University of Southern Queensland

Faculty of Health, Engineering and Sciences

Rural Catchment Modelling: Application in Ungauged Catchments

A dissertation submitted by

Joshua Maloney

in fulfilment of the requirements of

ENG4111 and ENG4112 Research Project

towards the degree of

Bachelor of Engineering (Honours) (Civil)

Submitted October 2020

Abstract

Analysis of ungauged catchments is a challenging endeavour with large degrees of uncertainty. The uncertainty stems from the lack of accurate inputs for modelling. Various efforts have been made to improve the availability of this information mainly through regionalisation of parameters. Several studies have been carried out on model specific parameters such as the Kc and m values for the RORB model however, loss parameters are still being properly developed. Loss parameters for ungauged catchments can only be sourced from ARR Datahub or from a specific regionalisation of nearby catchments for which initial loss and continuing loss variables have been derived.

This report investigated the use of unchanged loss parameters from nearby catchments and the use of ARR Datahub values obtained for the specific catchment. Four catchments were chosen with a pair in QLD and a pair in NSW. Each pair was similar in size, shape and proximity. The loss parameters were input into a simple DRAINS and RORBWin model for each catchment using default and ARR2019 recommended settings elsewhere. Model outputs of design storm AEP's were compared to FFA data for those sites. Results suggest that using neighbour site derived loss values provides a better approximation of actual loss values than the ARR Datahub source and should be used in preference for flood modelling. ARR Datahub values tended to underestimate flows making it unsuitable for flood modelling but may be applicable to water balance and reservoir storage estimations.

The average of the four catchments suggested the neighbouring loss values were a better approximation of site loss values however one site dramatically underestimated flows. Further study including refinement of the site FFA for that exception and including a much larger sample size is required to strengthen claims.

University of Southern Queensland

Faculty of Health, Engineering and Sciences

ENG4111/ENG4112 Research Project

University of Southern Queensland

Faculty of Health, Engineering and Sciences

ENG4111/ENG4112 Research Project

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Joshua Maloney

[redacted]

Acknowledgements

This research was carried out under the supervision of Dr. Rezaul Chowdhury who provided helpful feedback during analysis, thank you.

Appreciation is also given to Joshua Devitt and Michael Dawson for their report suggestions and thoughtful feedback.

Table of Contents

List of Figures

List of Tables

Glossary

AEP	Annual Exceedance Probability
ARR2019	Australian Rainfall and Runoff: A Guide to Flood Estimation 2019 (Ball et al. 2019)
ARR RFFE	Australian Rainfall and Runoff Regional Flood Frequency Estimator
BOM	Bureau of Meteorology
DRAINS FFA	In the DRAINS model at site derived loss values used
FFA	Flood Frequency Analysis
FFA Loss	Site derived loss parameters
GEV	Generalised Extreme Value
IL-CL	Initial Loss – Continuing Constant Loss model
LP3	Log Pearson III
RORB	Run Off Routing model
RORB FFA	In the RORB model at site derived loss values used

1 Introduction

1.1 Australia's Interest in Modelling

Hydraulic and hydrologic analysis continues to increase in importance throughout society. The role of engineers in water supply and flood management is significant and impacts on peoples' lives and economic prosperity. It is common for engineers to design hydraulic structures, bridges, roads, flood control measures and safe building levels in their daily activities. The design process now has software as an integral part, but the accuracy and competence of these programs requires constant scrutiny and engineering judgement. Programs such as DRAINS and RORBWin are standard across the stormwater engineering community, and a review of their use in rural ungauged catchments is necessary.

Australia has been very interested in water yield due to its dry climate and large agricultural use and has become the birthplace of many models of streamflow (Boughton 2005). The streamflow models are often broken down into their intended use, either for yield analysis or flooding with the main difference in the model of time step. As populations have grown so too has the clearing and development of land along rivers. This has helped spur the progress in flood modelling to protect people, infrastructure, and the environment. The goal of many researchers has been to create a model that is capable of translation between catchments, with a focus on translation of a model to ungauged catchments.

A model capable of estimating flows from ungauged catchments is an important goal. Many catchments around the world are not monitored and reasons vary from the large distances to financial reasons. The ability to model these catchments is very important in water balance and flood forecasting scenarios for the well-being of the environment and people connected to these catchments. The high degree of uncertainty, stemming from the lack of data, can lead to either overestimating or underestimating expected flows from storms. In a flooding context, overestimating can lead to excess money spent on over engineered structures and underestimating can lead to environmental and property damage as well as loss of life. For modelling ungauged catchments direct correlations between catchment characteristics and model parameters has been a point of focus but this has been difficult to establish (Ball et al. 2019; Boughton 2005; Hrachowitz et al. 2013). In theory establishing this connection would then generate confidence in results without the need for historical records to validate models.

The catchment itself has a few definitions based on its context. In the context of the physical world it could be described as an area of water collection based on topography. In the modelling context it could be described as a "black box", as noted by Bevin (2012), with models relating inputs and outputs without understanding of the actual processes occurring.

Simple catchment models of rainfall-runoff have been used for years, such as the Rational method that was a recommended model in the Australian Rainfall & Runoff: Guide to Flood Estimation (1987). The simpler models are usually highly conceptual in nature and parameters do not translate to actual measurable data. An example of this is the rational runoff coefficient "C" in the standard Rational method calculation. This runoff coefficient is not a direct measurement of any particular aspect of a catchment but rather a constant of proportionality relating rainfall and area to peak discharge for an occurrence (Young, McEnroe & Rome 2009). Part of the reason for the use of the simpler methods has been related to the availability of information to directly use in a more mechanistic model. Locations such as Australia have large distances between monitoring points and the use of a mechanistic model will not produce accurate results.

The current Australian Rainfall and Runoff (ARR2019) guide recommendation is the use of an initial loss – continuing loss (IL-CL) model for design flood estimation of both rural and urban catchments (Ball et al. 2019). This replaces the common ILSAX model that was recommended for computer simulation in the previous version of the Australian Rainfall and Runoff guide (1987). The IL-CL model while still conceptual, provides a link to losses through the soil and is derived from observed losses. Where site data exists IL and CL values should be derived but, in ungauged catchments, losses for use in flood estimation are only available through the Australian Rainfall and Runoff Datahub (ARR Datahub). The ARR Datahub loss values are regionalised from only 38 stations, predominantly coastal, around Australia and may not accurately represent rural catchment loss (Ball et al. 2019; Ladson 2019).

As part of the IL-CL model the initial losses are the losses that occur at the onset of a storm and typically include interception by vegetation, soil infiltration, depression storage and loss through stream channels. Whilst the continuing losses are representative of the continued infiltration into the soil over the storms duration (Lang et al. 2015). Figure 1.1 below shows the relationship between streamflow, rainfall and losses over time and is the basis of all IL-CL models.

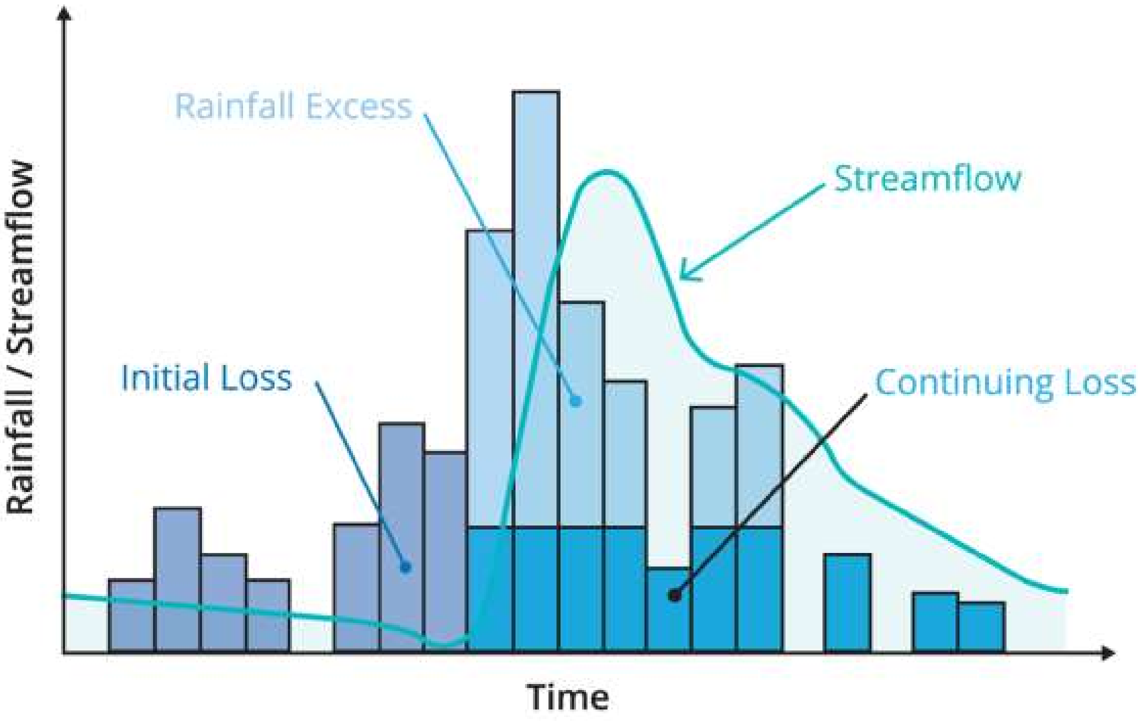

Figure 1.1. The Initial Loss - Constant Continuing Loss model - Fig 5.3.2 ARR2019 (Ball et al. 2019).

The larger the catchment the greater the effect that errors in parameter inputs have on model outputs (Ball et al. 2019). For example the largest recommended catchment utilising the Australian Rainfall and Runoff Regional Flood Frequency Estimator tool is 1000km^2 (Rahman et al. 2010). Further detailing of rainfall runoff models is required by inclusion of transmission or routing of stream flow.

Routing accounts for losses through the stream banks and stream bed as well as the hydraulic effects, like bank friction. Routing is described as the change in a discharge hydrograph over time and distance down a reach or the translation and attenuation of the discharge hydrograph (Bevin 2012). Whilst routing happens even at the small scale, it is at the larger scale where the routing effects are very useful and can reduce problematic floods preventing stream banks from overtopping and/or damage to structures. Routing model components typically require stream length and slope to model travel times.

Rainfall runoff models can be broadly classed into three categories, the lumped model, semi-distributed and grid distribution. An example of a typical lumped distribution model is shown in Figure 1.2A. They have been shown to underestimate small storm volumes and overestimate large volumes though Willems (2001) reports this bias can be corrected for. A possible disadvantage of the model is due to the spatially averaged nature of this model making it impossible to retrieve internal hydrologic variables (Tran, De Neil & Willems 2018).

The complex models can have many parameters and are heavily reliant on their accuracy (Sitterson et al. 2017). Many of these parameters are not being directly measured or their spacing is so large that great approximations are required. Examples of this include real-time evapotranspiration values, rainfall data across a catchment and soil moisture conditions including groundwater levels. The problem of applying complex mechanistic/physical models to catchment analysis is obtaining the data, hence the continued reliance on the simpler models (Li et al. 2015). Figure 1.2C below is a representation of a grid distribution system that produces a flow rate and depth at each boundary based on the characteristics of that grid. Distributed systems also may not handle channel routing well (ElSaadani et al. 2018).

The current method of addressing this is by utilising a hybrid approach, the semi-distributed model. This model shown in Figure 1.2B below attempts to remove some of the generalisations that can add up to large gross errors in estimations.

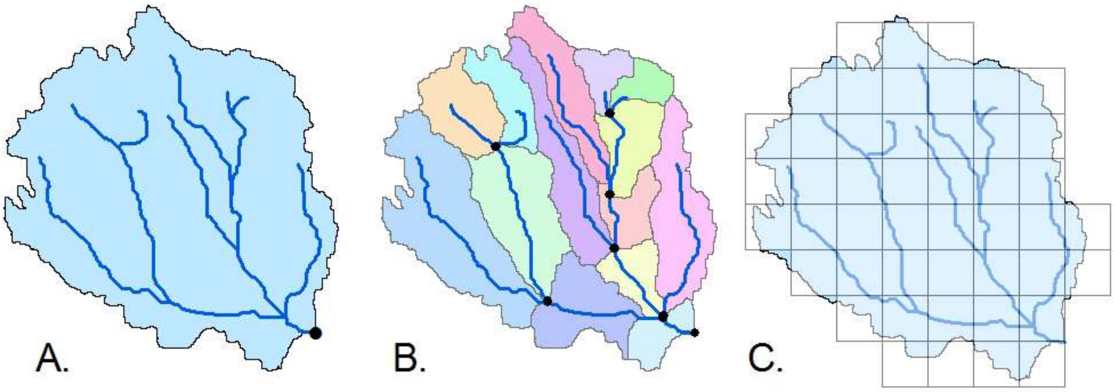

Figure 1.2. Structure of rainfall runoff models, A lumped model, B semi-distributed, C Grid distribution (Sitterson et al. 2017).

Catchment analysis has also been aided by the ARR Regional Flood Frequency Estimator (ARR RFFE). The ARR RFFE provides useful spatial data from the region and provides an estimate of design flows, this estimate is a good "first pass" for flood analysis and should be combined with other approaches to establish confidence in values (Babister et al. 2016; Ball et al. 2019). A part of the ARR RFFE is a feature where nearby gauged catchments' design hydrographs can be reviewed and compared. The ARR RFFE design storm hydrographs were generated from flood frequency analysis of available data using the LP3/L-moments method.

One of the Australian industry standards in catchment analysis software is the program DRAINS. It has several hydraulic and hydrologic models available to use in analysis of catchments both rural and urban. The DRAINS program contains the latest information from ARR2019, and it provides the new IL-CL model as well as the prior recommended ILSAX method. DRAINS also provides three storage routing models including Runoff Routing (RORB), Runoff Analysis and Flow Training Simulation (RAFTS) and Watershed Bounded Network Model (WBNM) and are non-linear storage runoff routing models, all of which have been calibrated to gauged catchments (Stack & O'Loughlin 2018). DRAINS only offers an event-based modelling approach and does not offer a continuous model such as in the stormwater quality monitoring software MUSIC and rival program XP-SWMM.

DRAINS provides references throughout its help menu for the user to question and learn further on many of the topics and helps build confidence in its use. With the flexibility of DRAINS a user that becomes familiar with the program can model a large range of stormwater scenarios across rural and urban environments.

DRAINS inputs are based on those recommended by the ARR2019 guide and DRAINS provides some help in the selection of the correct parameters. However, the program does not have an analysis module to provide feedback on the validity of the results. The user is still responsible for the "engineering judgement" aspect with DRAINS and is indeed a facet of modelling software encountered.

Like DRAINS, RORBWin is a software program for generation of flood hydrographs from rainfall. RORBWin is a software version of the RORB runoff routing model and is maintained by Monash University and Hydrology and Risk Consulting Pty Ltd (Laurenson, Mein & Nathan 2010). It is limited to just the one runoff routing model but also includes the latest ARR requirements and suggested Monte-Carlo framework options as inputs. The RORB model has long been used throughout Australia particularly for rural catchment modelling.

For model validation on gauged catchments, comparisons are made to actual recorded data. Flood frequency analysis (FFA) utilises previous recorded data and with the help of statistical tools provides a relationship between annual exceedance probability (AEP) and peak discharge. There are several statistics tools available, the current recommendation from ARR2019 is the use of the generalised extreme value (GEV) method, the prior recommended method was the log Pearson III (LP3) and is still used by the ARR RFFE. FFA is dependent on length of record and accurate recording of rainfall, with errors in these producing significant biases (Collier 2016). It is also noted by Lazaro et al. (2016) that FFA techniques can possibly under represent exceptional events and a poor correlation in return period between rainfall and peak flow can be produced.

To improve the length of record for a catchment Bomers, Schielen & Hulscher (2019) demonstrate that a reduction in confidence intervals for extreme events can be achieved by including more historic events even if those are highly uncertain themselves. In addition to improving results on gauged streams, this method of including historic events has also been trialled on ungauged catchments with some success (Nguyen, Gaume & Payrastre 2014).

Further model validation comes in the form of sensitivity analysis on data inputs. This provides information on how a model responds to variations in inputs, helping to assign an importance level to the accuracy required for certain data (Bevin 2012, pp. 237-239; Collier 2016). The M*onte Carlo simulation* technique makes many runs of a model with each run utilising a random parameter set and is the basis of many sensitivity analysis techniques. The parameter sets generally follow a distribution within limits to make the information reflect possible variables from nature generating a "realistic" data set.

For model loss inputs, parameter estimation using the regionalisation approach has been shown to be a better predictor of input parameters than catchment characteristics, with the regionalisation approach appearing to work better in wet climates than dry (Merz & Bloschl 2005). Application of the regionalisation method across Australia may not be the best approach with its dry climate but a combination of regionalisation and catchment attributes would likely yield the greatest results. Again, the problem for Australian catchments is distance between monitoring points rendering comparisons difficult.

Inputs required for modelling including rainfall and its temporal and spatial variability are not explored here, neither is the antecedent moisture condition. An analysis of these is considered beyond the scope of this report and their effects on catchments are well documented in ARR2019 (Ball et al. 2019).

The aim of this report is to compare software models design hydrographs using various sources of IL and CL parameters. This will help determine the best source of model parameters for use in DRAINS and RORBWin for particular use on ungauged catchments. Efforts will also be made to determine any connection between catchment size and accuracy as well as catchment proximity on the accuracy of neighbour loss values.

In summary establish:

- The best model out of DRAINS and RORB.
- If ARR Datahub loss values or Neighbouring loss values perform best.
- If a correlation between catchment size and accuracy exists.
- If a correlation between accuracy of neighbouring loss values and distance between catchments exists.

2 Literature Review

2.1 Ungauged Catchments

There is a large amount of research on models for ungauged catchments. The research into these models for ungauged catchments primarily mimicked the recorded results in a gauged catchment, which resulted in models that were poorly understood (Bevin 2012). From review of popular literature, the focus of current modelling efforts appears to be on obtaining exact information about a catchment and combining every component to form an accurate complex model. This approach is not useful for many parts of Australia with large distances between monitoring points, a more general model is required to account for the lack of available information.

In the last decade there has been a focus on increasing the accuracy of rainfall runoff models used on ungauged catchments, the International Association of Hydrological Sciences has made efforts to collect and drive research in this area (Hrachowitz et al. 2013; Bevin 2012). This has provided incremental progress in the field, with several models recognised, but there has not been a significant uptake of any one model based on its accuracy across a range of catchment conditions. The simpler models still provide reasonable estimates and there have been many comparisons of existing models to more complex mechanistic models.

Further study on transferring parameters of one catchment to another using the Australian Water Balance Model (AWBM) has been done by Boughton (2009) and others. Conclusions drawn from this were that it was possible to achieve high degrees of accuracy though more research was needed.

Both Bomers et al. (2019) and Lazaro et al. (2016) investigate the use of historical flood events in FFA. These were shown to provide good flood estimate guides even on ungauged catchments.

RORB rainfall runoff routing model has had some research carried out on ungauged catchments. This ungauged catchment research has centred around determining the correct model parameters for use being k_c and m. Attempts at regionalisation of model parameters were undertaken as far back as 1978 by Weeks and Stewart where they applied relationships to regions in Queensland and Western Australia (Pearse, Jordan & Collins 2002). Another summary of research into this model came from Dyer et al. (1994) and further highlighted connections between peak flows and model parameter k_c. The latest ARR2019 uses equations for k_c based extensive research and provides the best estimate of this model parameter. RORB models have been calibrated on ungauged catchments but this is done by doing a DESIGN run and trying to fit an event peak flow as done by Pearcey et al. (2014).

