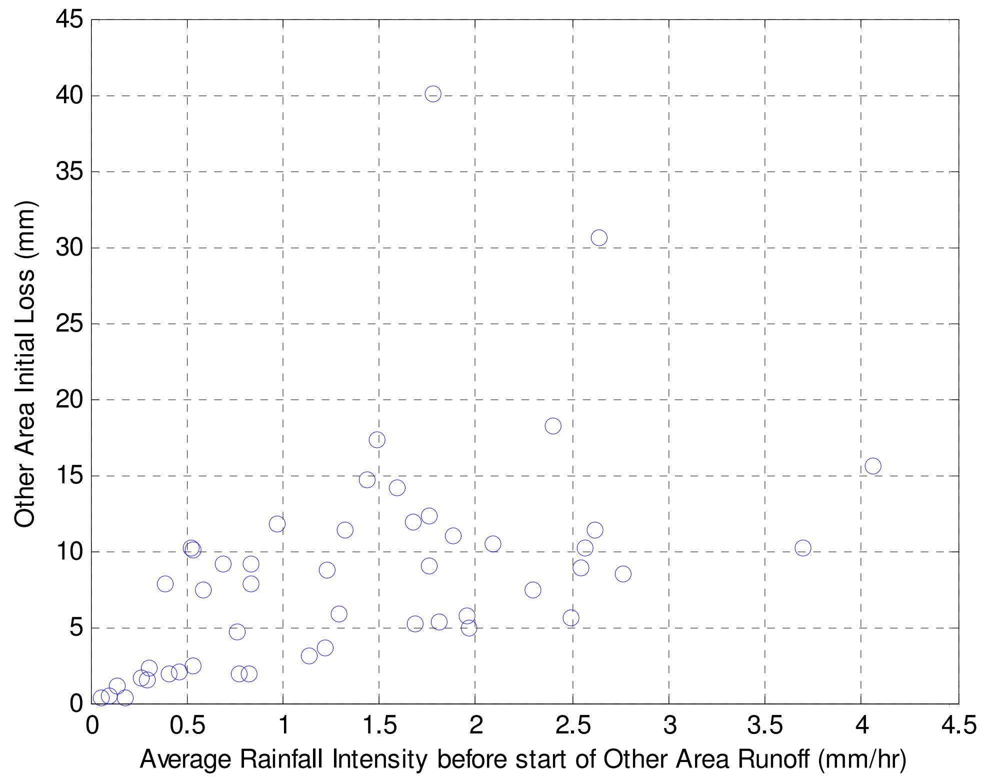
Powells Creek (NSW)



Albany Drain (WA)



McArthur Park (NT)



Argyle Street (TAS)

Figure D-3. Correlation Analysis – Other Area Initial Loss vs Average Rainfall Intensity prior to Other Area Runoff

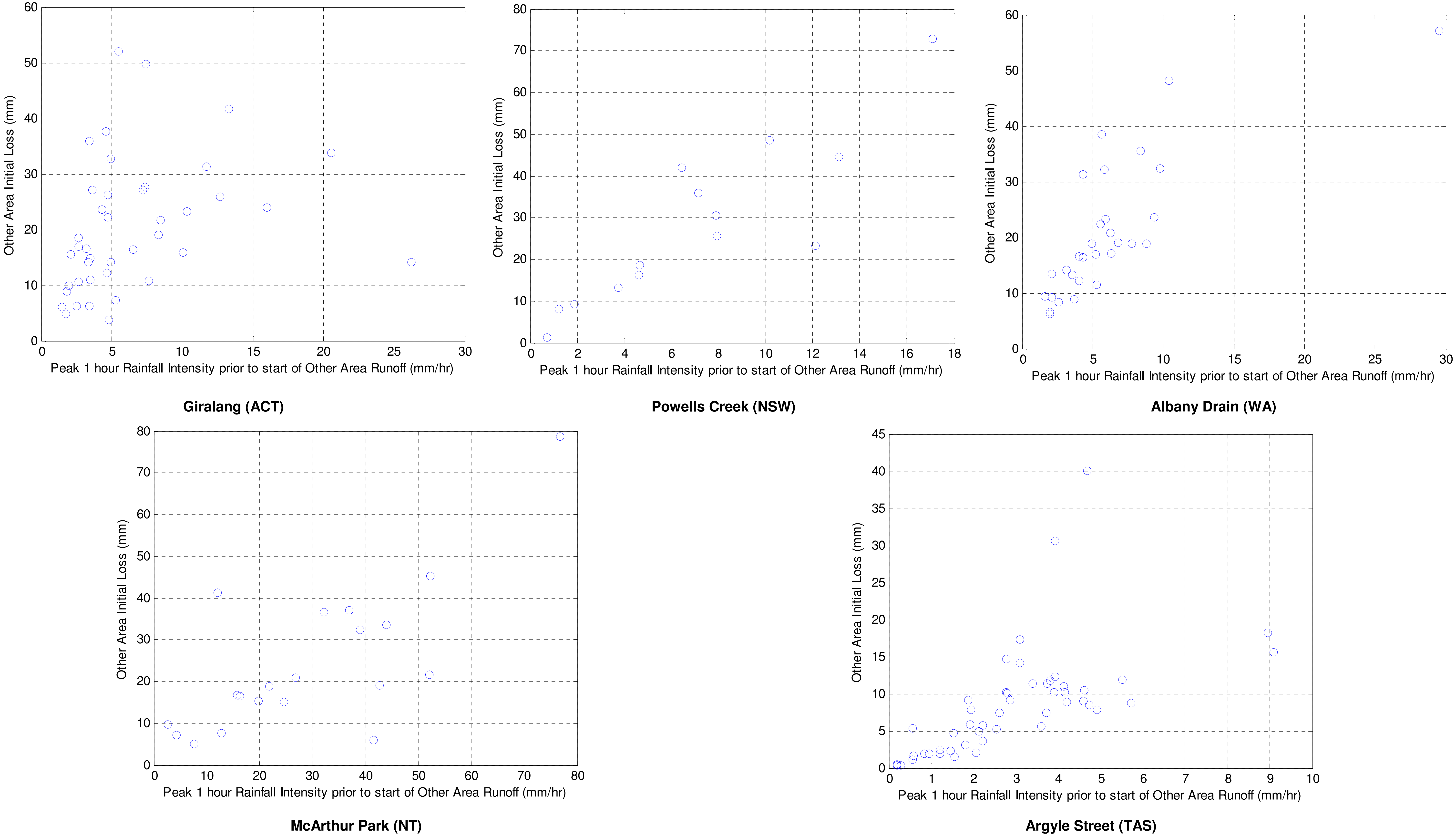
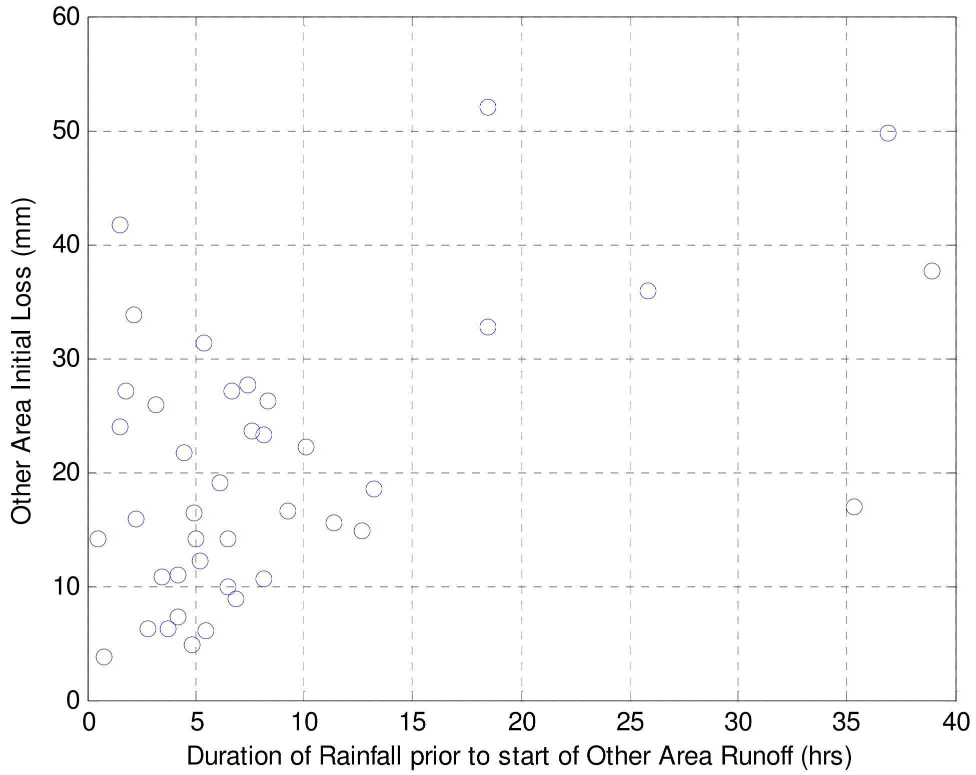
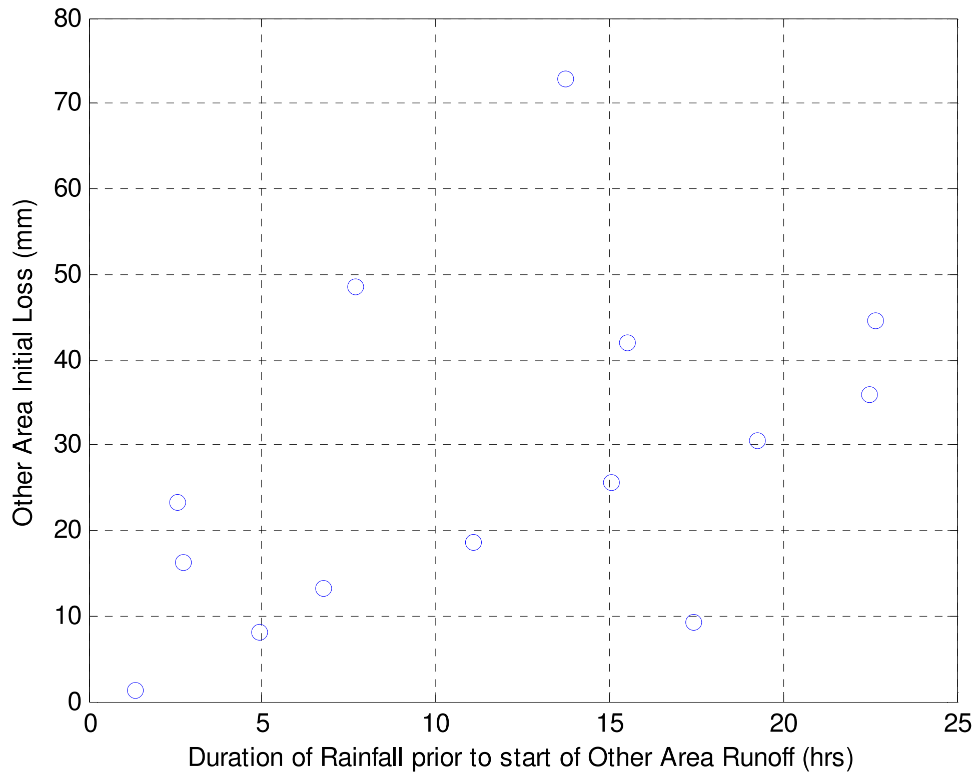


