



Acheron Flood Hydrology: Final Report


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Glossary

Annual Exceedance Probability (AEP)	The likelihood of occurrence of a flood of a given size or greater occurring in any one year. AEP is expressed as a percentage (%). For example, if a peak flood discharge of 1,000 ML/D has an AEP of 1% there is a 1% chance of a flood with a peak of 1,000 ML/D or greater occurring in a given year. AEP is reciprocal of ARI (see below). The convention of AEP has been adopted for this study.
Average Annual Damages (AAD)	The average annual damage is the average cost in dollars per year that would occur in a particular area from flooding over a very long period of time.
Australian Height Datum (AHD)	The national height datum that approximately corresponds to mean sea level. Elevation is in meters.
Average Recurrence Interval (ARI)	An estimate of the average period in years between floods of a given magnitude or greater. For example, the 50 year ARI flood will occur on average once every 50 years.
BoM	Bureau of Meteorology
Catchment	The area of land draining to a particular location and may include the catchments of tributary streams as well as the main stream.
DEM	Digital Elevation Model – Three dimensional computer representation of terrain
DEPI	Department of Environment and Primary Industries
Design Flood Event	A hypothetical flood representing a given probability.
Design Rainfall	The hypothetical rainfall event representing a given probability.
DTM	Digital Terrain Model – Three dimensional computer representation of terrain
FFA	Flood Frequency Analysis
FI	Fraction Imperviousness – The fraction of the catchment that is impervious, that is, land which does not allow infiltration of water
Flood Model	A computer model developed to represent the flood behaviour within the study area, including both the hydrologic and hydraulic models.
FO	Flood Overlay
Floodplain	Area of land subject to inundation by floods up to and including the probable maximum flood (PMF) event.
GBCMA	Goulburn Broken Catchment Management Authority

Glossary

ICSM	Intergovernmental Committee on Surveying and Mapping
LiDAR	Light Detection and Ranging – Ground survey taken from an aeroplane typically using a laser. Using the laser pulse properties the ranging and reflectivity is used to determine properties of the laser strike, soil type/tree/building/road/etc. It is usual to filter non-ground strikes (trees/buildings/etc) from the LiDAR before it is used to generate a DEM.
LSIO	Land Subject to Inundation Overlay
ML	Mega-Litre (1,000,000 L)
Hydraulic Model	A computer model developed to extent, depth and velocity of surface water based on the Shallow Wave equations. .
Hydrologic Model	A computer model that converts rainfall into runoff. The URBS modelling package was adopted for this study.
Hydrograph	A graph showing discharge versus time at a particular location.
Hyetograph	A graph showing rainfall versus time at a particular location.
Manning's n	Hydraulic roughness due to ground conditions, typically averaged over an area of relative homogeneity, e.g. it's harder for water to flow through an area of heavy brush and trees than maintained grass.
MSC	Murrindindi Shire Council
Pluviograph	A rain gauge measuring the depth of rainfall over a small period of time (much less than a day). Often used to produce a graph of rainfall over time.
PMF	Probable Maximum Flood – the flood resulting from the PMP (see below).
PMP	Probable Maximum Precipitation - The probable greatest depth of precipitation meteorologically possible for a given duration, for a given size storm area, with no allowance made for long-term climatic trends.
PSM	Permanent Survey Mark
Rating Curve	The relationship defining discharge for a given stage (water level) at a particular recording location.
RCBC	Reinforced Concrete Box Culvert (also referred to as a Rectangular Culvert).
RCP	Reinforce Concrete Pipe (also referred to as a Circular Culvert)
Runoff	The amount of rainfall from a catchment that is converted to flowing water.

Glossary

Stage	Refers to the water level, often to a local datum, at a particular location typically stream gauges.
TUFLOW	A 1D / 2D finite difference numerical model that simulates hydrodynamic behaviour in rivers, floodplain and urban drainage environments. This is the hydraulic modelling package adopted for this study.
URBS	A hydrologic modelling software package used to simulate a catchments runoff response to rainfall. This is the hydrologic modelling package adopted for this study.
VFD	Victorian Flood Database

1 Introduction

1.1 Study background

The Acheron River catchment area is located approximately 80km to the north-east of Melbourne as shown in Figure 1-1 and incorporates the towns of Marysville, Buxton and Taggerty. There are known flood issues in these towns and this, coupled with development pressure on the area, has led the Goulburn Broken Catchment Management Authority (GBCMA) to commission the Acheron Basin Flood Hydrology Study (the Study). The Study was funded by the Victorian State Government.

The aim of this study is to determine flood hydrographs for the application to a TUFLOW hydraulic model that will be constructed by the GBCMA. The flood hydrographs will be calculated using a fully calibrated URBS hydrologic model which was used to determine design flows. The design hydrographs were applied to the TUFLOW hydraulic model to determine the extent of flood risk to the towns in the Acheron Basin.

1.2 Previous reports

Whilst no flood studies of Buxton, Marysville or Taggerty have been undertaken, the Goulburn Broken Regional Floodplain Management Strategy (2018-2028) (GBCMA, 2018) has identified these towns in the strategy. This report identified Buxton as a high priority for revision of flood overlay controls and improvements in flood intelligence and the Municipal Flood Emergency Management Plan. Taggerty and Marysville are medium priorities for these updates to planning controls and flood intelligence.

1.3 Catchment description

The catchment area of the Acheron River to its confluence with the Goulburn River is 725 km² and it generally flows from south to north as shown in Figure 1-2. The major tributary of the Acheron River is the Steavenson River the confluence of which is located near Buxton.

The southernmost part of the catchment drains the Yarra Valley Ranges National Park and the State Forest to its immediate north. The Black Range State Forest and Cathedral Range State Park also form part of the upper part of the catchment. The lower lying land within the catchment is predominately agricultural, mixed with rural living areas. The catchment also includes the towns of Buxton, Marysville and Taggerty.

The catchment was severely affected by the 'Black Saturday' bushfires (7th February 2009) and the native vegetation throughout the catchment is now recovering (see Photo 1-1).

1.4 Historic flooding

At this stage only limited information is available regarding the flood history in the Acheron Basin. The largest discharge recorded on the Acheron River at Taggerty streamflow gauge was 15,200 ML/d (176 m³/s) on the 5th September 2010 which, according to the The Age¹ (reported on the 6th September 2010) led to closures on the Marysville Road between Buxton and Marysville. The 28th

¹ <http://www.theage.com.au/victoria/road-closures-due-to-flooding-20100906-14wfj.html>

Introduction

November 2010 event (4,700MI/d (54m³/s) on the Acheron River at Taggerty led to a minor flood warning being issued by the Bureau of Meteorology² (BoM).

Notable floods are reported to have occurred in the area in 1913 and 1934 with the 1934 flood believed to be the largest on record.



Photo 1-1 The Acheron catchment showing evidence of the recent bushfires (2009)

1.5 Study aims

This study of the flood hydrology of the Acheron River Basin is intended to determine a set of flood hydrographs that can be used to investigate flood risks in the following areas:

- The township of Buxton;
- The township of Marysville;
- The township of Taggerty;
- Rural areas around these townships, and
- Areas zoned Rural Living between Marysville and Buxton.

The purpose of a hydrologic assessment is to determine the flood response of a catchment, i.e. the conversion of rainfall to runoff (flow). In this Study, the catchment's response has been determined through flood frequency analysis (FFA) and by undertaking rainfall-runoff (hydrologic) modelling. Both a regional and at-site approach to FFA has been undertaken. The FFA analyses produce peak flow estimates whereas the rainfall runoff approach produces a flood hydrograph (a timeseries of flow). Specifically, the Study aims will be achieved by undertaking a detailed hydrologic assessment of the catchment using a variety of techniques including:

- Regional flood frequency estimation;

² <http://www.theage.com.au/victoria/massive-rainfall-causes-flooding-20101128-18bxa.html>

Introduction

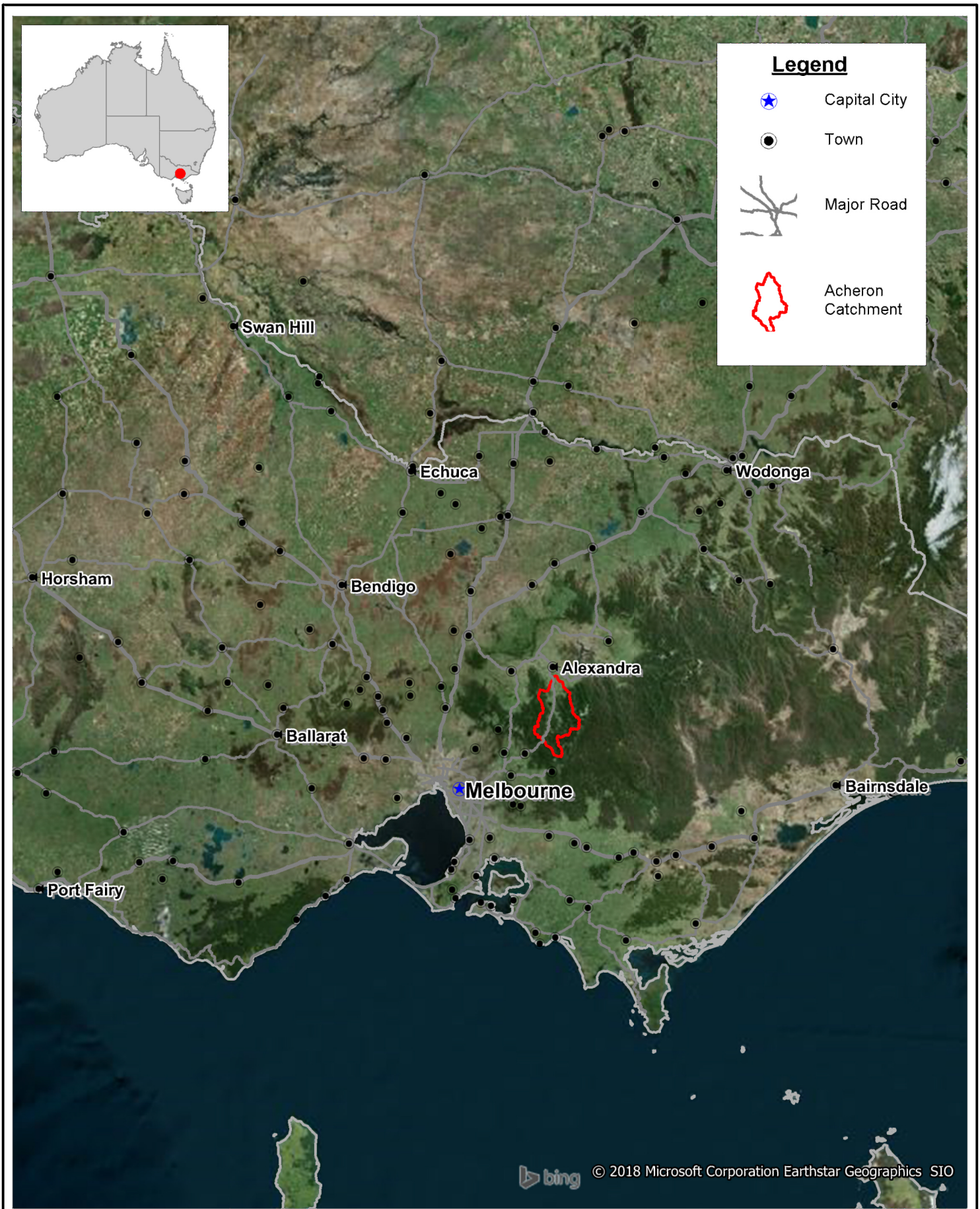
- At-site flood frequency analysis; and
- Rainfall-runoff routing.

The analysis for each of these is presented under the corresponding heading below.

Specifically, flood hydrographs for the events listed in Table 1-1 will be determined.

Table 1-1 Events to be investigated as part of the Study

Event	Description					
AEP	10%	5%	2%	1%	0.5%	0.2%
Historic	1996	1998	2010			
Flood Class Level			Major			

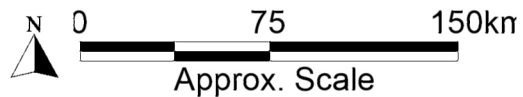


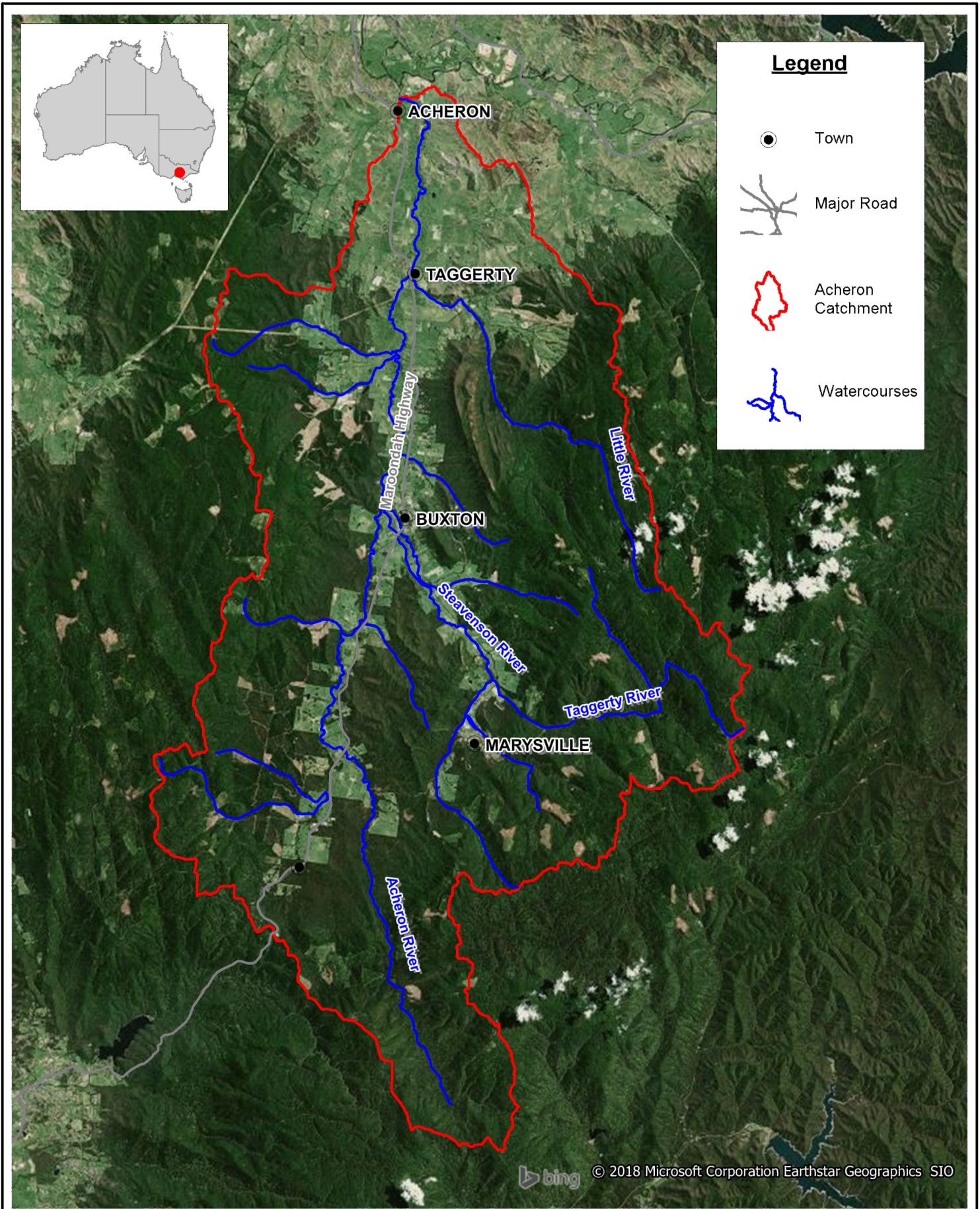
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 Locality Map**

Figure:
1-1

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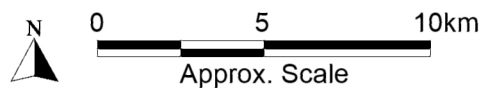


Title:
**Acheron Flood Hydrology
 Study Area**

Figure:
1-2

Rev:
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2 Data Collation

The following section documents the data collected for the Study. As part of the Study, datasets and information were obtained from a variety of organisations as discussed below.

2.1 Site inspection

A preliminary site visit was undertaken by BMT on the 27th July 2014 and an additional site visit was undertaken during the week commencing the 6th October 2014. During the additional site visit, BMT was accompanied by GBCMA. This site visit will include inspections of the Acheron River and major tributaries, the streamflow gauging station at Taggerty, the major towns of the Acheron Basin and other hydrologically significant features.

2.2 Topographic data

A Digital Terrain Model (DTM) of the catchment and surrounds was provided by the DELWP, this dataset was:

- VicMap Elevation DTM 10m (DELWP).

The DTM is shown in Figure 2-1 and the quoted vertical accuracy of this DTM is +/- 5m (DSE, 2008). This dataset was used to derive catchment boundaries for hydrologic modelling of the catchment.

2.3 GIS data

To undertake the Study, project related GIS data was required. This data will include:

- Aerial photography, including aerial flood photography collected during historical flood events.
- Flood overlays.
- Historical flood extents.
- Cadastral information.
- Planning zones and other government zones.

2.4 Rainfall data

All data from rainfall stations within and surrounding the Acheron River catchment were obtained. This included eight daily rainfall and six pluviograph stations as listed in Table 2-1. These datasets were obtained from the Bureau of Meteorology (BoM) and the Victorian Water Monitoring site³. The location of these stations is shown in Figure 2-2.

³ <http://data.water.vic.gov.au/monitoring.htm>

Data Collation

Table 2-1 List of rainfall stations

Site	Site name	Start	End	Lat	Lon	Height (m)	Type
88131	Narbethong	1926	2010	-37.4998	145.6793	345	Daily
88130	Buxton	1970	..	-37.4234	145.7085	265	Daily
88044	Marysville (Post Office)	1904	..	-37.51	145.7472	420	Daily
86009	Black Spur	1910	..	-37.5909	145.6236	567	Daily
83060	Lake Mountain (Echo Flat)	1964	1985	-37.5	145.8833	1372	Daily
88103	Marysville Golf Course	2001	..	-37.4958	145.7475	400	Daily
88119	Acheron River @ Taggerty	1945	..	-37.3167	145.7167	..	Daily
88000	Alexandra (Acheron)	1930	..	-37.2514	145.7178	180	Daily
88068	Rubicon Sec	1943	1993	-37.3389	145.8547	838.2	Pluviograph
86142	Toolangi	1965	2006	-37.572	145.5014	595	Pluviograph
88164	Eildon Fire Tower	1995	..	-37.2091	145.8423	637	Pluviograph
88023	Lake Eildon	1957	..	-37.2313	145.9124	230	Pluviograph
88119	Acheron River @ Taggerty	1945	..	-37.3167	145.7167	..	Pluviograph
405837	Marysville Golf Club	2001	..	-37.4958	145.7478	..	Pluviograph

2.5 Streamflow data

There are three stream gauges within the Acheron River catchment and all available flow and stage data was acquired. These stations are listed in Table 2-2 and their locations are shown in Figure 2-2. The data from each of these three streamflow gauges was obtained from the Victorian Water Monitoring site⁴.

The most recent rating table at each of the streamflow gauges was also obtained.

Table 2-2 List of streamflow gauges

Station No.	Station Name	Start	End	Lat	Lon	Zero Gauge	Catchment Area (km ²)
405209	Acheron River @ Taggerty	1961	..	-37.318	145.713	198.177	619
405328	Steavenson River at Falls Road Marysville	2009	..	-37.526	145.774		
405331	Taggerty River at Lady Talbot Drive near Marysville	2010	..	-37.490	145.841		

In addition, streamflow gauges from other watercourses in the upper Goulburn catchment were also obtained. The details of these are shown in Table 2-3.

⁴ <http://data.water.vic.gov.au/monitoring.htm>

Table 2-3 List of upper Goulburn streamflow gauges

Station No.	Station Name	Start*	End	Lat	Lon	Zero Gauge	Catchment Area (km ²)
405215	Howqua River @ Glan Esk	1973	..	-37.230	146.207	306.393	368
405218	Jamieson River @ Gerrang	1959	..	-37.291	146.188	306.523	368
405219	Goulburn River @ Dohertys	1968	..	-37.331	146.131	298.435	694
405227	Big River @ Jamieson	1970	..	-37.368	146.057	296.361	619

*Start dates are for the instantaneous series, there is a daily series the precedes these.

2.6 Catchment characteristics

A number of catchment characteristics were calculated for each of the stations in the upper Goulburn with the exception of the Steavenson River and Taggerty River given their small catchment size. These are presented in Table 2-4.

The catchment characteristics presented in Table 2-4 have been derived from the VicMap Elevation DTM 10m, the VicMap Planning Layer and the streamflow records obtained from the Victorian Water Monitoring site. Note the average annual discharges in Table 2-4 were calculated from the instantaneous discharge records.

Table 2-4 Catchment characteristics

Station No.	Station Name	Catchment area (km ²)	Av annual discharge (ML/d)	% Urban	% Forested	% Farming	Max. Discharge m ³ /s	Year of Peak
405209	Acheron River @ Taggerty	626	766	1.9%	77.5%	20.5%	293	2010
405215	Howqua River @ Glan Esk	370	459	1.0%	97.2%	1.8%	127	2010
405218	Jamieson @ Gerrang	367	562	0.1%	99.4%	0.5%	193	2010
405219	Goulburn River @ Dohertys	702	882	0.3%	99.7%	0.0%	247	2010
405227	Big River @ Jamieson	628	816	0.2%	99.8%	0.0%	322	2010

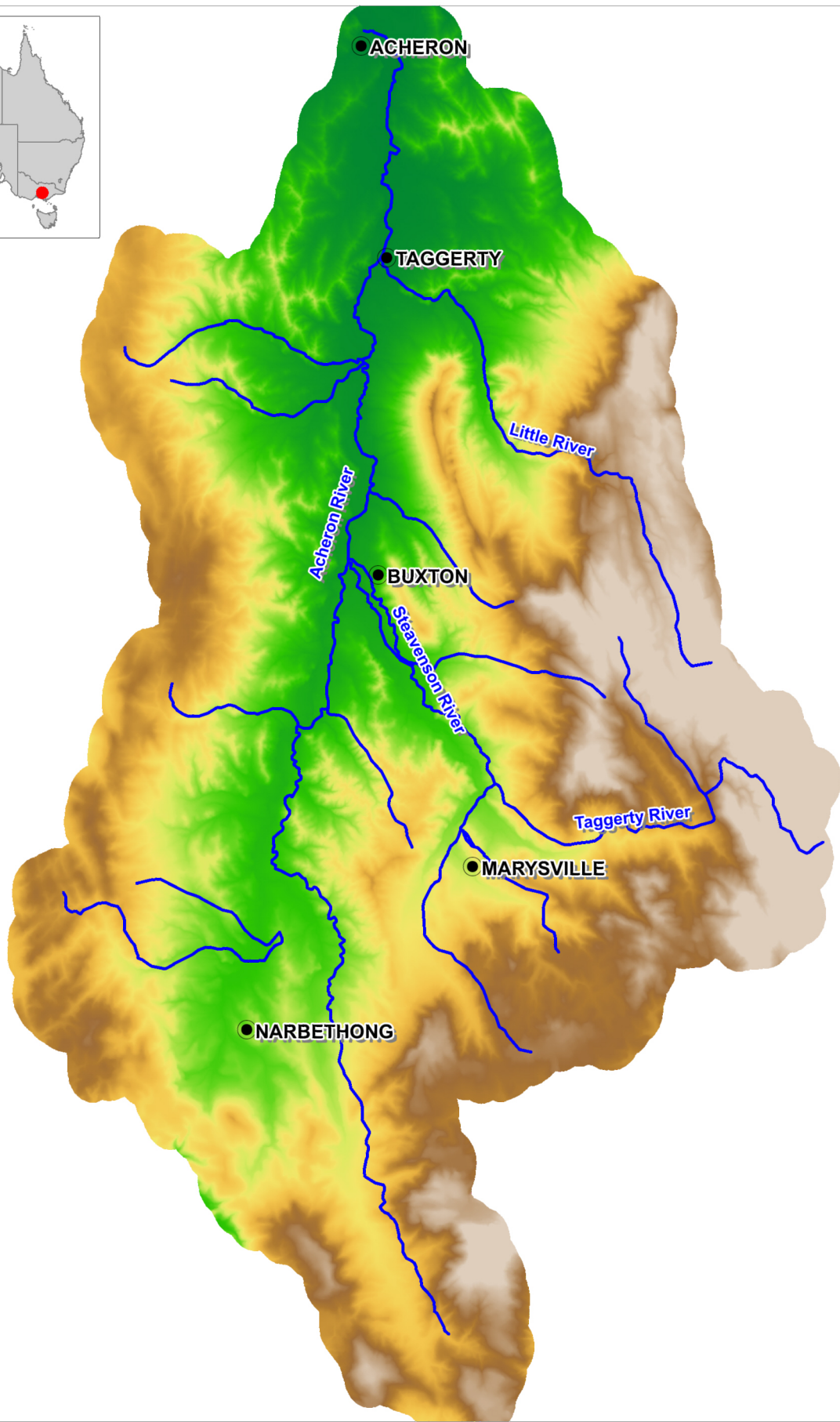
2.7 Flood history

There is a long flood history in the Acheron Basin with survey maps from 1866 identifying the land around the Acheron as subject to inundation (Victoria. Dept. of Crown Lands and Survey & Downey John, 1866). In 1870 there was a significant regional flood event which was considered to be the record (largest) flood at that time (Lloyd, 2006). Furniss and Turner (2014) report that large flood events occurred in 1912 and 1916. The 1916 flood event was reported to be similar to the 1870 event (Thornton, 1916), although it was not possible to establish which was greater. Further flood events were recorded in 1930 and 1934. The 1930 event was reported to have been influenced by releases from Sugarloaf Reservoir, which was completed in 1929 (The Standard, 1930). The wall of Sugarloaf Reservoir is located within (and submerged) by the water of Lake Eildon.