Studies of DRAINS software suitability for transfer to ungauged catchments appears to be poorly independently reviewed.

2.2 ARR2019, ARR RFFE and ARR Datahub

The NSW government has also conducted a review of the ARR design inputs and made recommendations to ARR. This report by the Office of Environment and Heritage (OEH) was designed to address the concerns of the ARR guidelines underestimating floods (Podger et al. 2019). The report subsequently demonstrated from comparison of the at site flood frequency analysis versus the design method of ARR2016 that flood estimates were too low. The report further outlined compensation measures for NSW catchments to be used in the application of the ARR guidelines to better approximate design extents. These recommendations have been introduced into the ARR Datahub and notably include Probability Neutral Burst Initial Loss values and modification factor for continuing loss models.

Section ARR2019 3.3.3 Table 5.3.1 provides a summary of approaches for estimating loss values including:

1. Empirical analysis of at site rainfall and streamflow records.

2. Regional information.

3. Reconciliation of design values with independent flood frequency estimates.

Of these approaches only regionalisation is applicable to ungauged catchments and this resulted in aspects of the ARR RFFE tool being developed.

Several catchments throughout Australia were selected and FFA has been performed on them as part of the development of ARR2019 RFFE techniques (Ball et al. 2019). These catchments can be selected by downloading the nearby catchments feature at the bottom of the ARR RFFE page. This page also displays the catchment characteristics of the surrounding gauged catchments included in the model.

For certain NSW catchments there is further FFA information available for use with a comparison to ARR design procedure and the data hub, Appendix C of the report by Podger et al. (2019).

2.3 Losses for Flood Estimation

ARR2019 recommends the use of the ARR Datahub losses for flood estimation when using the IL-CL model in ungauged catchments. These losses are derived from only 38 small catchments (Ball et al. 2019). Ladson (2019) reports from the Kucera Symposium that local loss values should be used where possible as these are not well represented in the ARR Datahub values. It has also been noted by Kemp & Daniell (2016) that the mean value of losses has not been related to a catchment's physical characteristics. They also note that there is no clear indication of the relationship between antecedent conditions and loss values. This inability to link loss values to infiltration rates hinders efforts for model use on ungauged catchments. Other helpful information regarding losses came from a review by Lang et al. (2015) providing some guidance on continuing losses for model timesteps less than one hour. Directly determining initial losses has been done by Hill et al. (1996) though this will not be undertaken here.

It had been the aim of the ARR Project to provide these loss characteristics however the generalisations made require further engineering judgement for each catchment, continued research and installation of monitoring stations is required to improve estimates of loss values. Updates to the existing LP3/L-moments method to GEV method is also required for the site FFA data available through ARR RFFE.

2.4 Reference Catchments from BOM

The bureau of meteorology (2015) has several reference catchments available that meet certain criteria, and these have been reviewed extensively. These are a quick way to find quality information for a catchment should that catchment or a model require validation.

2.5 Use of Software in Flood Modelling

DRAINS has been used through several flood studies for generation of discharge hydrographs for input into other hydraulic modelling software. The Murrumbateman, Bowning, Bookham and Binalong Flood Study for Yass Valley council uses DRAINS module RAFTS for its rural catchment aspects and ILSAX for its urban components to produce a discharge hydrograph for entry into the TUFLOW hydraulic model (Lyall & Associates 2020). Flood studies, such as those for Willoughby Council in NSW, have DRAINS for part of their hydrologic model. It appears that the use of DRAINS has been used primarily with urban flood studies to measure areas of interest, whilst other models with routing components, RORBWin (popular in part due to its free availability and maintenance by Monash University and Hydrology and Risk Consulting) and XP-RAFTS, make up the bulk of the hydrologic models.

DRAINS reviews are difficult to find however, van der Sterren et al (2008) share a comparison of XP-SWMM, DRAINS and MUSIC with these three often referred to as the Australian industry standards. Versatility of the XP-SWMM was praised but there was not a comprehensive review of model accuracies. Comparisons were of OSD basin stage and orifice discharge, but modelling was not verified or calibrated to anything known, comparisons were just to each other.

DRAINS has three run-off routing models that can be used including RORB, RAFTS and WBNM and these models are an optional module available to users.

Limitations of the DRAINS IL-CL model used in the proposed context includes ignoring the maximum suggested overland flow length of 100m. For overland flow lengths above this a runoff routing model, such as noted above, is recommended to better model routing effects (Stack & O'Loughlin 2020). However, with the use of this model at the head of a catchment, it is expected that accurate results are possible.

Software model selection appears dependent on the company and users and not on the strengths of a model from analysis of various flood reports available.

Other software programs for hydrologic analysis used in flood studies investigated include,

1. FLIKE - Flood frequency analysis software, used in Dubbo Regional Council flood study (Dubbo Regional Council 2019).
2. URBS – Runoff routing model used in Logan River Hydrological study (City of Gold Coast 2014).
3. RORB – Runoff routing software, used in Tamworth Regional Council flood studies (Tamworth Regional Council 2012).
4. XP-RAFTS (WBNM) – Runoff routing software, used in Leichardt Council flood study (Sydney Water Corporation 2009).
5. ILSAX – Rainfall runoff routing program, used in City of Port Adelaide stormwater flooding study (City of Port Adelaide Enfield 2005).
6. DRAINS (RAFTS and ILSAX) – Used in Yass Valley Council flood study (Yass Valley Council 2020).

3 Methodology

3.1 Catchments

3.1.1 Desirable Catchment Selection Criteria

Catchment selection is required to draw meaningful conclusions from the analysis. Catchment models are affected by many variables, not all of which are required by the model but will affect the results. The selection criteria were aimed at achieving simpler more accurate models and catchments that could be compared with very little variation from each other.

1. No discernible large water storages or reservoirs (to lower uncertainties in loss values, to allow neglecting baseflow).
2. Primarily rural catchment (to remove impervious aspect from model).
3. Catchment at head of river (to neglect baseflow, simplify model, remove some routing effects).
4. Proximity to rain gauge (to help reduce spatial rainfall errors).
5. Stream gauging station taking hourly recordings (to match time step recommended by ARR2019).
6. Stream gauging station that has greater than 30yrs recorded data (to generate confidence in production of design rainfall events if/when doing at-site FFA).
7. Catchment size is to be similar among those chosen (to remove associated variability).
8. Proximity to another catchment with similar characteristics if possible.
9. Existing data associated with the catchments for third party validation.

3.1.2 Chosen Catchment Characteristics

A review of QLD and NSW catchments was undertaken by first reviewing the Bureau of Meteorology reference stations list. From this list four catchments were chosen with one pair in QLD and one pair in NSW. A pair was defined as catchments similar in size, area, rainfall and proximity.

Table 3.1. Selected catchments physical characteristics summary.

Catchment	Area (km^2)	Stream Length (km)	Height diff. of stream (m)	Slope (%)	Mean Annual Rainfall (mm)	Distance Between Centroids (km)
Teviot Brook at Croftby (145011A)	85.1	20	Max 1327 Min 170 = 1157	5.8%	996	8.31
Burnett Ck at Up Stream Maroon Dam (145018A)	82.4	21	Max 1243 Min 233 = 1010	4.8%	1038	
Wollomombi River at Coninside (206014)	377.4	65	Max 1472 Min 908 = 564	0.9%	871	55.5
Henry River at Newton Boyd (204034)	398.9	76	Max 1340 Min 329 = 1011	1.3%	914	

Catchment data from QGIS analysis and mean annual rainfall from ARR Datahub, minor discrepancies between various reporting authorities on the sizes of catchments were noted but independent derivations have been used from topography analysis.

Catchment pairs meeting some or all of these criteria summarised in Table 3.1.and are presented below in Figure 3.1 and Figure 3.2.

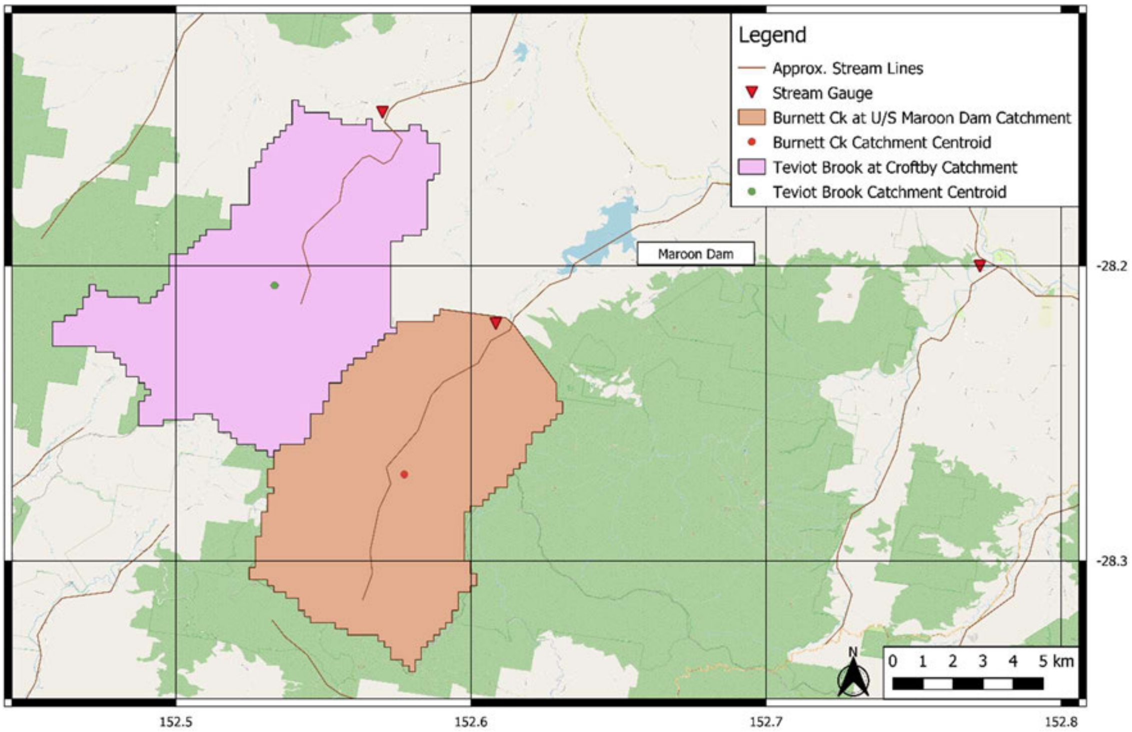

Figure 3.1. Teviot Brook at Croftby and Burnett Ck at Upstream Maroon Dam catchment boundaries, shape, and distance to each other (QLD catchments).

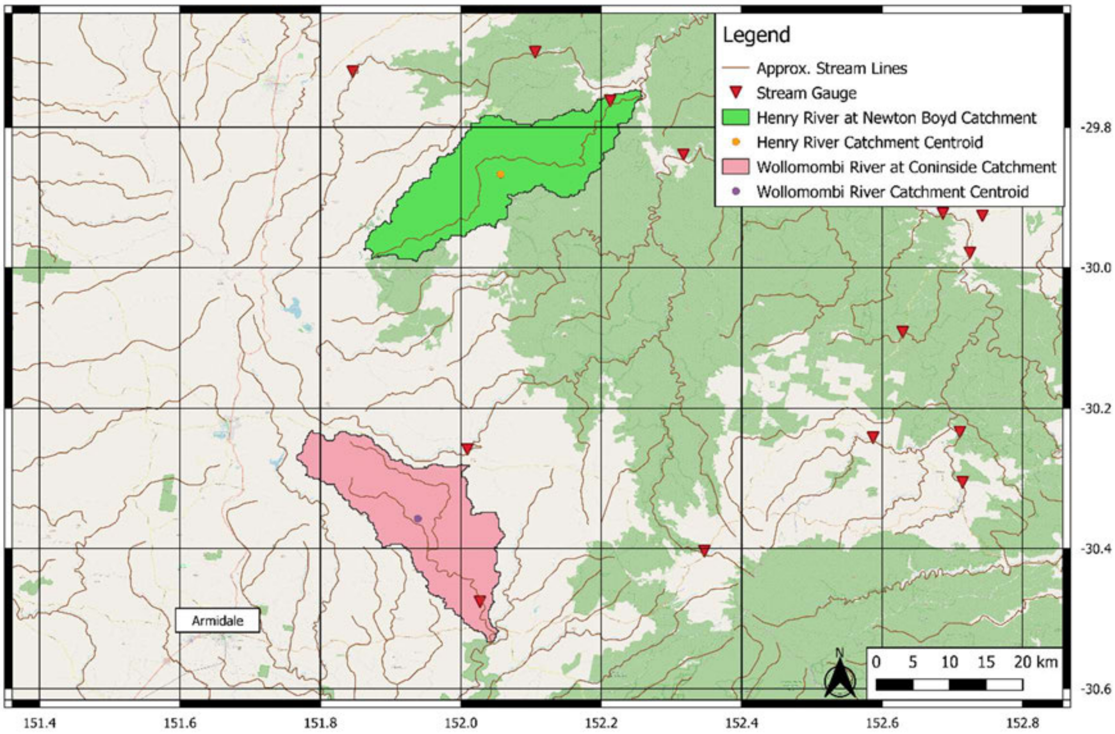

Figure 3.2. Wollomombi River at Coninside and Henry River at Newton-Boyd catchment boundaries, shape, and distance to each other (NSW catchments).

3.1.3 Catchment FFA Hydrograph Values

Teviot Brook at Croftby FFA values obtained from at site flood frequency analysis using the Log Pearson 3 (LP3) method, whilst this differs from the current ARR2019 generalised extreme value (GEV) recommendation, the LP3 was the previous recommended method and likely represents how the FFA values were obtained in the other catchments, this was not confirmed however. Assuming other catchments were analysed using the LP3 method this was again undertaken to reduce variability between catchments for more accurate comparisons. Teviot Brook at Croftby data sourced from the QLD Water Monitoring Portal (2020). Plot of Teviot Brook at Croftby FFA values shown in APPENDIX B FFA Results Figure 8.1 summary of catchment details in Table 3.2.

Table 3.2. Terviott Brook at Croftby recorded catchment data.

Teviott Brook at Croftby Catchment Data	
Stations ID	145011A
Length of data	1966→2020 or 54 years
Missing data	<0.5%
Years removed from analysis	1966, 2007 and 2020

The 1965/1966 and 2020/2021 water years were incomplete and were removed. Year 2007 was removed because of the extreme low flows disrupting the model stability.

Burnett Creek at U/S Maroon Dam FFA values from ARR Revision Project 7: Baseflow for Catchment Simulation (Murphy et al. 2009). These values were modified to AEP and do not suggest a 100yr flow as is commonly required for flood analysis, further analysis of site may be required to develop an estimate of this value.

Henry River at Newton Boyd and Wollomombi River at Coninside FFA values from a review of NSW design inputs by Podger et al (2019).

3.2 QGIS Sub Catchment Delineation

After catchment selection a GIS model was created for visualisation purposes, to generate an overall catchment boundary and for the purpose of creating sub-catchments for use modelling. The creation of the model would allow verification of recorded areas and catchment boundaries. Sub-catchments were created using catchment topography and a flow direction. Each sub-catchment within the catchment was then given a unique identification number modelling and colour for visualisation purposes.

Use of QGIS to determine watershed boundaries for use in model was done using the GRASS suite of tools.

1. Load Bureau of Meteorology web map service data into model.
    a. Specifically load hydrological models and reporting catchments to double check catchment mapping.
2. Load OpenStreetMap data.
3. Review catchments listed in Table 3.1.
4. Create catchment as a new polygon layer and isolate centroids.
5. Load digital elevation raster.
6. Measure distance of stream lengths and record.
7. Generate depression-less DEM for each catchment to remove errors in flow direction/watershed analysis.
8. Create watershed and modify to comply with RORB requirements.
9. Generate maps for each catchment.

Minor changes to shape, size and number of sub-catchments were undertaken in accordance with recommendations made in the RORB manual. Figure 3.3 and Figure 3.4 represent the New South Wales (NSW) catchments broken up into sub-catchments. Figure 3.5 and Figure 3.6 represent the Queensland (QLD) catchments broken up into sub-catchments.

The coloured areas denote the major catchments sub-catchments, the numbers were used in creation of the RORB model and represent the sub-catchments refer APPENDIX C.

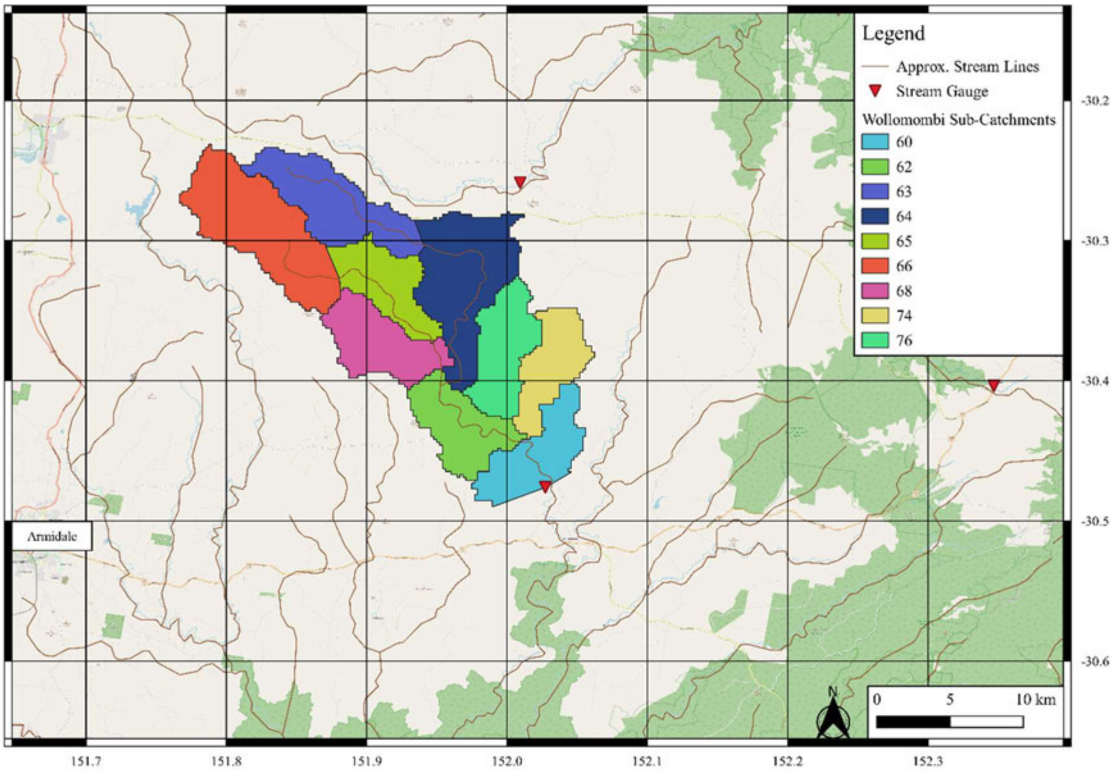

Figure 3.3. Wollomombi River at Coninside catchment watershed boundary with sub-catchment areas denoted by colour and the corresponding number used in RORB model setup for reference.