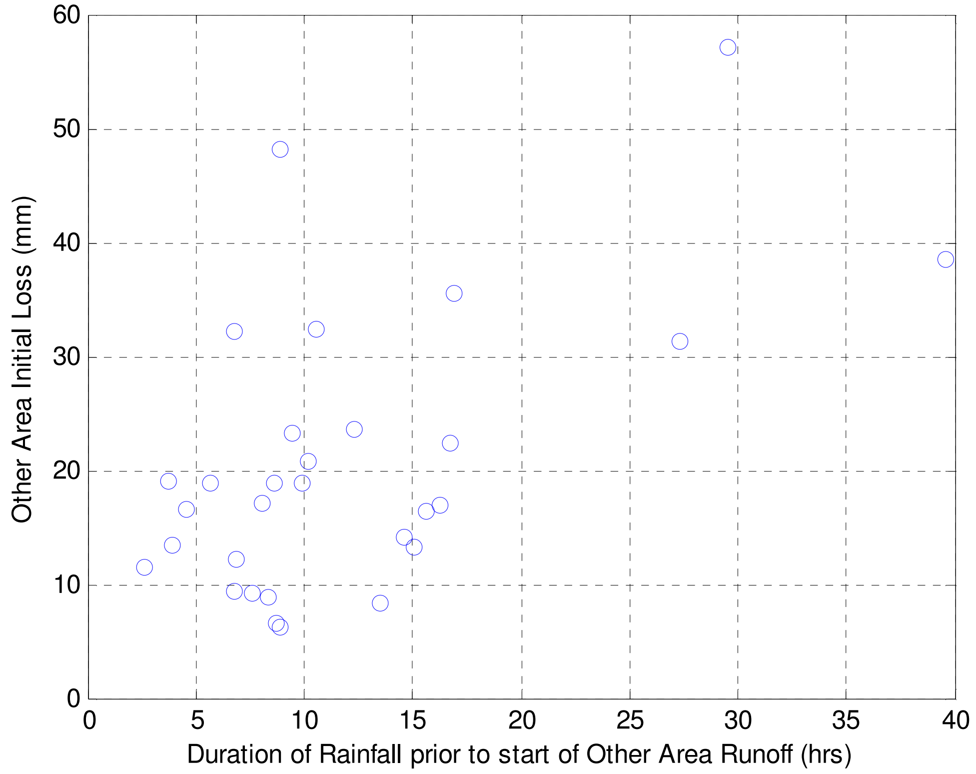
Figure D-4. Correlation Analysis – Other Area Initial Loss vs Peak 1 hour Rainfall Intensity prior to Other Area Runoff



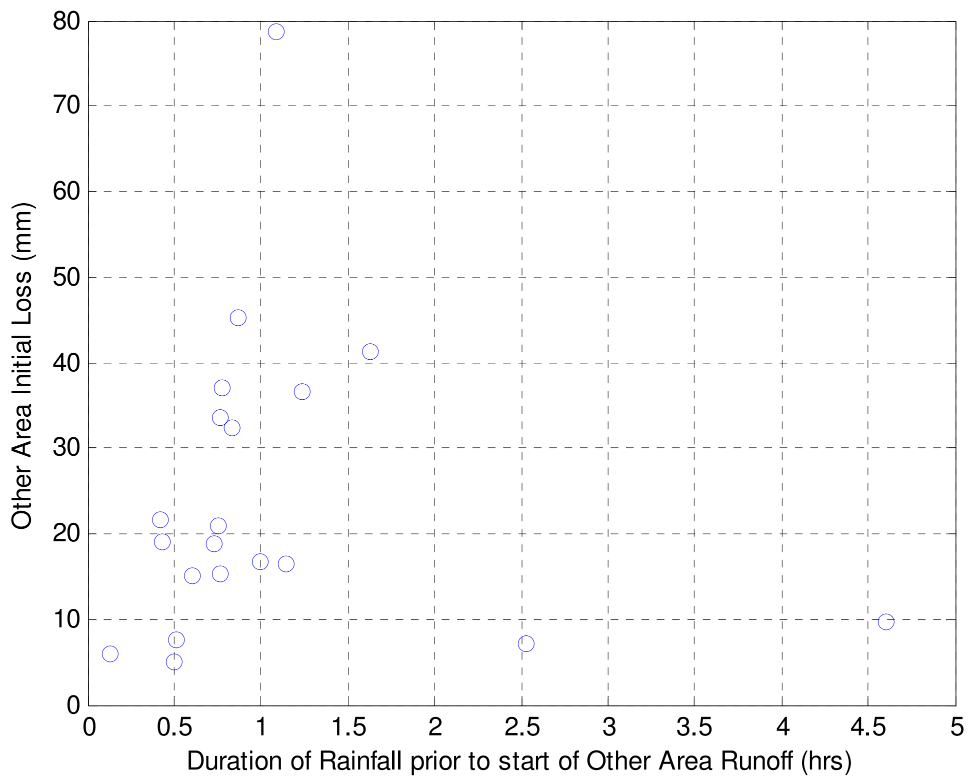
Giralang (ACT)



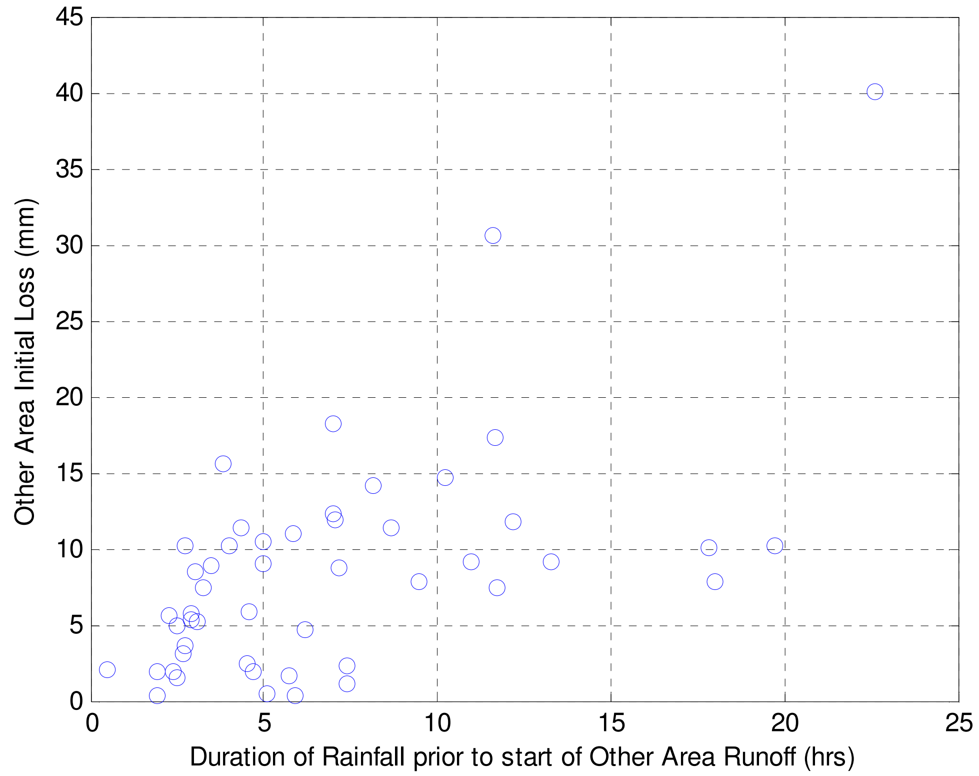
Powells Creek (NSW)



Albany Drain (WA)

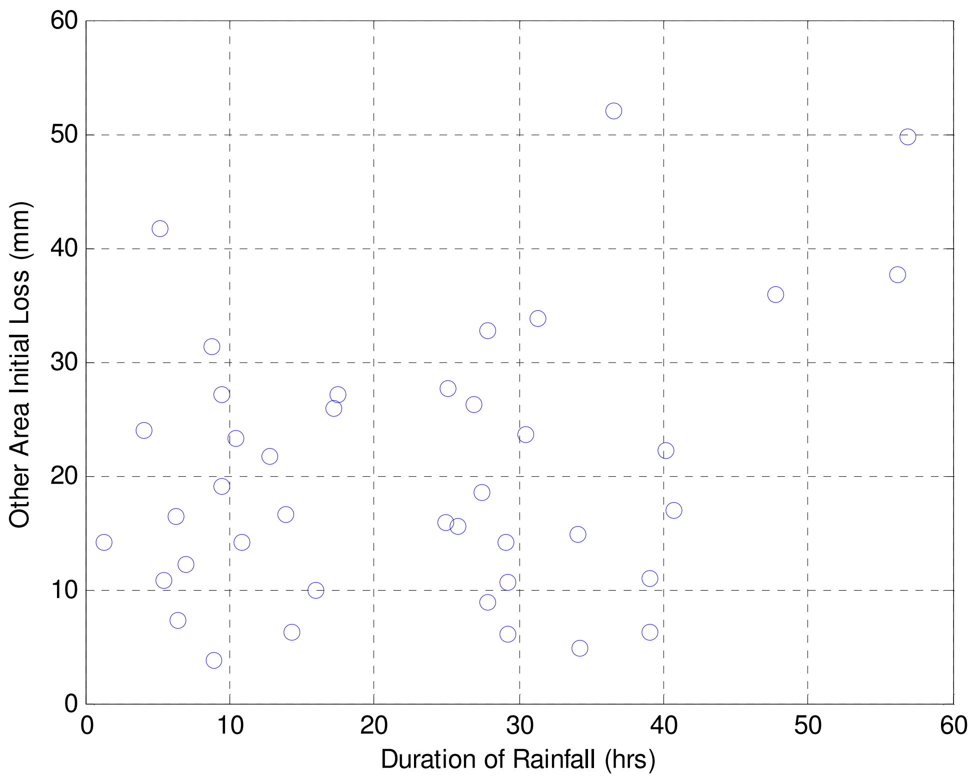


McArthur Park (NT)