Data Collation

It is of note that the focus of the events reported above was the Goulburn River; however, it is reasonable to assume that the Acheron Basin would have experienced similar conditions.

From the above information the largest flood events to occur in the Acheron Basin were in 1870 and 1916. However, the details available are not sufficient to determine the relative size of the events, to each other or events during the gauged record. Given the widespread reporting of the 1870 and 1916 events and the fact that they are referred to as the record floods, these events are considered likely to have been larger than any during the gauged record.

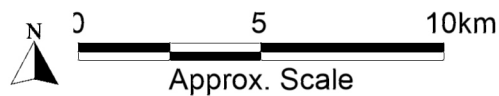


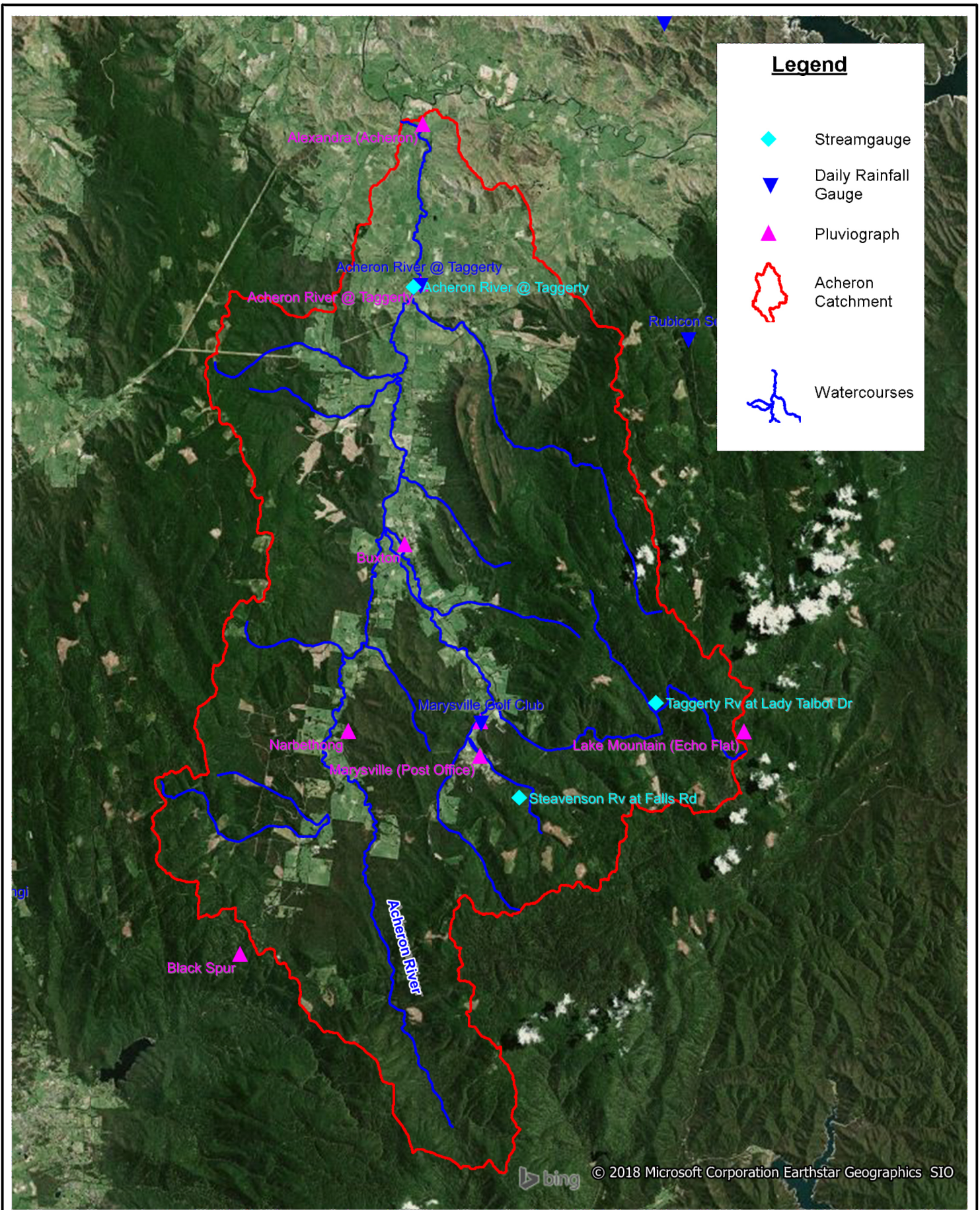
Title:
**Acheron Flood Hydrology
Digital Elevation Model**

Figure:
2-1

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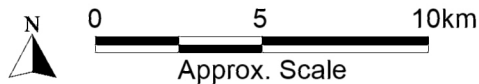


Title:
Acheron Flood Hydrology
Streamflow, daily rainfall and pluviograph gauges

Figure:
2-2

Rev:
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3 Rating Curve Review

As part of the data collection and review stage of the project, it was concluded that the rating table or rating curve at the Acheron River at Taggerty may have extrapolation errors. For this reason, a rating curve review was undertaken. This involved utilising hydraulic modelling results to develop a level flow relationship beyond the manually gauged records.

A 2D hydraulic model in the vicinity of the gauge was developed and a flow that steadily increase to 700 m³/s was applied to the model. The Manning's values were adjusted to match the manual rating.

The resulting rating curve is shown in Figure 3-1 together with published rating curve. These results show that the new rating curve reduces flow with stage, for higher stages and there are slight increases in flows for lower stages around 3.0 m.

Comparison of old and new rating curves

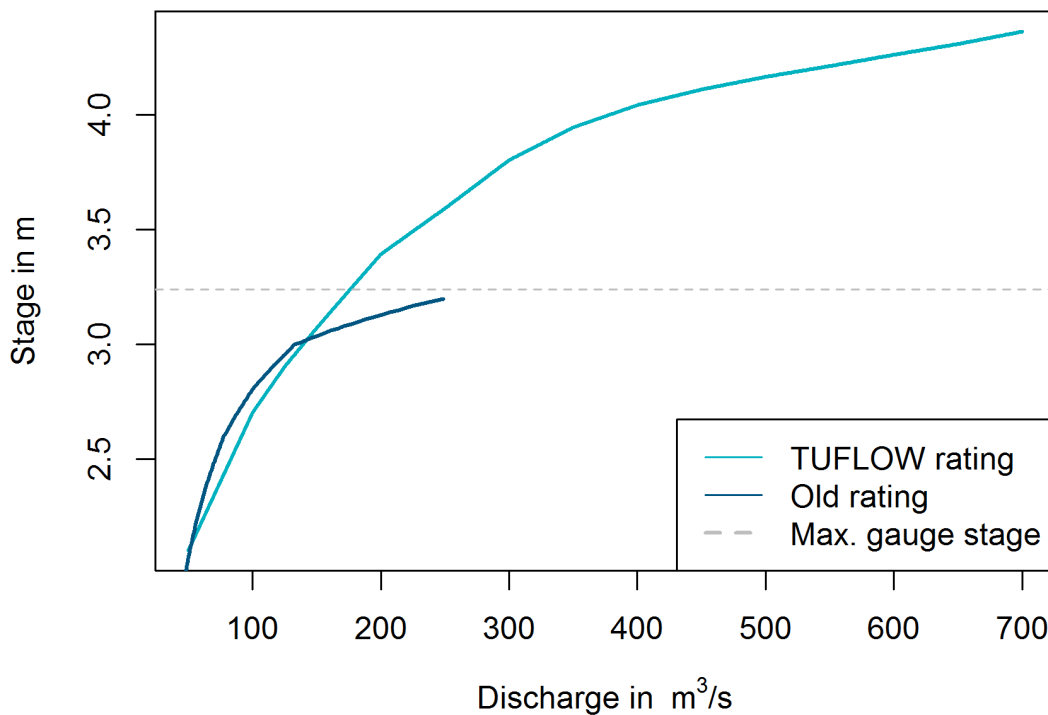


Figure 3-1 Comparison of old and new rating curves

Historic records were revised with reference to this rating and the revised peak flows are shown in Figure 3-2. These re-rated flows were used for the remained of the analysis.

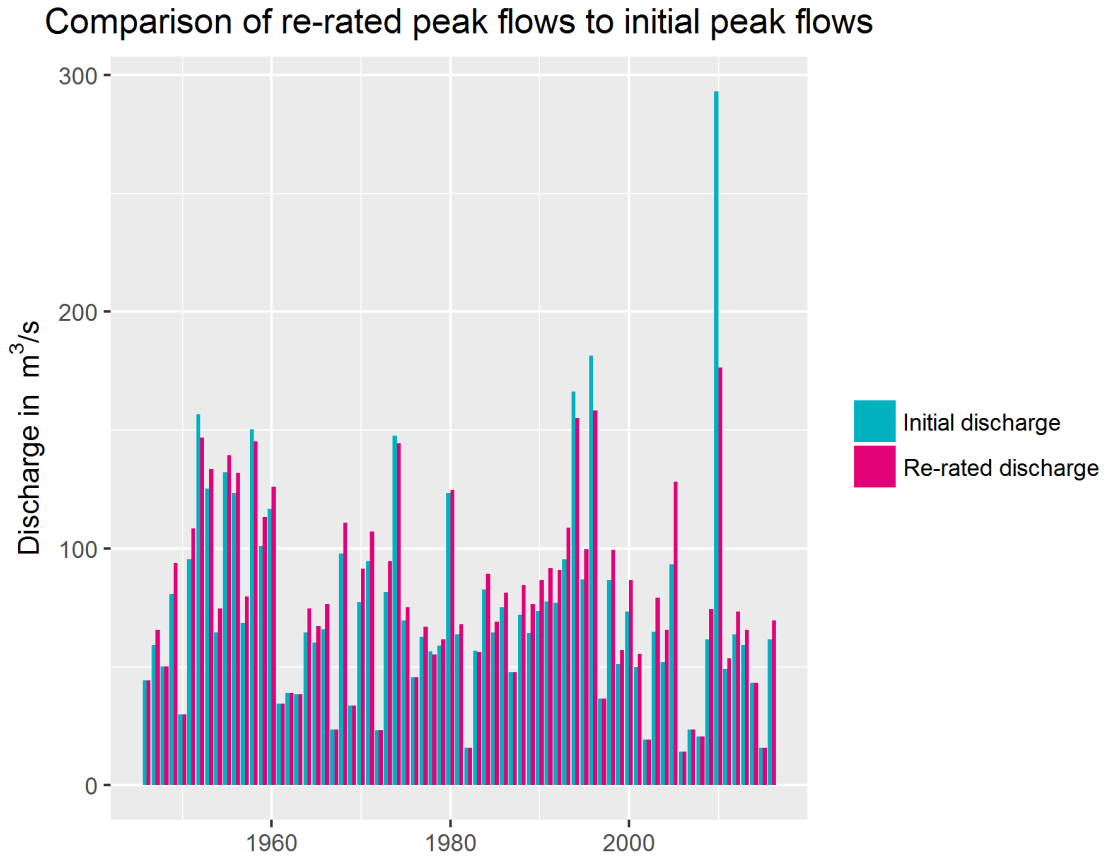


Figure 3-2 Comparison of re-rated peak flows to initial peak flows

4 Regional Information

One of the advantages of the Bayesian approach to flood frequency analysis is the ability to incorporate prior information about distribution parameters; that is, regional information can be incorporated into the analysis. This can lead to significant improvements to flood frequency estimates and reduce the uncertainty in the estimates (Pedruco et al., 2014). In the case of the Acheron River use of regional information is particularly relevant given the proximity of the upper Goulburn catchments.

The regional information was obtained through:

- Analysis of the upper Goulburn catchments, namely:
 - Big River;
 - Goulburn River;
 - Howqua River; and
 - Jamieson River.
- Regional Flood Frequency Analysis (RFFE) for each of the upper Goulburn rivers, the Acheron River at Taggerty, the Steavenson River @ Marysville and Taggerty River @ Marysville

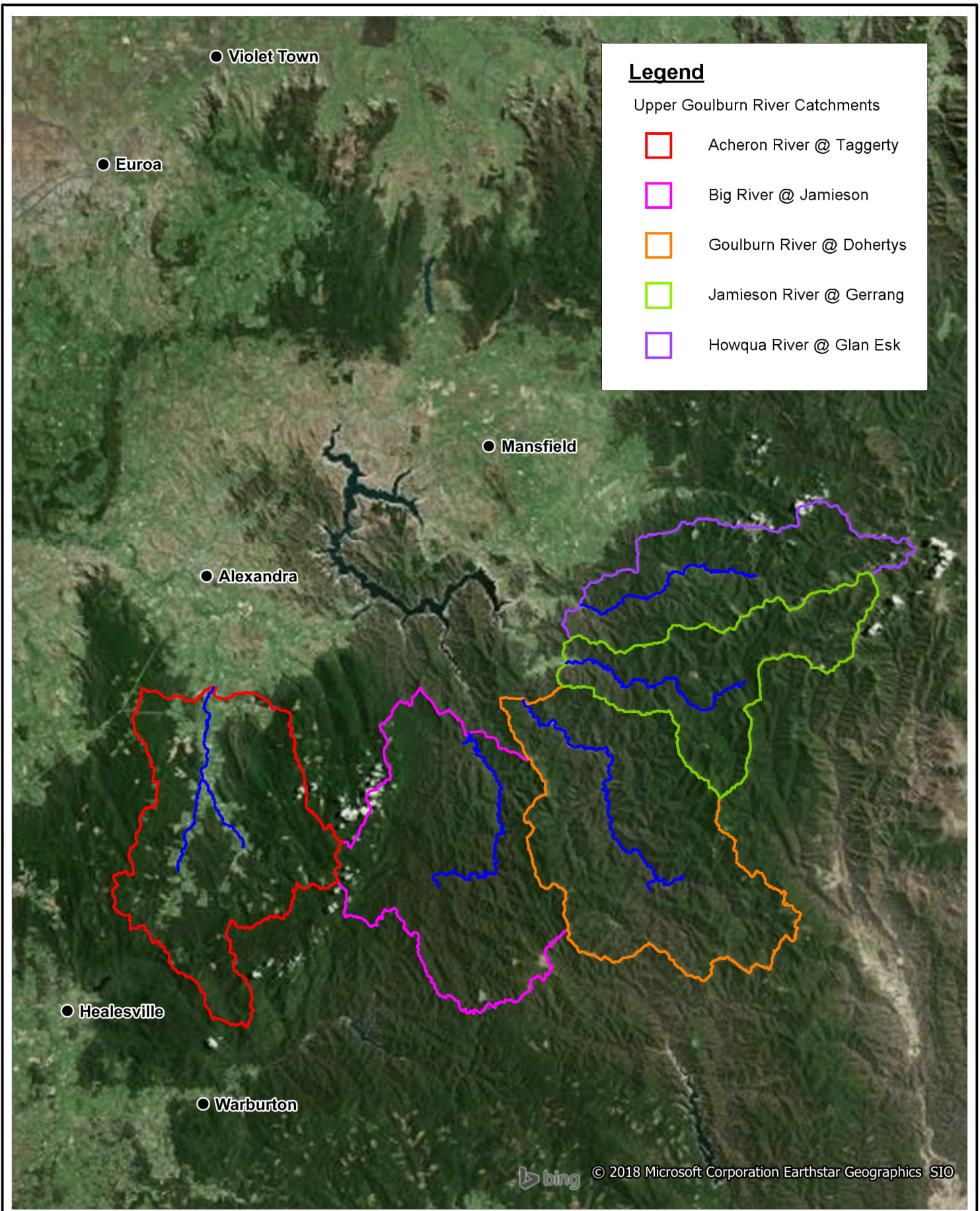
Details of this are provided below.

4.1 Catchment similarity

In addition to the RFFE presented in Section 4.3, records from nearby catchments in the upper Goulburn were obtained and the following analysis undertaken:

- Concurrent flooding amongst the catchments i.e. if it is flooding in one catchment is it likely to be flooding in the other catchments.
- Hydrologic similarity
- Regional Log-Pearson Type III parameters.

There are a number of gauged catchments in the upper Goulburn as shown on Figure 4-1. These catchments as well as selected catchment characteristics are shown in Table 2-3. The annual maximum series from these streamflow stations were extracted as described in Section 5.1 with the resulting annual maximum series shown in Figure 5-5.

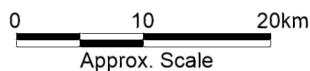


Title:
**Acheron Flood Hydrology
 Upper Goulburn Catchments**

Figure:
4-1

Rev:
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4.1.1 Concurrent flooding

The first step in the regional analysis was to determine if peak flow were driven by similar events. To achieve this, Pearson's product-moment correlation coefficients between each of the annual maximum series were calculated. The results of these calculations are shown in Table 4-1. Spearman's rho was also calculated with consistent (and stronger) findings. These correlation coefficients were all significant at the 1% levels (with $n = 41$), indicating there was a strong relationship between AM series, that is, when there is a large AM flow on one of these rivers it is likely that there will be a large AM flow on the other rivers.

Table 4-1 Upper Goulburn rivers annual maximum correlation matrix

	Acheron River	Goulburn River	Howqua River	Big River	Jamison River
Acheron River	1.00	0.58	0.56	0.73	0.60
Goulburn River	0.58	1.00	0.83	0.84	0.91
Howqua River	0.56	0.83	1.00	0.79	0.90
Big River	0.73	0.84	0.79	1.00	0.82
Jamison River	0.60	0.91	0.90	0.82	1.00

A scatterplot matrix was then prepared between each annual maximum series as shown in Figure 4-2. In this figure the annual maximum series in ML/d is listed along the diagonal through the figure and the scatterplot is presented for each vertical and horizontal combination. The green line in the represents the linear fit to the data. Each of the diagonals has a density plot for the relevant AM series. A density plot can be thought of as continuous histogram. This Figure 4-2 confirms the strong relationship between each of the annual maximum series for the stations in the upper Goulburn.

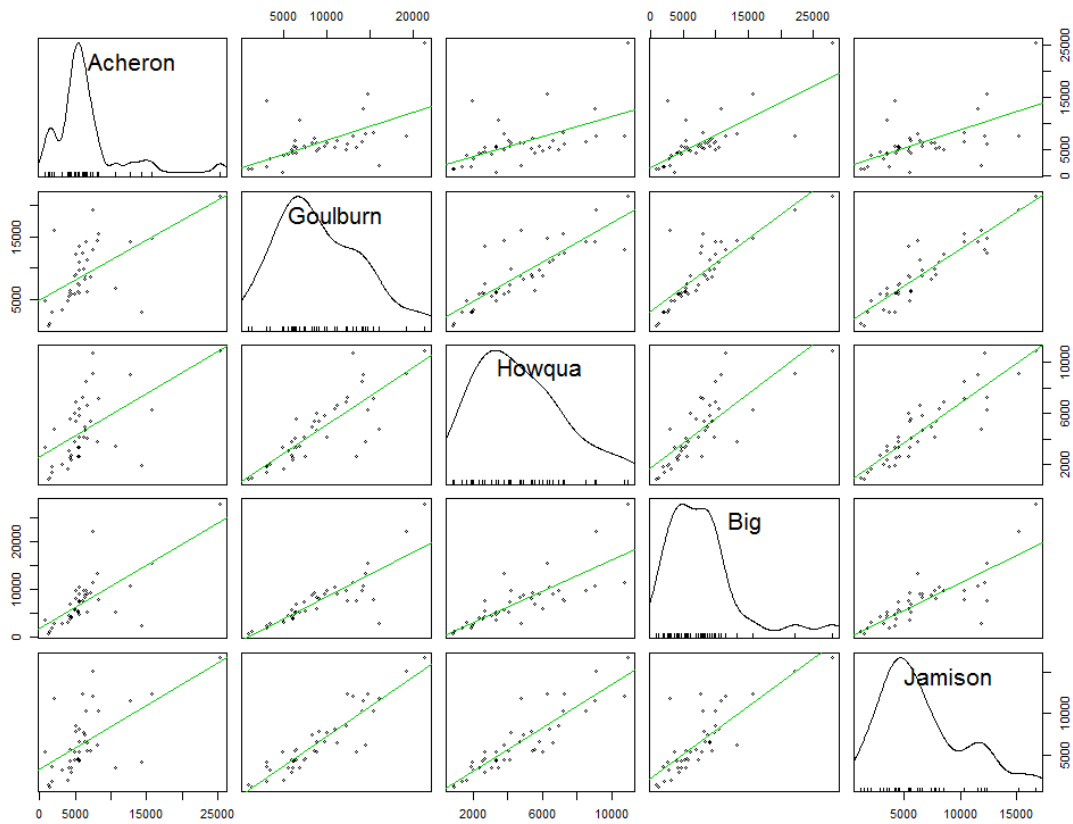


Figure 4-2 Scatterplot matrix for annual maximum series for each of the stations in the upper Goulburn

The timing of the annual maximum discharge of each of the rivers in the upper Goulburn was also investigated. A comparison of the timing of the annual maximum discharge on the Goulburn and Acheron Rivers is presented in Figure 4-3. There are nine panels in this plot with the three in the top right hand corner being the mirror image of the three in the bottom right hand corner. Along the diagonal from the top left hand corner to the bottom right hand corner are density plots of; the annual maximum of Acheron River; the annual maximum of the Goulburn River; and the difference in days between the annual maximum on the Acheron and Goulburn Rivers.