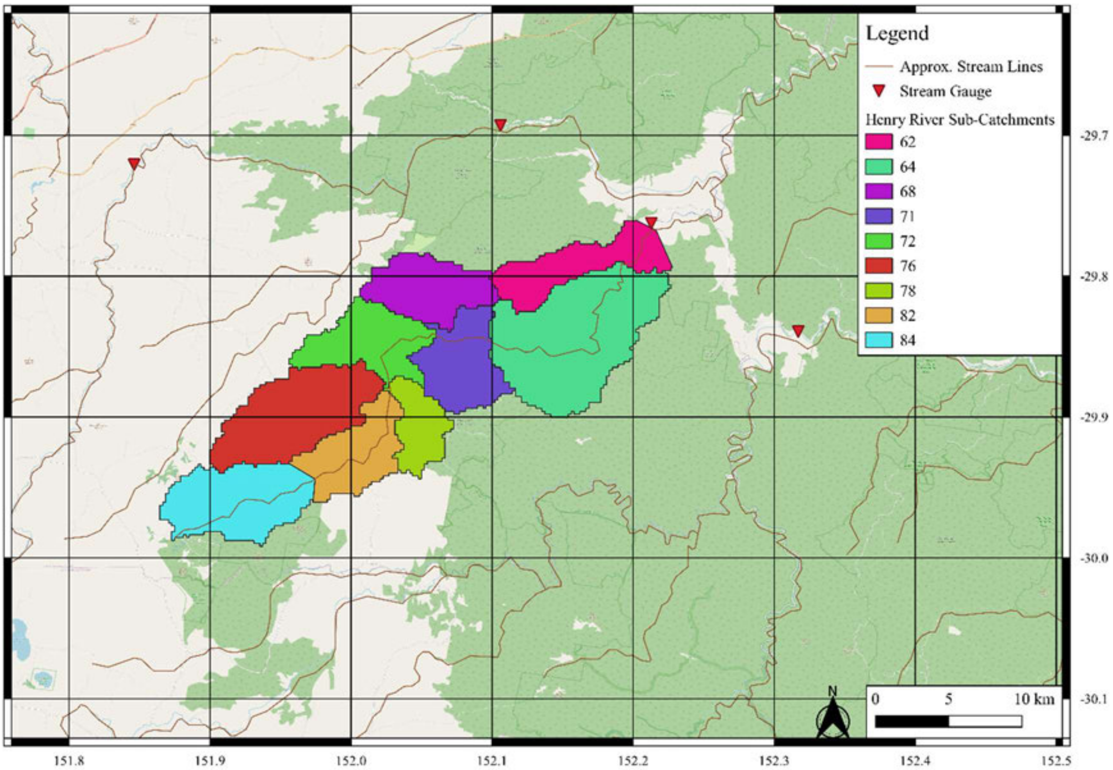

Figure 3.4. Henry River at Newton Boyd catchment watershed boundary with sub-catchment areas denoted by colour and the corresponding number used in RORB model setup for reference.

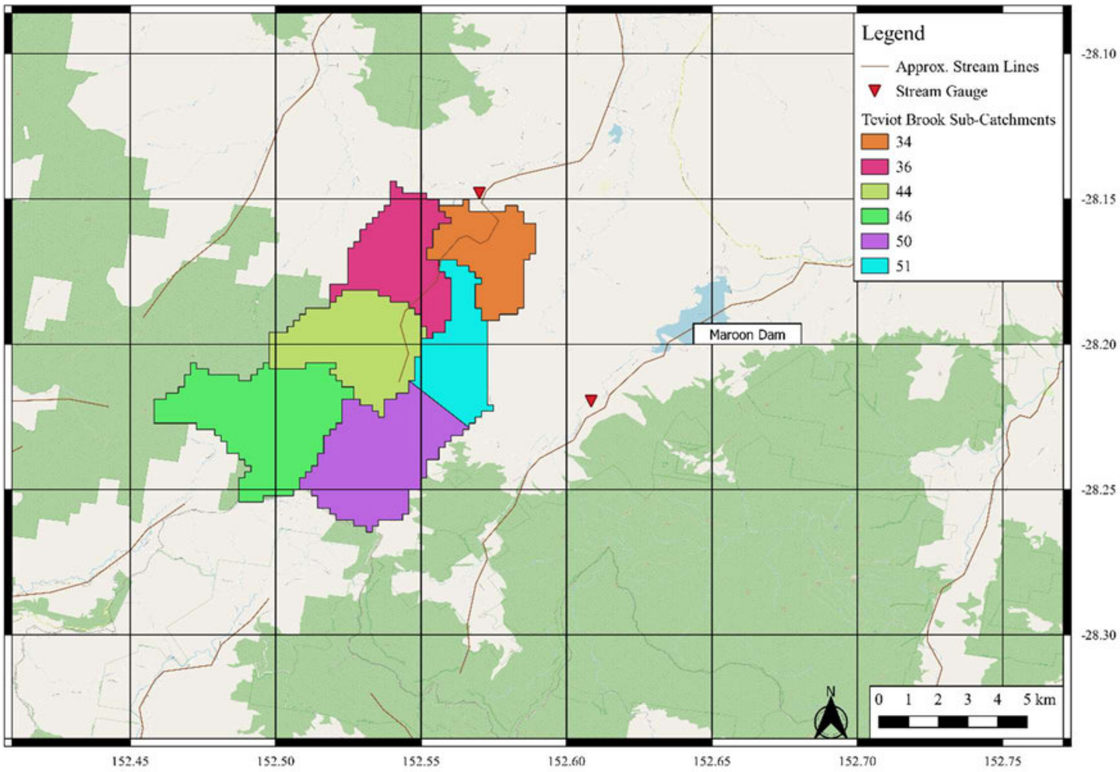

Figure 3.5. Teviot Brook at Croftby catchment watershed boundary with sub-catchment areas denoted by colour and the corresponding number used in RORB model setup for reference.

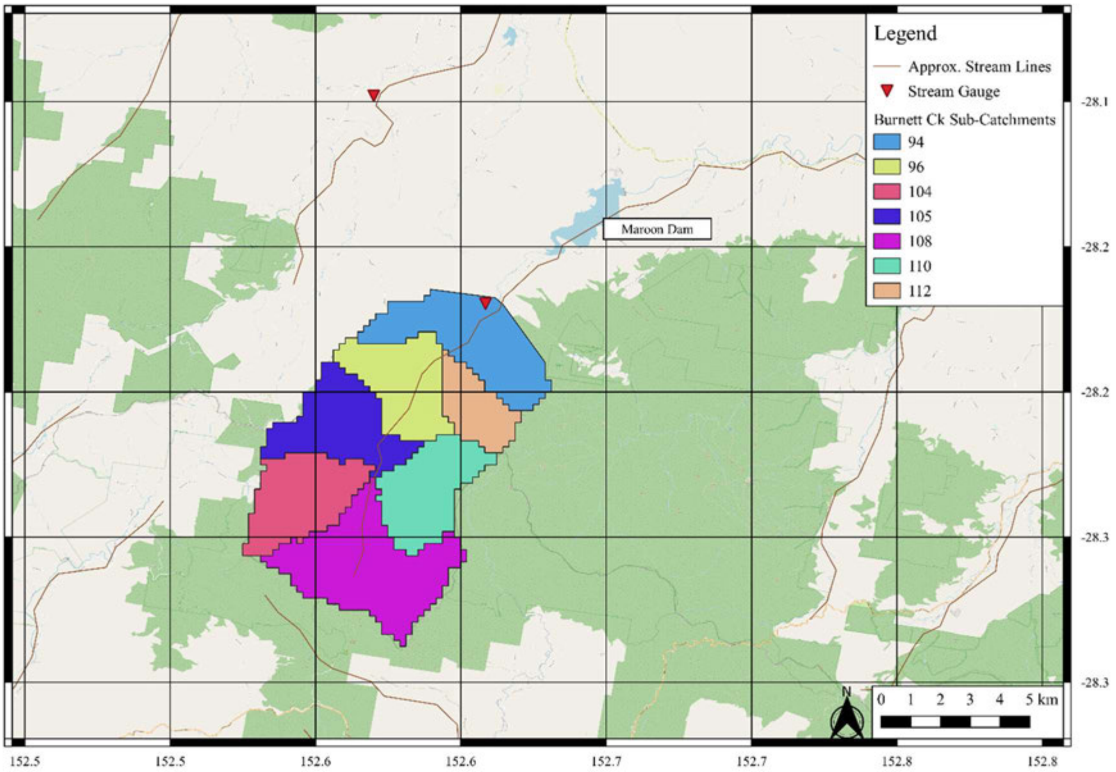

Figure 3.6. Burnett Creek at U/S Maroon Dam Catchment watershed boundary with sub-catchment areas denoted by colour and the corresponding number used in RORB model setup for reference.

3.3 Model Parameters

3.3.1 Loss Values

ARR losses were determined by using the locations of the catchment outlets and entering them into the ARR Datahub website, results were then recorded for storm initial losses and storm continuing losses. Modifications were made to the loss values in accordance with NSW requirements.

Site derived losses were obtained from reviews of flood studies for the Queensland catchments and the report by Podger et al. (2019) for NSW catchments. All loss values are summarised in Table 3.3. The least representative of these IL-CL site derived values is the Burnett Creek at U/S Maroon Dam catchment which consists of an average of IL-CL determined from storm events and where these values were used in calibrating a model and were deemed a “good fit” by the study authors. Given further time, an analysis of site flows could have derived more precise values.

Values represented in Table 3.3 by IL FFA and CL FFA refer to site derived loss values and are not necessarily from a FFA.

Table 3.3. ARR Datahub IL and CL (storm) figures for each catchment and IL-CL derived from site data (ARRa 2019; ARRb 2019; Podger et al. 2019).

Catchment	**IL (mm)**	**IL (mm) FFA**	**CL (mm/hr)**	**CL (mm) FFA**
145011A	38	30[1]	4.2	1.0[1]
145018A	47	42[2]	4.5	3.1[2]
204034 (I10)	53	50[3]	2.36*	0.3[3]
206014 (I14)	8	29[3]	2.24*	0.004[3]

*Indicates datahub output after multiplying by NSW factor 0.4.

[1] = (Ilahee 2005), [2] = (City of Gold Coast 2014) , [3] = (Podger et al. 2019)

3.3.2 Catchment Model Factors

Additional parameters for the DRAINS model include a surface roughness factor for use in the kinematic wave equation. The DRAINS help file has suggestions from ARR and the “Short Grass Prairie” option was chosen with the middle value of the range chosen i.e. n* = 0.15 for each catchment.

Flow path lengths entered into the model were approximately half the stream length noted in Table 3.1.

Model parameters for the RORB model are determined from the recommended values present in the program, these are based on ARR2019 Book 7 Eq 7.6.8 and Eq 7.6.13. The K_c value for a RORB model can be considered an adjustment factor with it playing a large part in model lag. Estimates of K_c value have been determined from extensive regionalisation studies and its value varies from state to state.

For NSW:

$$K_c = 1.18A^{0.46} \tag{3.1}$$

where A = Area (km^2).

For QLD:

$$K_c = 0.88A^{0.53} \tag{3.2}$$

where A = Area (km²).

The remaining non-linearity factor, m, is generally assumed to be 0.8 although it can be adjusted during model calibration. However, for an ungauged catchment the recommended value is 0.8 and has been adopted here.

Further factors are downloaded from the ARR website such as areal reduction factors.

3.4 DRAINS

The DRAINS model created was a super simplified representation of the IL-CL model with an overland flow kinematic wave for routing. An error in version number of DRAINS with the flood routing module necessitated a revised design. A model closer to industry standards was made with the RORBWin program later. The results of this model were very interesting particularly with the smaller QLD catchments, so its use was retained despite its poor representation of routing. Section 3.4.1 describes the basics of the model setup within the program and section 3.4.2 describes the calculations undertaken by the model.

3.4.1 Project Setup

1. Open new project.
2. Project → Hydrological Models.
3. Add IL / CL Model,
    a. Enter model name (<catchment> IL-CL),
    b. Enter Remaining Area Initial Loss (mm),
    c. Enter Remaining Area Continuing Loss (mm/hr),
    d. For overland flow use - leave as Kinematic wave equation.
4. Project → Project Options,
    a. Option 1 Ensure using ARR2019 Procedures and Ensembles of storms (for matching design rainfall events if time allows for full at-site FFA).
5. Project → Rainfall Data,
    a. Option 1 – Event based comparison,
        i. Enter name for storm event,
        ii. Enter the corresponding 5min intensity (mm/hr) for the event.
    b. Option 2,
        i. Use current BOM IFD,
        ii. Import BOM data,
        iii. Add previously downloaded data for site.
6. Select Storms,
    a. Option 1 – Event Comparison,
        i. Project → Select major storms,
        ii. Select storms → from drop down select the storm manually entered.
    b. Option 2 – Design storm comparison,
        i. Project → Select Major/Minor Storms,
        ii. Select AEP, Burst Duration and all storms add for major and minor.

7. Draw → Sub-Catchment and select position.
8. Draw → Node and place just overlapping previously placed Sub-Catchment and then edit,
    a. Enter sub-catchment name,
    b. Enter area,
    c. Either make sure all other hydrologic models are deleted or select IL-CL model made earlier,
    d. Select "more detailed data",
    e. Pervious Area set to 100, (Effective Impervious and Remaining Impervious Area zero)
    f. Constant time set to zero (done as it uses kinematic/Friends eq),
    g. Enter Flow path length,
    h. Enter Flow path slope,
    i. Retardance coefficient. (a value of 0.15 has been chosen for all)

3.4.2 Modelling

The IL-CL model is not explicitly stated in DRAINS but it assumed to follow a similar set of equations to that presented in the RORB manual and is shown below in section 3.5.2.

Kinematic wave is used to describe the flow in the DRAINS model created, DRAINS does this as shown in equation (3.3):

$$t = \frac{6.94(L.n)^{0.6}}{I^{0.4}S^{0.3}} \tag{3.3}$$

where t = overland flow travel time (min)

L = length of flow path (m)

n = surface roughness

I = rainfall intensity (mm/h)

S = surface slope (m/m)

3.5 RORB

The RORB model was setup using manufacturer and ARR2019 settings with the latter taking precedence when two options were presented. Model setup consisted of a series of sub-catchments, junctions and reaches. Sub-catchments were from QGIS watershed delineation and the numbers representing them in Figure 3.3, Figure 3.4, Figure 3.5 and Figure 3.6 are shown in Figure 8.2, Figure 8.3, Figure 8.4 and Figure 8.5 respectively as the model sub-catchment. Reaches were created by taking the distance of one catchment centroid to the next with occasional junctions where two catchment streams intersected. Section 3.5.1 is the model creation process and section 3.5.2 highlights the RORB calculations used.

3.5.1 Project Setup

1. Open the Graphical editor
    a. Enter a model name
    b. Add nodes (typically positioned at the centroid of each sub-catchment).
        i. Enter area in km².

        ii. Enter sub-catchment name to mirror QGIS watershed output.
    c. Add junction nodes where appropriate.
    d. Add end of model node and select print type “1. Print calculated discharge (Code 7)” at this node for a design hydrograph.
    e. Create reaches from sub-catchment nodes to nodes along the streamlines to outlet.
        i. Reach type “Natural”
        ii. Enter name and reach length.
    f. Save model and quit graphical editor.
    g. Refer APPENDIX C for catchment models as created in the graphical editor.
2. Select edit run specification and input:
    a. Input Files
        i. Separate catchment and generated design storm(s)
        ii. IFD data type – ARR2016
        iii. Catchment file browse to selected catchment created above.
    b. Parameter configuration
        i. Single set of parameters for whole catchment
        ii. Initial loss/ continuing loss model
    c. Run Options
        i. DESIGN (loss parameters specified by user)
    d. Output options
        i. Flows and all input data
        ii. Model/catchment file
        iii. Model/catchment file
    e. Select ok
3. Design Rainfall Specification (ARR2016)
    a. Data Hub files
        i. Text file downloaded from ARR Datahub.
        ii. Areal Increments downloaded csv
    b. IFD data
        i. Bom downloaded depths_-xx.xx_xx.xx_all_design.csv
    c. Simulation details
        i. Monte-Carlo
        ii. Duration 12hr to 72hr
        iii. Time increments default (200)
    d. Temporal pattern details
        i. Leave default
    e. Spatial pattern details
        i. Leave default
    f. Pre-burst
        i. Leave unchecked
    g. Areal Reduction Factor details
        i. Leave unchecked
    h. Loss Factor details
        i. Constant Losses
    i. Output directory
        i. Same as catchment and parameter file
    j. Select ok
4. Parameter Specification
    a. Select ?? and then under “Regional” select either NSW or QLD depending on catchment and click adopt.

    b. Enter m value of 0.80
    c. Enter IL and CL values from Table 3.3 as required for each run.
5. Select plot
6. Monte-Carlo Simulation
    a. Stratified Sample
        i. Leave default (rainfall divisions 50 and samples per division 20)
    b. Initial loss selection
        i. Monte-Carlo sample (leave default)
    c. Output details
        i. Print individual run results
    d. Select ok
7. Frequency plot site selection
    a. Single site and select envelope and review
    b. Select text output and scroll to bottom for summary

3.5.2 Modelling

1. Loss model in RORB is comprised of two parts, the initial loss and the continuing loss, these are explained in the RORB manual by Laurenson, Mein and Nathan (2010) and are summarised below.

Initial loss in RORB (in this rural context) for each sub area is calculated from:

$$IL_i = (1 - F_i)IL_{perv} \tag{3.4}$$

Continuing loss is calculated from:

$$C_i = F_iC_{imp} + (1 - F_i)C_{perv} \qquad C_{perv} \leq C_{imp} \tag{3.5}$$

$$C_i = C_{imp} \qquad C_{perv} > C_{imp} \tag{3.6}$$

$$CL_i = (1 - F_i)CL_{perv} \tag{3.7}$$

where C = Runoff coefficient

IL = Initial loss

F = Fraction impervious

Subscripts *i, imp* and *perv* represent the i^{th} sub area, the impervious area and pervious area, respectively.

2. Routing in RORB with reach storage represented by:

$$S = kQ^m$$

(3.8)

where S = storage (m³)

k = $k_c k_r$

k_c = RORB calibration factor applicable to catchment

k_r = relative delay time applicable to individual reach storage

m = non-linearity factor

Q = flowrate (m³/s)

3.6 Analysis

Results are compared to the flood frequency analysis for each site, to aggregate this data from all catchments results will be standardised to the FFA for each site. This can be taken as the difference from the model to the FFA value as a percentage, the results are also multiplied by minus one to represent a positive value overestimating site FFA values and is represented by:

$$D_i = \frac{FFA_i - M_i}{FFA_i} \times 100 \times -1$$

(3.9)

where D_i = variation from FFA for model and configuration *i* (%)

FFA_i = FFA discharge (m³/s)

M_i = Model Discharge (m³/s)

3.6.1 Root Mean Square Error

The root mean square error (RMSE) is used for comparison of model calculated flow rates against FFA values. It is essentially an indicator of the spread of the residuals created from the comparison. The RMSE is determined by:

$$RMSE = \sqrt{\sum_{\mathrm{i}=1}^{N} \frac{(Model_i - FFA_i)^2}{N}}$$

(3.10)

where Model = DRAINS or RORB flowrate output for *i*th AEP event

FFA = FFA flowrate output for *i*th AEP event

N = number of AEP events

4 Results

The first comparisons included FFA hydrographs to those available through ARR RFFE and are presented for each catchment as shown in Figure 4.1, Figure 4.2, Figure 4.3 and Figure 4.4.