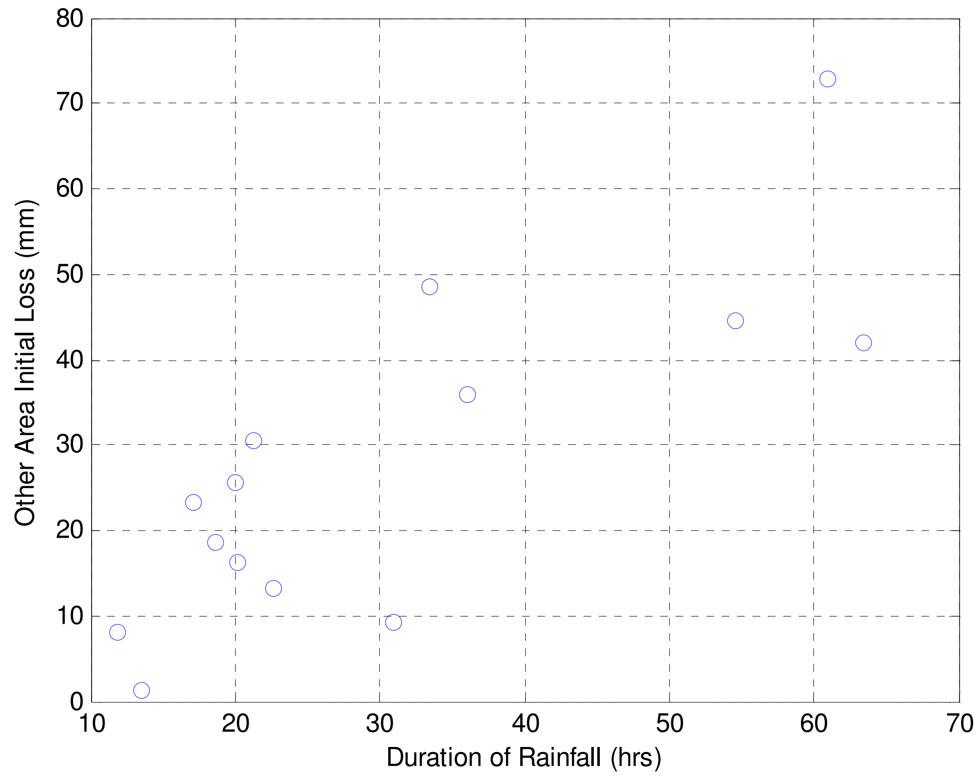


Argyle Street (TAS)

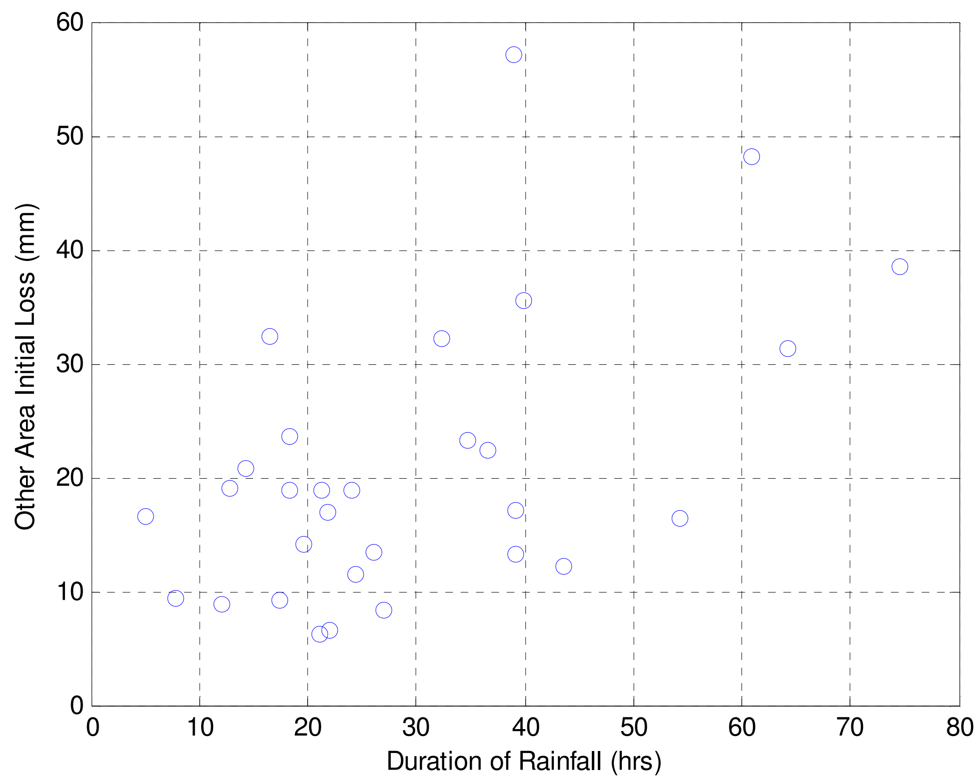
Figure D-5. Correlation Analysis – Other Area Initial Loss vs Duration of Rainfall prior to Other Area Runoff



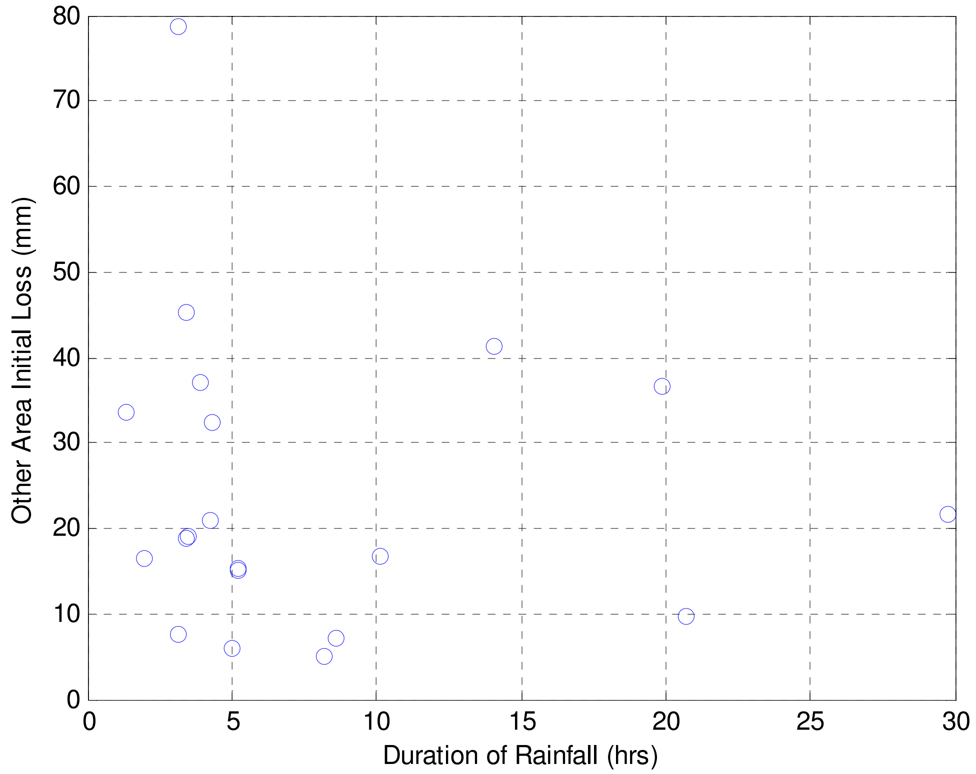
Giralang (ACT)



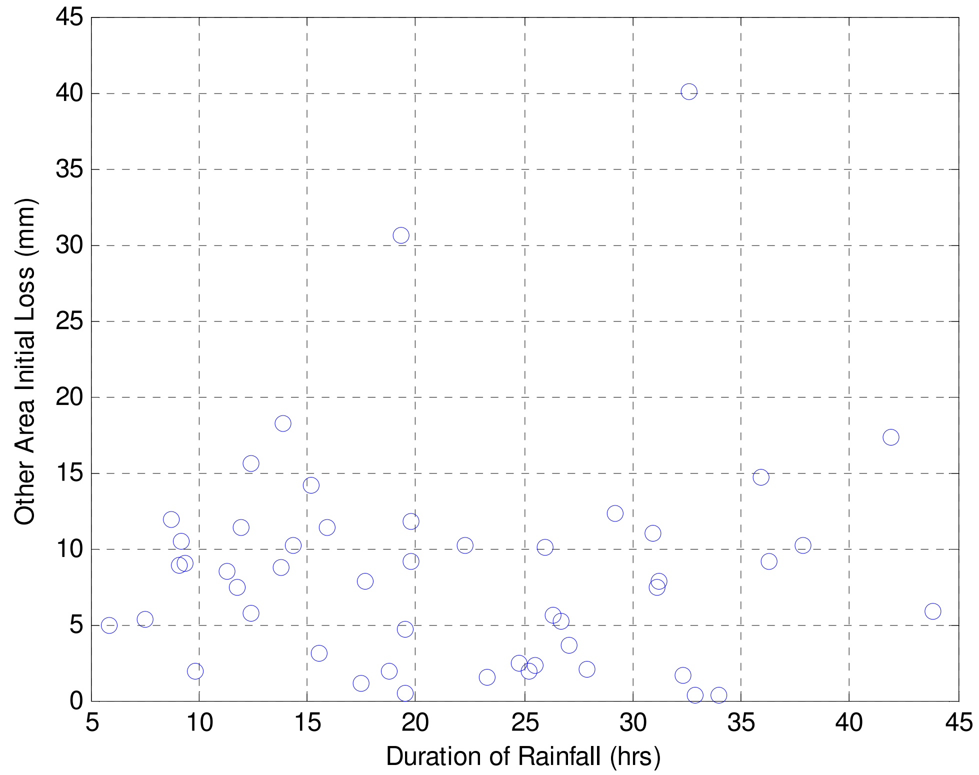
Powells Creek (NSW)



Albany Drain (WA)



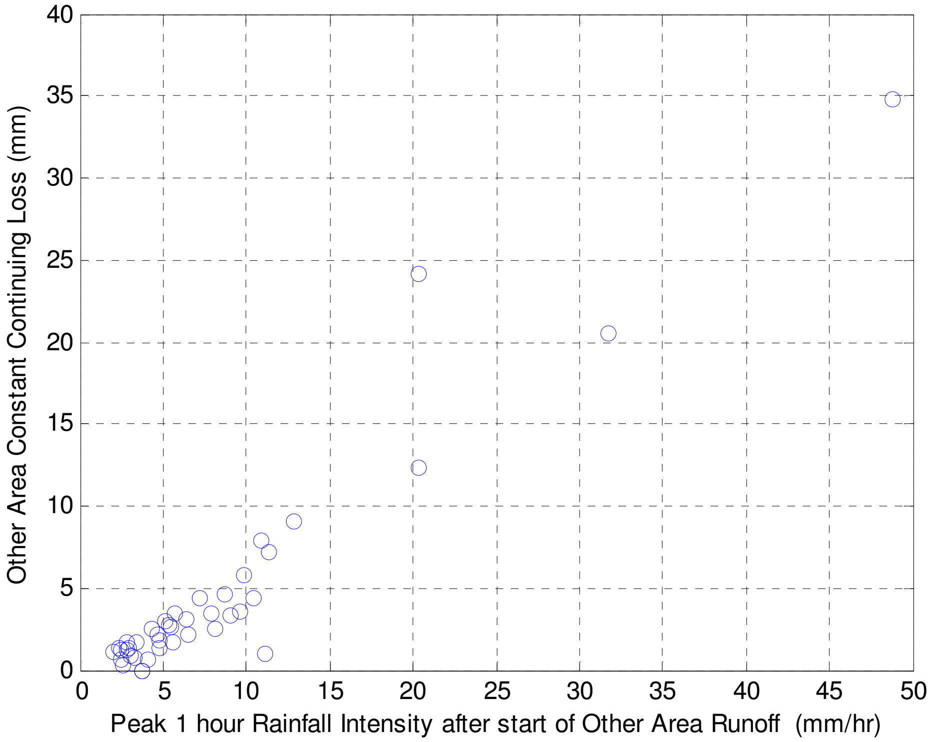
McArthur Park (NT)