The panels adjacent to the Acheron and Goulburn panels are plots of the annual maximum discharge on the Acheron River versus the annual maximum discharge on the Goulburn River in the units of ML/d. The green line is the linear line of best fit or regression line.

The remaining four panels are plots of the difference in days between the annual maximum on the Acheron and Goulburn Rivers versus the annual maximum discharge on the Acheron and Goulburn Rivers. The green line is the linear line of best fit or regression line.

A further nine plots, for each combination of rivers in the upper Goulburn, are presented in Appendix C in Figure 10-6 through to Figure 10-14.

The top four right hand panels of Figure 4-3 appear in Figure 4-2 and demonstrate there is a strong relationship between the peak discharges on the Acheron and Goulburn Rivers. The remaining

five panels demonstrate that the annual maxima tend to occur on, or near, the same day and further, that this relationship is more pronounced for larger flood events. The two panels directly above the difference in days panel have most points falling on a vertical line around zero days difference with some scatter either side. Similarly, in the two panels to the left of the difference in days panel most of the points fall approximately on horizontal line around zero days difference. This is confirmed by the green line or line of best fit.

The difference in days panel presented a density plot of the difference in days (which can be thought of as a continuous histogram). This density plot peaks around zero, again confirming that the annual maximum flood discharges on the Acheron and Goulburn Rivers are likely to occur on, or near, the same day.

Similar results were found in Figure 10-6 through to Figure 10-14 for the remaining combinations of upper Goulburn Rivers.

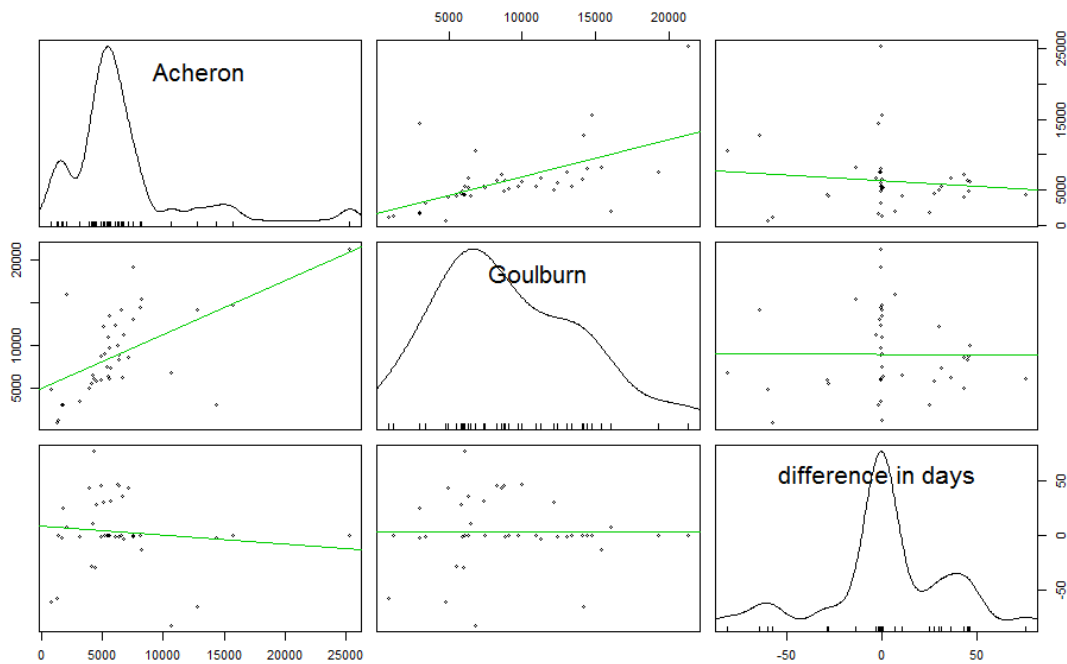


Figure 4-3 Timing of annual maximum discharges on the Goulburn River and Acheron River

The analysis presented above has demonstrated that large flood events in the upper Goulburn tend to be regional events, that is, when one of the rivers in the upper Goulburn is in flood it is likely that the other rivers in the upper Goulburn will also be in flood. This also indicates that the flood forming events (storms) in the upper Goulburn are consistent across the region.

4.1.2 Hydrologic similarity

The information in Table 2-4 shows that the catchments of the upper Goulburn are similar in terms of area, average annual runoff, maximum discharge and the year of peak discharge. The similarity in these characteristics is even stronger when an allowance for catchment area is made. The least similar characteristic between the Acheron River and all other catchments is landuse.

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The Acheron catchment has a higher proportion of urban area, around 2%, with all other catchments with 1% or less urban. While there is a difference between the proportions of urban area in the catchments, this difference is not considered to be significant given the small proportions involved. The Acheron catchment also has the highest proportion of farming landuse; around 20% compared less than 2% in the other catchments. There is a weight of evidence that urbanisation has a significant impact on runoff generation including flood events (see for instance Leopold, 1968 or Mein and Goyen, 1988); however, for other landuse changes the impacts are not as clear.

The removal of vegetation from a catchment reduces interception storage thereby increasing runoff (Ladson, 2008). The Flood Risk Management Research Consortium (FRMC) in the UK undertook a program of research between 2004 and 2012 to investigate the impact of landuse management on flood risk. This program concluded (McIntyre, et al. 2012) that at the local scale landuse management practices could significantly impact flood generation; however, at the catchment scale any benefits from the local scale mitigation were likely to be small.

The majority of farming in the Acheron catchment is in the lower catchment on the floodplain. The majority of the flood event runoff will be generated from the upper catchment, that is the still forested portion which is similar to the other upper Goulburn catchments. Further, the runoff from the lower catchment where the farmland is will respond before the arrival of the flood peak from upstream. Given this, and the finding of the FRMC, the upper Goulburn catchments can be considered hydrologically similar.

4.2 Upper Goulburn LP3 Parameters

One of the advantages of using Bayesian framework to fit flood frequency distributions is the ability to incorporate prior information about the extreme value distribution parameters. In particular, the higher order parameters (the standard deviation and skew) benefit from this sort of analysis as there tends to be consistency in these parameters between hydrologically similar catchments.

Estimates of the LP3 parameter sets for each of the rivers in the upper Goulburn were determined using Flike. The annual maximum series for each gauge was extracted from the instantaneous flow record only. An LP3 distribution was fitted using the method outlined in Section 5 which included filtering of Probable Influential Low Flows (PILF), incorporating historic events and the resulting parameters. Details of the resulting parameters are provided in Section 5.2.

The resulting peak flow estimates and LP3 parameter sets for each of the upper Goulburn rivers are presented in Section 5.2.4.

4.3 Regional Flood Frequency Estimates

Regional Flood Frequency Estimates (RFFE⁵) were completed at the streamflow gauging locations (and catchments) shown in Figure 2-2 and the AEP events listed in Table 1-1. This has been completed using the methodology developed as part of Project 5 of the ARR revision, which was released in December 2016. This method uses the catchment location, shape, catchment area and design rainfall intensity as predictor variables and calculates flood quantiles for a number of

⁵ <http://rffe.arr-software.org/>

Regional Information

AEP events together with uncertainty bounds. The model coefficients are estimated from a set of nearby gauged catchments (region-of-influence approach) using Bayesian generalised least squares (GLS) regression. The model coefficients have been estimated at over 600 gauged catchment locations in Australia including Victoria. A leave-one-out validation technique has shown that the method provides accurate flood quantile estimates over a wide range of circumstances (Haddad and Rahman, 2012).

The variables used in the RFFE model are outlined in Table 4-2. The catchment area, catchment centroid and outlet co-ordinates were determined from an analysis of VicMap Elevation DTM 10m. In this analysis, sub-catchments were generated to the location of the streamflow gauges listed in Table 2-2.

The results from the RFFE Model for each of the gauges are presented in Table 5-6 together with key catchment characteristics. The sub-catchments for each location are shown in Table 4-1.

The results from the RFFE method, peak flows and LP3 parameter sets, are presented in Section 5.2 to allow easy comparison with the peak flows determined from the at-site FFA. These results indicate that the 1% AEP flood discharge on the Taggerty River ($25\text{m}^3/\text{s}$) is slightly larger than the corresponding event on the Steavenson River ($23\text{m}^3/\text{s}$), despite its smaller size. This result is due to the higher rainfall fall intensity in the Taggerty River catchment.

The 1% AEP flood discharge for the upper Goulburn rivers are:

- Acheron River at Taggerty - $361\text{m}^3/\text{s}$
- Big River at Jamieson – $270\text{m}^3/\text{s}$
- Goulburn River at Doherty's – $383\text{m}^3/\text{s}$
- Howqua River at Glan Esk – $219\text{m}^3/\text{s}$
- Jamieson River at Gerrang – $259\text{m}^3/\text{s}$

Regional Information

Table 4-2 RFFE input variables

Location	Catchment Area (km ²)	Centroid latitude (decimal degrees)	Centroid longitude (decimal degrees)	Outlet latitude (decimal degrees)	Outlet longitude (decimal degrees)
Taggerty River @ Lady Talbot Drive	15	-37.4875	145.8542	-37.4901	145.8411
Steavenson River @ Falls Road	17	-37.5499	145.7843	-37.5258	145.7735
Acheron River @ Taggerty	626	-37.5001	145.7264	-37.3177	145.7129
Big River @ Jamieson	628	-37.5028	146.0370	-37.3675	146.0569
Goulburn River @ Doherty's	702	-37.4849	146.2933	-37.33139	146.1311
Howqua River @ Glan Esk	370	-37.1984	146.4146	-37.2294	146.2072
Jamieson River @ Gerrang	367	-37.2970	146.3977	-37.2917	146.1878

4.3.1 Regional information summary

The catchment characteristics presented in Table 2-4 demonstrates a strong similarity between the catchments of the upper Goulburn. This data coupled with the analysis above demonstrates that these catchments are hydrologically similar.

Given that the catchments are hydrologically similar it is considered appropriate to use regional information, such as regional estimates of Log Person Type III parameters. This information can be used prior information in the Bayesian Framework.

5 At-site Flood Frequency Analysis

Flood Frequency Analysis (FFA) at the gauging stations within the catchment, namely the Acheron River at Taggerty and Steavenson River at Falls Road were undertaken. At-site FFA Taggerty River at Lady Talbot Drive was not undertaken as this flow record was too short and of poor quality. The at-site FFA for the Steavenson River was only possible when combined with regional parameter information.

At-site FFA was also undertaken for the upper Goulburn rivers, although the purpose analysis was to produce LP3 parameters for use as prior parameter information.

The FFA was completed using the methods outlined in the [ARR⁶](#) Book 3: Peak Flow Estimation Chapter 2: At-site Flood Frequency Analysis. The FFA was completed using the TUFLOW-Flike Software package (Kuczera, 1999). This package provides a Bayesian framework for comprehensive at-site flood frequency estimation that allows the inclusion of ungauged historical events and prior information as well as an error model to account for rating curve extrapolation error. It also allows the incorporation of regional estimates of parameters (output of ARR RFFE Model) to be used as prior information to enhance the accuracy of the at-site flood quantile estimates. This is particularly useful when the at-site record length is relatively short.

The fitting of flood frequency distributions using Flike was undertaken with the following steps:

- Collect gauged streamflow data
 - Undertake standard data checks on the streamflow data including checking error codes, cataloguing data gaps and undertaking visual inspections;
 - Extract the annual maxima series and check peaks for independence; and
 - Extend the streamflow records where possible.
- Fit an extreme value distribution using Flike, this involves:
 - Censoring low flows: low flows were systematically removed using a multiple Grubbs Beck test from the data to ensure that the distributions are 'aware' of the full length of record as opposed to block censoring the data; and
 - ARR RFFE Parameters: Distribution parameter estimates from the RFFE model were applied to Flike as prior information.

5.1 Collect gauged streamflow data

As outlined in Section 2.5, streamflow data for Acheron River at Taggerty, Steavenson River at Falls Road and Taggerty River at Lady Talbot Drive were collected from the Victorian State Government's Water Monitoring web site⁷. Details of these dataset are provided in Table 2-2. Additionally, streamflow data were collected for the Howqua River @ Glen Esk, Jamieson River @ Gerrang, Goulburn River @ Dohertys and Big River @ Jamieson. Details of these are provided in Table 2-3.

⁶ <http://book.arr.org.au/s3-website-ap-southeast-2.amazonaws.com/>

⁷ <http://data.water.vic.gov.au/monitoring.htm>

5.1.1 Streamflow data checks

A number of data checks were completed on the collected streamflow data in the Acheron catchment. These data checks were not performed for the streamflow data from the upper Goulburn catchments, as these catchments were not the focus of the Study.

The data checks for the Acheron catchment included:

- Checking the dataset for completeness;
- Checking error codes; and
- Comparison of nearby gauge records to ensure consistency of events throughout an area.

To check the datasets for completeness the entire flow time series from each gauge was plotted as shown in Figure 5-1. Inspection of this figure shows that there are no significant periods of missing data for the three datasets with the exception of the Taggerty River dataset. In this figure a small period of missing data can be seen in 2012. To confirm this, the datasets were inspected for missing data and any periods of missing data were listed in Table 5-1. This table demonstrates that there were no significant missing periods.

Table 5-1 Missing periods from stream gauges

Series name	From	To	Number of Days
Acheron River daily flow	20/01/1961	20/01/1961	1.0
Acheron River Instantaneous flow	2/06/2011 15:45	8/06/2011 11:30	5.8
Steavenson River	19/11/2009 0:00	19/11/2009 17:00	0.7
Taggerty River	29/07/2010 0:00	29/07/2010 12:15	0.5
Taggerty River	4/10/2012 15:30	8/10/2012 23:00	4.3

The quality code statistics presented in Table 5-2 indicate that the streamflow records for the Acheron River are of high quality with greater than 90% of records rated as good quality data. Further details of the quality code (QC) statistics are presented in Table A-1 together with a description of the QC. The percentage of good quality data on the Steavenson River and the Taggerty River were less. The Steavenson River dataset has approximately 20% of the data described as extrapolated or estimated with the corresponding percentage for the Taggerty River approximately 7%. For this reason, the records of the Steavenson River were considered to be of low reliability.

While the overall quality codes for the three streamflow gauges is reasonable, the quality of the annual maximum discharges was lower. The quality codes for each of the annual maximum records are presented in Appendix A in Table A-3 and Table A-4 for the Acheron River, Steavenson River and the Taggerty River respectively. The Acheron River records are rated as good quality with the exception of the 2010 and 2012 records which were extrapolated. All records for the Steavenson River and the Taggerty River, with the exception of 2013 and 2014 respectively, were extrapolated.

Table 5-2 Details of streamflow gauges quality

Record	Acheron River daily flow	Acheron River Instantaneous flow	Steavenson River	Taggerty River
Start date	13/12/1945	12/12/1973	19/11/2009	29/07/2010
End date	11/12/1973	-	-	10/02/2013
No. Records	10,225	838,369	252,986	89,037
% Good quality data (Code 2, 15 and 50)	100.0%	96.4%	78.3%	92.6%
% Record manually est. (Code 104)	0.0%	0.0%	0.0%	0.0%
% Irregular (Code 100)	0.0%	0.0%	0.00	6.9%
% Extrapolated (Code, 148, 149 and 150)	0.0%	3.5%	21.7%	0.0%
% Not recorded (Code 180)	0.0%	0.1%	0.0%	0.5%

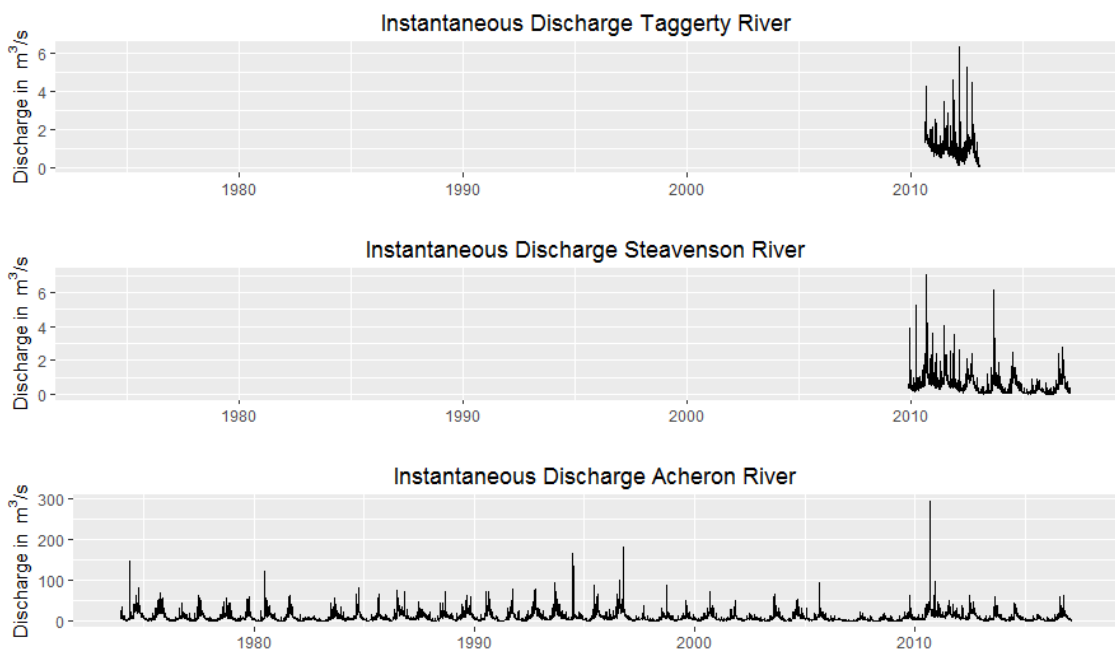


Figure 5-1 Timeseries of discharge for the Acheron, Steavenson and Taggerty Rivers

5.1.2 Data checking summary

The streamflow records for the Acheron River at Taggerty, the Steavenson River at Falls Road and the Taggerty River at Talbot Drive have been reviewed. The Acheron River streamflow (discharge) series is considered to be of good quality and suitable for undertaking flood frequency analysis and hydrologic model calibration. There are some significant issues with the Taggerty River and Steavenson River streamflow records namely the number of low quality records and short record length. For these reasons these are not considered to be suitable for flood frequency analysis and hydrologic model calibration. The stage or stream level records from the Steavenson River and Taggerty River are considered to be reliable and are suitable for further analysis such as peak level

regression modelling. However, the Steavenson River gauge information can be used with the RFFE information to provide an indication of flood quantiles.

5.1.3 Extract the annual maxima series

Annual maximum discharges were extracted for each gauged location in the Acheron catchment and also in the upper Goulburn catchment. These are discussed under the appropriate headings below. As the focus of the study was the Acheron catchment, more detailed analysis was undertaken on the data from these stations.

Acheron catchment

For the Steavenson River and Taggerty River the entire record was instantaneous data. However, the gauged record on the Acheron River at Taggerty had two distinct periods; a period from 1945 to 1973 which are denoted as average daily flows; and a period from 1974 to 2014 which contains an instantaneous flow record. For the Acheron River, it was therefore possible to extend the annual maximum series.

Extension of annual maximum series

It is understood that the average daily flow records are in fact the discharged measured at a particular time of the day, say 9:00am. In order to extend the record, the annual maximum flow from the average daily flow period was extracted from the time series and the annual maximum flow from the instantaneous flow period was extracted.

The average daily flow, however, systematically underestimates maximum instantaneous flow. To correct for this a linear model, using natural logarithms, was constructed using the 9:00am (average) daily discharge to predict the maximum instantaneous discharge from the instantaneous period, that is:

$$\ln(Q_{inst}) = m \times \ln(Q_{av}) + b$$

where Q_{inst} is the maximum instantaneous discharge, Q_{av} is the average daily discharge, m is the slope of the fitted line and b is the intercept. This model was then used to adjust the average daily flow record for the period preceding the instantaneous flow record, effectively extending the annual maximum record.

The annual maximum instantaneous flow was initially extracted from the Taggerty River at Acheron gauge. From the same series the annual maximum 9:00am flow was also extracted. The date of the annual maximum instantaneous flow and the annual maximum 9:00am flow were compared and if the annual maximum daily flow occurred more than +/- one day from the annual maximum, the 9:00am flow on the day of the annual maximum or following day (which ever was the larger) was extracted. This occurred on eight separate occasions.

The 1945 and 2017 records were removed as these were not full years. The resulting paired flow series together with the dates and times are presented in Table 5-3.

At-site Flood Frequency Analysis

Table 5-3 Paired annual maximum instantaneous and average discharge for Acheron River at Taggerty bore rerating

Year	Instantaneous max (m ³ /s)	9am max (m ³ /s)	Datetime AM	Datetime 9am
1974	148	67	15/05/1974 19:00	16/05/1974 09:00
1975	70	61	18/09/1975 02:00	18/09/1975 09:00
1976	46	42	21/09/1976 04:30	21/09/1976 09:00
1977	63	57	30/06/1977 15:30	30/06/1977 09:00
1978	56	51	27/09/1978 19:00	27/09/1978 09:00
1979	59	58	12/10/1979 06:30	12/10/1979 09:00
1980	123	86	29/06/1980 20:15	30/06/1980 09:00
1981	64	63	15/08/1981 05:30	15/08/1981 09:00
1982	16	9	25/01/1982 21:00	26/01/1982 09:00
1983	57	57	03/09/1983 09:30	03/09/1983 09:00
1984	83	66	03/10/1984 22:30	04/10/1984 09:00
1985	65	57	23/08/1985 16:45	24/08/1985 09:00
1986	75	59	04/07/1986 17:15	05/07/1986 09:00
1987	48	35	22/06/1987 15:30	23/06/1987 09:00
1988	72	54	11/09/1988 02:15	11/09/1988 09:00
1989	64	64	01/09/1989 09:15	01/09/1989 09:00
1990	74	73	20/08/1990 08:45	20/08/1990 09:00
1991	78	75	19/09/1991 04:30	19/09/1991 09:00
1992	77	75	11/10/1992 01:45	11/10/1992 09:00
1993	95	87	02/09/1993 11:45	02/09/1993 09:00
1994	166	156	25/06/1994 07:15	25/06/1994 09:00
1995	87	53	09/06/1995 17:00	10/06/1995 09:00
1996	181	93	01/10/1996 20:00	02/10/1996 09:00
1997	36	30	08/09/1997 00:00	08/09/1997 09:00
1998	87	57	23/09/1998 17:15	24/09/1998 09:00
1999	51	40	08/08/1999 19:45	09/08/1999 09:00
2000	73	66	11/09/2000 14:15	11/09/2000 09:00
2001	50	38	06/11/2001 16:45	06/11/2001 09:00
2002	19	17	05/07/2002 19:45	06/07/2002 09:00
2003	65	48	24/08/2003 22:00	25/08/2003 09:00
2004	52	43	11/09/2004 17:15	12/09/2004 09:00
2005	93	92	31/08/2005 08:00	31/08/2005 09:00
2006	14	7	13/03/2006 21:00	14/03/2006 09:00
2007	24	19	05/07/2007 14:00	06/07/2007 09:00
2008	21	21	16/08/2008 12:00	16/08/2008 09:00
2009	62	50	28/09/2009 15:30	28/09/2009 09:00
2010	293	152	05/09/2010 00:45	05/09/2010 09:00
2011	49	41	18/07/2011 18:00	18/07/2011 09:00
2012	64	63	22/06/2012 07:00	22/06/2012 09:00

Year	Instantaneous max (m ³ /s)	9am max (m ³ /s)	Datetime AM	Datetime 9am
2013	59	56	23/08/2013 22:15	24/08/2013 09:00
2014	43	40	10/07/2014 02:15	10/07/2014 09:00
2015	16	16	07/08/2015 06:00	07/08/2015 09:00
2016	62	54	04/10/2016 21:15	05/10/2016 09:00

The natural logarithms of the resulting paired discharge series were plotted as shown in Figure 5-2. This figure indicates that there is a strong relationship between the two discharge series, as expected and was confirmed by the linear modelling results (see straight line on Figure 5-2).