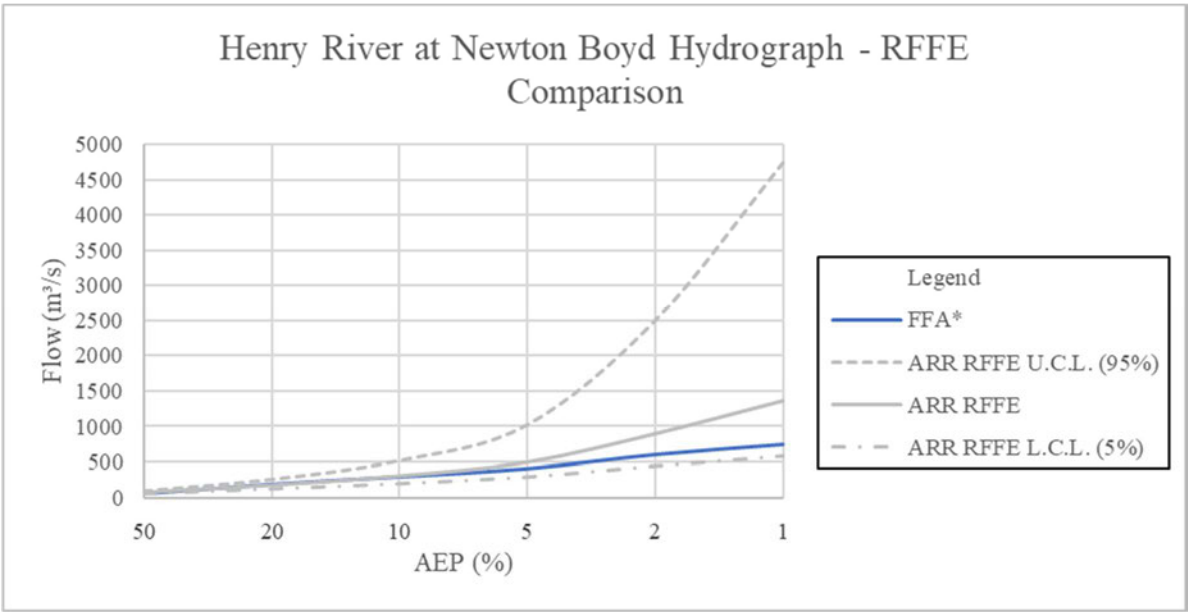

Figure 4.1. Henry River at Newton Boyd FFA and RFFE comparison.

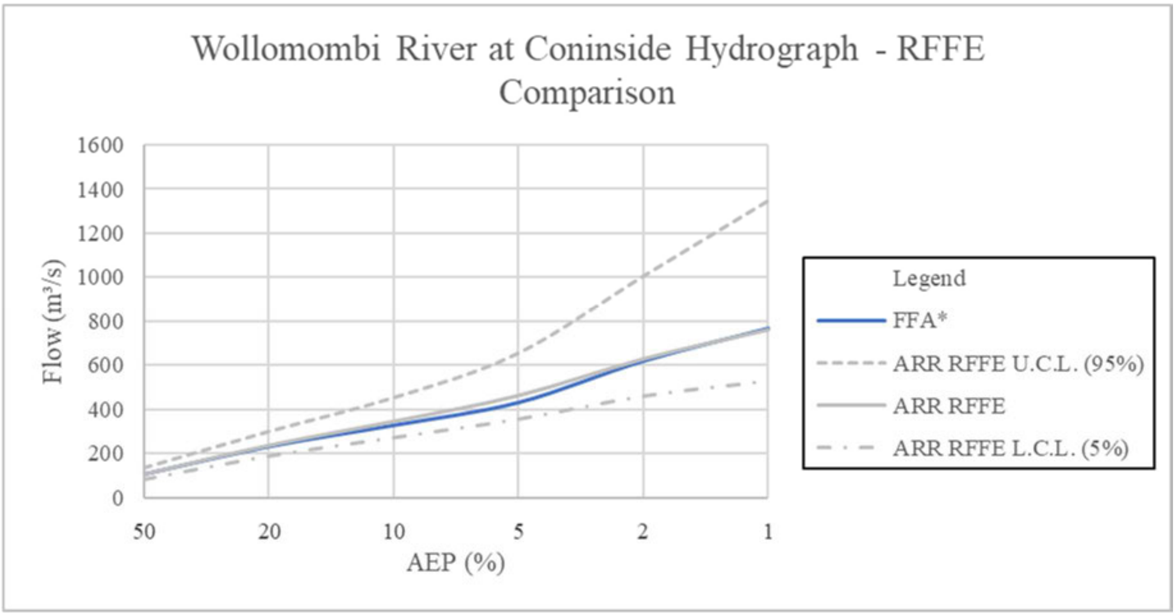

Figure 4.2. Wollomombi River at Coninside FFA and RFFE comparison.

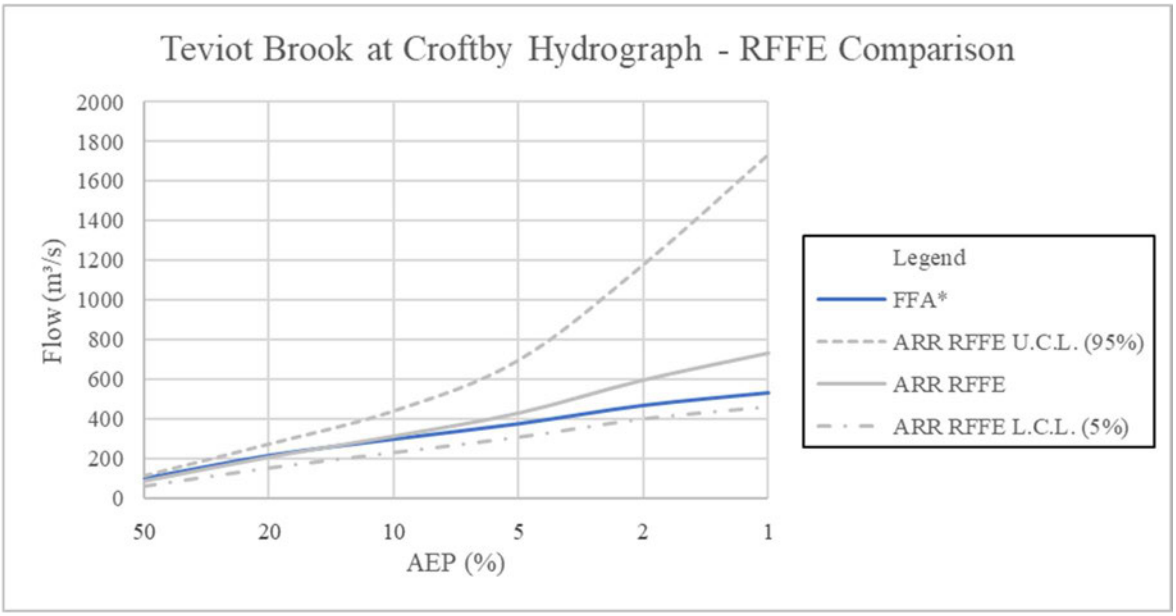

Figure 4.3. Teviot Brook at Croftby FFA and RFFE comparison.

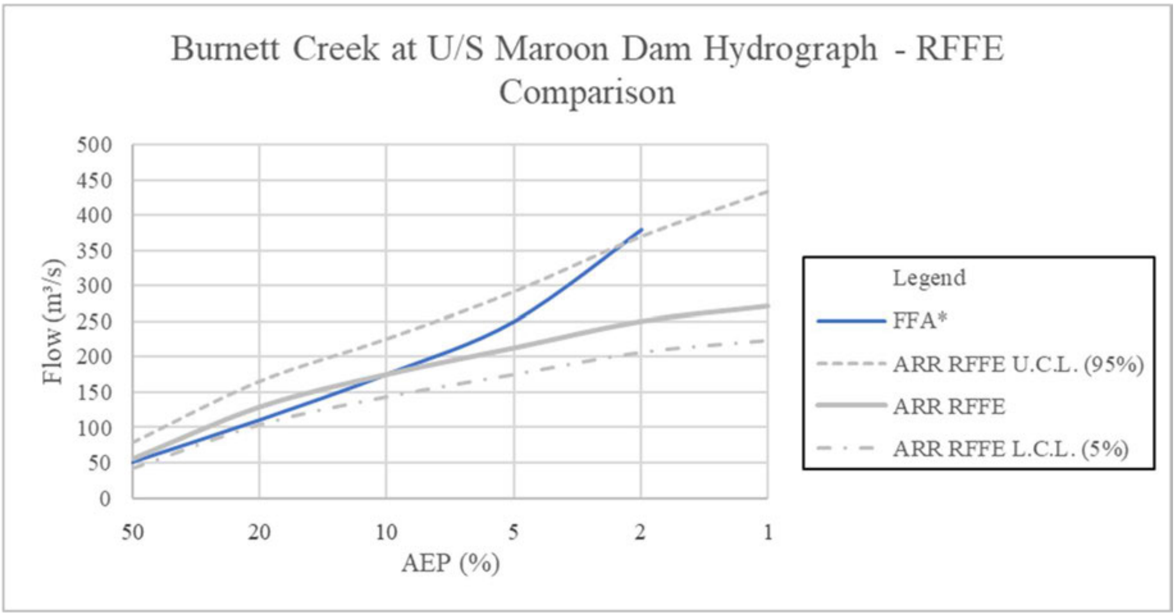

Figure 4.4. Burnett Creek at U/S Maroon Dam FFA and RFFE comparison.

Initial comparisons shown in Figure 4.4 show large underestimation by the ARR RFFE LP3 toward the more extreme events. Figure 4.1 and Figure 4.3 show the ARR RFFE LP3 values very similar to independent FFA though becoming a little conservative toward the extreme events. Figure 4.2 shows the ARR RFFE LP3 has a very close relationship to independent FFA values.

Models were set up using site derived IL CL values and hydrographs were generated to show how accurate the models were to FFA values; these are shown for each catchment in Figure 4.5, Figure 4.6, Figure 4.7 and Figure 4.8.

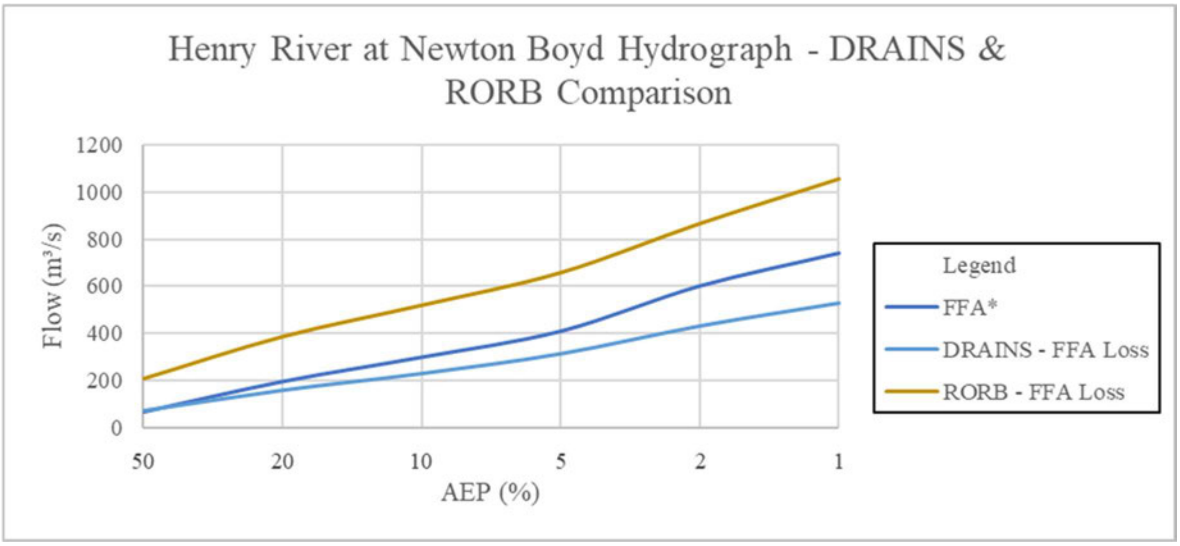

Figure 4.5. Henry River at Newton Boyd DRAINS and RORB model comparison for site.

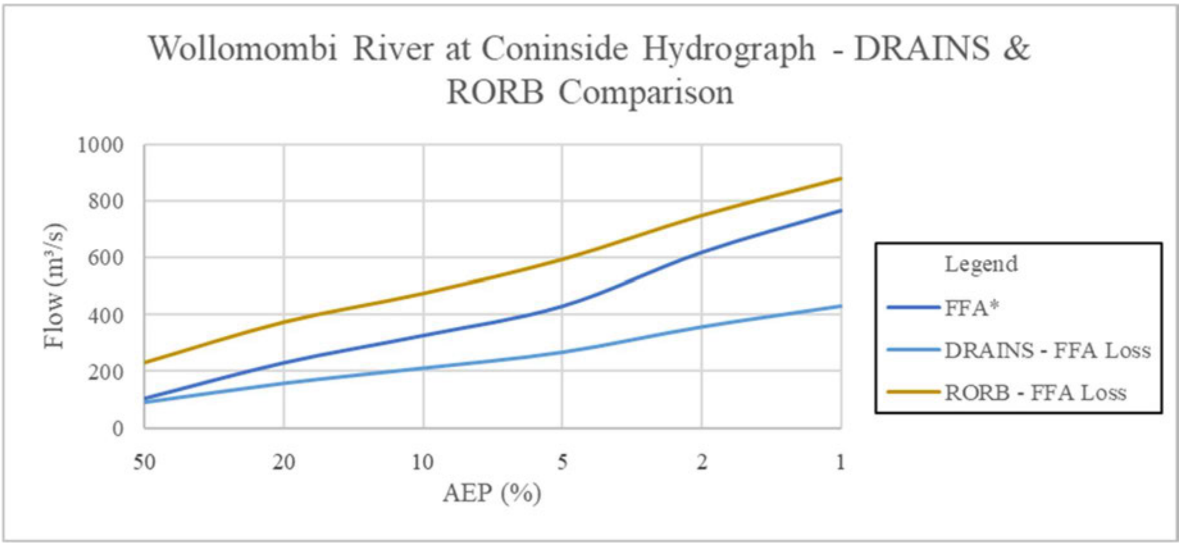

Figure 4.6. Wollomombi River at Coninside DRAINS and RORB model comparison for site.

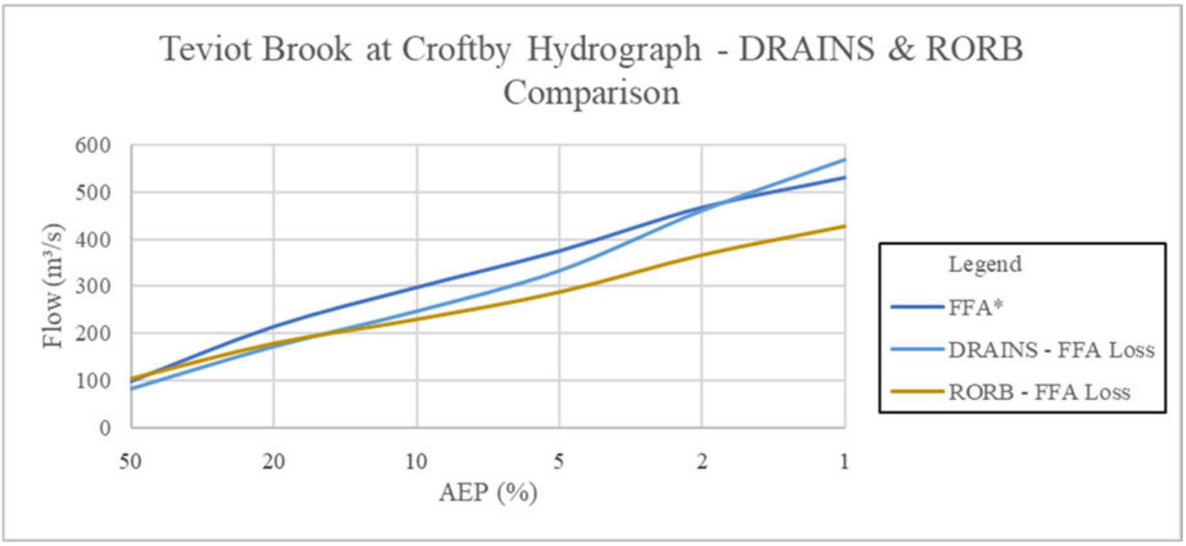

Figure 4.7. Teviot Brook at Croftby DRAINS and RORB model comparison for site.

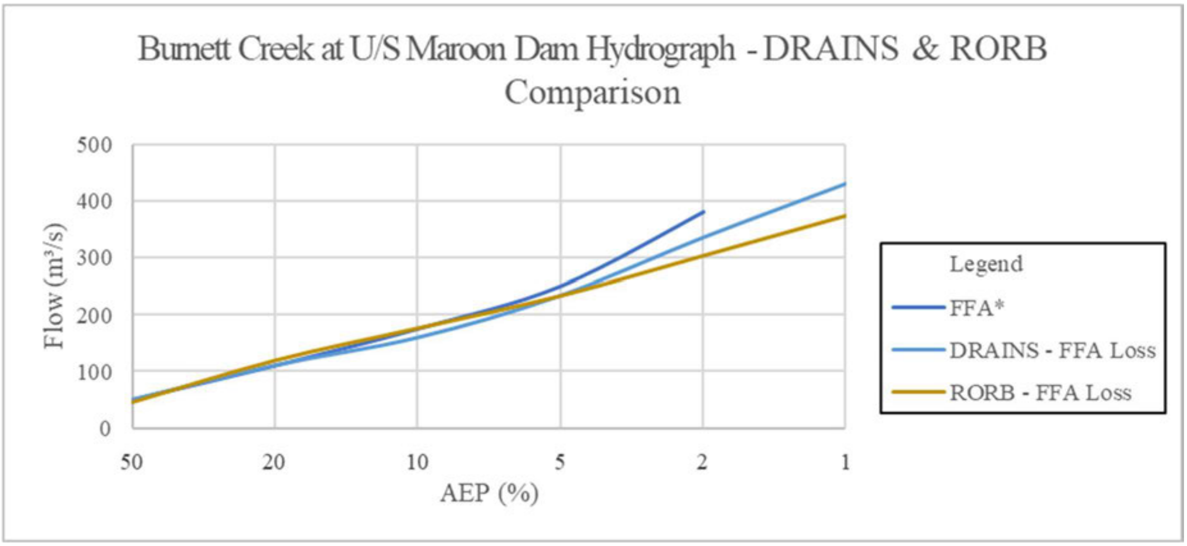

Figure 4.8. Burnett Creek at U/S Maroon Dam DRAINS and RORB model comparison for site.

Comparison of DRAINS and RORB models shown in Figure 4.5 and Figure 4.6 appear similar with RORB over estimating and DRAINS underestimating. Results shown in Figure 4.7 and Figure 4.8 are closer to FFA values and the models have reversed with the DRAINS model generating a higher estimate than the RORB model.

Models were set up using site ARR Datahub IL CL values and hydrographs were generated to show how accurate the models were to FFA values; these are shown for each catchment in Figure 4.9, Figure 4.10, Figure 4.11 and Figure 4.12.