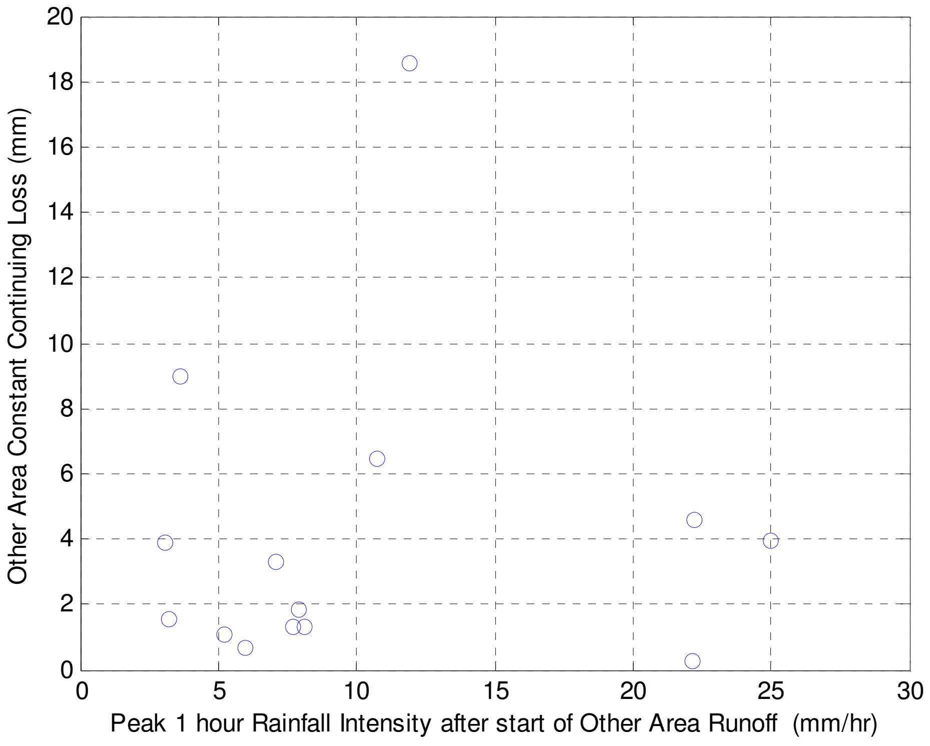
Argyle Street (TAS)

Figure D-6. Correlation Analysis – Other Area Initial Loss vs Duration of Rainfall

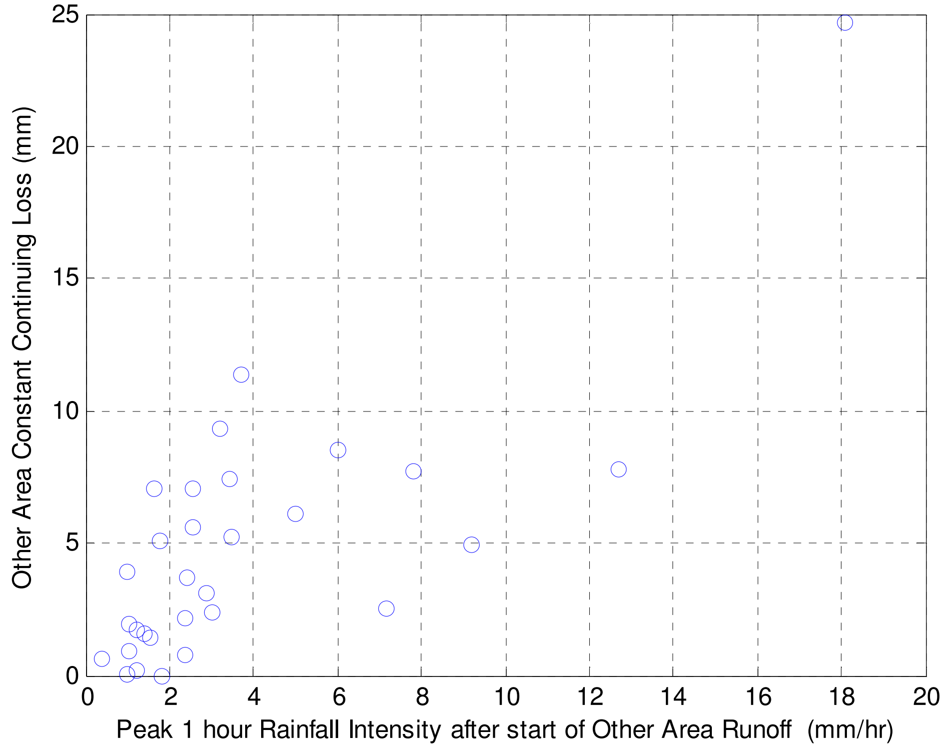
Appendix E – Other Area Continuing Loss Correlation Analysis



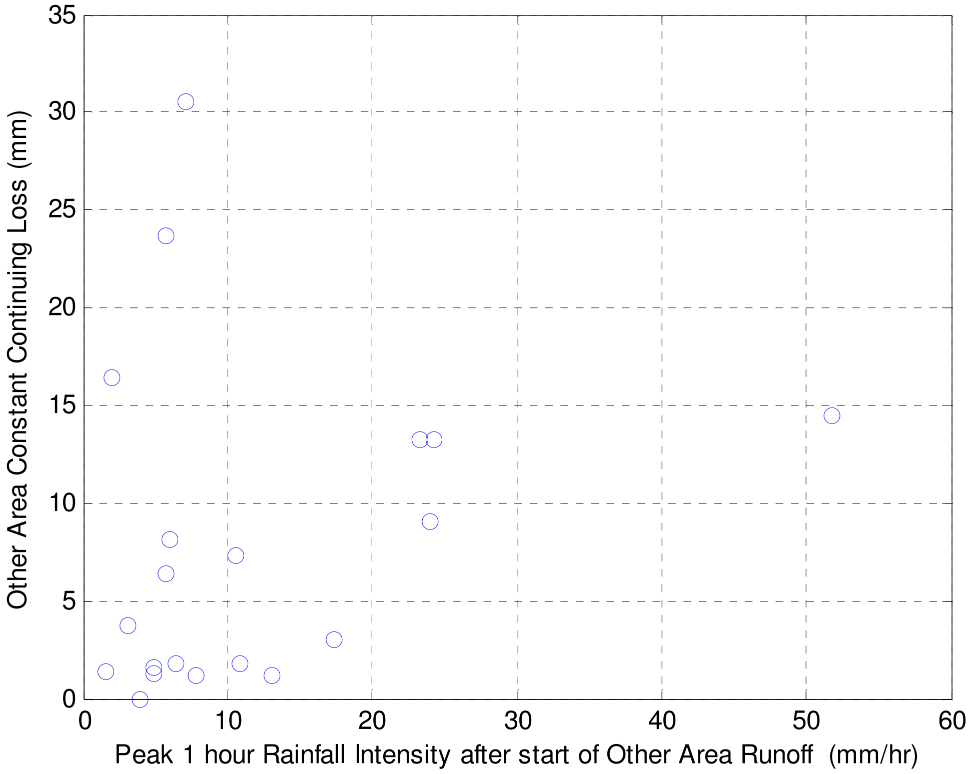
Giralang (ACT)



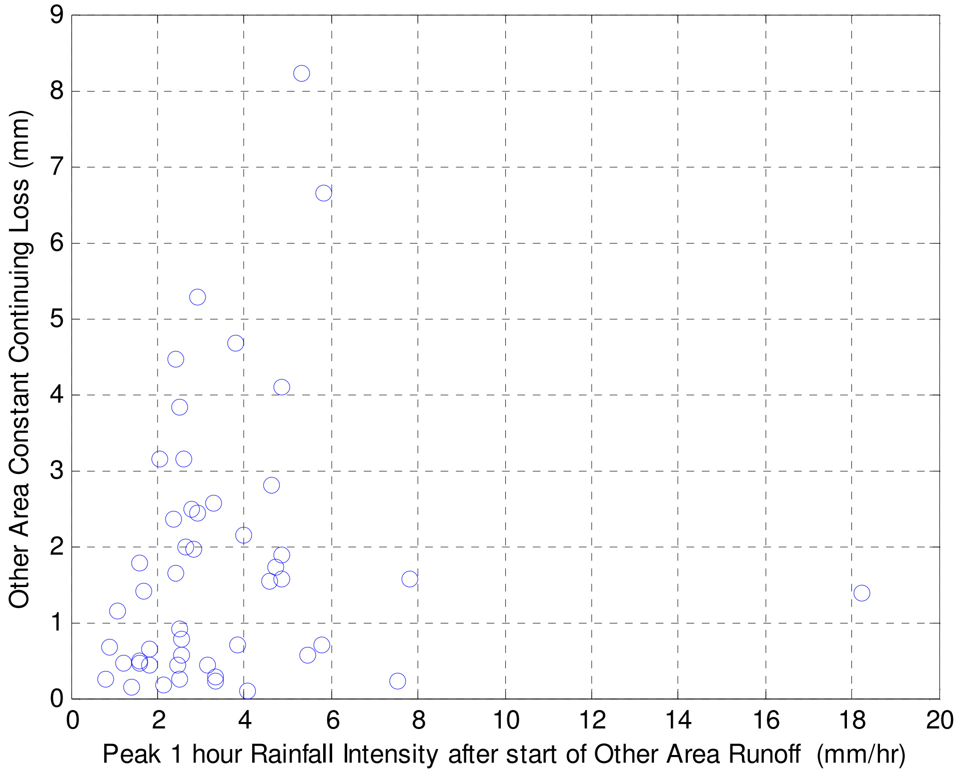
Powells Creek (NSW)



Albany Drain (WA)



McArthur Park (NT)



Argyle Street (TAS)

Figure E-1. Correlation Analysis – Other Area Constant Continuing Loss vs Peak 1 hour Rainfall Intensity