The resulting linear model fitted to this data was:

$$\ln(Q_{inst}) = 1.033\ln(Q_{av})$$

where m was significantly different from 0 at the 0.1% level. Note that the intercept term was set to 0. The model had a coefficient of variation (R^2) value of 0.999. These values confirm that there is a strong relationship between the peak instantaneous discharge and the 9:00am discharge on the Taggerty River at Acheron.

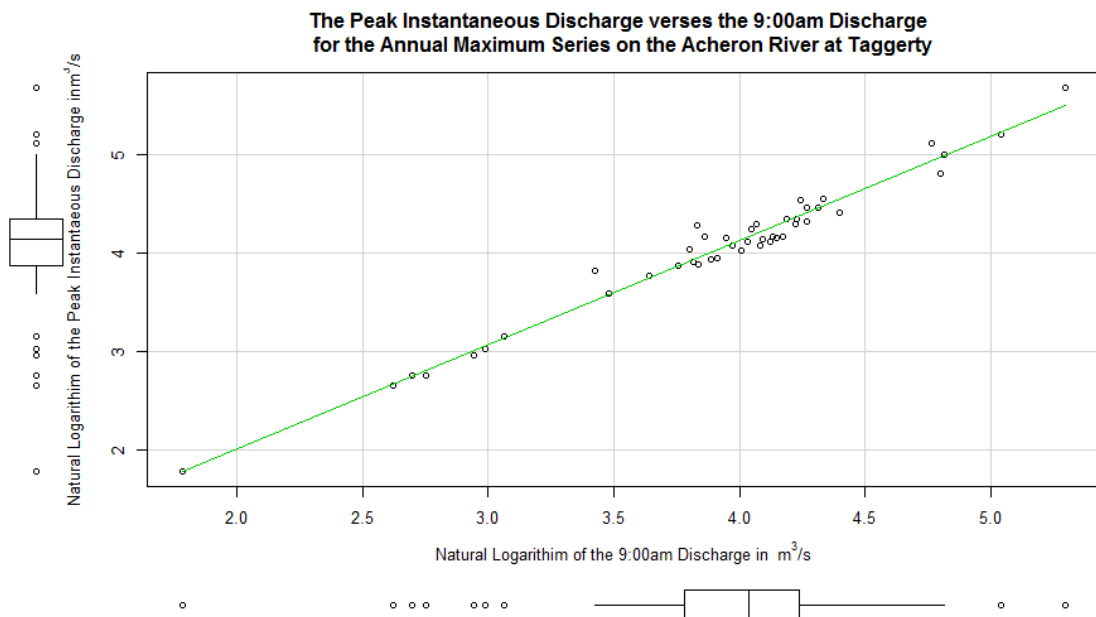


Figure 5-2 Annual maximum instantaneous discharge versus average discharge for Taggerty River at Acheron

Model diagnostics were undertaken as described in Appendix B. These model diagnostics indicate that the model assumptions are generally met, with the exception of normality of the dependent variable. Initially the distributions of both the dependent and independent variables were investigated using histograms. These histograms suggested that the distributions of these variables were not normally distributed and a log transform was applied.

Further attempts to improve the normality of the dependent variable were undertaken using a Log-Log transform and a Power Transform. However, the resulting linear models using these transforms did not significantly improve the performance of the models. Given, the added complexity of these models did not result in a significantly better fit the single log transform was the preferred form of the model.

The resulting extended annual maxima series for the Taggerty River at Acheron is shown in Figure 5-3.

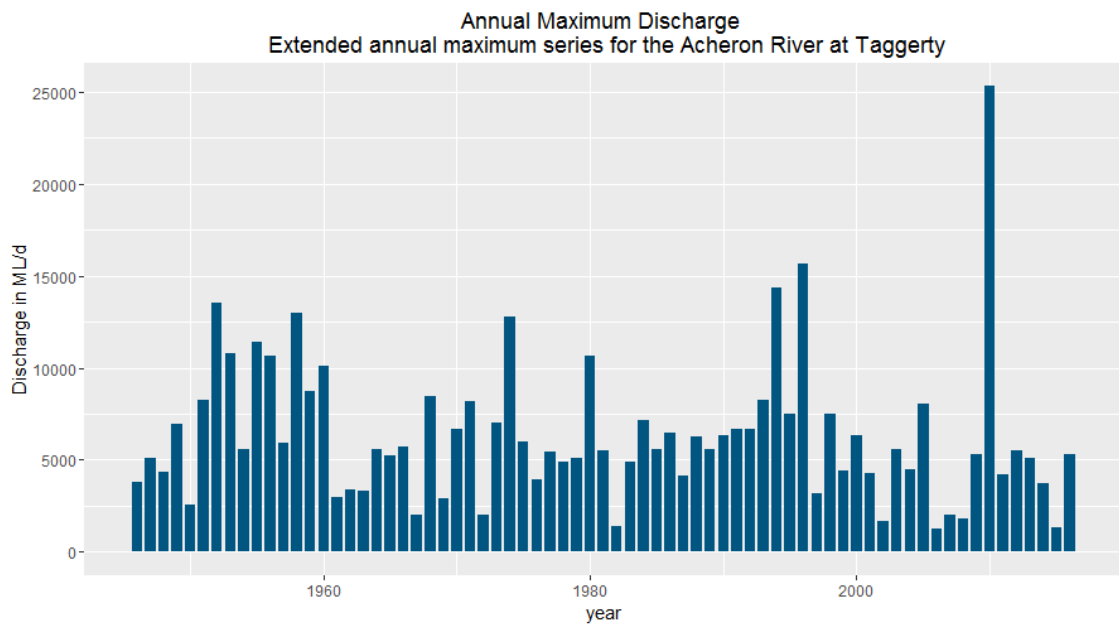


Figure 5-3 Extended annual maximum series for the Acheron River at Taggerty Note these values have not been rated

Adopted annual maximum series

Following the adjustment of the daily flow record of the Acheron River at Taggerty the annual maximum series for each gauge was extracted. The Acheron River at Taggerty the annual maximum series was then re-rated as outlined in Section 3. The results are presented in Figure 5-4. Tabular data of the annual maximum series are presented in Appendix A (Table A-2 Table A-3 and Table A-4).

Inspection of Figure 5-4 indicates that the largest flow to occur on the Acheron River and Steavenson River was in 2010, whereas the largest flow to occur on the Taggerty River was in 2012. However, the peak annual water stage for the Taggerty River, reported in Table A-4, occurred in 2010. For this reason, the discharges reported for the Taggerty River gauge are considered unreliable.

The rating curve for Taggerty River was reviewed as discussed in Section 3.

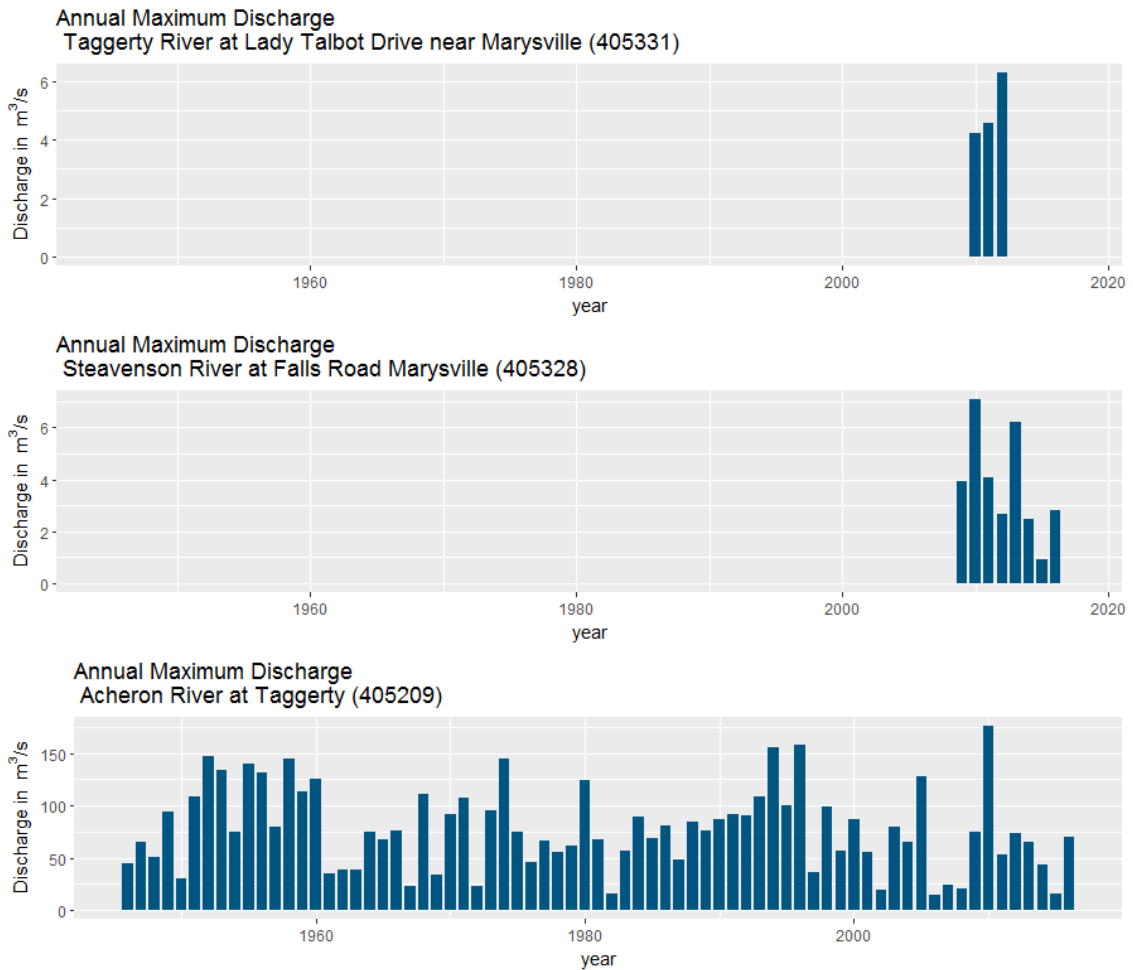


Figure 5-4 Annual maximum series for Acheron, Steavenson and Taggerty Rivers Note the Acheron River at Taggerty values have been related

Upper Goulburn annual maximum series

Given the proximity of the upper Goulburn catchments, an analysis of these catchments was undertaken including FFA. The annual maximum series for the upper Goulburn catchments were extracted from the period of instantaneous record. As these stations were not in the study catchment the streamflow record was not extended. The resulting annual maximum series are shown in Figure 5-5.

It is of note that the maximum annual streamflow at all four stations occurred on the 5th September 2010

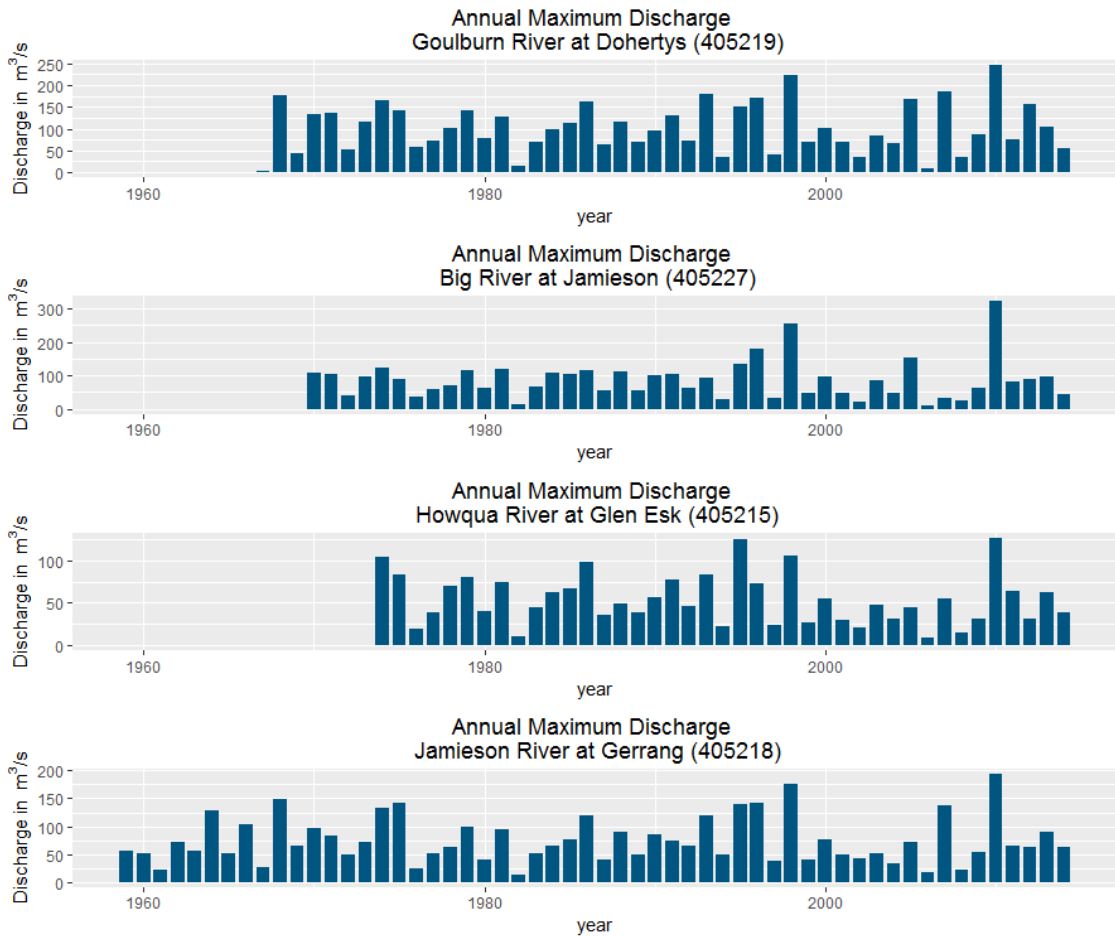


Figure 5-5 Annual maximum discharge for the upper Goulburn stations

5.2 Fit an extreme value distribution

Flood frequency analysis for the Acheron River at Taggerty was undertaken using Flike. This involved fitting an extreme value distribution to the annual maximum series determined above. As Flike uses a Bayesian approach to the fitting of statistical distributions it is possible to incorporate prior information regarding the distribution's parameters as well as historic information. This parameter information was determined from regional analysis discussed in Section 3 and the historic information is presented in Section 5.2.1. In addition, censoring probable influential low flows (PILF) was also undertaken (Section 5.2.2).

Initial FFA results indicated that the 2010 was greater than the 1% AEP event and further that this estimate of the 1% AEP event was significantly less than the RFFE estimate. While the 2010 event was a significant event it did not lead to the significant impacts normally associated with a 1% AEP event. For these reasons detailed work on both regional flooding and historical flood events was undertaken. This work is presented below.

5.2.1 Historic information

Historic flood information or floods that occurred outside of the gauged record have been sourced as outlined in Section 1.4. Two notable events occurred outside of the gauged record; in 1870 and 1916; however, as noted above, it is not possible to determine which event was the largest although it is considered extremely likely that both events were larger than the 2010 event.

While these events were not specific to the Acheron River, they were upper Goulburn events, and as demonstrated above, when a large event occurs on one tributary of the upper Goulburn rivers it is likely to occur on all upper Goulburn rivers.

For this reason, the 1916 event was incorporated into the At-site FFA for all rivers. The 1870 event was not included as information about this event was less extensive than the 1916. Sensitivity runs were undertaken including the 1870 event. These runs found that the results were not significantly impacted with the 1% AEP peak flow increasing by less than 7%.

5.2.2 Censoring of low flows

Probable Influential Low Flows (PILF) can unduly influence the fit of the upper tail of distributions in FFA and it is good practice to remove these records from the annual maximum series used to fit the distribution. However, the frequency information needs to be retained. This was completed using the multiple Grubbs Beck test (Cohn et al., 2013) incorporated into Flike.

The number of discharge records censored and the threshold for removal (i.e. less than Xm^3/s) for each catchment are listed in Table 5-4.

Table 5-4 PILF summary

Catchment	Number of peaks censored	Censoring threshold (m^3/s)	Record length
Acheron River	14	43.0	71
Big River	2	14.5	45
Goulburn River	3	14.1	48
Howqua River	0	-	41
Jamieson River	0	-	56
Steavenson River	0	0	9

5.2.3 Regional parameter information

As outline above, regional parameters were obtained from two sources:

- Analysis of the upper Goulburn rivers; and
- The RFFE.

The results of these analyses are presented below.

Upper Goulburn

At-site FFA was undertaken for the following upper Goulburn rivers:

- Big River
- Goulburn River
- Howqua River
- Jamieson River,

using the following procedure:

- AM series was extracted from the instantaneous records, with partial year's records being removed. Note that these series were not extended in the way that the Acheron River at Taggerty gauge was as these are not the focus of the study.
- LP3 distribution was fitted with Flike
 - PILF were removed (see Table 5-4 for details)
 - The 1916 flood was included as historic information under the assumption that this was the largest flood
 - Regional parameters from RFFE were **not** included in the analysis

The adopted peak flows are presented in Table 5-5 and the LP3 parameter sets were collated and are presented below in Figure 5-6. In this figure the following naming convention has been used for the AM series fit:

- XXXX_River means the AM fitted to the LP3 distribution
- XXXX_River_Priors mean the AM fitted to the LP3 distribution with RFFE parameters as priors.
- XXXX_River_Hist the AM fitted to the LP3 distribution with the 1916 flood as the largest on record.

The rationale for the adopted peak flows is outlined below.

Table 5-5 Upper Goulburn At-Site FFA peak flows

Event	Big River Discharge (m ³ /s)			Goulburn River Discharge (m ³ /s)			Howqa River Discharge (m ³ /s)			Jamieson River Discharge (m ³ /s)		
	Quantiles	5% CL	95% CL	Quantiles	5% CL	95% CL	Quantiles	5% CL	95% CL	Quantiles	5% CL	95% CL
50% AEP	73.0	61.0	87.4	94.0	80.7	110	48.5	41.0	57.5	67	58	77.3
20% AEP	130	109	156	150	132	170	77.9	67.7	89.5	107.9	94.9	122.8
10% AEP	174	145	212	183	163	206	95.8	84.5	109	135.1	118.8	154.4
5% AEP	220	180	277	212	189	241	111	98.6	128	160.8	140	188.6
2% AEP	286	226	385	245	216	292	129	113	155	193.2	164.1	239.4
1% AEP	339	258	485	267	232	333	141	122	178	216.7	179.5	281.5

RFFE

The RFFE analysis was undertaken as discussed in Section 4.3. This analysis produced parameters for the LP3 distribution which have been included as priors in at-site FFA for the upper Goulburn rivers.

The RFFE peak flows estimates for the Acheron catchment are presented in Table 5-6.

The resulting LP3 parameters for the upper Goulburn rivers have been plotted in Figure 5-6 and the resulting peak flows are presented Table 5-7. Note that the RFFE LP3 parameters are used as prior information to the Bayesian analysis in Flike. Flike then undertakes a process to find the posterior parameters which will generally be different to the prior parameters.

Table 5-6 RFFE Peak Flow Estimates Acheron catchment– Discharge m³/s

Event	Taggerty River Discharge (m ³ /s)			Steavenson River Discharge (m ³ /s)			Acheron River Discharge (m ³ /s)		
	Quantiles	5% CL	95% CL	Quantiles	5% CL	95% CL	Quantiles	5% CL	95% CL
50% AEP	5.17	2.18	12.3	4.83	2.05	11.4	77.1	28.6	206
20% AEP	8.96	3.97	20.4	8.42	3.75	19.1	133	51.9	339
10% AEP	12.0	5.32	27.6	11.3	5.03	25.9	178	70.2	452
5% AEP	15.4	6.69	35.8	14.5	6.33	33.7	227	89.3	577
2% AEP	20.4	8.57	49.1	19.3	8.10	46.4	300	116	774
1% AEP	24.7	10.1	61.0	23.3	9.50	57.9	361	139	945

Table 5-7 RFFE Peak Flow Estimates upper Goulburn catchment– Discharge m³/s

Event	Big River Discharge (m ³ /s)			Goulburn River Discharge (m ³ /s)			Howqa River Discharge (m ³ /s)			Jamieson River Discharge (m ³ /s)		
	Quantile	5% CL	95% CL	Quantile	5% CL	95% CL	Quantile	5% CL	95% CL	Quantile	5% CL	95% CL
50% AEP	71.5	28.8	177	94.0	38.5	228	47.6	19.7	114	63.7	26.1	154
20% AEP	114	47.4	275	154	66.0	360	81.6	34.9	190	104	45.0	242
10% AEP	147	61.3	350	201	86.2	468	109	47.2	250	136	58.6	315
5% AEP	181	76.1	429	251	107	592	139	60.2	319	170	72.2	401
2% AEP	230	97.3	543	323	135	779	182	79.4	421	218	90.6	529
1% AEP	270	114	639	383	157	942	219	95.2	505	259	105	643

Comparison of parameter sets

In Figure 5-6 the first panel presents the resulting LP3 mean parameter, the second panel presents the resulting LP3 standard deviation parameter and the third panel the resulting LP3 skew parameter. The dark horizontal line inside the box is the location or mean of the parameter with the box and 'whiskers' representing the first standard deviation and 1.96 x the standard deviation (to get the 95% confidence limits) respectively.

Comparison between the upper Goulburn and RFFE parameters is provided below. This section compares the LP3 parameters from the AM series fit to the parameters from the AM and historic fit.

From the first panel in Figure 5-6 it is evident that the mean parameter for all techniques (AM, AM plus historic and AM plus priors) for each river are similar. That is, the mean is well estimated from the AM series as expected given the length of record (all are greater than 40 years).

The standard deviation (std dev) parameter is consistent when comparing the AM and AM plus historic techniques with the AM plus historic having smaller uncertainty bounds. The AM plus priors technique results in similar values (with the exception of Big River) and tighter uncertainty bounds.

There is a significant difference for the skew parameter between the AM and AM plus historic to the AM with prior technique as shown in Figure 5-6. The priors technique has considerably tighter uncertainty bounds, and for all rivers with the exception of Big River and Acheron River, significantly different skew values. In all cases the resulting skew parameter from AM plus prior technique has a positive skew value, whereas the other techniques have negative skew values. This means the AM plus prior distributions are lower bounded, that is, they have no upper bound. The AM and AM plus historic results are upper bound, that is the peak flows asymptote to a theoretical upper bound.

The resulting Flood Frequency curves for the Howqua River for all three techniques are plotted in Figure 5-7, Figure 5-8 and Figure 5-9. In these figures the best fit to the data is provided by the AM plus historic followed by the AM technique. The poorest fit is provided by the AM plus priors. This is consistent across all four of the upper Goulburn catchments.