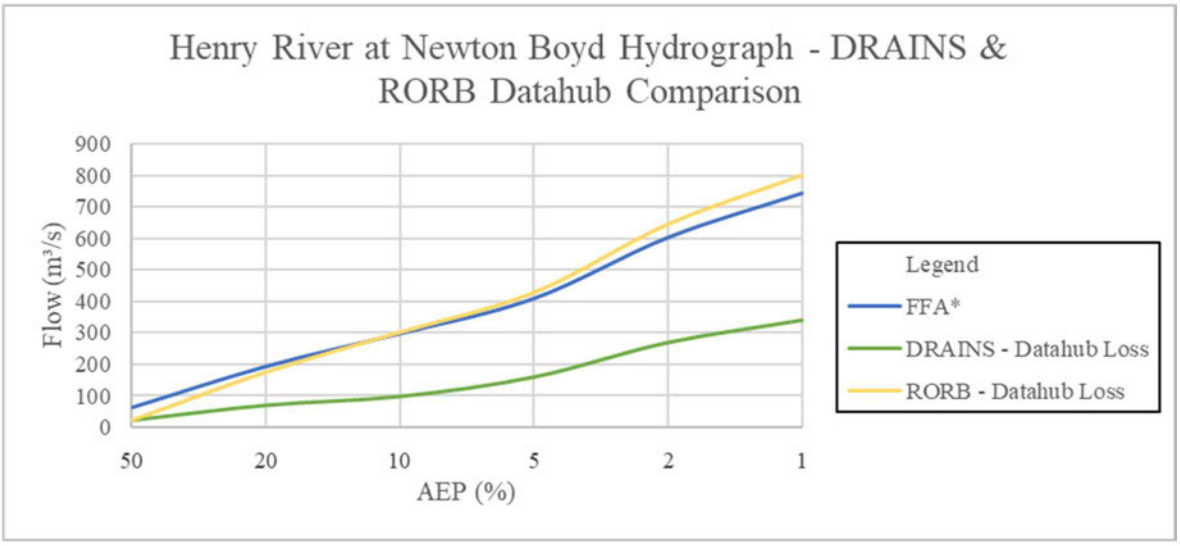

Figure 4.9. Henry River at Newton Boyd Datahub loss comparison for site.

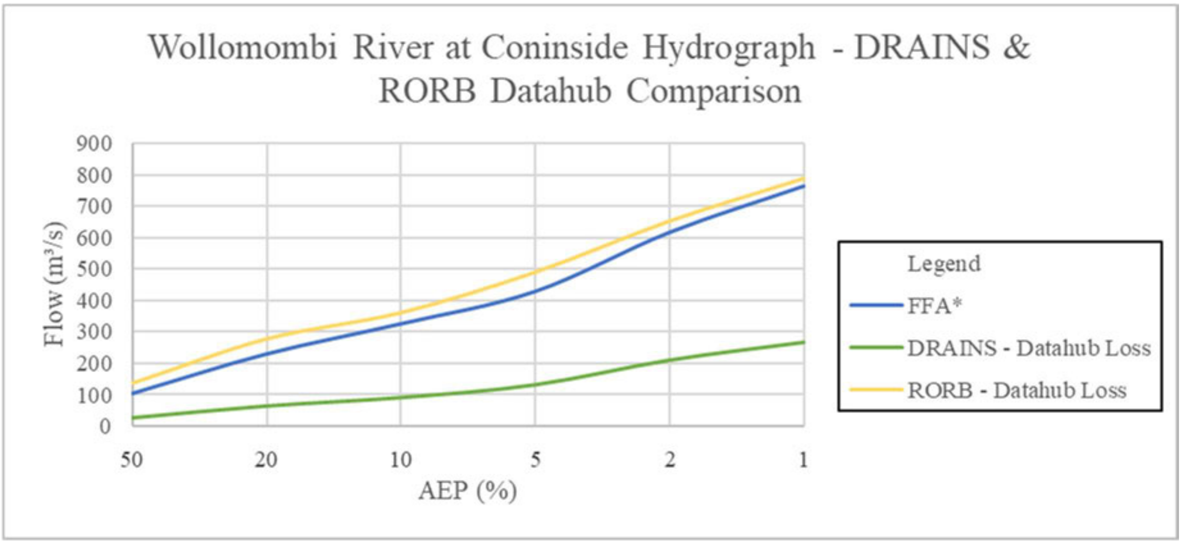

Figure 4.10. Wollomombi River at Coninside Datahub loss comparison for site.

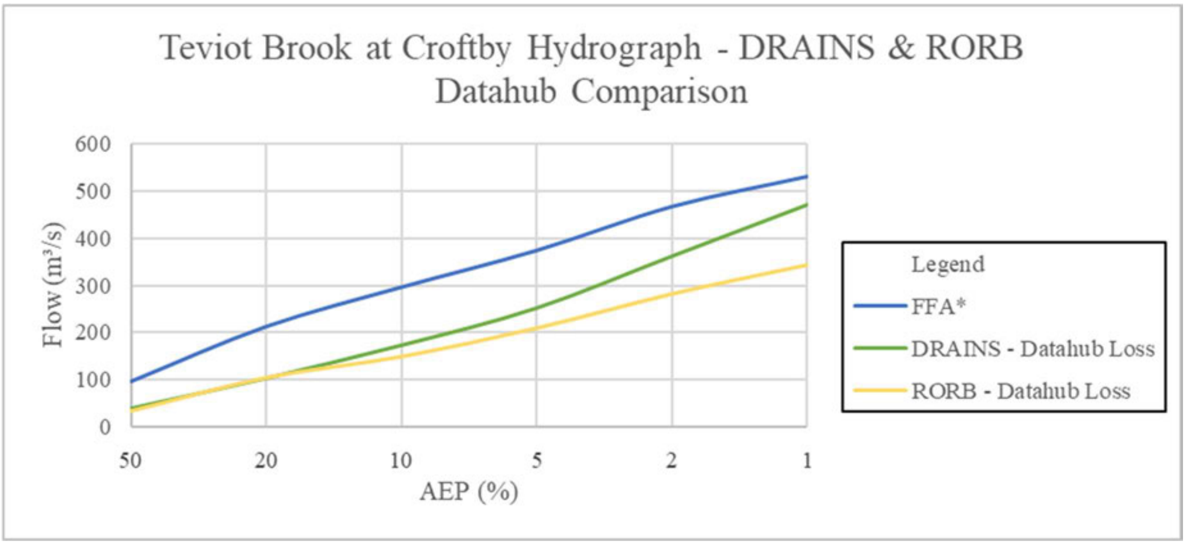

Figure 4.11. Teviot Brook at Croftby Datahub loss comparison for site.

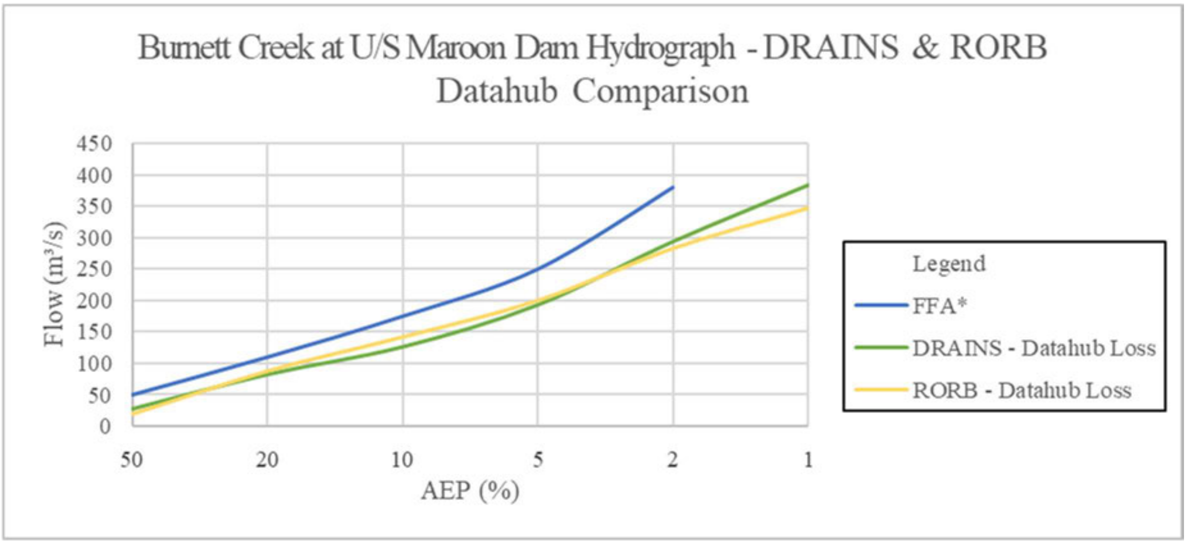

Figure 4.12. Burnett Creek at U/S Maroon Dam Datahub loss comparison for site.

Comparison of DRAINS and RORB models shown in Figure 4.9 and Figure 4.10 show a distinct separation of the models with the DRAINS model displaying significantly lower flowrates through all event frequencies. Results in Figure 4.11 and Figure 4.12 show a little more similarity in output though both underestimate the FFA values.

A DRAINS model (DM) and a RORB model (RM) for each catchment was used to generate a hydrograph using the neighbouring site derived IL and CL values; these are shown in Figure 4.13, Figure 4.14, Figure 4.15 and Figure 4.16.

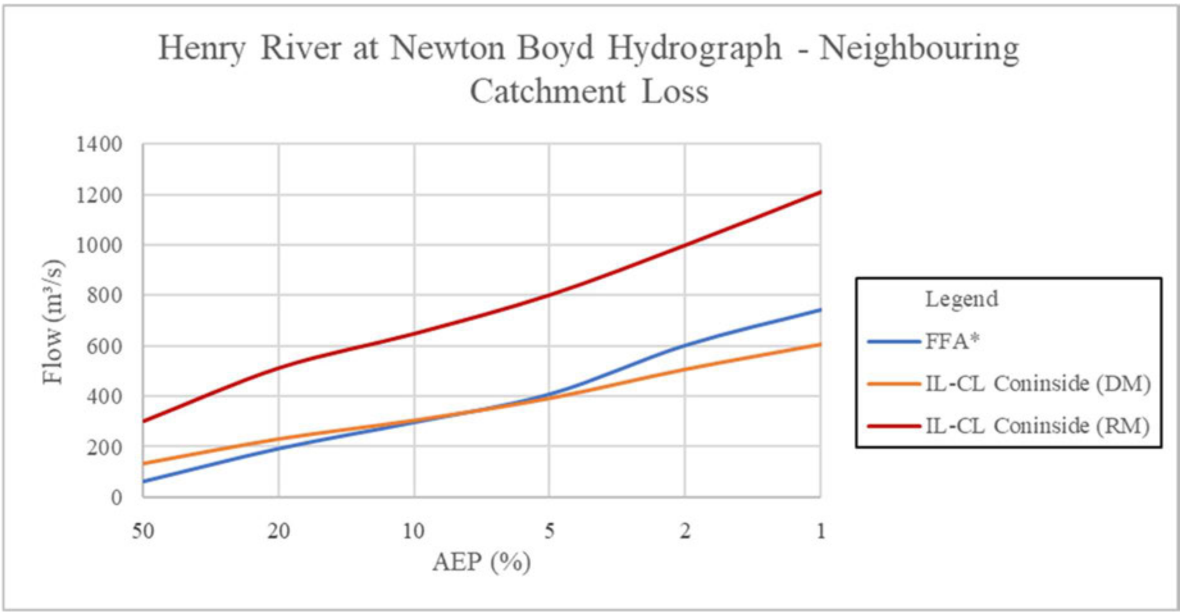

Figure 4.13. Henry River at Newton Boyd FFA and neighbour loss comparison.

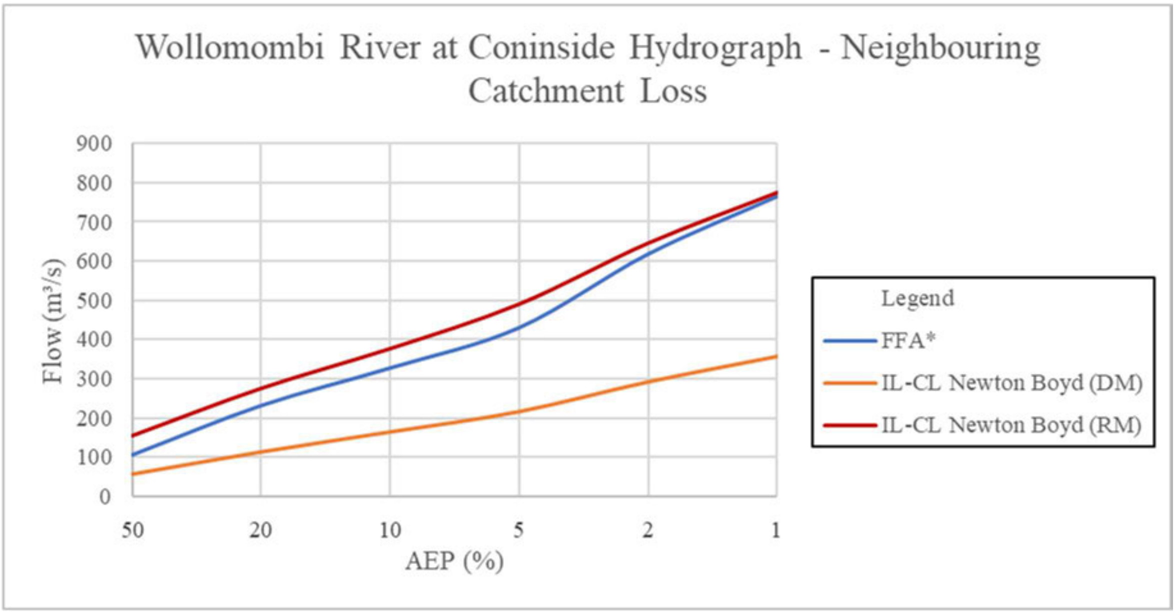

Figure 4.14. Wollomombi River at Coninside FFA and neighbour loss comparison.

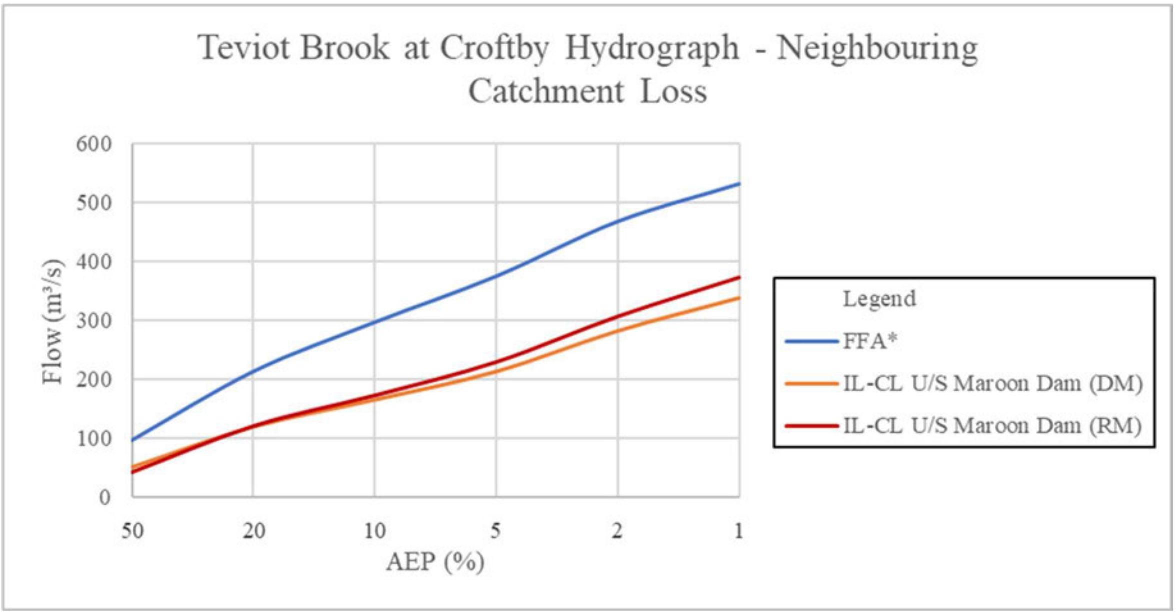

Figure 4.15. Teviot Brook at Croftby FFA and neighbour loss comparison.

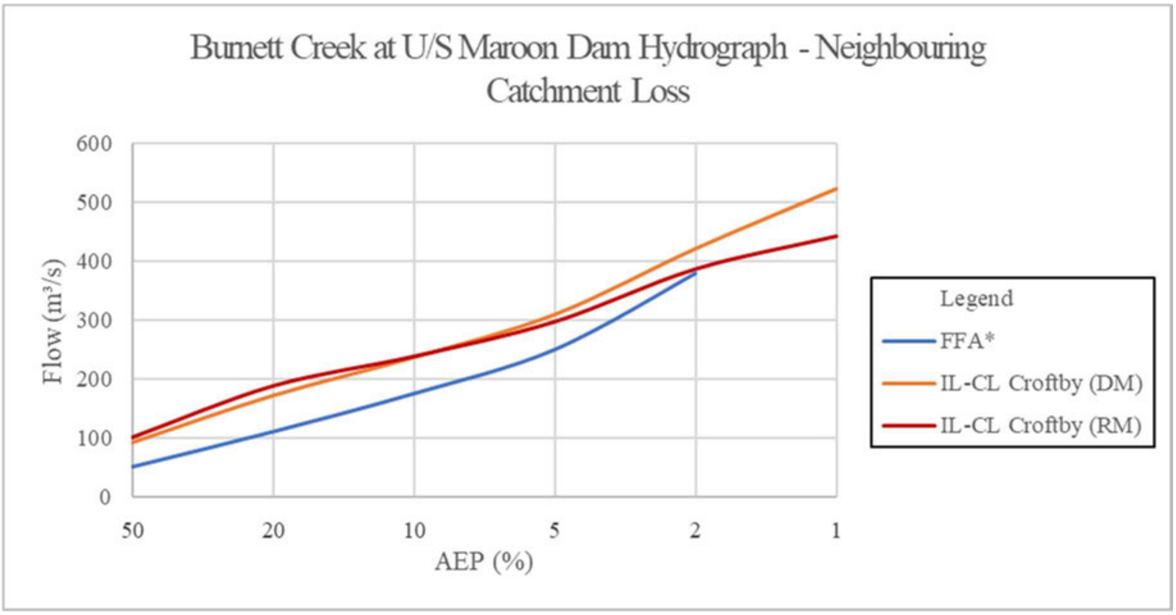

Figure 4.16. Burnett Creek at U/S Maroon Dam FFA and neighbour loss comparison.

Results in Figure 4.13 show the RORB results significantly overestimating FFA values. Figure 4.14 shows the DRAINS model dramatically underestimating FFA values. Figure 4.15 and Figure 4.16 there is less difference between the models however for one catchment they both over estimate and for the other they both underestimate.

Further parameter variation was undertaken in RORB by changing the initial loss condition from Monte-Carlo sampling, represented by 'RORB-FFA Loss', and fixed, represented by 'RORB – FFA Loss – Fixed' in Figure 4.17. Results suggest there is little difference when between adjustment of the initial loss characteristic when adjusted up or down by 3mm in the Monte Carlo sample.