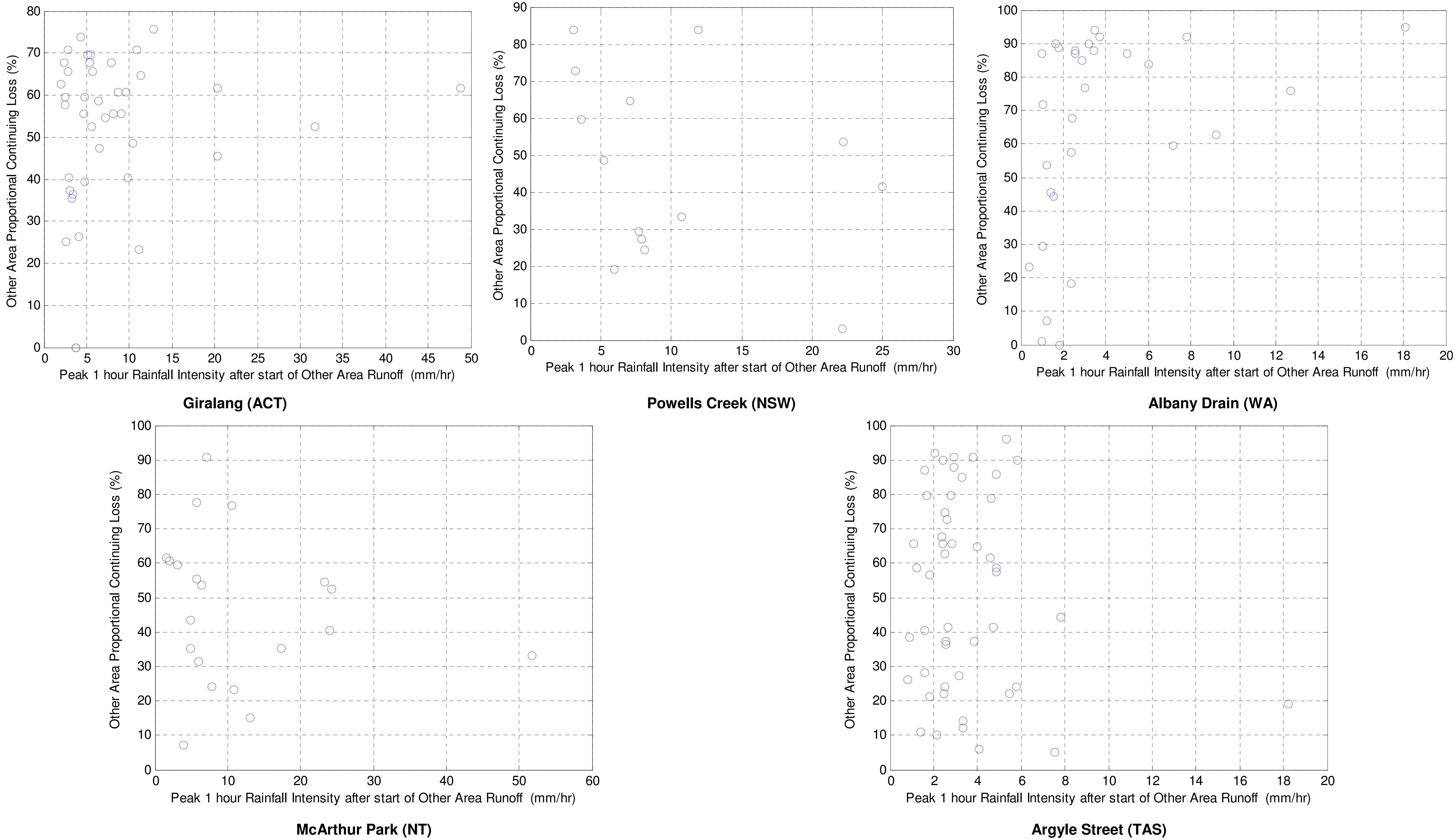
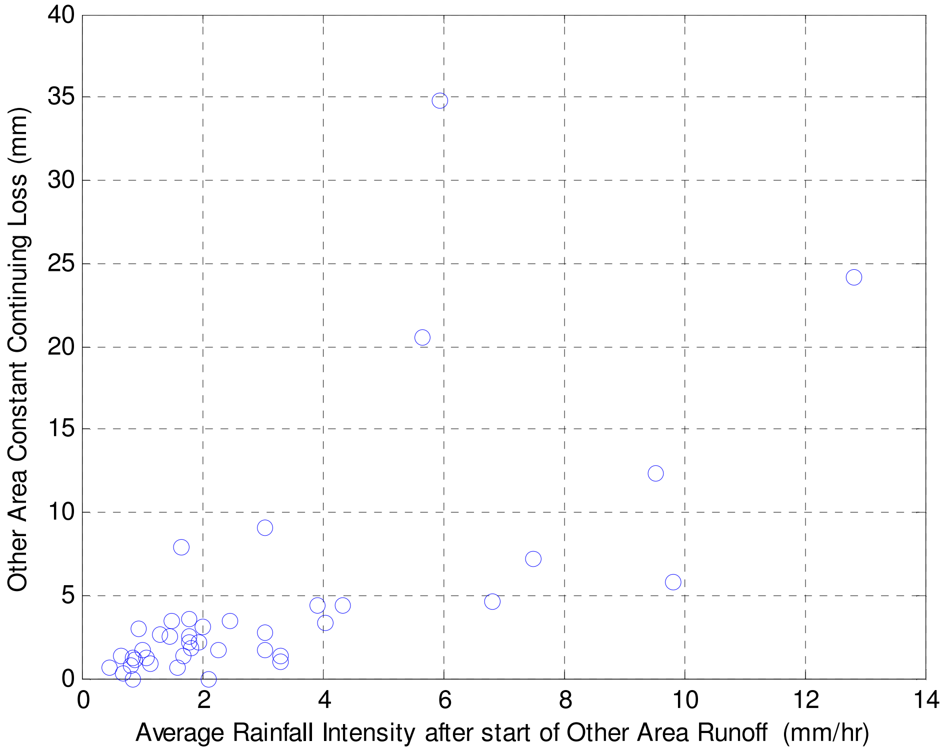
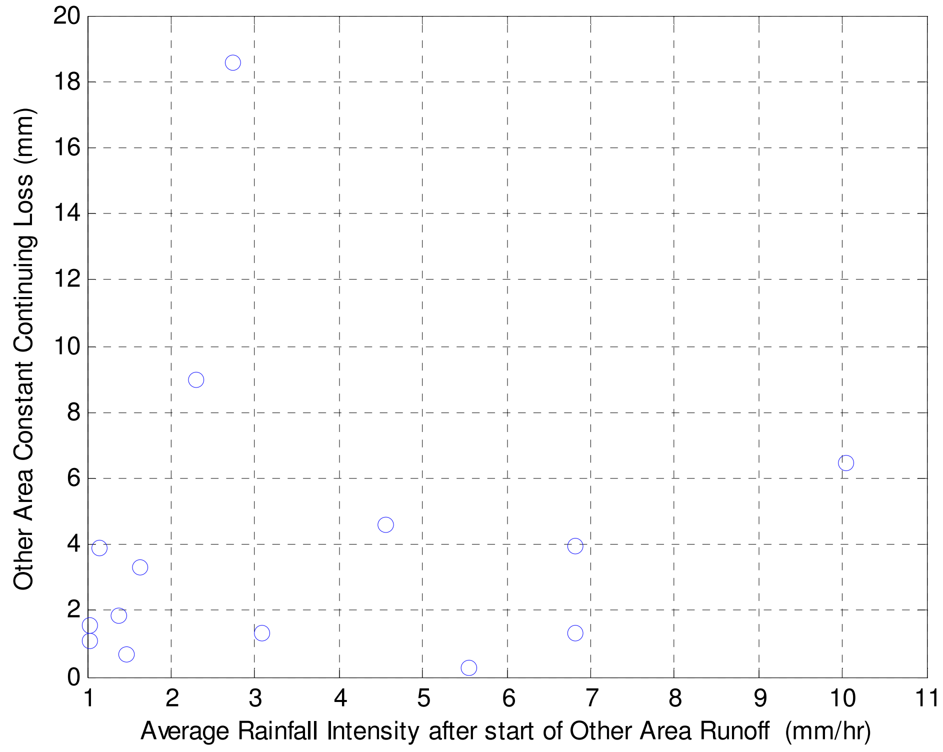


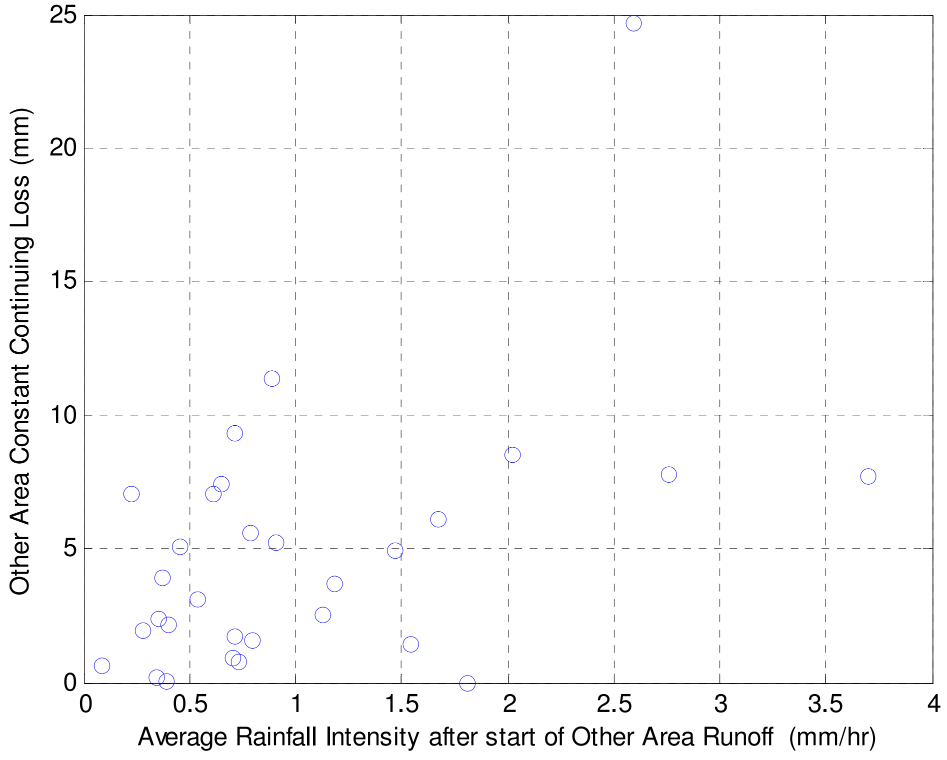
Figure E-2. Correlation Analysis – Other Area Proportional Continuing Loss vs Peak 1 hour Rainfall Intensity