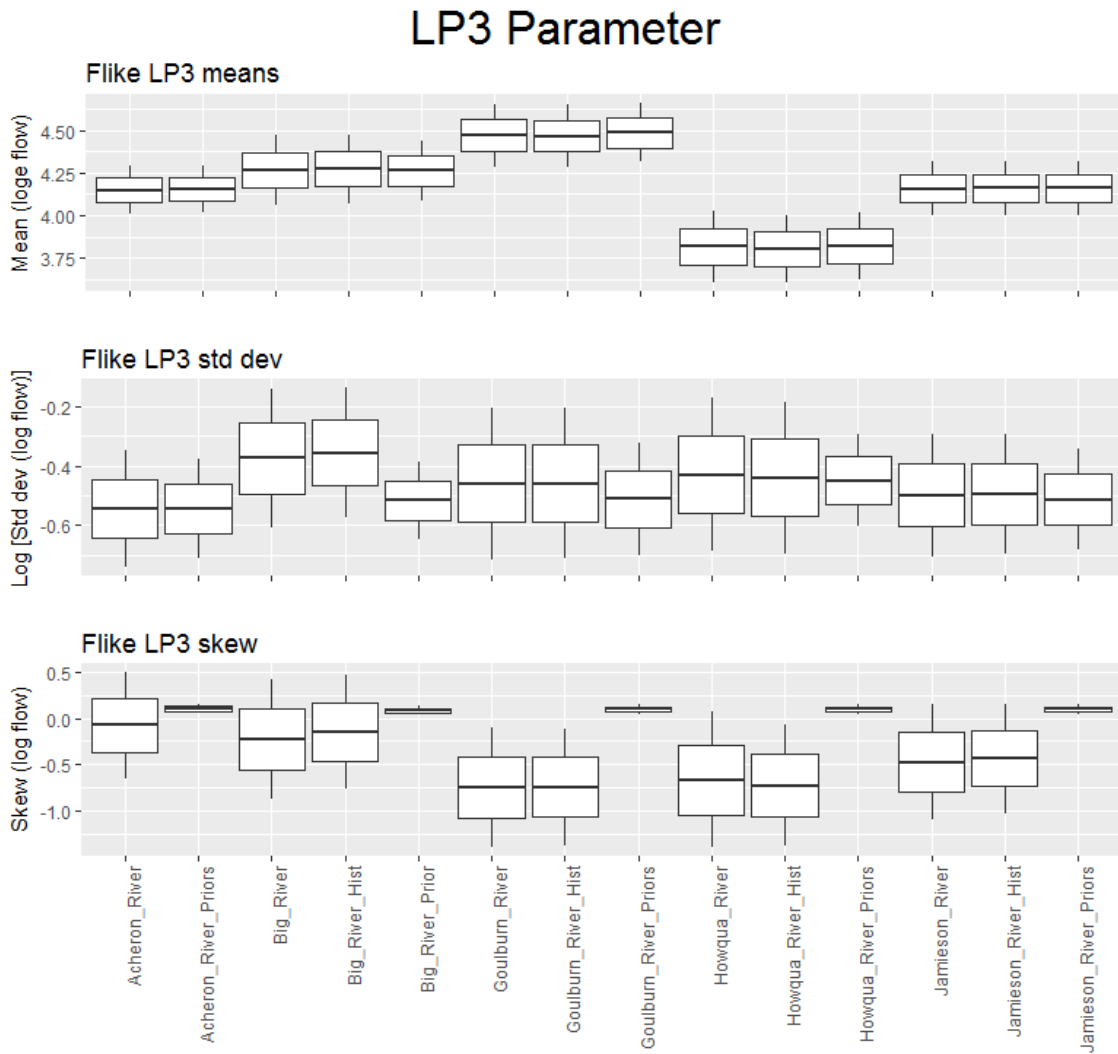


Figure 5-6 Comparison of LP3 parameters for upper Goulburn catchments

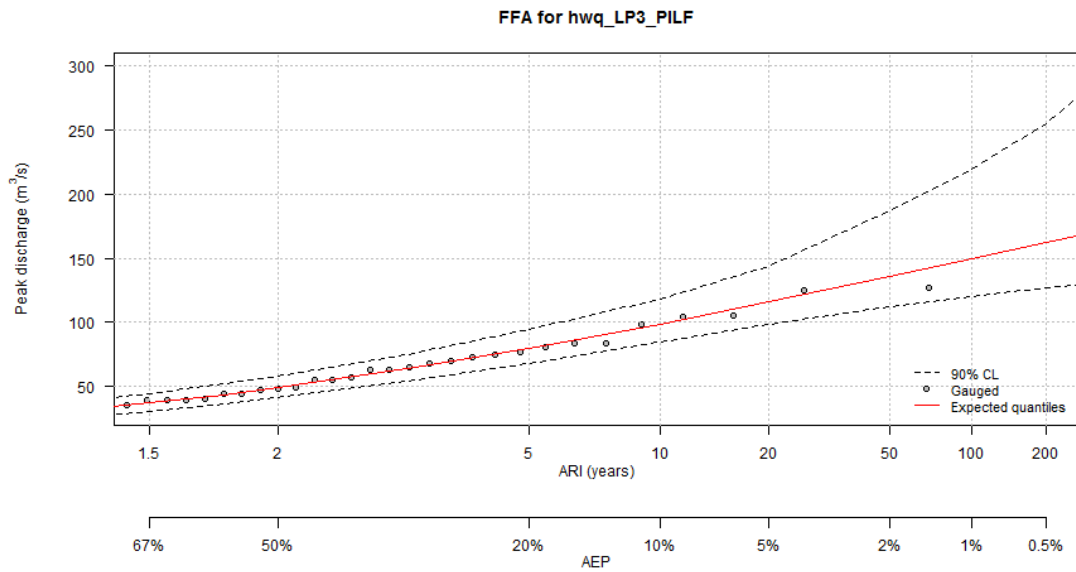


Figure 5-7 At-site FFA: Howqua River AM

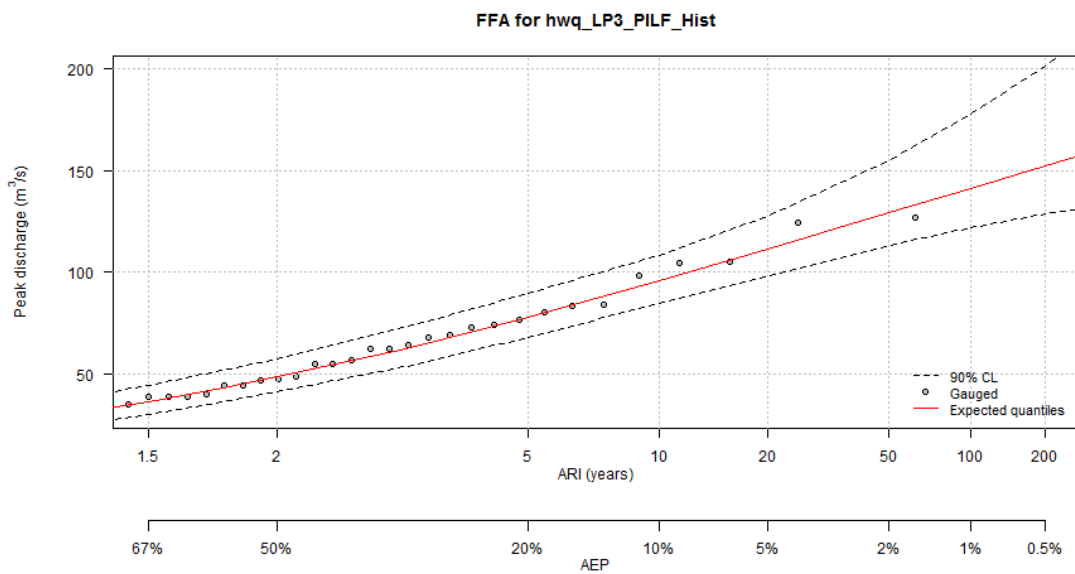


Figure 5-8 At-site FFA: Howqua River AM plus Historic

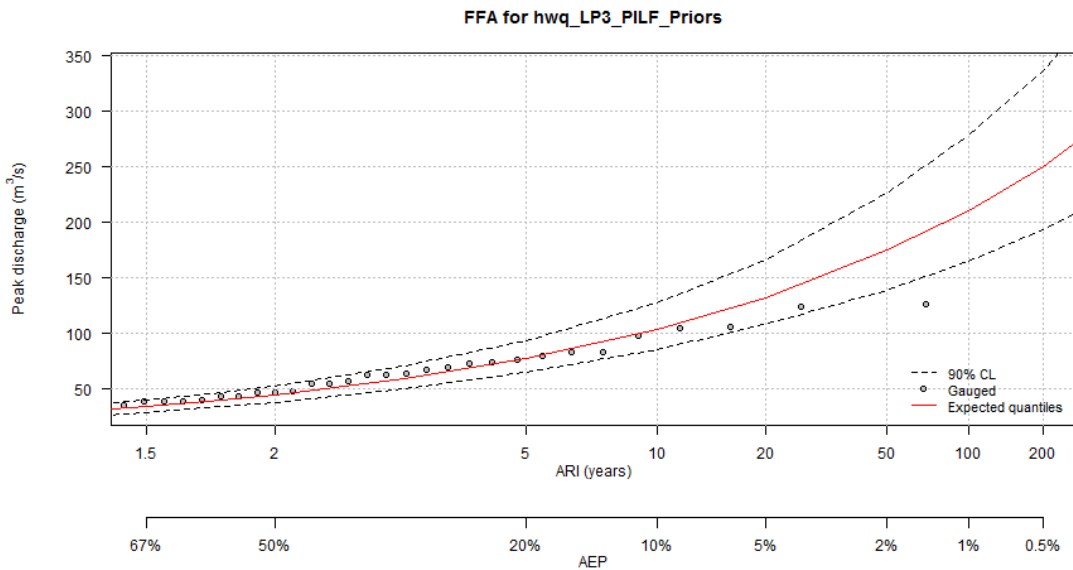


Figure 5-9 At-site FFA: Howqua River AM plus Priors

Adopted LP3 parameter set

Given the analysis above and the consistency of the results it was concluded that the parameters determined from the upper Goulburn rivers, rather than the RFFE parameters, were more suitable. To generate parameter set for input into the Flike At-site FFA for the Acheron River, the mean and standard deviation for each LP3 parameter was calculated from the LP3 parameters from each of the upper Goulburn rivers as well as a correlation matrix. These values are presented in Table 5-8.

Table 5-8 Adopted prior LP3 parameter set for Acheron River

Parameter	Mean	Standard Deviation	Correlation		
Mean (log flow)	4.1757	0.2784	1.0		
Log [Std dev (log flow)]	0.6464	0.0390	0.0880	1.0	
Skew (log flow)	-0.51507	0.2817	0.2029	0.6361	1.0

5.2.4 FFA Results

At-site FFA for the Acheron River at Taggerty and Steavenson River @ Marysville was undertaken. The procedure and input data are outlined below with the peak flow results presented in Table 5-9. Plots of the final at-site FFA are shown in Figure 5-10 and in Figure 5-11 for the Steavenson River.

These results for the Acheron River are based on the following:

- Extended AM series and re-rating as discussed in Section 3
- The filtering of PILF using the mGBt

At-site Flood Frequency Analysis

- The incorporation of the 1916 flood event as the largest on record; and
- Prior LP3 parameter information determined from a regional analysis of the upper Goulburn catchments.

These results for the Steavenson River are based on the following:

- AM series; and
- Prior LP3 parameter information determined from a regional analysis of the upper Goulburn catchments.

Table 5-9 At-site FFA Peak Flow Estimates for the Acheron catchment in m³/s

AEP	Acheron River @ Taggerty m ³ /s			Steavenson River @ Marysville m ³ /s		
	Quantile	5% CL	95% CL	Quantile	5% CL	95% CL
50%	72.3	64.3	80.8	3.09	2.16	4.40
20%	113	102	124	5.02	3.67	7.10
10%	136	124	151	6.27	4.57	8.90
5%	157	142	177	7.41	5.42	10.6
2%	179	160	209	8.80	6.36	13.5
1%	194	170	233	9.77	6.87	15.5

Comparing the at-site FFA results to the RFFE results for the Acheron River, the at-site results are smaller than the RFFE results for all quantiles with the 1% AEP from the at-site analysis around 194m³/s and the RFFE results around 361m³/s. These values compare to the peak gauged flow of 176m³/s (in 2010); that is, the AEP of this event is more frequent than the 1% event, using the at-site FFA results.

The at-site FFA undertaken indicates that the AEP of the 2010 event was approximately the 1 in 50 year AEP event. To place this in context, the 2010 peak flows from other nearby catchments together with the estimated AEP of the event is provided in Table 5-10. The estimate of the AEP of the 2010 Acheron event is similar to the other large upper Goulburn catchments having AEPs of around 2%.

Table 5-10 Approximate AEP of 2010 event at various stations

Catchment	2010 peak flow (m ³ /s)	Approximate AEP (1 in Y year AEP)
Acheron River	293	2%
Big River	322	Between 2% and 1%
Goulburn River	247	2%
Howqua River	127	2%
Jamieson River	193	1%
Steavenson River	7.1	20%

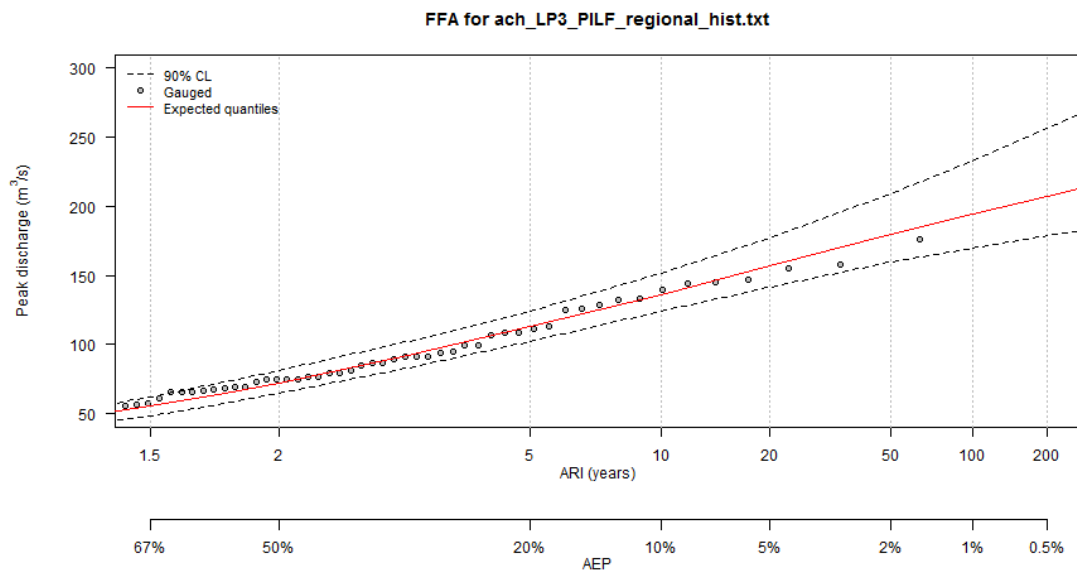


Figure 5-10 At-site FFA: Acheron River

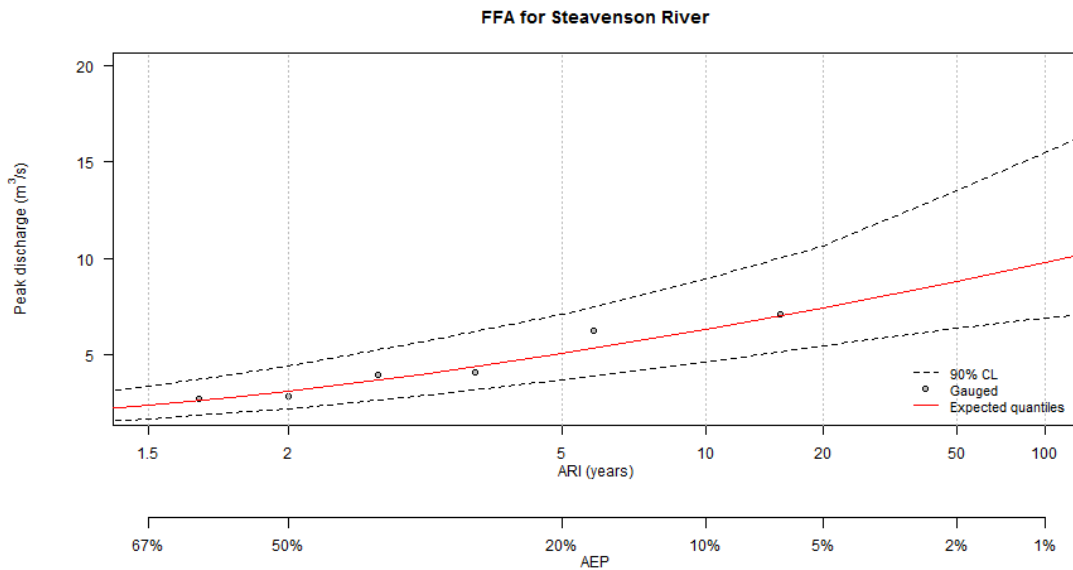


Figure 5-11 At-site FFA: Steavenson River

5.3 Discussion

At-site FFA was undertaken for the Acheron River at Taggerty and the Steavenson River at Maryville using a Bayesian fitting technique. This method allowed for the inclusion of regional LP3 parameter information and historic flood events. Analysis of the upper Goulburn rivers demonstrated that they were hydrologically similar, and therefore suitable for a regional analysis. The regional parameter information was determined from an analysis of the upper Goulburn rivers including the:

- Big River at Jamieson
- Goulburn River at Doherty's
- Howqua River at Glan Esk
- Jamieson River at Gerrang

The resulting LP3 parameter set together with their standard deviations and correlation matrix were incorporated into the Bayesian analysis.

One of the interesting outcomes of the analysis of the upper Goulburn rivers was that the AEP of the 2010 event was consistent across the upper Goulburn gauges including the Acheron River.

A further observation of the upper Goulburn rivers, is that there has not been a significant flood event in the gauge record. This could mean there is a systematic underestimation of the peak of rarer floods when using at-site FFA.

When undertaking at-site FFA at gauges with short records consideration of climatic persistence is required. The Steavenson River has a short record of seven years, and this period has coincided with a relatively normal climatic period with the exception of the 2010-2011 period which corresponded a larger La Nina. While the length of record would normally exclude meaningful FFA

being undertaken, the use of the regional parameter information and the fact that the gauge record coincides with a relatively normal climatic period provides comfort that the results are reasonable. However, the confidence in the resulting flood quantiles rarer than the 10% AEP is low, as reflected in the uncertainty bounds.

6 Bushfire Hydrology

The Acheron River catchment was severely affected by the February 2009 bushfires, with approximately 85% burnt during this event as shown in Figure 6-2. This section discusses the impact of bushfires on the flood hydrology of the catchment.

6.1 Background

The impact of bushfires on hydrology has been researched in Australia, for instance Kuczera (1985 and 1987), van Dijk et al. (2006), Doarr et al. (2003), SKM (2007) and Lane et al. (2007). This research has been focused on change in catchment yield, that is, the proportion of rainfall that is converted to runoff and there has been little research on the impact of bushfires on flood hydrology.

Catchment yield following a bushfire has been described by Kuczera curves (Kuczera, 1985), whereby yield initially increases for a short period and then reduces as the vegetation re-establishes increasing evapotranspiration. For a burnt catchment to recover to pre-fire yields, takes a number of years with Kuczera reporting 60-200 years for a Mountain Ash forest. The exact timing of the recovery is dictated by a number of factors such as, severity of burn, tree death, percent of the catchment burnt, forest type, soil type, etc. The effect of bushfires on catchment yield was the fifth ranked risk to the Murray Basin water supply by the CSIRO study (van Dijk, 2006).

As noted above, there has been little research on the effect of bushfires on event based runoff. This is due to the difficulties in collecting consistent dataset to analyse. Doarr et al. (2003) present four conceptual models of how runoff is affected by bushfires. These models suggest that event based runoff could either increase or decrease depending on a number of factors.

Given there is no guidance on how to assess the impacts of bushfire a simple assessment was undertaken as presented below.

6.2 Impacts of bushfire on flood hydrology

To investigate the impact of bushfires on the flood hydrology of the Acheron River a comparison between a flood event immediately following the 2009 bushfires and a similar historic event was undertaken. A moderate flood event occurred in September 2009 with a peak flow of 62m³/s was selected as the “post-bushfire” event. This event was selected as it was first significant event following the bushfires and considered the most likely to show an impact from the bushfires. Using the September 2010 event in this analysis was also considered; however, there were significant data gaps in the Buxton rainfall gauge. For this reason, the 2010 event was not considered at this stage, it may be revisited once the hydrologic model calibration is undertaken.

The September 2009 flood event was characterised by the event generating rainfall, the time of year and antecedent conditions. The rainfall was derived from the Buxton daily rainfall station (088130). The daily rainfall stations at Marysville (088044) and Marysville Golf Course (88103) were investigated for use in this assessment; however, the data for the corresponding events were unavailable or incomplete. The Marysville rainfall gauge was missing data from the 3rd February 2009 to 3rd August 2013. The Marysville Golf Course rainfall gauge has numerous data gaps, including the period from 12th August 2009 to 15th September 2009 and the period from 20th August

2009 to 21st August 2009, therefore the antecedent conditions could not be characterised for this gauge.

The rainfall at Buxton on the 26th September 2009 was aggregated over two days. The rainfall at Buxton was compared to the rainfall at Marysville Golf Course in Table 6-1. The information in this table indicates that there was a broadly similar pattern of rainfall at the two rainfall stations. Given this, it has been assumed that the rainfall on 25th September 2009 was less than 5mm, that is, the majority of the rainfall fell on the 26th September.

Table 6-1 Comparison of September 2009 rainfall at Buxton and Marysville Golf Course

Date	Buxton (mm/day)	Marysville Golf Course (mm/day)
2009-09-22	15.0	13.8
2009-09-23	0.4	0.6
2009-09-24	0.8	3.4
2009-09-25		4.4
2009-09-26	45.0	49.2
2009-09-27	8.5	16.8
2009-09-28	6.2	34.6

The antecedent conditions were characterised using the Antecedent Precipitation Index (API) (Shaw, 1994) with a *k* value of 0.85 and period of 15 days. The resulting characteristics are shown in Table 6-2. The hydrograph for the 2009 event are shown in Figure 6-1.

Table 6-2 Characteristics of the September 2009 event

Date of Rainfall at Buxton	Daily rainfall in mm	API in mm	Date of Flood Peak: Acheron River	Peak discharge m ³ /s	Volume ML
2009-09-26	45.0*	6.6	2009-09-28	62.0	27,400

*Rainfall aggregate over 2 days

The rainfall records from Buxton and Marysville were reviewed for similar events. The closest match was the June 1990 event as shown in Table 6-3. This event had a similar rainfall and antecedent conditions (APIs) to the September 2009 event. Also, both events occurred during the winter early spring periods. The hydrograph for this event is shown in Figure 6-1.