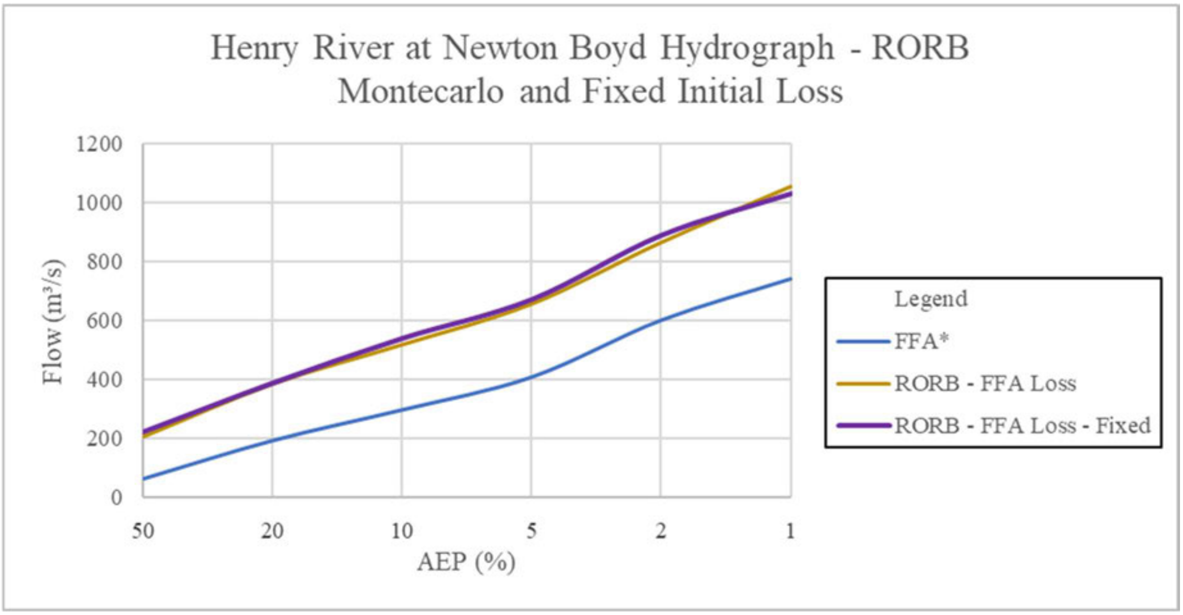

Figure 4.17. Comparison of RORB Monte Carlo and Fixed Initial Loss.

Comparison of ARR RFFE hydrographs was also undertaken with Burnett Creek at U/S Maroon Dam producing a large variation between the site values, represented by ARR RFFE, and entering the centroid, outlet, and area, represented by ARR RFFE – Cent. Outlet in Figure 4.18. It appears care should be exercised when using the manual input method if this is part of the initial assessment of an ungauged catchment.

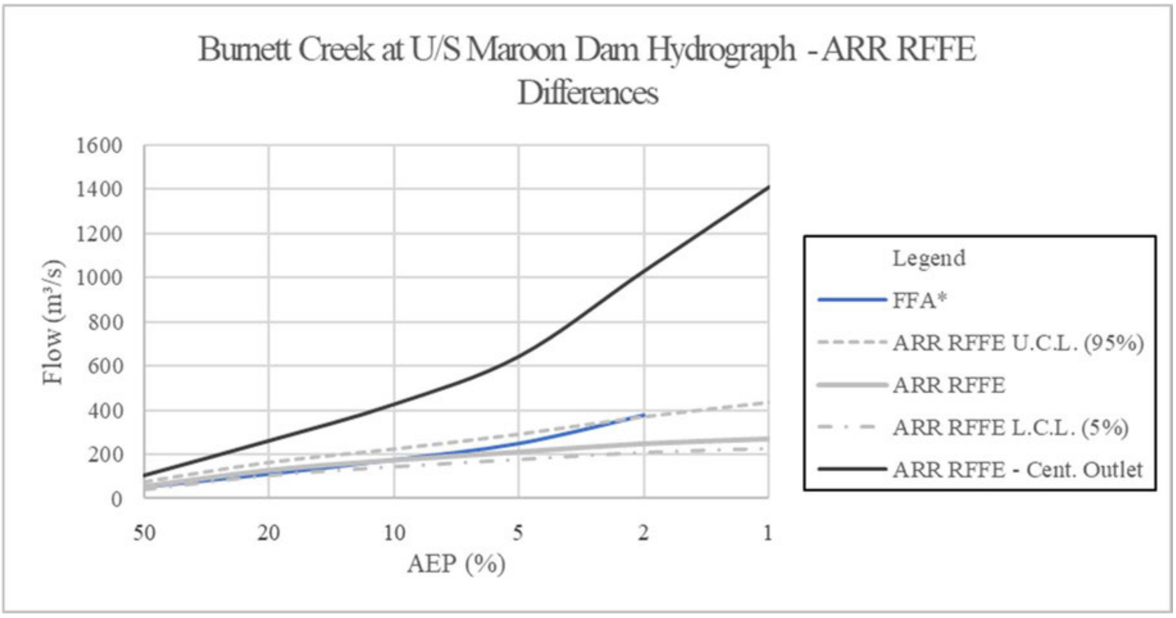

Figure 4.18. Comparison of RFFE Centroid/Outlet method and site calculated values.

To provide an estimation of the “closeness” of the models to the FFA values the RMSE was taken for each of the catchments and is presented in subsequent tables for each catchment. The AEP columns 50 to 1 are the difference of the model from the FFA value with negative values representing underestimation. The residuals calculated for each of the AEP events were then used to determine the RMSE which, is calculated using eq (3.10). The lower the RMSE the closer the match to the FFA values, these were then ranked from lowest RMSE to highest representing the least variation to the greatest variation from FFA.

Table 4.1. Henry River at Newton Boyd models design-storm estimate rank.

AEP (%)	**50**	**20**	**10**	**5**	**2**	**1**	**RMSE**	**Rank**
ARR RFFE	1.02	-24.62	-0.39	81.3	290.77	619.39	281.4866	6
DRAINS - FFA Loss	9	-34	-67	-94	-169	-212	121.1521	3
DRAINS - Datahub Loss	-42	-124	-200	-249	-332	-401	255.0052	5
RORB - FFA Loss	142	190.5	219.6	247	262.2	311.5	235.042	4
RORB - Datahub Loss	-41.4	-18.1	4	19	42.5	57.8	35.50976	1
IL-CL Coninside (DM)	71	38	7	-17	-96	-138	76.46677	2
IL-CL Coninside (RM)	237.9	319.7	352	395	400	471	369.814	7

From Table 4.1 of Henry river catchment, the DRAINS model performed better than the RORB model with site derived loss values and was the most similar to the FFA values of the two. The RORB datahub values were the most accurate overall in representing the FFA values.

Table 4.2.Wollomombi River at Coninside models design-storm estimate rank.

AEP (%)	**50**	**20**	**10**	**5**	**2**	**1**	**RMSE**	**Rank**
ARR RFFE	-0.56	5.07	18.87	33.79	12.47	-1.47	16.74078	1
DRAINS - FFA Loss	-12	-71	-114	-161	-260	-334	192.8981	5
DRAINS - Datahub Loss	-79	-167	-236	-298	-407	-497	313.9236	7
RORB - FFA Loss	128	145.2	149.9	166	132.7	116	140.5693	4
RORB - Datahub Loss	32.4	47.4	35.1	60.8	35.3	23.9	40.91143	2
IL-CL Newton Boyd (DM)	-48	-117	-162	-213	-325	-407	244.5676	6
IL-CL Newton Boyd (RM)	48.5	43.6	49.1	59.8	27.6	9.6	42.99996	3

From Table 4.2 of Wollomombi river catchment, the RORB model performed better than the DRAINS model with site derived loss values and was the most similar to the FFA values of the two. The ARR RFFE was the closest overall but the RORB model using the datahub values was the next closest overall.

Table 4.3. Teviot Brook at Croftby models design-storm estimate rank.

AEP (%)	50	20	10	5	2	1	RMSE	Rank
ARR RFFE	-14.4	-9.7	12.6	51.2	125.9	197.8	98.36776	3
DRAINS - FFA Loss	-14.3	-40.8	-49.4	-41.3	-6.2	38.2	35.38564	1
DRAINS - Datahub Loss	-58.3	-110.8	-124.4	-123.3	-106.2	-60.8	101.1013	4
RORB - FFA Loss	5.7	-35.8	-68.4	-88.3	-102.2	-104.8	76.61316	2
RORB - Datahub Loss	-64.7	-110	-148.4	-165.3	-185.2	-186.8	149.9033	7
IL-CL U/S Maroon Dam (DM)	-45.8	-93.8	-131.4	-161.3	-185.2	-192.8	144.7127	6
IL-CL U/S Maroon Dam (RM)	-56.3	-94.1	-125.4	-146.4	-161.6	-158.8	129.4312	5

From Table 4.3 of Teviot Brook catchment, the DRAINS model performed better than the RORB model with site derived loss values and was the most similar to the FFA values of the two and overall.

Table 4.4. Burnett Creek at U/S Maroon Dam models design-storm estimate rank.

AEP (%)	50	20	10	5	2	1	RMSE	Rank
ARR RFFE	6.1	19.4	0.3	-37.6	-130.2		61.28533	7
DRAINS - FFA Loss	-1	0	-16	-17	-45		22.67598	1
DRAINS - Datahub Loss	-22	-27	-48	-56	-85		52.68396	3
RORB - FFA Loss	-3.7	10.1	2.1	-15.8	-75.9		35.01588	2
RORB - Datahub Loss	-31.8	-23.1	-33.4	-49.9	-96.4		53.7464	4
IL-CL Croftby (DM)	42	62	62	60	42		54.43528	6
IL-CL Croftby (RM)	50.033	77.6	63	47	6.7		54.31013	5

From Table 4.4 of Burnett creek catchment, the DRAINS model performed better than the RORB model with site derived loss values and was the most similar to the FFA values of the two and overall.

5 Discussion

5.1 FFA Analysis

As most of the comparisons are made to the flood frequency analysis results, two sources for this were desired. One source was from the ARR RFFE resource, the FFA values are obtained via LP3/L-moments and is the support source for this project. The main source was from independent flood studies and was to the primary comparison value with several reports suggesting that the RFFE over estimates flows for extreme events (Podger et al. 2019). Comparisons shown in Figure 4.1, Figure 4.2 and Figure 4.3 show the ARR RFFE value equal to or greater than the independent FFA though all values were within the ARR RFFE confidence limits. Figure 4.4 however shows a dramatic underestimation by ARR RFFE though true values of the independent FFA were inconclusive toward the higher AEP values. Overall, the independent FFA values were chosen for the comparison benchmark though additional studies or independent review of the Burnett Creek at U/S Maroon Dam catchment is warranted.

In summary the ARR RFFE tool appears to be closely linked through much of the AEP design range but begins to overestimate toward the extreme AEP's, this is likely a conservative approach to apply a safety factor for flooding assessment. This result is at odds to the reports by Podger et al. (2019) that commented on the underestimation of the IL and CL factors. It was assumed that IL CL factors and RFFE discharge hydrographs would be linked but it appears they were independently determined.

5.2 Model Accuracy

The check of the most accurate model using site derived loss values was undertaken to understand a models' behaviour under default program conditions and settings. The improved understanding would allow for better estimates of model outputs when no calibration of the model was possible. Determination of the most accurate model requires identifying the reason for the models' creation in the first place. Models designed for use in determining water yield for reservoirs will require a model that underestimates flows, whilst a model for flood modelling will require a model that overestimates flows. This over/under estimation is being conservative to account for errors in the modelling and/or recorded data. Problems can occur when an over estimation factor is applied on a model that already dramatically underestimates flow in a flood modelling scenario or vice versa in reservoir accounting.

Initial efforts were undertaken to determine how accurate a DRAINS and RORB model would be using default and recommended settings along with known initial loss and continuing loss parameters. Results shown in Figure 4.5, Figure 4.6, Figure 4.7 and Figure 4.8 were summarised in Figure 5.1 and are presented as the difference from the flood frequency analysis value where a positive variation is an overestimation and a negative variation is an underestimation of flow. The root means square error was also used to rank the model outputs and these are presented in Table 4.1, Table 4.3 and Table 4.4 where the DRAINS model was ranked higher and Table 4.2 where the RORB model was ranked higher.

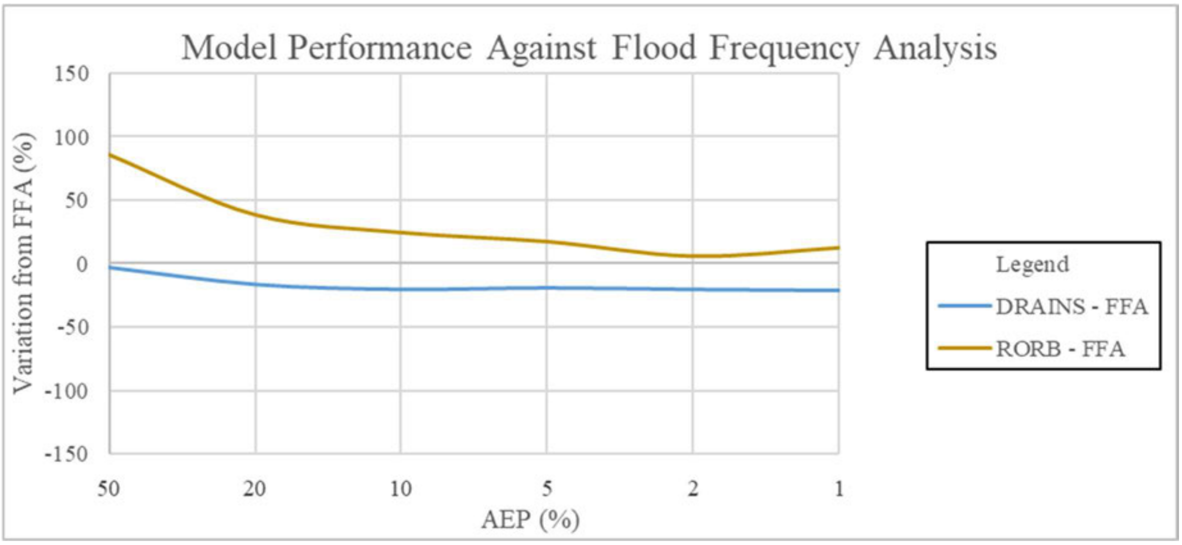

Figure 5.1. Overall performance of each model with site derived IL and CL values.

Results of the DRAINS and RORB models indicate that total variation from the site FFA is the least with the DRAINS model as indicated by the blue line in Figure 5.1. The problem with this conclusion is that for flood modelling it will underestimate all flows and by as much as 22% at the 1% AEP. For flood modelling the RORB model performs best at the 2% and 1% AEP and would be the best choice as its variation is at worst 6-12% conservative. This variation between the models and within them indicates that further work is needed in basic model creation to better match values.

5.3 Catchment Size

The effect of catchment size was analysed to determine if there appeared to be any connection between catchment size and model accuracy. Preliminary observations of results suggested there may be a connection, these were analysed by making them all relative to the site FFA and grouping them into pairs. The two NSW catchments were considered medium sized ranging from 377 – 399 km² and the two QLD catchments were considered small ranging from 82 – 85 km².

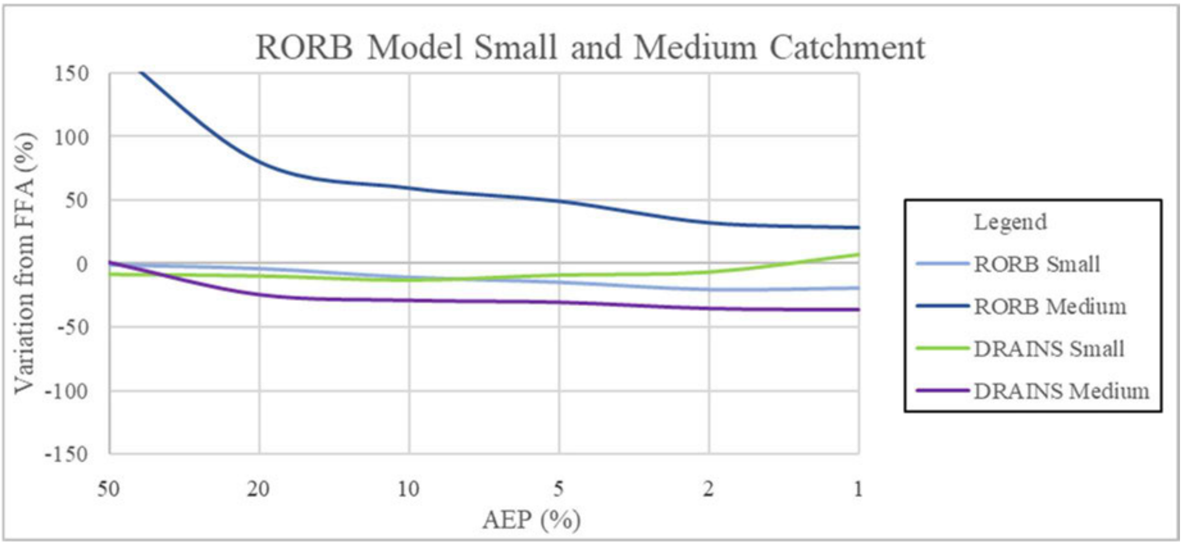

Figure 5.2. Small catchment versus medium catchment in the DRAINS and RORB models.

Both RORB and DRAINS models performed best on the smaller catchments of Teviot Brook at Croftby and Burnett Creek at Upstream Maroon Dam. This is shown in Figure 5.2 above with the light blue and green lines representing the small catchments in the RORB and DRAINS models respectively. These lines do not deviate strongly either positively or negatively from the FFA baseline. The dark blue line in Figure 5.2 shows high variation from the FFA baseline particularly for the smaller design AEP events, it does start to approach the FFA values toward the extreme AEP events. The DRAINS model of the medium catchments simply diverges further and further from the FFA baseline with larger AEP events at a reasonably constant rate.

The more accurate representation from the models on the smaller catchments was to be expected. Smaller catchments have less variance in parameters including reduced rainfall variability across the site, meaning there is reduced need to account for temporal and spatial patterns of rainfall. When determining runoff from ungauged catchments the smaller the catchment the more likely it will be for the model to represent the actual catchment.

5.4 Loss Parameters

The loss parameters were from two sources, ARR Datahub and site derived values. Investigation into the preferred source was undertaken with the goal of making analysis of ungauged catchments more accurate. The first assessment was which model responded the best to the ARR Datahub values and the results are presented in Figure 4.9, Figure 4.10, Figure 4.11 and Figure 4.12. The average of the results are summarised in Figure 5.3 below as the difference from the FFA as a percentage.

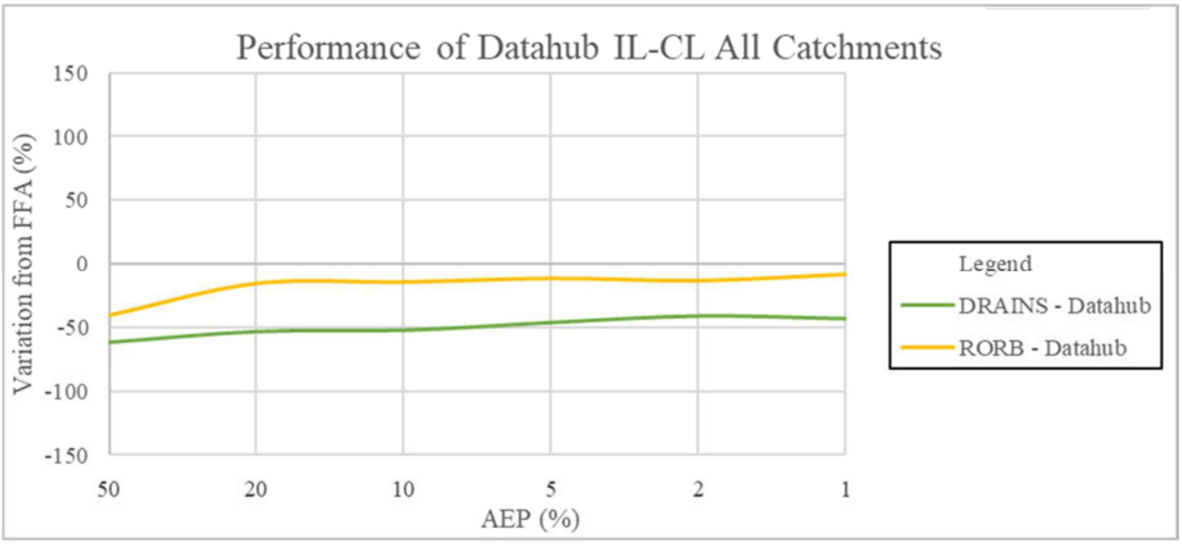

Figure 5.3. Comparison of DRAINS and RORB models using Datahub IL CL values across all catchments.