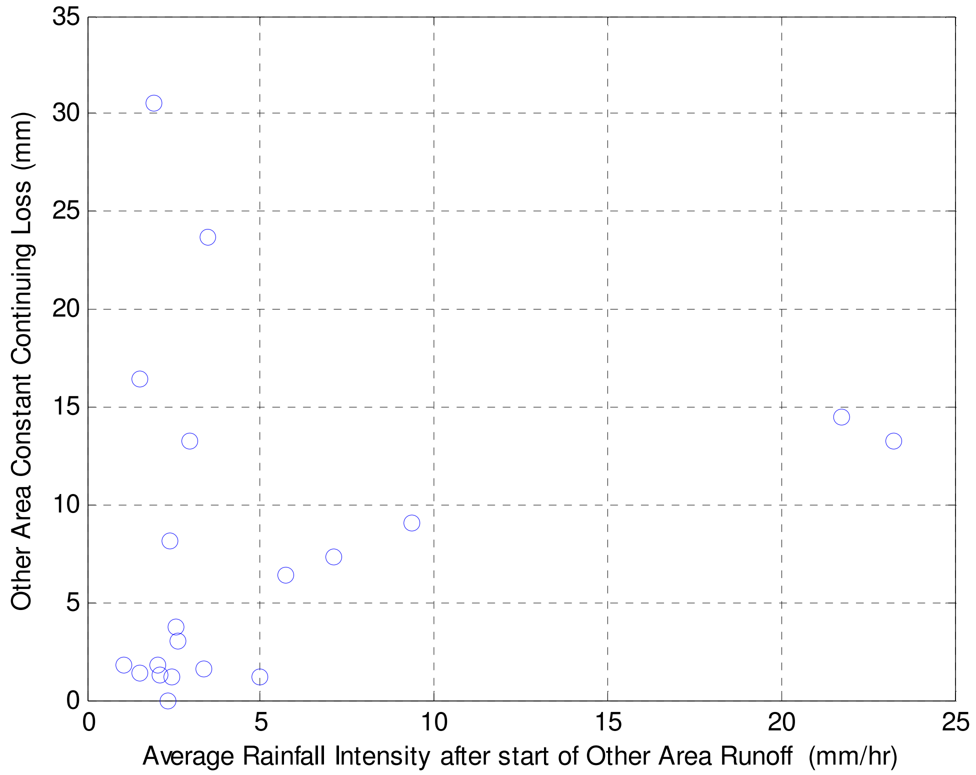
Giralang (ACT)



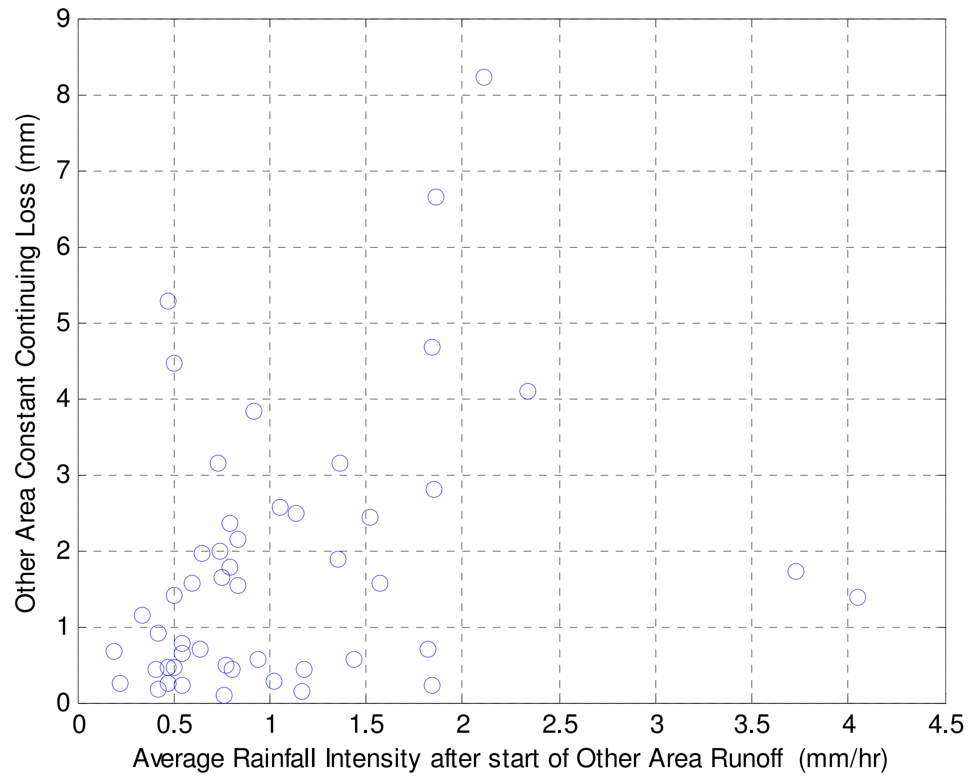
Powells Creek (NSW)



Albany Drain (WA)

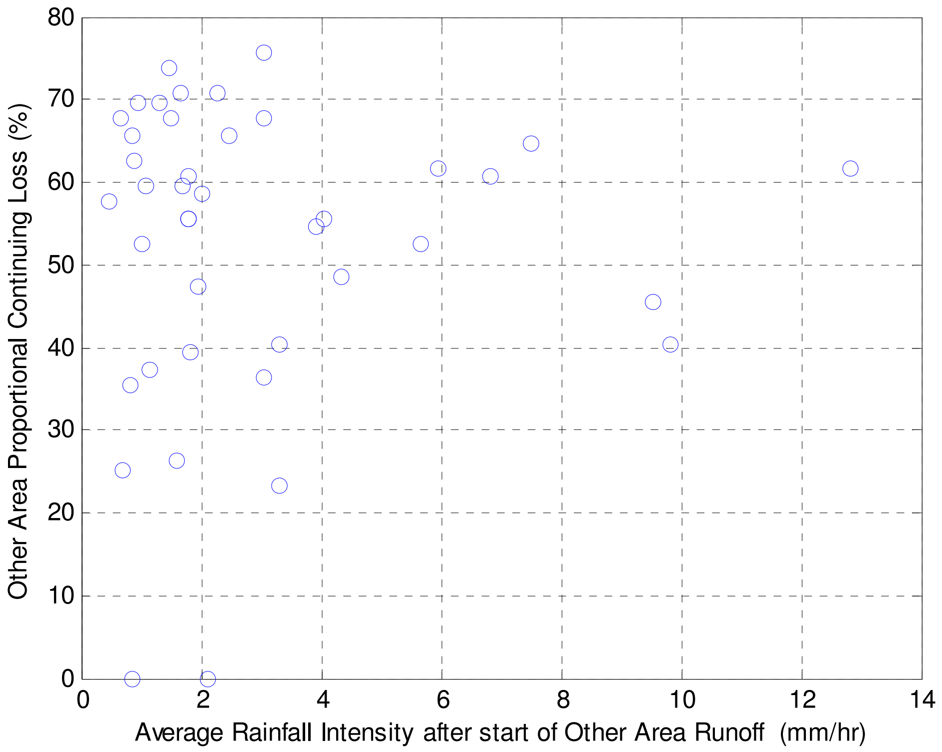


McArthur Park (NT)

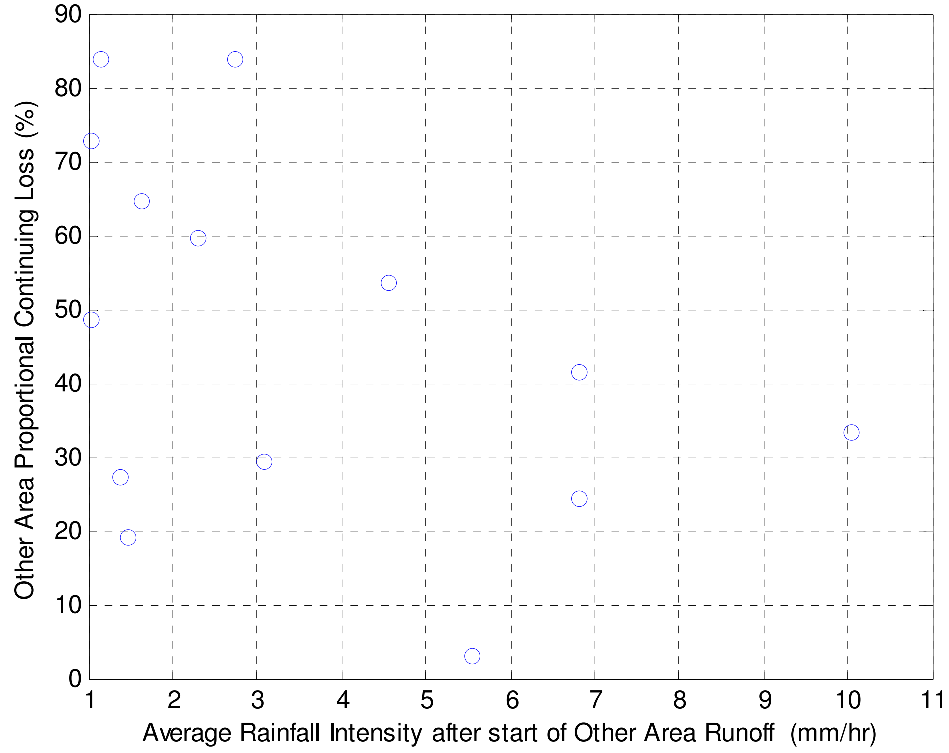


Argyle Street (TAS)

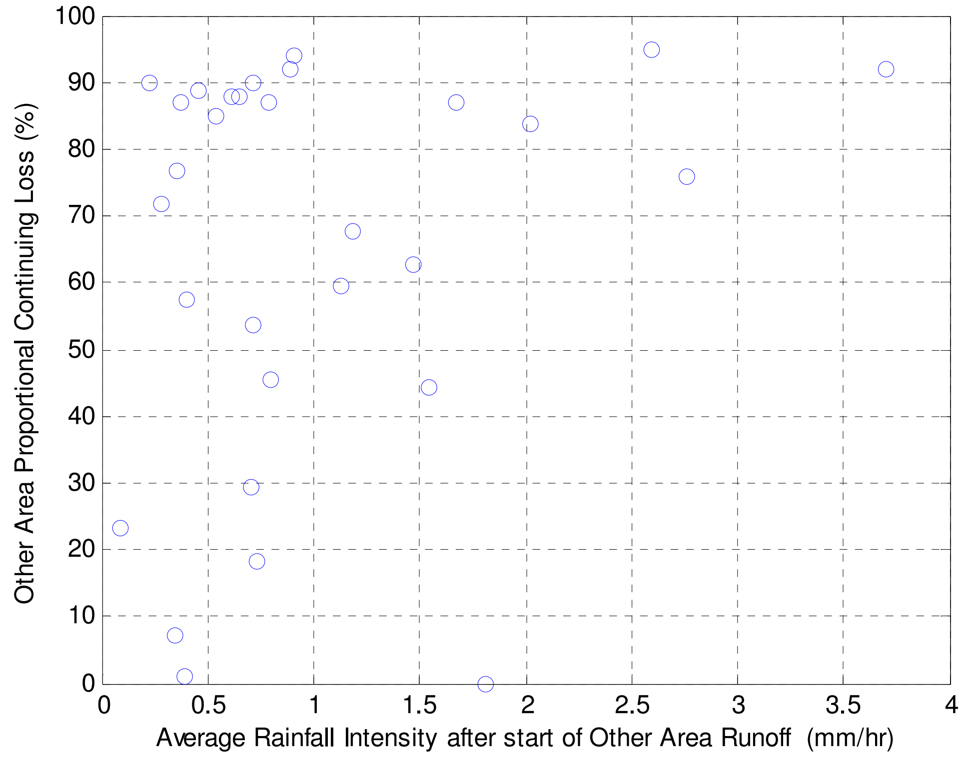
Figure E-3. Correlation Analysis – Other Area Constant Continuing vs Average Intensity