Table 6-3 Characteristics of the June 1990 event

Date of Rainfall at Buxton	Daily rainfall in mm	API in mm	Date of Flood Peak: Acheron River	Peak discharge m ³ /s	Volume ML
1990-06-28	42.0	5.9	2009-09-28	19.9	4,500

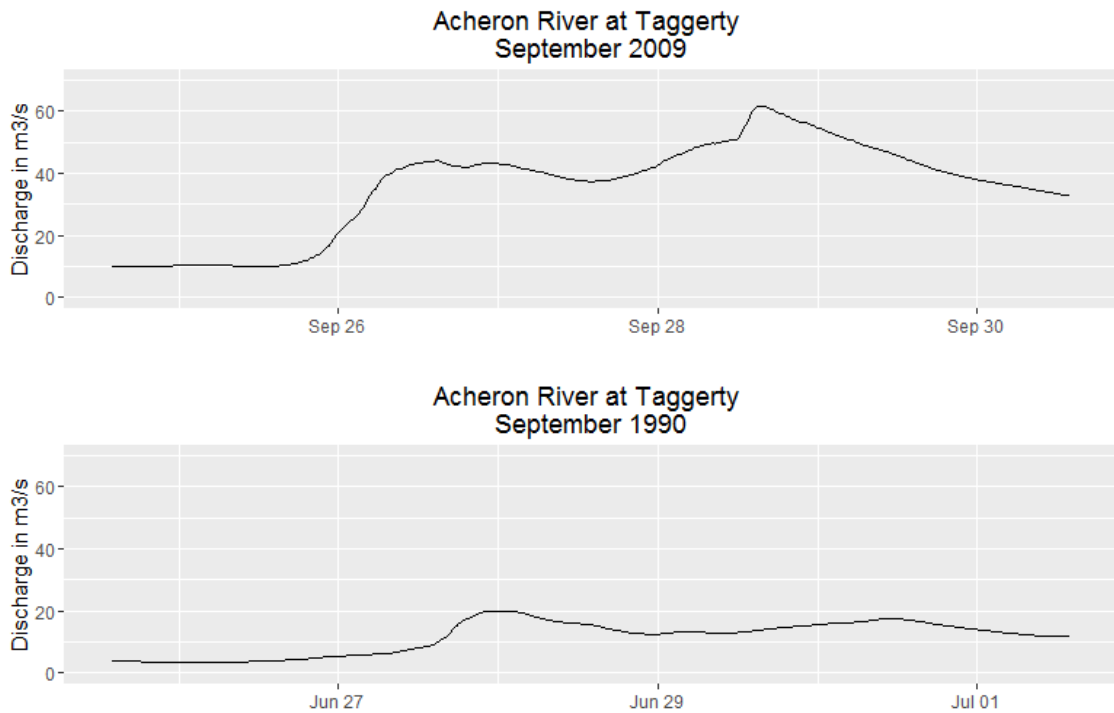
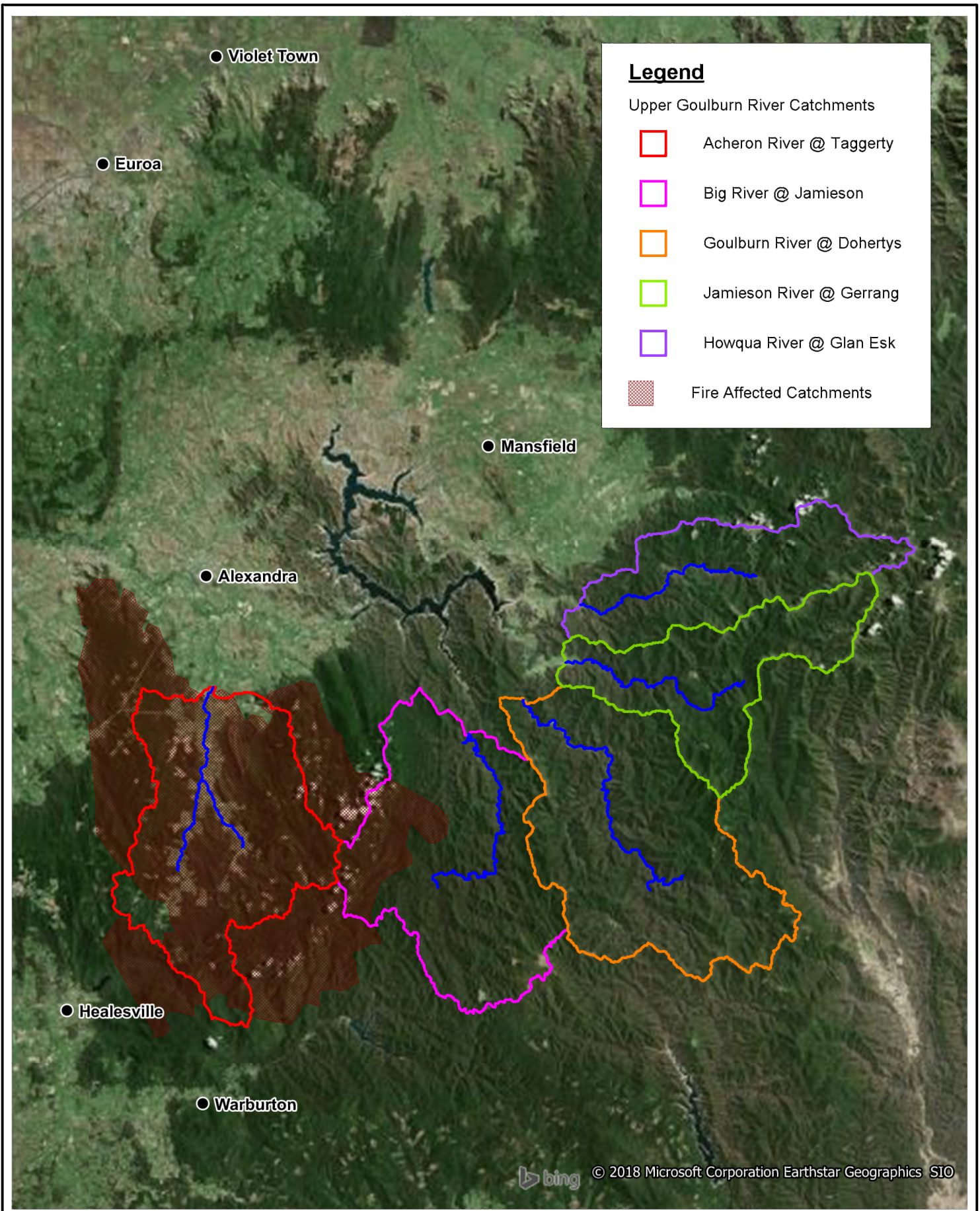


Figure 6-1 Comparison of June 1990 and September 2009 peak flow events

6.3 Conclusions

A comparison of key properties of the flood events is shown in Table 6-2 and Table 6-3 with the hydrographs shown in Figure 6-1. This information indicates that the events had significantly different peak flows and volumes which suggest that runoff increased during the immediate post-fire period. While this analysis is not considered exhaustive and there are a number of limitations in the data, it indicates that for the Acheron River at Taggerty there was a significant impact on the flood hydrology from the 2009 bushfires. Care should be taken in extrapolating these results to other catchments, as the percentage of catchment burnt was relatively small and the measurement location significantly downstream from the burnt area. Further, the rainfall data coverage was limited and only one gauge in the catchment has been analysed for one event.



Title:
**Acheron Flood Hydrology
 Catchment Burnt during the February 2009 Bushfires**

Figure:
6-2

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7 Rainfall Runoff Modelling

Rainfall-runoff modelling or hydrologic modelling, of the Catchment was undertaken with the URBS hydrological modelling package. The output from the URBS model provided inputs into the TUFLOW hydraulic model. A new hydrologic models of the Acheron catchment was developed to meet the requirements of this study.

This chapter is presented in the following format:

- Hydrological modelling
 - URBS model development
 - Calibration and Validation of the URBS model
 - Design event modelling

7.1 URBS Model

Rainfall runoff modelling is a method utilised to estimate the amount of runoff produced by a catchment for a given rainfall event, taking into account the hydrologic characteristics of that catchment.

URBS simulates the linkages between sub-catchments as reach storages with the storage discharge relationship with calibration parameters α , and m .

7.1.1 Model Description

The URBS model covers an area of approximately 725 km². To ensure accurate representation of the hydrological response at the required flood mapping locations (listed below) of the overall catchment, the model was divided into 70 individual sub-catchments. Conceptual reaches (approximate overland flow paths) were defined.

The one of the purposes of the hydrologic modelling was to provide flows into a hydraulic model of the Acheron valley at key locations to flood map the towns, namely:

- Taggerty
- Buxton
- Marysville

This requirement drove the sub-catchment breakup.

7.1.2 Sub-Catchment Definition


The catchment and sub-catchment boundaries were initially determined using the software package CatchmentSIM, based on the provided digital elevation datasets. The catchment breakup was then refined to ensure that consistency in sub-catchment size and shape was achieved as best as the catchment topology would allow with a final total of 70 individual sub-catchments. Further the catchment breakup was compared to topographic maps of the area. The sub-catchment breakdown is shown in Figure 7-1.

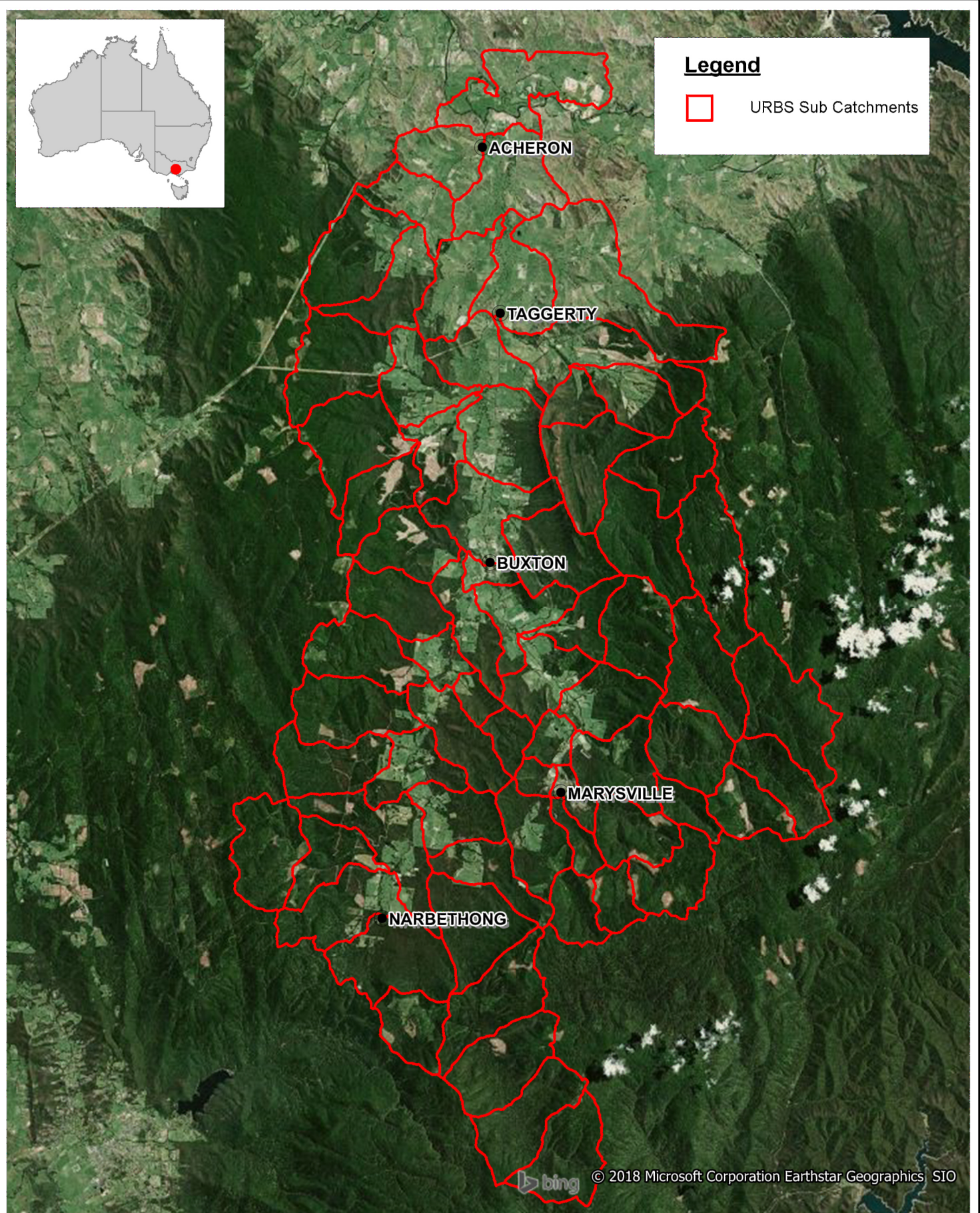
7.1.3 Fraction Impervious

The catchment is predominately rural and forested, particularly the upper catchment, with only minor urban areas (as described in Table 2-4). For this reason, it was not considered necessary to explicitly incorporate fraction impervious values into the model.



Legend

 URBS Sub Catchments

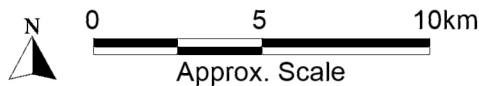


Title:
**Acheron Flood Hydrology
URBS Model Layout**

Figure:
7-1

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BMT WBM endeavours to ensure that the information provided in this map is correct at the time of publication. BMT WBM does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.



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7.2 Calibration and Validation

To establish that the hydrologic modelling is suitably representing runoff behaviour of the catchment, and in turn providing reasonable inputs for the hydraulic modelling process, model calibration and validation to actual flood events is undertaken; initially six events were selected for calibration; however, this was refined to five events due to poor data availability. The model was first calibrated to five events, from the individual parameter sets a representative parameter set was generated which was then validated against the same five events whilst only varying the loss parameters. The calibration and validation process is described in detail below. The calibration and validation results were assessed visually, combined with comparisons of peak flow and total volume at each gauge in combination with the Nash-Sutcliffe Efficiency (NSE) value.

7.2.1 Calibration and Validation Process

The hydrologic modelling calibration process involves the following steps:

- (1) Collect, collate and verify relevant data including streamflow hydrographs, rainfall pluviographs and daily rainfall totals.
- (2) Choose the historical storm events to be used in the calibration and validation process based on the available data and the nature of the event.
- (3) Create the storm event inputs to be used in the calibration and validation process.
- (4) Apply the calibration storm event to the URBS model and optimise the model parameters to achieve model calibration.
- (5) From the individual parameter sets determine representative parameter set for validation and design events.
- (6) Validate the model parameters against an original storm events using aggregated parameter set.

The following sections detail these processes and outline the assumptions used in the hydrologic calibration and validation process.

7.2.2 Calibration events

The largest six events as measured by peak flow are the Acheron River at Taggerty gauge with available pluviography data were considered for calibration. These events were:

2010; 1998; 1996; 1994; 1980 and 1974.

7.2.3 Stream Gauge Information

The Acheron River at Taggerty was selected as the calibration point for the hydrologic model given its reliable length of record and proximity to towns that were to be flood mapped.

7.2.4 Rainfall Selection and Distribution

There are a number of pluviograph stations in and around the catchment as shown in Figure 2-2. The pluviograph data was supplemented by daily rainfall data obtained from the Australian Water

Availability Project (AWAP) available from the Bureau of Meteorology. AWAP is a gridded rainfall dataset that covers Australia in a 5x5 km and contains daily records of rainfall data.

Of the available pluviography stations only the Acheron River at Taggerty and Marysville Golf Club stations were in the catchment. The Marysville Golf Club gauge was not suitable given its short record length, high proportion of missing data and it did not cover any of the events and for this reason this gauge was not considered suitable for calibration. Of the other stations listed in Table 2-1, the BoM was only able to supply Eildon Fire Tower (88164) and Lake Eildon (88023). For all the calibration events modelled, the pluviographs were used to distribute the temporal rainfall within the model. The availability of data for the three pluviographs are listed in Table 7-1.

The Acheron River at Taggerty was the preferred pluviograph station where data was available which was for 1994, 1996, 1998 and 2010 events. For the 1974 and 1980 events Lake Eildon was preferred.

Table 7-1 Availability of pluviography data

Station	Name	Station open	Station closed
405209	Acheron River @ Taggerty	6/03/1993	N/A
88023	Lake Eildon	16/10/1957	N/A
88164	Lake Eildon Fire Tower	6/12/1995	N/A

The areal distribution of rainfall was determined by the AWAP rainfall data. Rainfall depths for the events listed above were calculated and are shown in Figure 7-2

7.2.5 Calibration and Validation Event Selection

The selection of the calibration and validation events was based on the following criteria:

- The availability of rainfall and streamflow data;
- The requirements for calibration of the hydraulic model, e.g., the availability of recorded flood levels across the floodplain
- A preference to test the hydrologic (and hydraulic) model on floods of different magnitudes;
- Expectations in the community that a particular event, e.g. largest in living memory, will be modelled

Both rainfall and streamflow data at a resolution commensurate with hydrological response of the study catchment are required to calibrate a hydrological model. The hydrological response of the catchment to the gauge is of the order of 0.5 - 2 days. It was therefore necessary to have data at a sub-daily scale to adequately model the catchment's response.

As discussed in Section 1 there is a long history of flood events in the catchment which have impacted the townships. For the calibration of the URBS model five events were considered. These events represent the largest event as well as a range of flow rates than should ensure that the model is representative over a range of flood frequencies. The events selected were:

- 1974, 1980; 1994; 1996; 1998; and; 2010.

The data available for 1974 and 1980 event, in particular pluviograph data, was not suitable for calibration. For all other events, pluviography data was available for the Acheron River at Taggerty gauge and given this gauge's proximity to the catchment centroid it was the preferred pluviograph for all events.

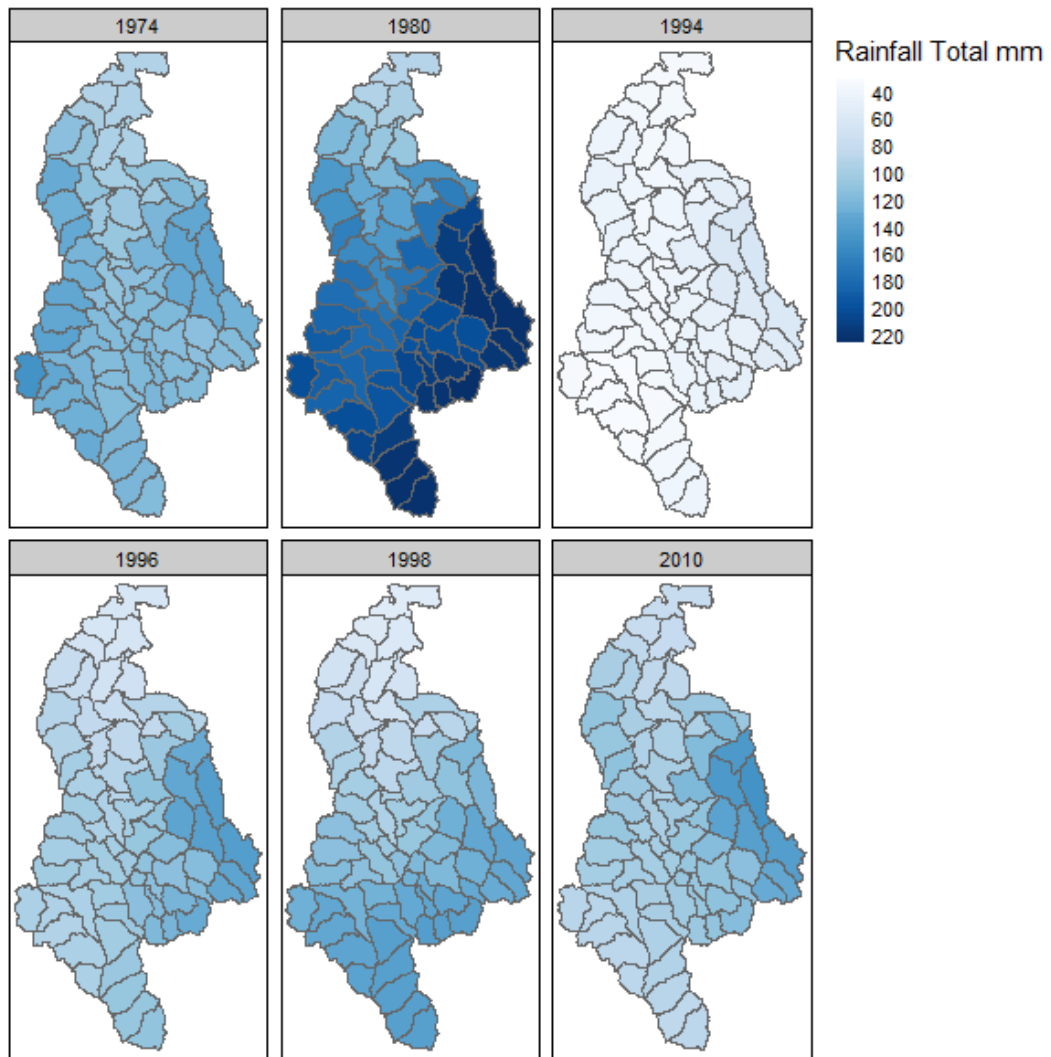


Figure 7-2 Distribution of AWAP rainfall for calibration events

7.2.6 Calibration Parameters

The URBS parameters that are available for calibration are; α , m , and initial loss (IL) and continuing loss (CL). The URBS program provides the facility to manually adjust the calibration parameters until an acceptable fit is found. URBS also provided a number of summary statistics including difference in observed and calculated hydrograph volumes, differences in peak flow and

differences in the time to peak. In addition, the Nash-Sutcliffe Efficiency (NSE) was also calculated. This is a statistical measure to evaluate a model's performance against observed data.

The NSE is a measure of how much of the residuals (the difference between the calculated and observed) variance is explained by the model. A value of 1 indicates a perfect fit to the model data whereas a value of zero indicates simply modelling the average value would perform equally well. A value of less than 0 indicates unacceptable model performance. NSE is defined as:

$$NSE = 1 - \frac{var(Res)}{var(hyd)}$$

where $var(Res)$ is the variance of the model residuals or the difference between the observed and calculated flows, and $var(hyd)$ is the variance of the observed hydrograph.

Guidance on interpreting NSE values has been published by Ladson (2008) and is reproduced below (Table 7-2) to aid the interpretation of the calibration and validation results.

Table 7-2 Guide to interpret NSE values (Ladson, 2008)

Classification	NSE value Calibration	NSE value Validation
Excellent	NSE >= 0.93	NSE >= 0.93
Good	0.8 <= NSE < 0.93	0.8 <= NSE < 0.93
Satisfactory	0.7 <= NSE < 0.8	0.6 <= NSE < 0.8
Passable	0.6 <= NSE < 0.7	0.3 <= NSE < 0.6
Poor	NSE < 0.6	NSE < 0.3

7.2.7 June 1994 Calibration Results

The best fit for the calibration parameters are listed in Table 7-3 together with the NSE and Volume difference values. The resulting fit is illustrated in Figure 7-3.

The calibration resulted in a satisfactory fit to the observed record. Primarily the poor timing of the peaks resulted in a NSE of 0.77 with the peaks offset by more than 24 hours.