The results of the best model is clearly shown in Figure 5.3 with the RORB model demonstrating the least variation from the site FFA values. The DRAINS model showed a consistent fifty percent underestimation of the FFA values. As a rule, this is a further 25% underestimation of flows from the model of site derived values, the only reason for this must be the loss value difference.

Next a comparison of the models was made using neighbour site derived initial loss and continuing loss values. These values were unchanged when interchanged for both the adjacent catchments of Teviot Brook and Burnett Creek and the catchments separated by 55km of Wollomombi River and Henry River. The results are similar to those of the datahub loss values in terms of the smaller catchments shown in Figure 4.15 and Figure 4.16 having strong similarities in the models. The larger catchments have the increased model variance from each other as shown in Figure 4.13 and Figure 4.14. The average of the results, when taken as variation from the FFA values, are shown below in Figure 5.4.

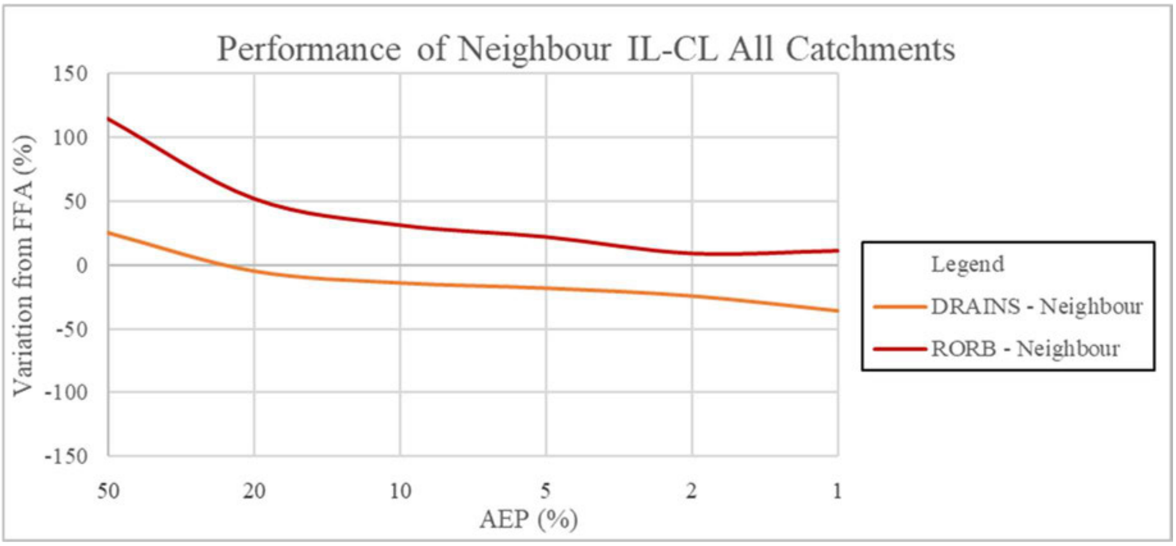

Figure 5.4.Comparison of DRAINS and RORB models using neighbour IL and CL values across all catchments.

As shown in Figure 5.4 the performance of each model across all the catchments is clear with a distinct separation of the DRAINS and RORB models. The DRAINS model shown in orange dips away toward the more extreme AEP and would likely be unsuitable for flood analysis. The RORB model, shown by the red line, starts off with a large overestimation at the more frequent AEP but closely approximates FFA values at the more extreme AEP events.

Of the models using ARR Datahub values the RORB model performed best overall showing the least variation from the FFA values and slightly underestimated flows through the design storm range. Of the models using the neighbour site derived IL CL values the results are mixed between the two uses with the RORB model performing best at the extreme AEP for flooding and DRAINS model performing best for frequent AEP events.

5.5 Catchment Proximity on Accuracy

An effort was made to determine if there was any effect of catchment proximity on the effectiveness of using the IL CL values of the neighbour catchment using the RORB model. The large variation shown in Figure 4.13, Figure 4.14, Figure 4.15 and Figure 4.16 is possibly more strongly linked to catchment size than proximity. These figures were summarised as the difference from the FFA estimate and presented in Figure 5.5 below.

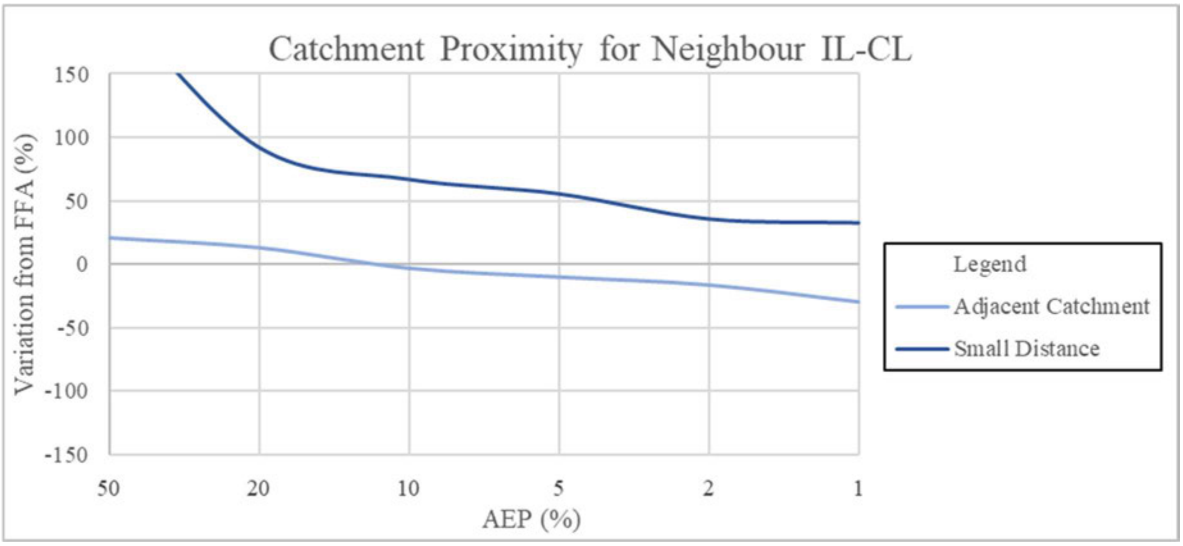

Figure 5.5. Effect of catchment proximity on model output when using neighbour IL-CL.

The results shown in Figure 5.5 indicate what would be expected in that the adjacent catchments with their IL and CL values swapped show a closer relationship to the actual FFA values than catchments that are separated by distance. However, when plotted alongside the results of the catchment size for the RORB model using site derived IL CL values, there is very little deviation. This similarity makes it difficult to draw any strong conclusions about the effect of catchment proximity on accuracy of models.

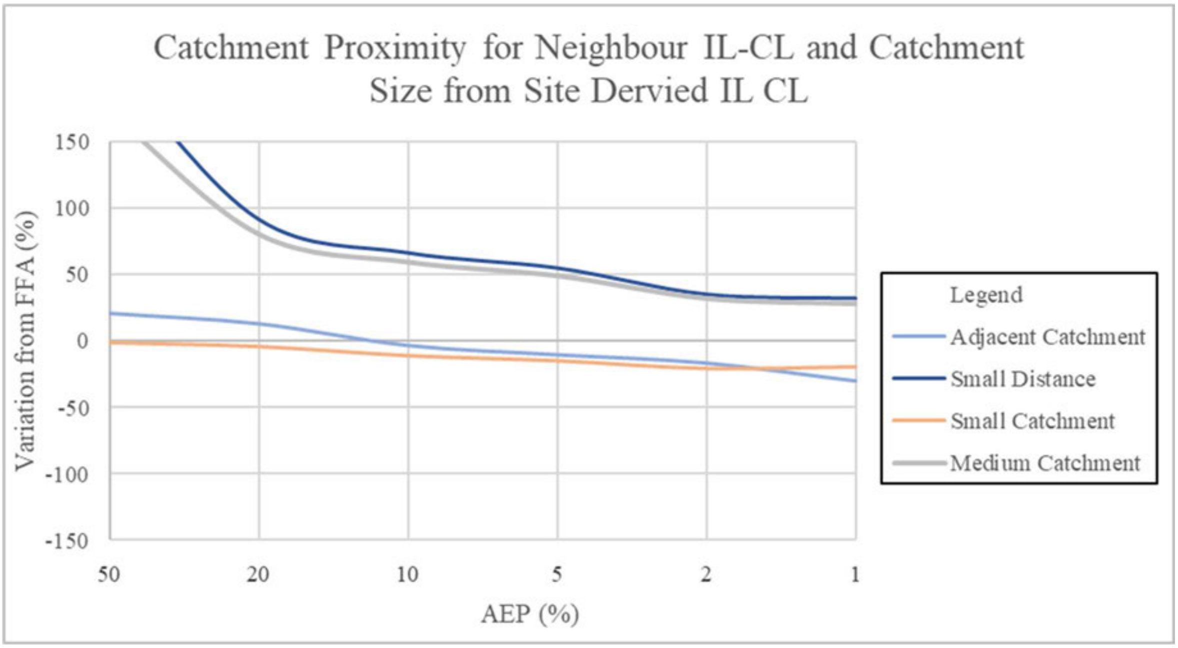

Figure 5.6. Catchment proximity and catchment size results comparison.

The similarity of medium sized catchment and small distance is very closely matched but to determine if there was any difference a statistical comparison was made. Chi square analysis for goodness of fit was undertaken of the two variables at the 5% significance level.

n_0: There is no statistically significant difference between the two.

n_1: There is a difference between the two.

p Value	0.07672209
test statistic	9.94800115
critical statistic	11.0704977

Here the p-value was greater than 0.05 so we fail to reject the null hypothesis. Also, the test statistic is less than the critical value, so we fail to reject the null. There is no statistically significant difference between medium sized catchments and catchment proximity on the accuracy of transferred loss parameters.

Chi square analysis for goodness of fit was also carried on adjacent catchments and small catchments at the 5% significance level.

n_0: There is no statistically significant difference between the two.

n_1: There is a difference between the two.

p Value	0.00326974
test statistic	17.7549452
critical statistic	11.0704977

Here the p-value is less than 0.05 and the test statistic is greater than the critical value therefore we can reject the null hypothesis and conclude there is a statistically significant difference. This indicates that some of the variation noted may be attributable to differences in model inputs but, it would be expected that of the two this comparison would produce a closer relationship than the larger catchments further away not the opposite.

The conflicting values indicate that the test catchments are unsuitable or insufficient for determining if a relationship exits. Further work is needed to establish a relationship between catchment proximity and accuracy of the IL CL values. This comparison would likely benefit from all catchments of the same size and sampling of a greater number of catchments.

5.6 Model and IL CL Data Source

Choosing the IL CL data source that worked best across the two models was made difficult due to the variation between the two QLD and two NSW catchments. There existed a clear differentiation in the modelling that skewed the results. An aim of the report was to create a generalisation for recommended input loss parameters so despite the differentiation in modelling, all catchments were grouped together for final analysis.

For use in the DRAINS program, using the over simplified catchment model, the best IL CL source is using the neighbour loss parameters.

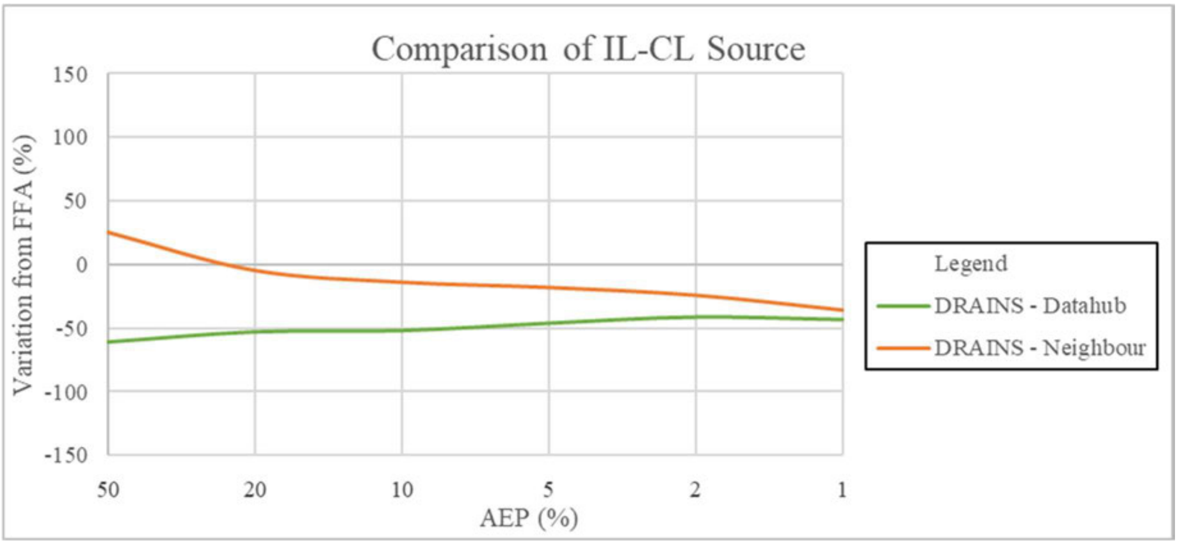

Figure 5.7. Overall comparison of IL CL source in DRAINS model.

As shown in Figure 5.7 the DRAINS model using datahub values underestimated flows by approximately 50% across the design AEP and would be unsuitable for flood analysis and is shown by the green line. The neighbouring loss parameters are shown in orange and show a lesser deviation from the FFA values and forms the basis of the recommendation of neighbouring loss parameters for a DRAINS model of ungauged catchments.

For use in the RORBWin program the best IL CL source is also the neighbour loss values with slightly conservative results for the rare AEP events and this is shown below in Figure 5.8.

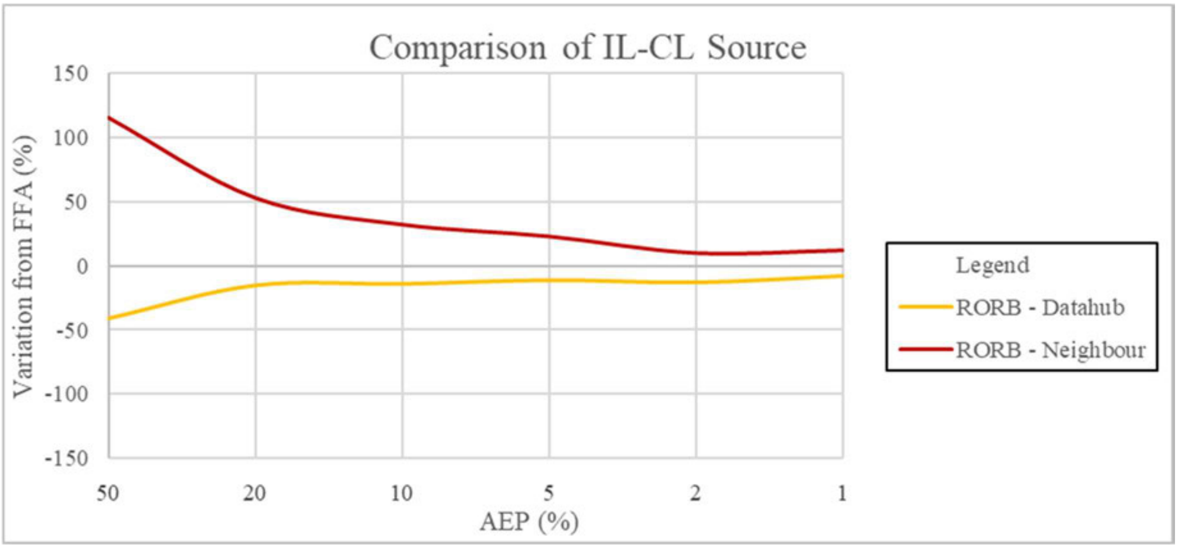

Figure 5.8. Overall comparison of IL-CL source in RORB model.

Displayed in Figure 5.8 are the average of the catchment outputs for the RORB model from the two loss sources. The ARR Datahub values are shown in yellow and underestimates FFA values but is a closer match overall to the site FFA values. The neighbour loss values are shown in red and results overestimated flows throughout the AEP events, but it was particularly erroneous for the more frequent AEP events. For flooding analysis an overestimate is still preferred to be conservative and account for possible errors.

Overall, the RORB model using neighbour site derived loss values performed the best for flood analysis of the extreme AEP events being close to site FFA values while being slightly conservative.

6 Conclusion

The initial loss and continuing loss model parameters are among the most important and as such efforts to improve the accuracy of these continue to develop. For the current state of available initial and continuing loss parameters an accurate source was desired for use on ungauged catchments and this consisted of analysing neighbour site-derived values and the ARR Datahub. The optimal source appears to be using site derived neighbour loss parameters in preference to the ARR Datahubs efforts at regionalisation. The ARR Datahub regionalisation of initial loss and continuing loss variables depends on too few catchments and further work will be required to strengthen the accuracy of the service. Model validation on ungauged catchments can only be done by comparing to a mark or level from a historic flood event, this involves working backwards from the hydraulic analysis and should be done where possible.

As it stands creating models for ungauged catchments still have large degrees of uncertainty, using default and standard settings from the programs and ARR2019 for a catchment still failed for the medium sized catchments analysed in the DRAINS and RORB models. DRAINS and RORB models of the smaller catchments appeared to be comparable to at site FFA results.

In the absence of available at-site information, an ungauged catchment, the results of this report suggest using neighbouring initial and continuing loss parameters as a first step for hydrological models used in flood analysis. The use of the ARR Datahub values generally provided results that underestimated flows from a catchment and is unsuitable for flood modelling for all events.

The preferred choice of program, DRAINS or RORBWin, could not be determined in this study, the additional flood module was not available with the latest release version of DRAINS so a direct comparison could not be made to RORBWin and the FFA values.

Analysis of additional catchments is required to strengthen claims that neighbouring loss values provide a better estimate of loss values than ARR Datahub. The additional catchments would help determine at what distance neighbouring loss parameters are less effective than ARR Datahub, results from this report were inconclusive.

7 References

ARRa 2019, *ARR Data Hub*, viewed 26 May 2020, <https://data.arr-software.org/>.

ARRb 2019, *Catchment Losses Map*, viewed 26 May 2020, <https://data.arr-software.org/catchmentlosses/map>.

Babister, M, Trim, A, Testoni, I & Retallick, M 2016, 'The Australian Rainfall & Runoff Datahub', *37th Hydrology and Water Resources Symposium*, Queenstown, NZ.

Ball, J, Babister, M, Nathan, R, Weeks, W, Weinmann, E, Retallick, M & Testoni, I 2019, 'Australian Rainfall and Runoff: A Guide to Flood Estimation', Commonwealth of Australia, Geoscience Australia.