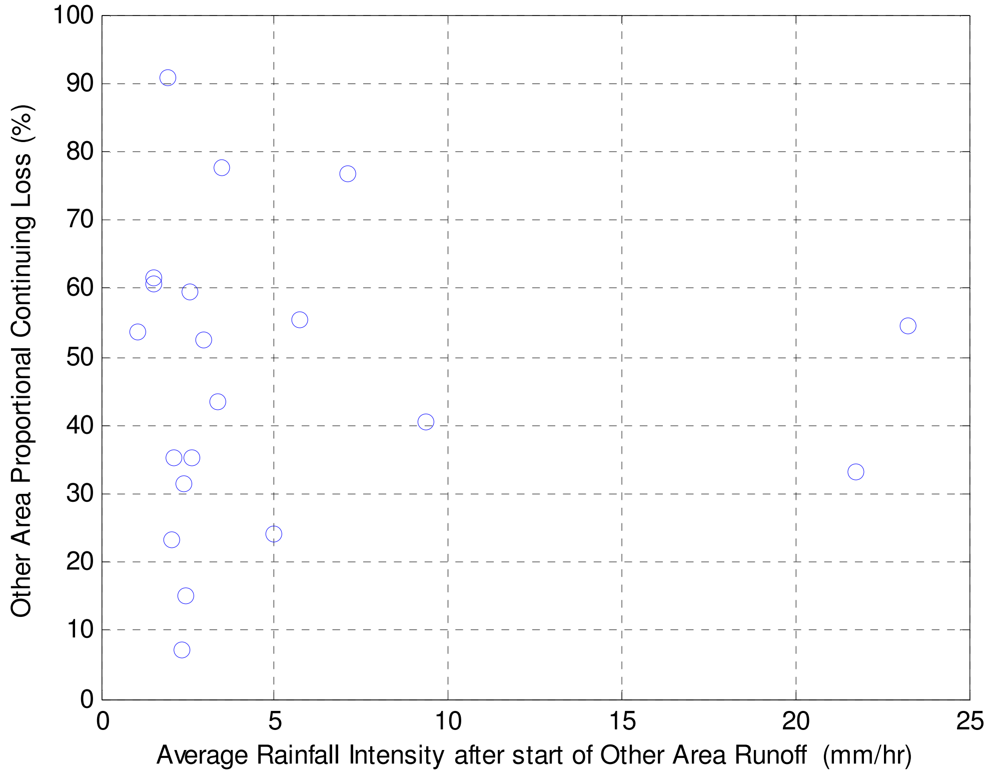
Giralang (ACT)



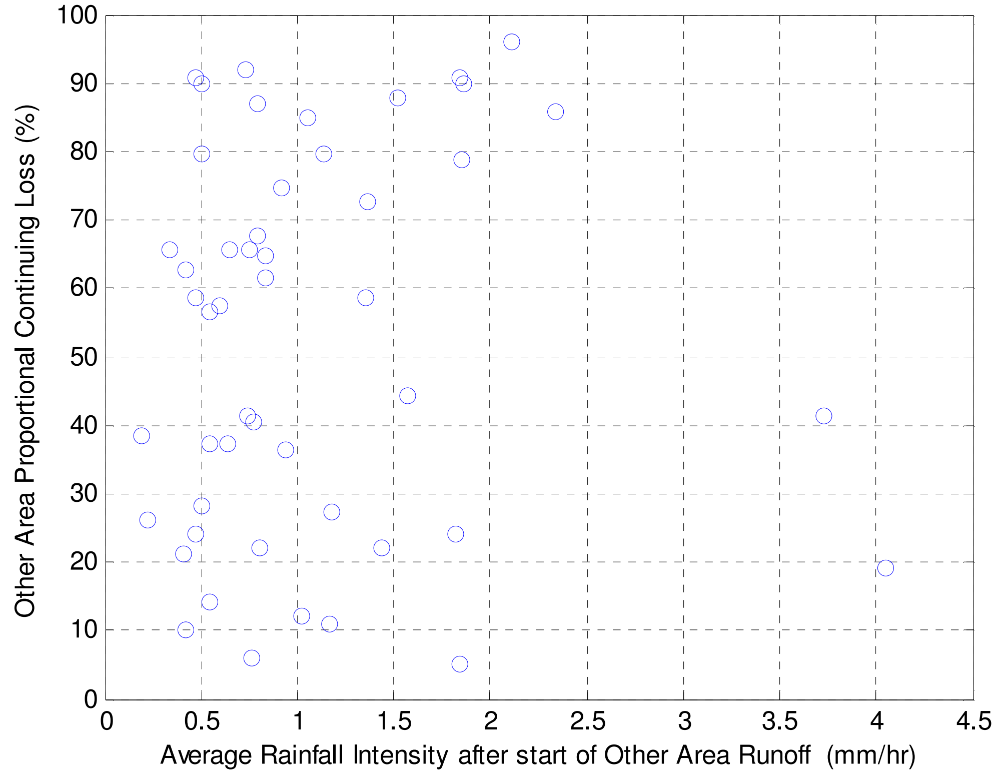
Powells Creek (NSW)



Albany Drain (WA)



McArthur Park (NT)



Argyle Street (TAS)

Figure E-4. Correlation Analysis – Other Area Proportional Continuing Loss vs Average Intensity

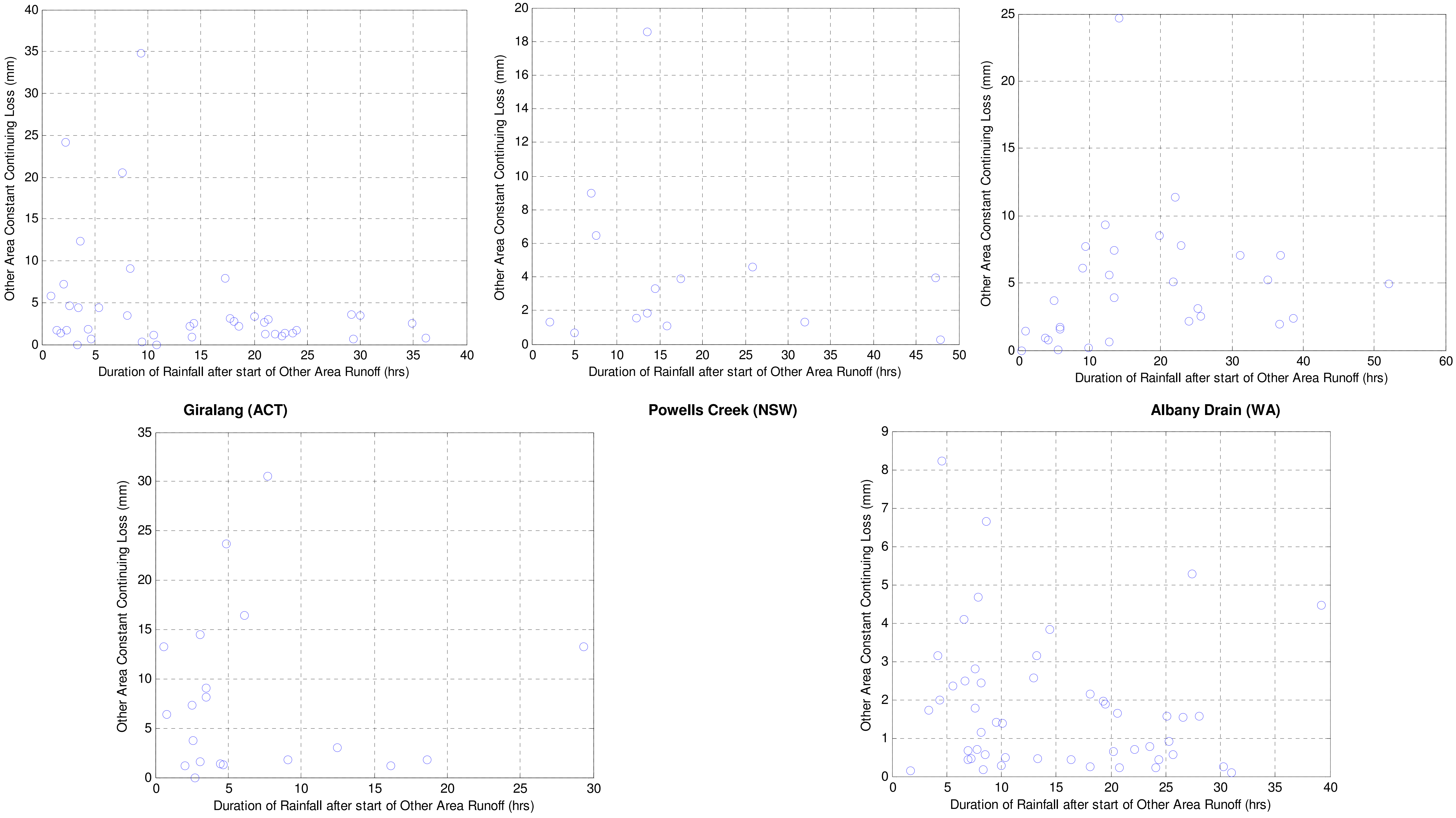
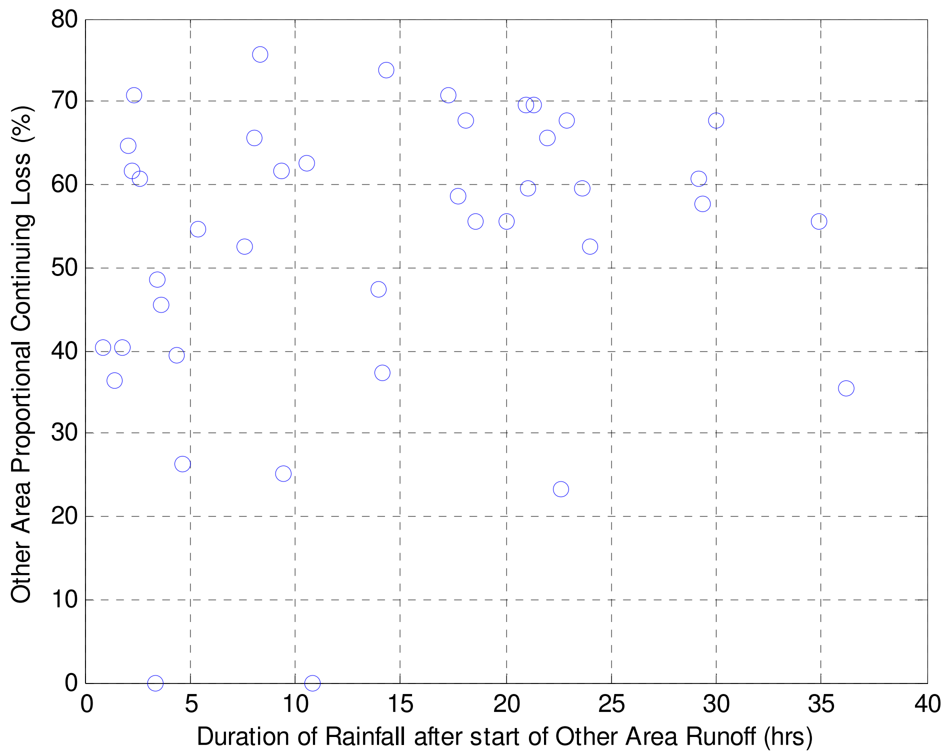
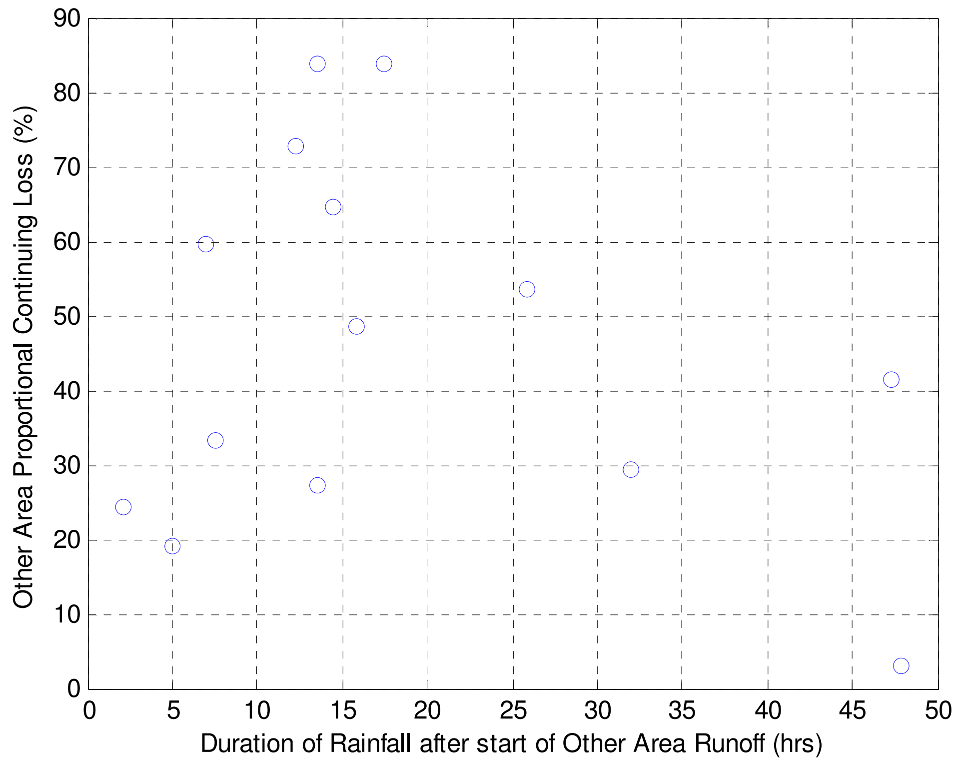