Table 7-3 Calibrated Parameters and Values for June 1994

Station	α	m	IL (mm)	CL (mm/hr)	NSE	Vol ratio	Peak ratio
Acheron River at Taggerty	1.69	0.80	48	1.8	0.77	1.03	0.79

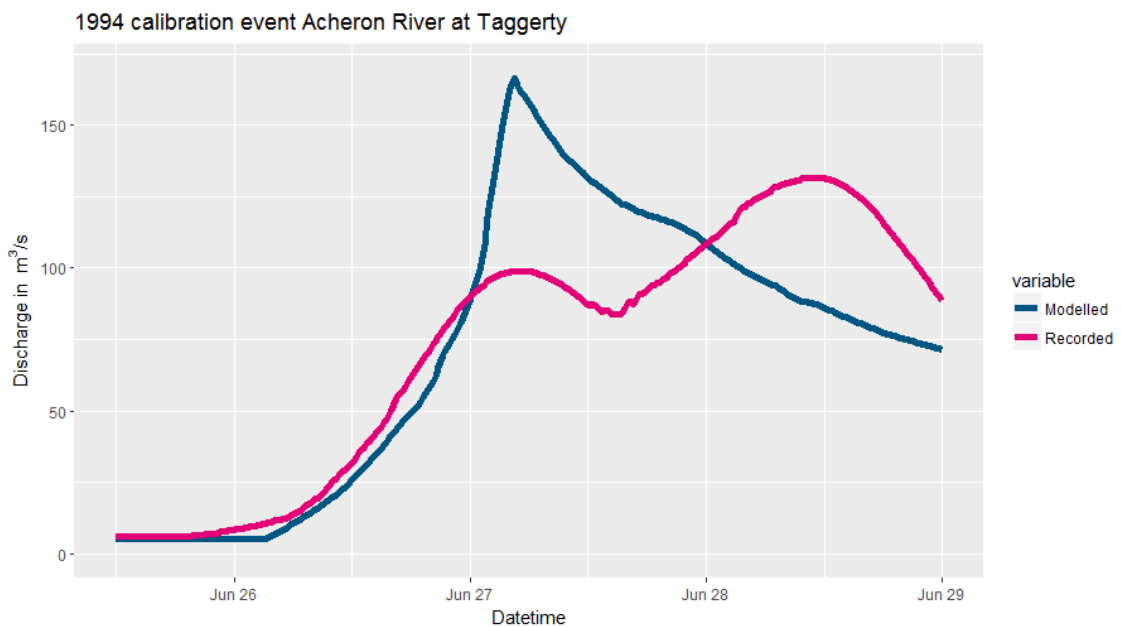


Figure 7-3 Calibrated Hydrograph Comparison for June 1994

7.2.8 October 1996 Calibration Results

The best fit for the calibration parameters are listed in Table 7-4 together with the NSE, Volume and Peak flow ratios. The resulting fit is illustrated in Figure 7-4.

Note that joint calibration of the hydraulic model found that flood levels along the Steavenson River upstream of Buxton and for this reason the losses upstream of this were increased.

The calibration resulted in a good fit to the observed record. This is confirmed by an NSE of 0.89, and strong volume and peak flow ratios.

Table 7-4 Calibrated Parameters and Values for September 2010

Station	α	m	IL (mm)	CL (mm/hr)	NSE	Vol ratio	Peak ratio
Acheron River at Taggerty	1.99	0.80	55 ^a 80 ^b	1.5 ^a 1.5 ^b	0.89	0.94	0.86

^a Losses for Acheron River sub-catchment

^b Losses for Steavenson River sub-catchment

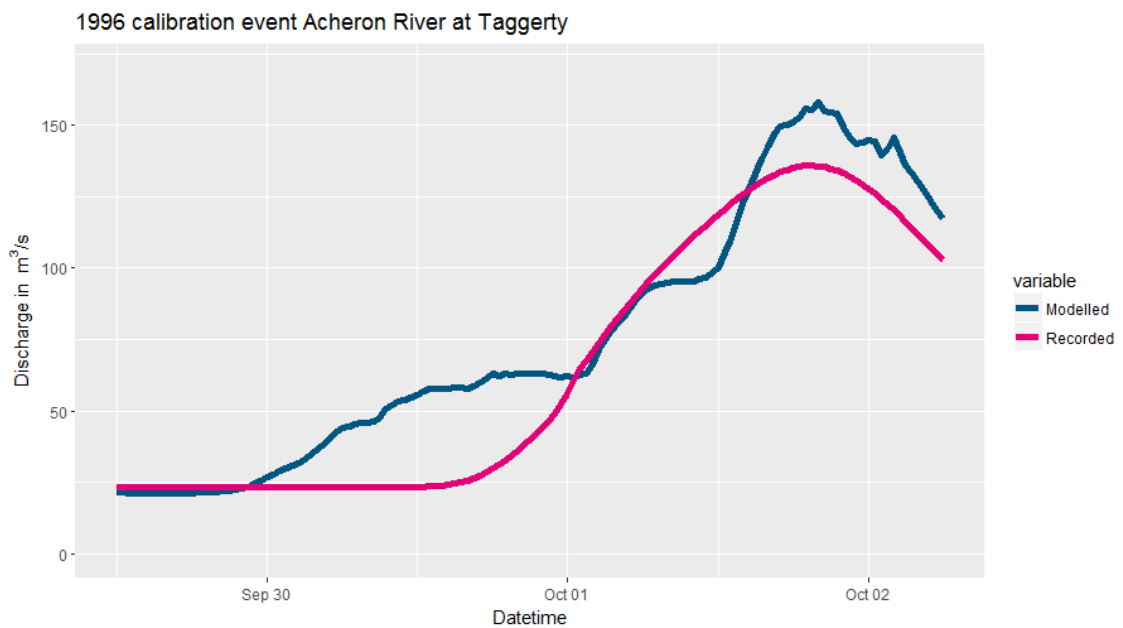


Figure 7-4 Calibrated Hydrograph Comparison for October 1996

7.2.9 September 1998 Calibration Results

The best fit for the calibration parameters are listed in Table 7-5 together with the NSE and Volume difference values. The resulting fit is illustrated in Figure 7-5.

The calibration resulted in a satisfactory fit to the observed record. The timing of the peaks was offset by approximately 24 hours and the magnitude and volume were very good with the observed record. This resulted in an NSE value of 0.70.

Table 7-5 Calibrated Parameters and Values for September 1998

Station	α	m	IL (mm)	CL (mm/hr)	NSE	Vol ratio	Peak ratio
Acheron River at Taggerty	2.0	0.80	9.7	4.9	0.70	1.0	1.1

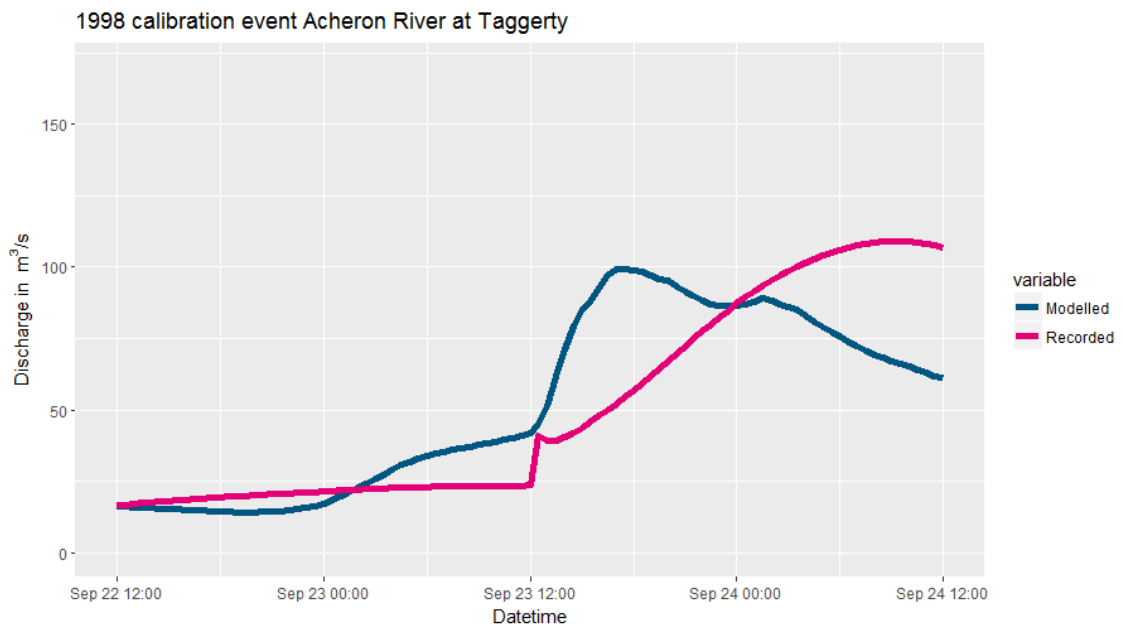


Figure 7-5 Calibrated Hydrograph Comparison for September 1998

7.2.10 September 2010 Calibration Results

The best fit for the calibration parameters are listed in Table 7-6 together with the NSE and Volume difference values. The resulting fit is illustrated in Figure 7-6.

Note that joint calibration of the hydraulic model found that flood levels along the Steavenson River upstream of Buxton and for this reason the losses upstream of this were increased.

The calibration resulted in an excellent fit to the observed record. The timing of the peaks coincided and the overall shape, magnitude and volume were very good. This resulted in a good NSE value of 0.98, with strong volume and a peak flow rate matching.

Table 7-6 Calibrated Parameters and Values for September 2010

Station	α	m	IL (mm)	CL (mm/hr)	NSE	Vol (diff)	Peak Flow (diff)
Acheron River at Taggerty	1.2	0.80	15.0 ^a 20.0 ^b	6.0 ^a 7.0 ^b	0.98	1.1	1.0

^a Losses for Acheron River sub-catchment

^b Losses for Steavenson River sub-catchment

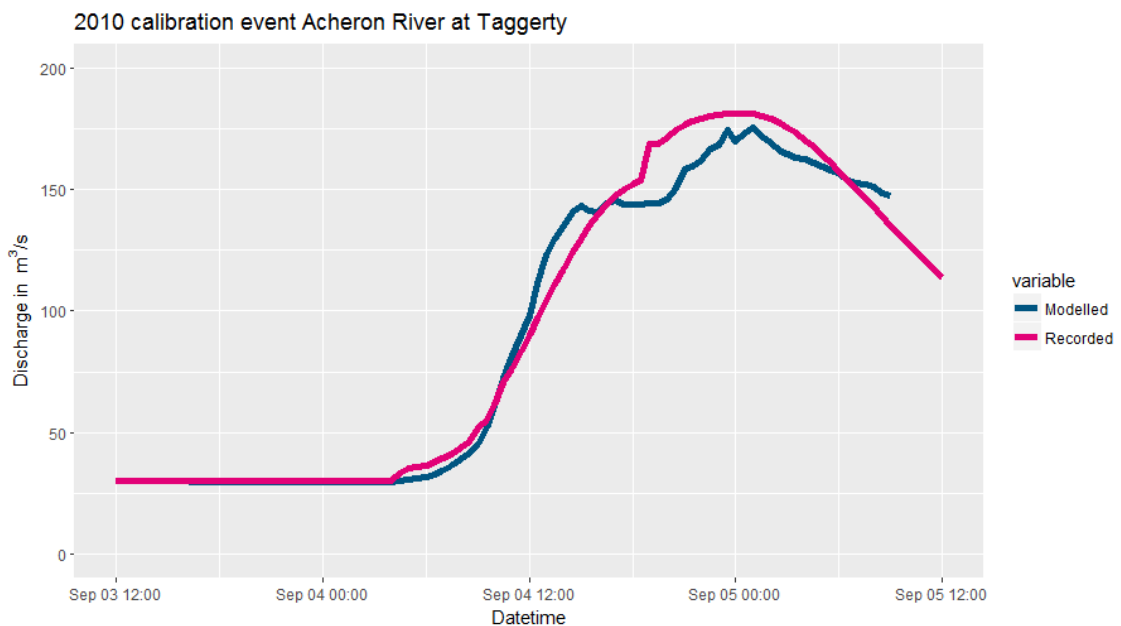


Figure 7-6 Calibrated Hydrograph Comparison for September 2010

7.2.11 Calibration Summary

The URBS model parameters for the catchment from the individual calibration of each event are summarised in Table 7-7 below.

The calibration of the catchment produced a wide range of potential parameter sets and did not converge on a single range. The α varied from 0.10 to 0.30 whilst there was generally less variability in the loss parameters. The losses recording the best fit for each event typically favours higher initial losses and lower continuing losses.

Table 7-7 Calibrated Parameters and Values Summary

Event	α	m	IL (mm)	CL (mm/hr)	NSE	Observed Peak Flow (m ³ /s)	Observed Volume (m ³)
Jun '94	1.69	0.8	48	1.8	0.77 – Satisfactory	166	23,883
Sep '96	1.99	0.8	71	1.1	0.89 – Good	158	21,507
Sep '98	2.0	0.8	9.7	4.9	0.70 – Satisfactory	99	11,114
Dec '10	1.2	0.8	0.4	5.9	0.98 – Excellent	1.75	21,204

7.2.12 Final Parameters

The final parameter set was determined by taking the weighted mean and standard deviation of each parameter presented in Table 7-7. The parameters were weighted by the NSE values.

Table 7-8 Adopted Calibrated Parameters Set

Parameter	α	IL	CL
α	1.6	27	3.6

7.2.13 Validation Results

The adopted parameters listed in Table 7-8 were applied to the calibration events to validate the model. The URBS model parameters for the catchment from the individual validation of each event are summarised in Table 7-9 below.

The validation process produced results similar to the calibration results. The exception being October 1996 event which produced an NSE of 0.19 down from 0.89. With the exception of the October 1996 event all other events had an NSE greater the 0.65 indicating satisfactory or better fits with the observed record.

Table 7-9 Validation Parameters and Values Summary

Event	α	m	IL (mm)	CL (mm/hr)	NSE	Volume ratio	Peak flow ratio
Jun '94	1.6	0.8	0.0	0.20	0.77 – satisfactory	1.02	0.80
Oct '96			58.5	3.6	0.19 – poor	0.60	0.42
Sep '98			0.0	9.7	0.65 – satisfactory	0.95	1.15
Sep '10			14	5.3	0.94 – excellent	1.05	1.03

7.2.14 Calibration / Validation Conclusions

The URBS model of catchment has been calibrated to the four events including the largest on record, the September 2010 flood event. The model was then validated to the same events using a common parameter set derived from the calibration results.

Overall the calibration and validation of the model produced satisfactory to excellent results with the exception of the validation for the October 1996 event. Whilst there was some variability in α during the calibration process, a satisfactory (excluding October 1996) fit to the same events using a common parameter set was found during the validation process. The calibration process favoured large values of α and this is considered to reflect the heavily forested nature which is able to absorb rainfall and slow release this due to deep soils. Also affecting the results was the lack of pluviograph data throughout the catchment meaning there was some uncertainty regarding the temporal spread of rainfall.

7.3 Design Event Modelling

The design event modelling utilises the parameter set derived through the calibration of the hydrologic model to determine the flows for a series of events with a specific AEP (eg: the 1% AEP flood event).

7.3.1 Global Parameters

The URBS model parameters for design event modelling are summarised in Table 7-10. The parameters α and m were adopted from the calibration process.

The loss model adopted was the “initial loss/continuing loss” model.

Table 7-10 URBS design parameters

Parameter	Value
Catchment Area	725 km ²
Initial Loss	Variable - event specific (See section 7.3.5 for details)
Continuing Loss	Variable - event specific (See section 7.3.5 for details)
α	1.6
m	0.8
Fraction Impervious	0.0

7.3.2 Design Event Probabilities

Hydrologic analysis was undertaken for the 0.2%, 0.5%, 1%, 2%, 5%, 10% and 20% Average Exceedance Probability (AEP) design storm events.

7.3.3 Design Rainfall

In order to define the design rainfall for AEP events, Intensity Frequency Duration (IFD) parameters for the Catchment were generated by the Bureau of Meteorology (<http://www.bom.gov.au/water/designRainfalls/reviced-ifd/?year=2016> accessed 25/09/2017). IFD tables were extracted at points covering the catchment and grid of IFD was generated the resulting 48 hour 1% AEP grid is shown in Figure 7-7. The catchment average IFD values are listed in Table 7-11.

Table 7-11 catchment average IFD values in mm

	12 hour	24 hour	48 hour	72 hour	96 hour	120 hour	144 hour
50% AEP	51	68	90	104	113	121	127
20% AEP	65	90	119	137	149	156	163
10% AEP	76	105	140	160	173	181	186
5% AEP	87	121	161	184	197	204	209
2% AEP	103	144	194	221	235	244	248
1% AEP	115	164	221	251	267	275	279
0.5% AEP	-	179	255	283	295	301	304
0.2% AEP	-	206	302	332	342	346	348
0.01% AEP	-	228	341	372	382	386	389

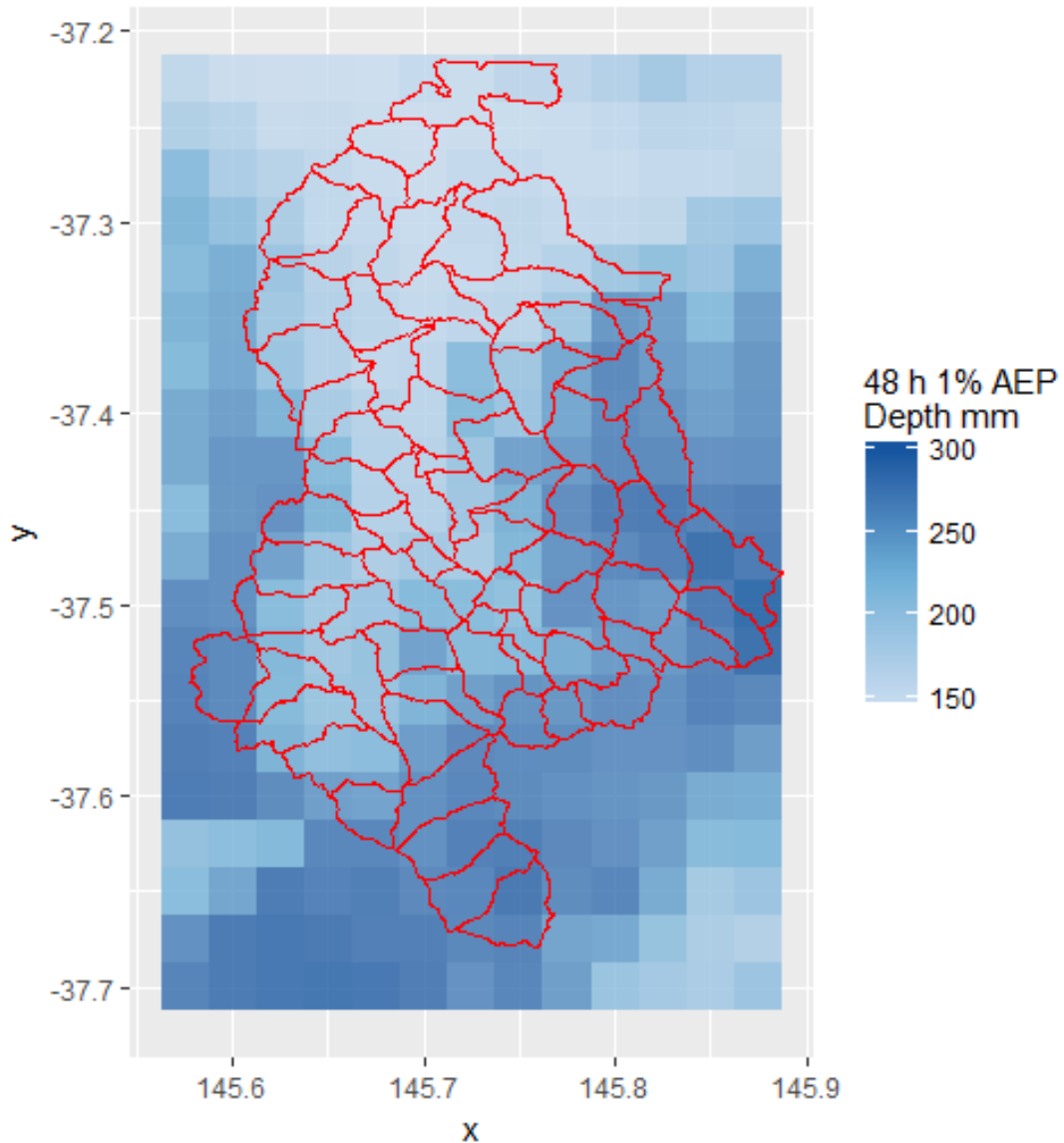


Figure 7-7 48 hour 1% AEP rainfall depth grid

7.3.4 Temporal Patterns and Aerial Reduction Factors

Temporal patterns derived as per Australian Rainfall and Runoff 1987 were used for this study. Aerial reduction factors outline in ARR2016 were adopted for this Study. While the use of ARR87 temporal patterns with ARR2016 aerial reduction factors is not usual recommended, peak model discharge was adjusted to match the flows from the FFA. Therefore, the selection of aerial reduction factors and temporal patterns is not paramount as these will be adjusted to match the measures data.

7.3.5 Design Event Losses and Results

With a suitably calibrated hydraulic model the URBS design events were calibrated to the peak flow estimates from the FFA as described in Section 5. This was undertaken by holding the CL constant at 0.5 mm/hour and the IL varied to match the peak flows from the FFA.

The URBS hydrology parameters are presented in Table 7-12 below.

Table 7-12 URBS Hydrology: Design Event Calibration Values

AEP	α	m	IL (mm)	CL (mm/hr)
20%	1.6	0.80	35	3.0
10%			40	3.5
5%			53	4.0
2%			63	5.0
1%			60	6.0
0.5%			60	6.0
0.2% AEP			60	7.5

Peak flows for each design event probability modelled were extracted from the hydrologic model at key locations near towns, and are presented in Table 7-13, Table 7-14 and Table 7-15. Hydrographs of the peak flow for each AEP events are shown in Figure 7-8.

Table 7-13 URBS Hydrology: Design Peak Flow Values (m³/s) at Steavenson River at Marysville

AEP	20%	10%	5%	2%	1%	0.5%	0.2%
Peak Flow (m ³ /s)	15	18	20	22	23	27	29
Critical Event in hours	24	24	24	24	24	24	24

Table 7-14 URBS Hydrology: Design Peak Flow Values (m³/s) at Steavenson River at Buxton

AEP	20%	10%	5%	2%	1%	0.5%	0.2%
Peak Flow (m ³ /s)	58	69	78	88	92	104	115
Critical Event in hours	72	72	72	48	48	24	48

Table 7-15 URBS Hydrology: Design Peak Flow Values (m³/s) at Acheron River at Taggerty

AEP	20%	10%	5%	2%	1%	0.5%	0.2%
Peak Flow (m ³ /s)	112	138	157	179	197	224	259
Critical Event in hours	48	48	48	48	48	48	48

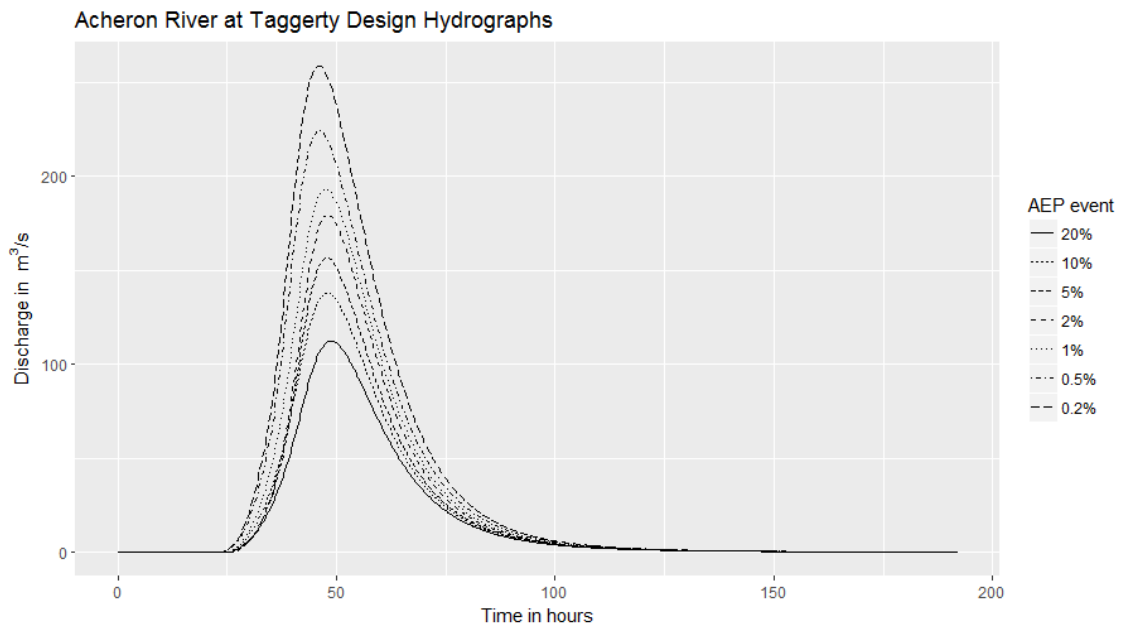


Figure 7-8 URBS Hydrology: Design Hydrographs

7.3.6 Critical Event Derivation

The results indicated that the 24 to 72 hour events were critical. A summary of the critical durations at the key towns are presented in Table 7-13, Table 7-14 and Table 7-15.