Bevin, KJ 2012, *Rainfall-Runoff Modelling: The Primer*, 2nd edn, John Wiley & Sons, Inc.

Bomers, A, Schielen, MJ & Hulscher, SJMH 2019, 'Decreasing uncertainty in flood frequency analyses by including historic events in an efficient bootstrp approach', *Natural Hazards and Earth System Sciences*, no. 19, pp. 1895-1908.

Boughton, W 2005, 'Catchment water balance modelling in Australia 1960-2004', *Agricultural Water Management*, no. 71, pp. 91-116.

Bureau of Meteorology 2015, *Hydrologic Refernce Stations*, viewed 23 May 2020, <http://www.bom.gov.au/water/hrs/index.shtml>.

Bureau of Meteorology 2020, *Climate and oceans data and analysis*, viewed 14 April 2020, <http://www.bom.gov.au/climate/data-services/>.

City of Gold Coast 2014, *Technical Flood Reports - Logan River Catchment Hydrological Study*, viewed 20 July 2020, <https://www.goldcoast.qld.gov.au/technical-flood-reports-46099.html>.

City of Port Adelaide Enfield 2005, *Port Adelaide Seawater Stormwater Flooding Study*, viewed 20 July 2020, <https://www.renewalsa.sa.gov.au/wp-content/uploads/2016/11/Port-Adelaide-Seawater-Stormwater-Flooding-Study_Vol-1_Final-Report.pdf>.

Collier, CG 2016, *Hydrometeorology*, 1st edn, John Wiley & Sons, Inc.

Dubbo Regional Council 2019, *New/Updated Macquarie River Flood Study*, viewed 20 July 2020, <https://www.dubbo.nsw.gov.au/Public-Exhibition/macquarie-river-flood-study>.

Dyer, BG, Nathan, RJ, McMahon, TA & O'Neil, IC 1994, 'An Overview of Some Research into the RORB Model', *Water Down Under '94*, Engineers Australia, Barton, ACT.

ElSaadani, M, Krajewski, WF, Goska, R & Smith, MB 2018, 'An investigation of errors in distributed models' stream discharge prediction due to channel routing', *Journal of the American Water Resources Association*, vol 54, no. 3, pp. 742-751.

Hill, PI, Maheepala, UK, Mein, RG & Weinmann, PE 1996, 'Empirical analysis of data to derive losses for design flood estimation in South-Eastern Australia', CRC Report 96(5), CRC for Catchment Hydrology, Monash University.

Hrachowitz, M, Savenije, H, Bloschl, G, McDonnell, J, Sivapalan, M, Pomeroy, J, Arhemier, B, Blume, T, Clark, M, Ehret, U, Fenicia, F, Freer, J, Gelfan, A, Gupta, H, Hughes, D, Hut, R, Montari, A, Pande, S, Tetzlaff, D, Troch, P, et al. 2013, 'A Decade of Predictions in Ungauged Basins (PUB) - a review', *Hydrological Sciences Journal*, vol 58, no. 6, pp. 1198-1255.

Ilahee, M 2005, 'Modelling Losses in Flood Estimation', Partial PhD Thesis, Queensland University of Technology, Brisbane City.

Institution of Engineers, Australia 1987, *Australian Rainfall and Runoff: Guide to Flood Estimation*, Barton, ACT.

Kemp, D & Daniell, T 2016, 'Stuck in the 1960s - the need for fundamental change in flood hydrology in Australia', *37th Hydrology & Water Resources Symposium 2016: Water, Infrastructure and the Environment*, Engineers Australia, Barton, ACT.

Ladson, T 2019, *Australian Rainfall and Runoff: Highlights from the Kuczera Symposium*, viewed 2 May 2020, <https://tonyladson.wordpress.com/2019/06/14/australian-rainfall-and-runoff-highlights-from-the-kuczera-symposium/>.

Lang, S, Hill, P, Scorah, M & Stephens, D 2015, 'Defining and Calculating Continuing Loss for Flood Estimation', *36th Hydrology and Water Resources Symposium: The art and science of water*, Engineers Australia, Barton, ACT.

Laurenson, EM, Mein, RG & Nathan, RJ 2010, *RORB V6.14 - Runoff Routing Program - User Manual*, Monash University and Hydrology and Risk Consulting Pty Ltd.

Lazaro, JM, Navarro, JAS, Gil, AG & Romero, VE 2016, 'Flood Frequency Analysis (FFA) in Spanish catchments', *Journal of Hydrology*, no. 538, pp. 598-608.

Li, L, Lambert, MF, Maier, HR, Partington, D & Simmons, CT 2015, 'Assessment of the internal dynamics of the Australian Water Balance Model under different calibration regimes', *Environmental Modelling & Software*, vol 66, pp. 57-68.

Lyall & Associates 2020, *Flood Studies: Sutton and Gundaroo*, viewed 6 September 2020, <https://www.yassvalley.nsw.gov.au/our-services/water/stormwater/flood-studies-sutton-and-gundaroo/>.

Merz, R & Bloschl, G 2005, 'Flood frequency regionalisation - spatial proximity vs. catchment attributes', *Journal of Hydrology*, no. 302, pp. 283-306.

Murphy, R, Graszkiewicz, Z, Hill, P, Neal, B, Nathan, R & Ladson, T 2009, 'Australian Rainfall and Runoff Revison Project 7: Baseflow for Catchment Simulation', Stage 1 Report - Volume 1, Commonwealth of Australia, Geoscience Australia, ISBN 978-085825-9218.

Nguyen, CC, Gaume, E & Payrastre, O 2014, 'Regional flood frequency analyses involving extraordinary flood events at ungauged sites: further developments and validations', *Journal of Hydrology*, pp. 385-396.

Pearcey, M, Pettett, S, Cheng, S & Knoesen, D 2014, 'Estimation of RORB Kc Parameter for Ungauged Catchments in the Pilbra Region of Western Australia', *Hydrology and Water Resources Symposium*, Engineers Australia, Barton, ACT.

Pearse, M, Jordan, P & Collins, Y 2002, 'A Simple Method for Estimating RORB Model Parameters for Ungauged Rural Catchments', *Water Challenge: Balancing the Risks: Hydrology and Water Symposium*, Engineers Australia, Barton, ACT.

Podger, S, Babister, M, Trim, A, Retallick, M & Adam, M 2019, 'Review of ARR Design Inputs for NSW', Office of Environment and Heritage, WMA Water, Sydney.

Queensland Government 2020, *145011A Teviot Brook at Croftby*, viewed 1 August 2020, <https://water-monitoring.information.qld.gov.au/host.htm?ppbm=145011A&rs&1&rslf_org>.

Rahman, A, Haddad, K, Ishak, E, Weinmann, E & Kuczera, G 2010, 'Regional Flood Estimation in Australia: An Overview of the Study in Realtion to the Upgrade of Australian Rainfall and Runoff', *NSW Floodplain Management Conference*, Gosford.

Sitterson, J, Knightes, C, Parmar, R, Wolfe, K, Munche, M & Avant, B 2017, 'An Overview of Rainfall-Runoff Model Types', Office of Research and Development, National Exposure Research Laboratory, EPA/6006R-14/152, United States Environmental Protection Agency, Athens.

Stack, B & O'Loughlin, G 2020, 'DRAINS', version 2020.041 (64bit) - 21 July 2020, computer software, Watercom Pty Ltd, Wooli.

Sydney Water Corporation 2009, *Flooding in the Inner West - Cooks River Flood Study*, viewed 20 July 2020, <https://www.innerwest.nsw.gov.au/live/environment-and-sustainability/in-your-neighbourhood/rivers-and-waterways/flooding>.

Tamworth Regional Council 2012, *Flood Studies - Nundle and Woolomin Flood Study Report*, viewed 20 July 2020, <https://www.tamworth.nsw.gov.au/develop/development-engineering/flood-studies>.

Tran, QQ, De Neil, J & Willems, P 2018, 'Spatially Distributed Conceptual Hydrological Model Building: A Generic Top-Down Approach Strarting from Lumped Models', *Water Resources Research*, no. 54, pp. 8064-8085.

van der Sterren, M, Rahman, A, Shrestha, S & Thomson, A 2008, 'Urban Stormwater Modelling in Australia: Comparison of Three Commercial Software Packages', *Water Down Under*, ISBN 0-858-25735-1, Adelaide, Australia.

Willems, P 2001, 'Stochastic Description of the Rainfall Input Error in Lumped Hydrological Models', *Stochastic Environmental Research and Risk Assessment*, no. 15, pp. 132-152.

Yass Valley Council 2020, *Water - Murrumbateman, Bookham, bowning and Binalong Report*, viewed 22 August 2020, <https://www.yassvalley.nsw.gov.au/our-services/water/stormwater/flood-studies-sutton-and-gundaroo/>.

Young, CB, McEnroe, BM & Rome, AC 2009, 'Empirical Determination of Rational Method Runoff Coefficients', *Journal of Hydrologic Engineering*, vol 14, no. 12, pp. 1283-1289.

8 Appendices

APPENDIX A Project Specification

ENG4111/4112 Research Project

Project Specification

For:	Joshua Maloney
Title:	Investigation of DRAINS for use in catchment analysis of ungauged catchments.
Major:	Civil Engineering
Supervisors:	Dr. Rezaul Chowdhurry
Sponsorship:	N/A
Enrolment:	ENG4111 – EXT S1, 2020 ENG4112 – EXT S2, 2020
Project Aim:	To investigate the use of DRAINS on ungauged catchments (rural), define the major factors affecting results and provide guidance on its use.

Programme: Version 1.0, 18 March 2020

1. Research the background information on problems with modelling ungauged catchments to provide reference for report.
2. Isolate a series of existing gauged rainfall catchments to form data sets with known parameters for calibration and comparison.
3. Evaluate selected DRAINS models (ILSAX, Extended Rational and IL-CL) to simulate existing storms. (IL-CL first as the recommended from AR&R)
4. Analyse these models, or dominant model, against other known catchments that were not calibrated in DRAINS.
5. Evaluate these models and attempt to adjust parameters based on known characteristics of the catchment.
6. Formulate restrictions and parameter guidelines for use.

If time and resources permit:

7. Model further with other storage routing methods included with DRAINS either RAFTS or RORBS to evaluate use on larger catchments.

APPENDIX B FFA Results

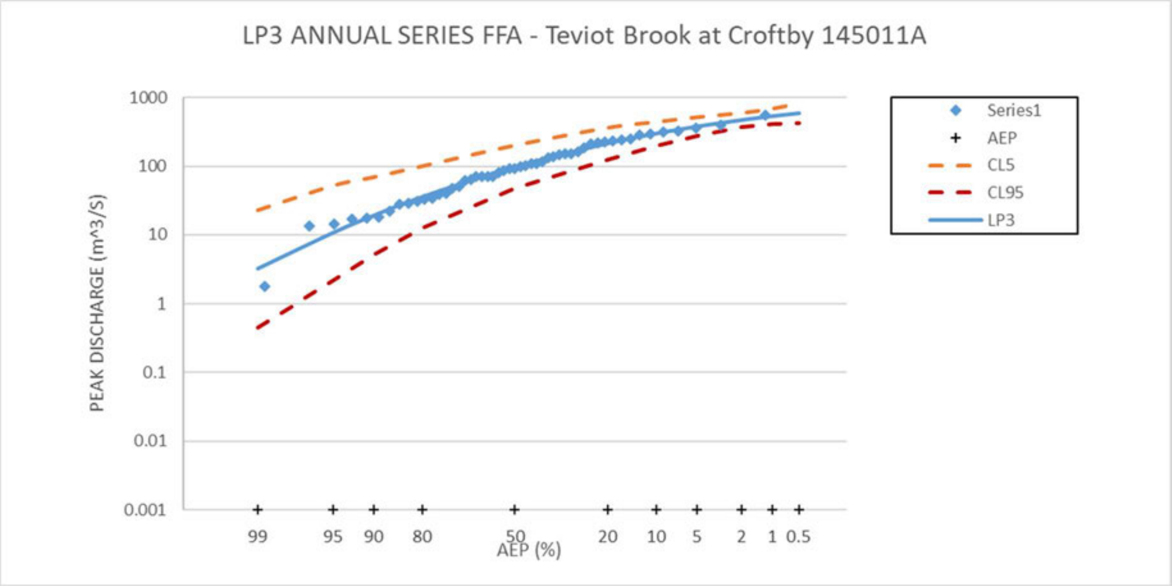

Figure 8.1. FFA output for Teviot Brook at Croftby station 145011A.

APPENDIX C RORB Models

1. Number inside the circle represents the sub catchment number shown in Figure 3.3, Figure 3.4, Figure 3.5 and Figure 3.6.

2. The number on the lines represents the name given to that reach, named after the upstream catchment followed by *r* for reach when connected to a catchment and *j* for junction when connected to a junction node.

3. *P* indicates the end of the model where the hydrograph was printed from.

4. Arrow pointing to circle indicates sub-catchment, arrow as part of line between catchments indicates flow direction.

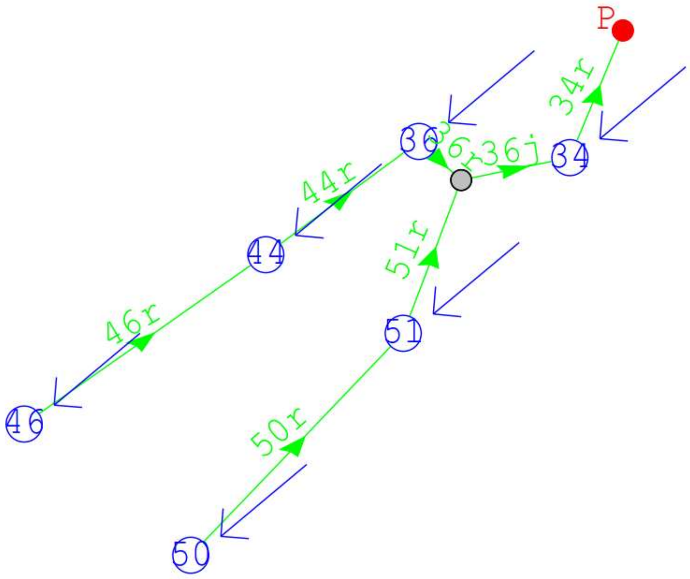

Figure 8.2. RORB model Teviot Brook at Croftby.

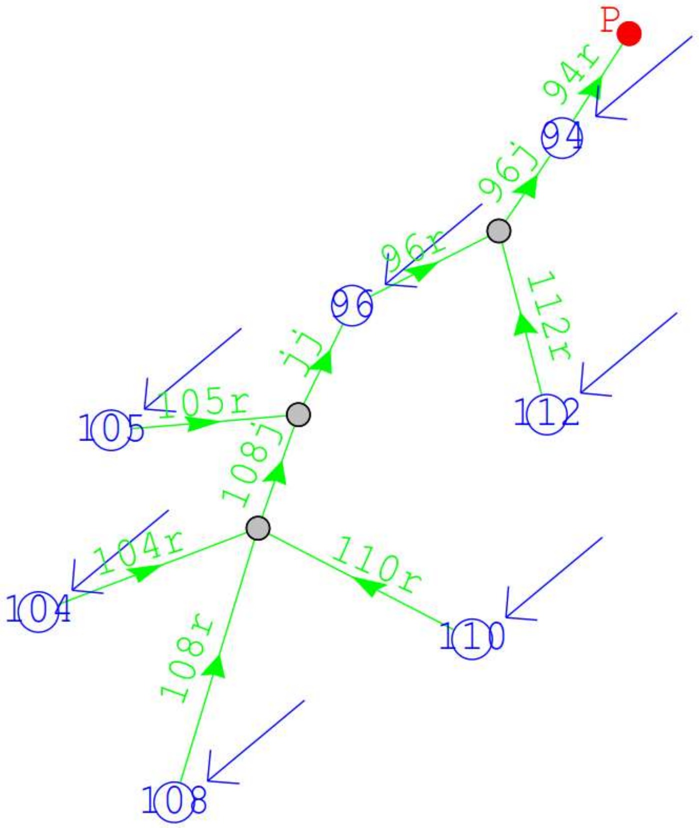

Figure 8.3. RORB model Burnett River U/S Maroon Dam.

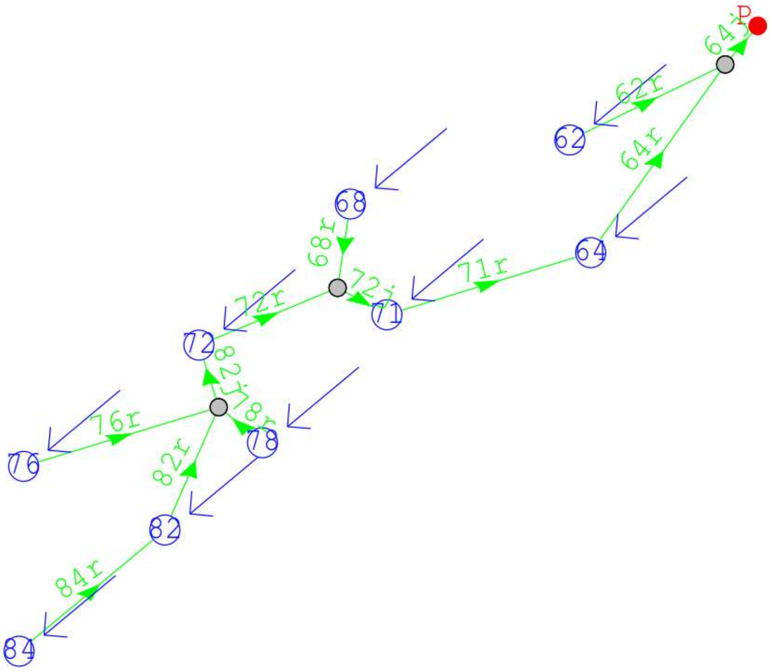

Figure 8.4. RORB model Henry River at Newton-Boyd.

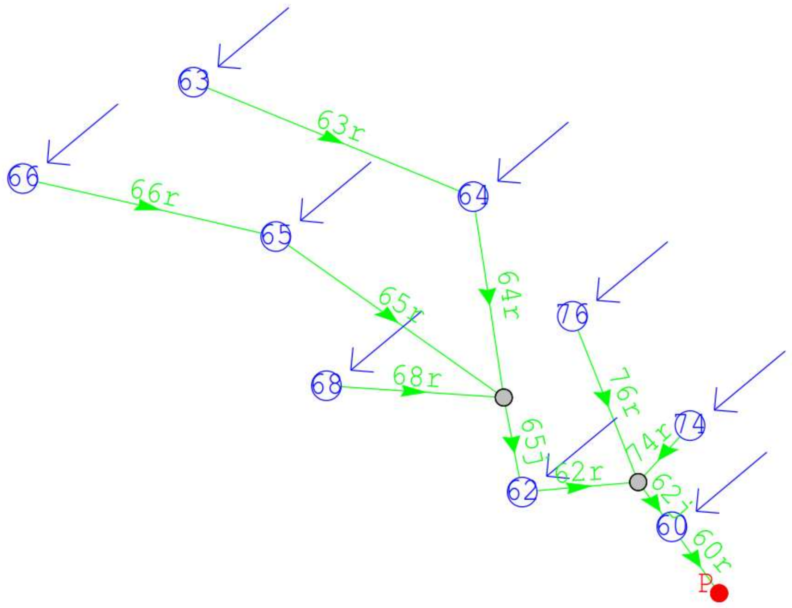

Figure 8.5. RORB model Wollomombi River at Coninside.