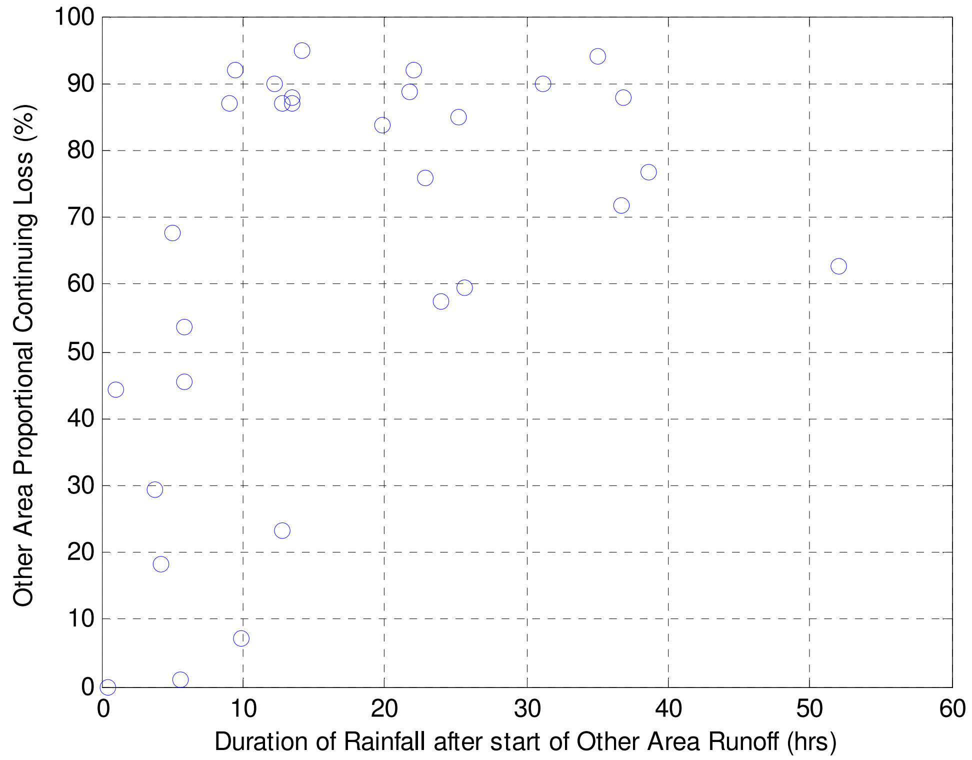
Figure E-5. Correlation Analysis – Other Area Constant Continuing Loss vs Duration after Other Area Runoff



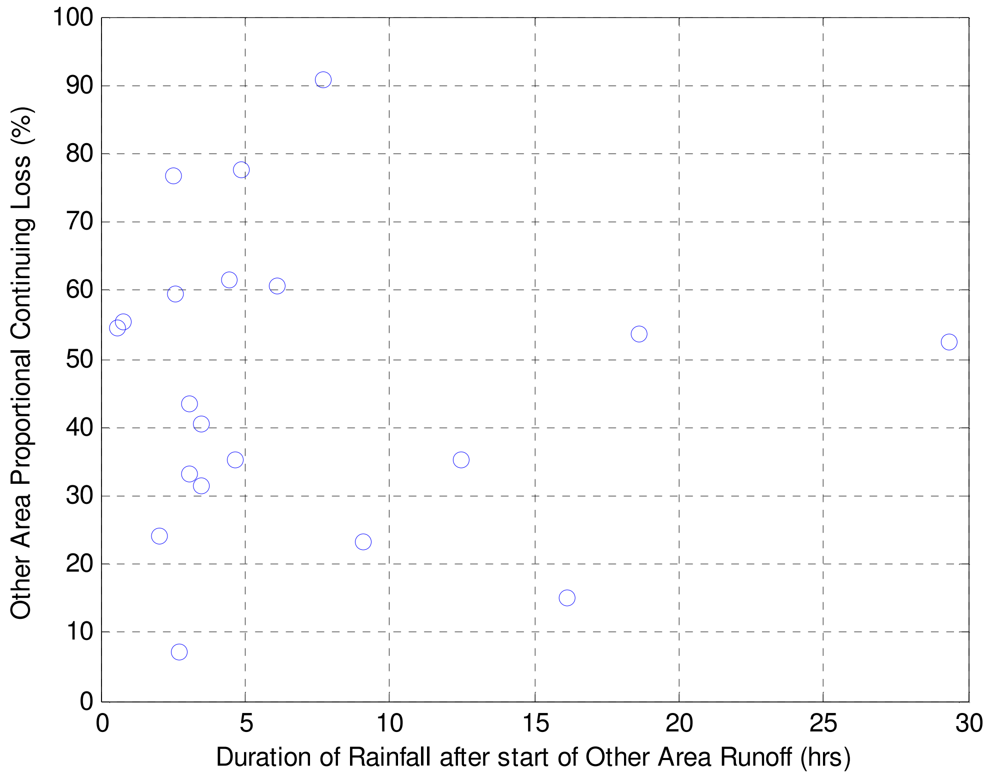
Giralang (ACT)



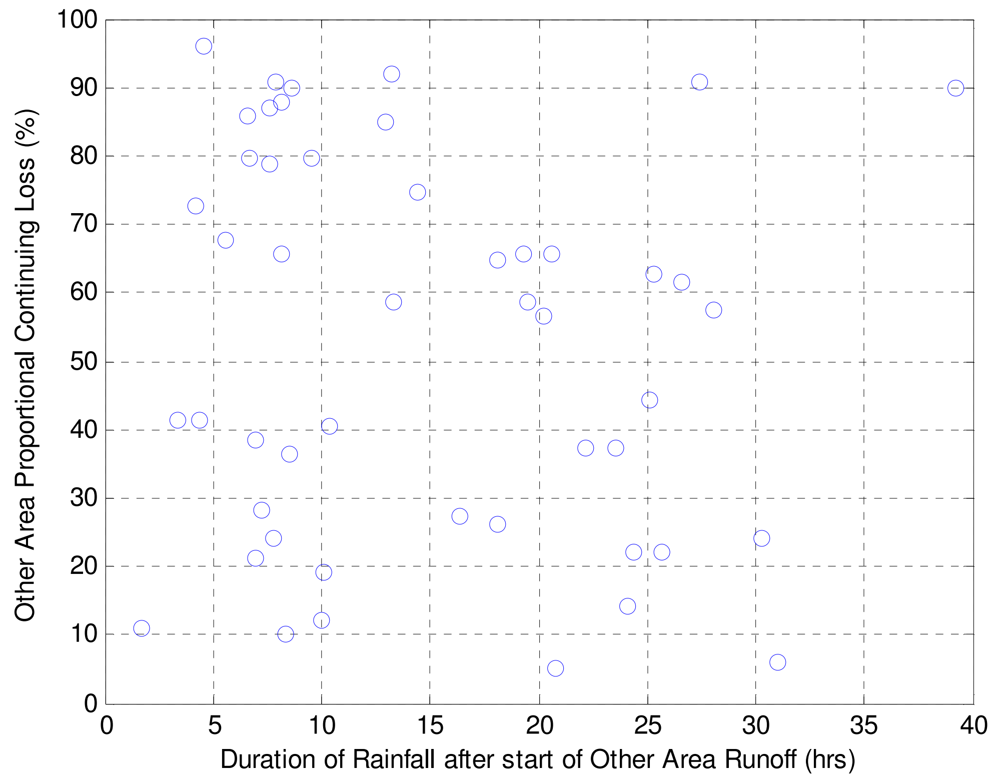
Powells Creek (NSW)



Albany Drain (WA)



McArthur Park (NT)



Argyle Street (TAS)

Figure E-6. Correlation Analysis – Other Area Proportional Continuing Loss vs Duration after Other Area Runoff