7.3.7 Climate Change

The assessment of the increase in risk due to increasing rainfall intensity associated with climate change was undertaken in line with the latest ARR guidance. This guidance recommends a stage process to assess the appropriate level of assessment for climate change. Each stage of this process is set out below.

Step 1 – Set the Effective Service Life or Planning Horizon

The predominant use of the outputs will be planning scheme amendments, insurances and emergency management. Hence the following effective service lives are considered appropriate:

- Planning Scheme - Design life of 100 years is reasonable

- Insurance - Current day is relevant
- Emergency Management - It is likely that this information will be revised in 20 years therefore current day estimates are relevant

Step 2 – Set the Flood Design Standard

The nominal design flood standard is the 1% AEP event for land use planning in Victoria (Victorian Floodplain Management Strategy).

Step 3 – Consider the Purpose and Nature of the Asset or Activity and Consequences of its Failure

Setting future residential development levels below the future 1% AEP would increase average annual damages and expose home owners to a lower standard of service that currently acceptable. Similarly, any major infrastructure should be designed to the future 1% AEP level to avoid frequent failure such as road closures and damages to bridges and the like.

Step 4 – Carry out a Climate Change Risk Screening Analysis

A screening assessment was completed. The basis of this assessment has been that the current day 0.5% AEP event will become the 1% AEP event in the future. Given there is an existing level of exposure of residential houses to flooding less than the current day 1% AEP event, it was concluded that the catchments were sensitive to potential changes to future flooding and therefore the sensitivity of the catchment to change in flood risk due to climate change is high. For this reason, it was necessary to consider Climate Change projections and their consequences

Step 5 – Consider Climate Change Projections and their Consequences

Given the sensitivity of the catchment is high, it is recommended that concentration pathway RCP 8.5 is used which results in a rainfall increase factor of 8.7% at 2050 and a factor of 18.7% at 2090 as outlined below.

In line with the guidance an increase in rainfall intensity in accordance with Equation 2 was adopted.

$$I_p = I_{ARR} \times 1.05^{Tm} \quad \text{Equation 2}$$

where I_p is the projected rainfall intensity or equivalent depth, I_{ARR} is the design rainfall intensity (or depth) for current climate conditions and Tm is the temperature at the midpoint (or median) of the selected class interval.

The rainfall intensities were factored as outlined above to account for the expected increases in rainfall intensity due to climate change. No allowance has been made for changed temporal patterns or changed rainfall losses due to the impact of climate change. This analysis has tested a single variable that will be impacted by climate change and a more detailed assessment may be required as the understanding of the impacts of climate change on hydrology and stream flow improves.

The URBS model was run for the 2050 and 2090 scenarios for a variety of AEP events with the resulting peak flows listed for the Acheron River at Taggerty in Table 7-16 and Table 7-17.

Comparing the peak flows between Table 7-16 and Table 7-17, the following observations were made:

- The peak flows at 2050 are approximately equivalent to one standard AEP event less frequent, so the future 2050 2% AEP event is equivalent to the current 1% AEP event.
- There was significant amplification of peak discharge at 2090 with the 20% AEP approximating the current 1% AEP event.

Typically, climate change peak flows at 2090 (or 2100) increase one standard AEP event, so the 20% AEP event becomes the 10% event. This was found to occur for the 2050 climate change results here. As noted above the 2090 results represented significant increases which were atypical. For this reason, it is recommended that 2050 climate change results are adopted for the Acheron Valley.

Table 7-16 URBS Hydrology: 2050 Climate Change Peak Flow Values (m³/s) at Acheron River at Taggerty

AEP	20%	10%	5%	2%	1%
Peak Flow (m ³ /s)	144	176	203	237	255
Critical Event in hours	48	48	48	48	48

Table 7-17 URBS Hydrology: 2090 Climate Change Peak Flow Values (m³/s) at Acheron River at Taggerty

AEP	20%	10%	5%	2%	1%
Peak Flow (m ³ /s)	190	232	271	321	338
Critical Event in hours	48	48	48	48	48

7.4 Discussion

An analysis of the design flows derived from the URBS model was undertaken to compare the peak flows determined with those determined from the site flood frequency analysis and regional flood frequency analysis. This analysis (Table 7-18) has shown that the URBS derived design flows are consistent with the flood frequency analysis as expected, although the RFFE estimates are considerably higher. Note the site specific information is considered to be the better estimate.

Table 7-18 Comparison of Peak Design Flows

Location	Peak Flow (m ³ /s)		
	URBS Model	Site FFA	RFFE
50% AEP		72.3	77.1
20% AEP	112	113	133
10% AEP	138	136	178
5% AEP	157	157	227
2% AEP	179	179	300
1% AEP	197	194	361
0.5% AEP	224		
0.2% AEP	259		

7.5 Summary

BMT has completed a site based and regional flood frequency analysis for Acheron River at Taggerty gauge and developed and calibrated an URBS model of the catchment. Comparison between the derived peak flows from the Flood Frequency Analysis, Regional Flood Frequency Analysis and the calibrated URBS models does provide good agreement (Table 7-18) for the range of flood event being investigated.

Consequently, BMT recommended that:

- The calibrated URBS model be used to generate design inflow hydrographs for the hydraulic model; and
- The parameters presented in Section 7.3.1 are adopted for the design event modelling.

8 Gauge relationships

The gauging relationship between elevation (m AHD), stage, discharge, AEP event and BoM Flood Class Level. These relationships are listed in Table 8-1

Table 8-1 Acheron River at Taggerty gauge relationships

Elevation (m AHD)	Stage	Discharge	AEP	FCL
200.28	2.1	50		
200.48	2.3	66		Minor
200.58	2.4	75		
200.78	2.6	91		Moderate
200.88	2.7	100		
200.98	2.8	113	20%	
201.08	2.9	125		
201.16	2.98	136	10%	Major
201.25	3.07	150		
201.29	3.11	157	5%	
201.41	3.23	175		
201.44	3.26	179	2%	
201.53	3.36	194	1%	
201.57	3.39	200		
201.77	3.59	250		

9 Conclusions

Hydrologic flood analysis has been completed for the Acheron Valley with the purpose of providing input into the hydraulic model to produce flood mapping. This was completed for design events from the 20% AEP event to the 0.2% (1 in 500) AEP event and for the 1994, 1996, 1998 and 2010 calibration events.

References

10 References

- Cohn, T.A., England, J.F., Berenbrock, C.E., Mason, R.R., Stedinger, J.R. and Lamontagne, J.R. (2013), A generalized Grubbs-Beck test statistic for detecting multiple potentially influential low outliers in flood series, *Water Resour. Res.*, 49, 5047-5058.
- Doerr, S.H., Shakesby, R.A., Blake, W.H., Chafer, C.J., Humphreys, G.S. and Wallbrink, P.J. (2006). *Effects of differing wildfire severities on soil wettability and implications for hydrological response*. *Journal of Hydrology*. 319, 295-311.
- Furniss, E. & Turner, (2014). *Acheron: a history of the district*. Acheron Mechanics' Institute Inc, Acheron.
- Haddad K and Rahman A (2012): Regional flood frequency analysis in eastern Australia: Bayesian GLS regression-based methods within fixed region and ROI framework – Quantile regression vs. parameter regression technique, *Journal of Hydrology*, 430-431, 142-161.
- Kuczera G.A. (1985). *Prediction of water yield reduction following a bushfire in Ash-mixed species eucalypt forest*. Water Supply Catchment Hydrology Research Report MMBW-W-0014, Melbourne and Metropolitan Board of Works, Melbourne;
- Kuczera, G. (1987). *Prediction of water yield reductions following a bushfire in ash-mixed species Eucalypt forest*. *Journal of Hydrology* 94: 215—236.
- Ladson, A. (2008). *Hydrology: An Australian Introduction*, Oxford University Press, South Melbourne, Victoria, 2008.
- Lane P., Sherwin C., Peel, M. and Freebairn A. (2007). *Impact of the 2003 Alpine Bushfires on Streamflow: Predicting the long-term impacts of bushfire on water yield*. Report for the Murray Darling Basin Commission (24/08).
- Leopold, L.B. (1968), *Hydrology for urban land planning - A guidebook on the hydrologic effect of urban land use*. U.S Geological Survey, Circular. Volume 554, pp.18, available at <http://pubs.usgs.gov/circ/1968/0554/report.pdf>
- Lloyd, B. E. (Brian Edmund) & Noble, Gerald W. (2006). *The Red Gate: a history of Alexandra, Alexandra and district*, Histec Publications and Murrindindi Historic Register, Brighton East, Vic
- McIntyre, N, Ballard, C, Bulygina, N, Frogbrook, Z, Cluckie, I, Dangerfield, I, Ewen, J, Geris, J, Henshaw, A, Jackson, B, Marshall, M, Pagella, T, Park J, Reynolds B, O'Connell E, O'Donnell, G, Sinclair F, Solloway, I, Thorne, C and Wheeler, H (2012) *The potential for reducing flood risk through changes to rural land management: outcomes from the Flood Risk Management Research Consortium Proc*. British Hydrological Society, Symposium, Dundee, 9-11 July 2012.
- Mein, R.G. and Goyen, A.G. (1988), *Urban runoff*. *Civil Engineering Transactions*. Volume CE30(4), pp.225-238.
- SKM (2007). *Impact of the 2003 Alpine Bushfires on Streamflow - Seasonal streamflow response*. Report for the Murray Darling Basin Commission (25/08).

References

- The Standard (1936), Alexandra and Yea Standard and Yarck, Gobur, Thornton and Acheron Express (Vic.: 1908-1949), 14 August, p. 2, viewed 29 October, 2014, <http://nla.gov.au/nla.news-article64729495>
- Thornton (1916), Alexandra and Yea Standard and Yarck, Gobur, Thornton and Acheron Express (Vic.: 1908-1949), 13 October, p. 2, viewed 29 October, 2014, <http://nla.gov.au/nla.news-article64752563>
- van Dijk, A, Evans, R, Hairsine, P, Khan, S, Nathan, R, Paydar, Z, Viney, N & Lu Zhang (2006). *Risks to the Shared Water Resources of the Murray-Darling Basin: Part II in a two part series on the shared water resources of the Murray-Darling Basin* prepared for the Murray-Darling Basin Commission, MDBC Publication 22/06, Canberra <http://www.clw.csiro.au/publications/waterforahealthycountry/2006/RisksSharedWaterResources.pdf>
- Victoria. Dept. of Crown Lands and Survey & Downey John surveyor, 19th cent & Noone, John, fl. 1858-1888 (1866), Plan of the township of Acheron, Dept. of Lands & Survey, Melbourne, (<http://trove.nla.gov.au/version/31439437>)

References

Appendix A Annual maximum series and quality codes

A.1 Quality codes for streamflow data

Table A-1 Quality code summary for the streamflow gauges

Code	Acheron River daily flow	Acheron River Instantaneous flow	Steavenson River	Taggerty River	Explanation
1	1	863545			Unedited data
2		597860	186432	50609	Good quality data - minimal editing required. Drift correction
15		18713	186432	18911	Minor editing. >+/-10mm drift correction
50		2529	762	5919	Medium editing >+/-30mm drift correction\044 significant single spike removal etc.
100				5512	Irregular data, Use with caution. Beyond QC=50 or unexplained
104		62			Records manually estimated
148			20535		Theoretical rating table applied (not to be applied to level data)
149		23082	29117	4597	Rating extrapolated within 1.5x Max Qm
150		6364	5347	3069	Rating extrapolated due to insufficient gaugings (see additional quality info)
180		560		415	Data not recorded, equipment malfunction
254				6	Rating table exceeded
255	981748		69	50	No Data Exists

A.2 Annual maximum series

Table A-2 Acheron River at Taggerty annual maximum discharges

Year	Datetime	Discharge m ³ /s	Quality Code
1946	02/08/1946 00:00	44.3	255
1947	05/11/1947 00:00	65.6	255
1948	06/11/1948 00:00	50.2	255
1949	22/11/1949 00:00	93.9	255
1950	28/10/1950 00:00	30	255
1951	23/07/1951 00:00	108.4	255
1952	14/07/1952 00:00	146.7	255
1953	21/10/1953 00:00	133.4	255
1954	21/11/1954 00:00	74.8	255
1955	23/09/1955 00:00	139.3	255
1956	02/09/1956 00:00	132	255
1957	20/09/1957 00:00	79.8	255

References

Year	Datetime	Discharge m ³ /s	Quality Code
1958	16/08/1958 00:00	145.3	255
1959	21/09/1959 00:00	113.4	255
1960	15/05/1960 00:00	126	255
1961	09/07/1961 00:00	34.5	255
1962	02/08/1962 00:00	39	255
1963	05/08/1963 00:00	38.5	255
1964	09/10/1964 00:00	74.8	255
1965	17/08/1965 00:00	67.3	255
1966	13/08/1966 00:00	76.4	255
1967	02/09/1967 00:00	23.5	255
1968	05/06/1968 00:00	110.9	255
1969	01/06/1969 00:00	33.7	255
1970	24/08/1970 00:00	91.4	255
1971	04/10/1971 00:00	107.1	255
1972	14/07/1972 00:00	23.3	255
1973	20/10/1973 00:00	94.8	255
1974	15/05/1974 19:00	144.4	1
1975	18/09/1975 02:00	75.1	1
1976	21/09/1976 04:30	45.6	1
1977	30/06/1977 15:30	66.8	1
1978	27/09/1978 19:00	55.1	1
1979	12/10/1979 06:30	61.5	1
1980	29/06/1980 20:15	124.8	1
1981	15/08/1981 05:30	68	1
1982	25/01/1982 21:00	15.8	1
1983	03/09/1983 09:30	56.3	1
1984	03/10/1984 22:30	89.3	1
1985	23/08/1985 16:45	69	1
1986	04/07/1986 17:15	81.3	1
1987	22/06/1987 15:30	47.8	1
1988	11/09/1988 02:15	84.5	1
1989	01/09/1989 09:15	76.6	1
1990	20/08/1990 08:45	86.6	1
1991	19/09/1991 04:30	91.6	1
1992	11/10/1992 01:45	90.9	1
1993	02/09/1993 11:45	108.6	1
1994	25/06/1994 07:15	155.1	1
1995	09/06/1995 17:00	99.7	1
1996	01/10/1996 20:00	158.2	1
1997	08/09/1997 00:00	36.5	1
1998	23/09/1998 17:15	99.5	2
1999	08/08/1999 19:45	57.2	2

References

Year	Datetime	Discharge m ³ /s	Quality Code
2000	11/09/2000 14:15	86.8	2
2001	06/11/2001 16:45	55.4	2
2002	05/07/2002 19:45	19.3	2
2003	24/08/2003 22:00	79.3	2
2004	11/09/2004 17:15	65.6	2
2005	31/08/2005 08:00	128.3	2
2006	13/03/2006 21:00	14.3	2
2007	05/07/2007 14:00	23.6	2
2008	16/08/2008 12:00	20.7	2
2009	28/09/2009 15:30	74.5	2
2010	05/09/2010 00:45	176.3	150
2011	18/07/2011 18:00	53.5	2
2012	22/06/2012 07:00	73.3	150
2013	23/08/2013 22:15	65.5	149
2014	10/07/2014 02:15	43.3	2
2015	07/08/2015 06:00	15.7	2
2016	04/10/2016 21:15	69.7	149

Table A-3 Steavenson River annual maximum discharges

Year	Datetime	Discharge m ³ /s	Quality Code
2009	22/11/2009 11:15	3.91	150
2010	04/09/2010 21:45	7.09	150
2011	22/06/2011 23:45	4.07	150
2012	27/02/2012 13:45	2.66	150
2013	23/08/2013 16:00	6.19	150
2014	12/07/2014 08:15	2.48	150
2015	11/05/2015 08:15	0.93	2
2016	04/10/2016 17:30	2.81	150

Table A-4 Taggerty River annual maximum discharges with quality codes

Year	Datetime	Discharge m ³ /s	Quality Code
2010	04/09/2010 12:00	4.22	150
2011	09/11/2011 22:15	4.56	150
2012	27/02/2012 13:00	6.29	150
2013	01/01/2013 09:30	0.12	2

Appendix B Extension of the annual maximum series

The flow record for the Taggerty River at Acheron was collected in two distinct periods; the average daily flow period; and the instantaneous flow period. The average daily flow period is understood to report flows that were read at a particular time of the day (say 9:00am) whereas the instantaneous flow period corresponds to a period where the flow was continuously monitored.

Clearly, the annual maximum flow from the average daily flow period will be lower than or equal to the corresponding instantaneous peak. As reported in the Section 5.1.3, a linear model was developed. This appendix provides details of the model diagnostics undertaken. The model diagnostics investigate whether the assumptions underlying the *Ordinary Least Squares Regression* have been met. These assumptions are:

- Normality – the residuals are normally distributed with a mean of 0.
- Independence – there is no dependence between samples
- Linearity - there is no systematic relationship between residuals.
- Homoscedasticity – there is constant variance.

Normality

The normality of the residuals can be investigated by examining the distribution of the residuals and also the quantile – quantile plots. If the normality assumption is met the distribution of the residuals plot would follow the normal distribution. The distribution of residuals has been prepared and is presented in Figure 10-1. This figure indicates that the residuals are not normally distributed. This skew in the distribution can be removed by taking an additional log transform, however, as discussed above the added complexity was not considered warranted. The quantile-quantile plot presented in Figure 10-2 confirms that the residuals are not normally distributed. Investigation of the largest residuals (1974, 1982, and 2006 (see Table 5-3)) indicates these occur when there is approximately 12 hours between the peak and the 9:00am flow. This demonstrates that the floods in the catchment can rise in around 12 hours, that is, the full cycle of the flood event can be completed between 9:00am readings. The resulting large residuals are therefore an artefact of the catchment response time for these particular events and the temporal structure of the analysis.

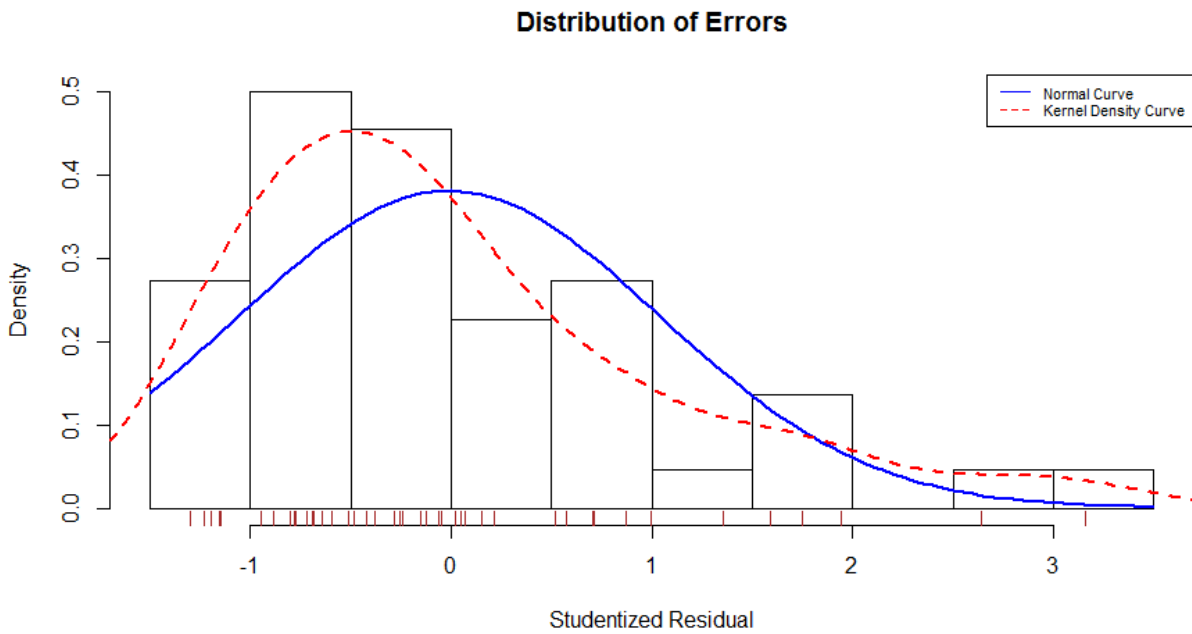


Figure 10-1 Acheron River Annual Maximum Extension: Distribution of Errors

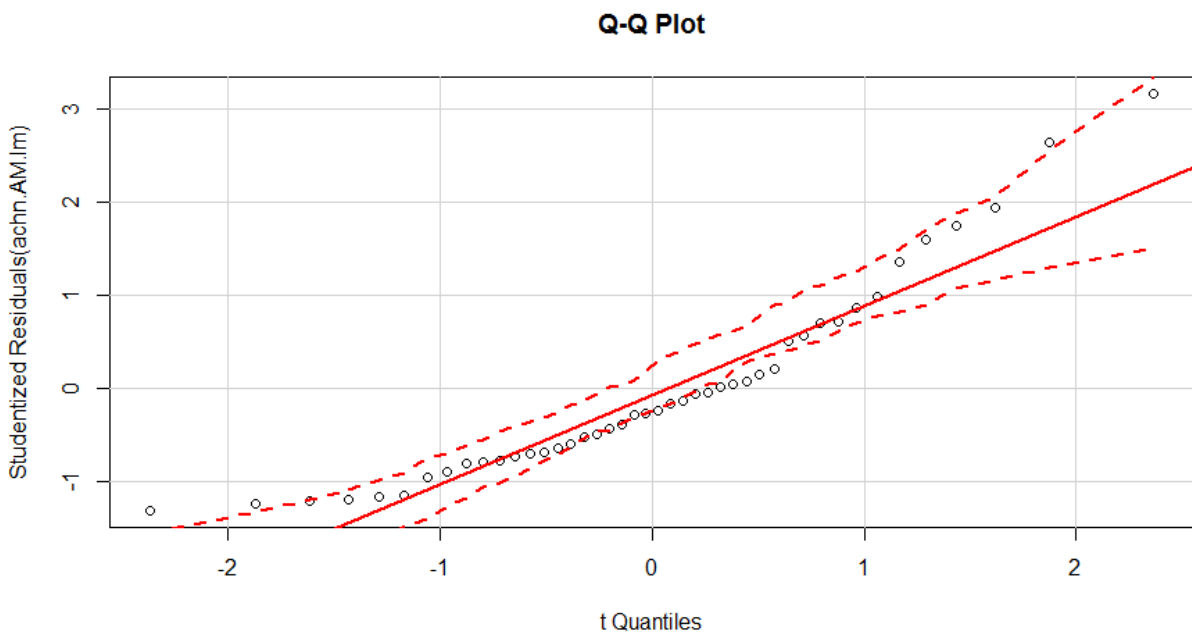


Figure 10-2 Acheron River Annual Maximum Extension: Quantile – Quantile Plot

Independence

The dates of the resulting annual maxima series show in Table 5-3 have been inspected and all peak flows are independent of each other.

Linearity

References

The model should account for the systematic relationships between the independent and dependent variables, that is, there should not be any curvilinear components in the residuals plot. A plot of residuals verses fitted values is presented in Figure 10-3. This plot indicates there are no significant deviations from linearity with residuals approximately distributed round the zero line. Note that the labelled values (the largest residuals) are still relatively small.

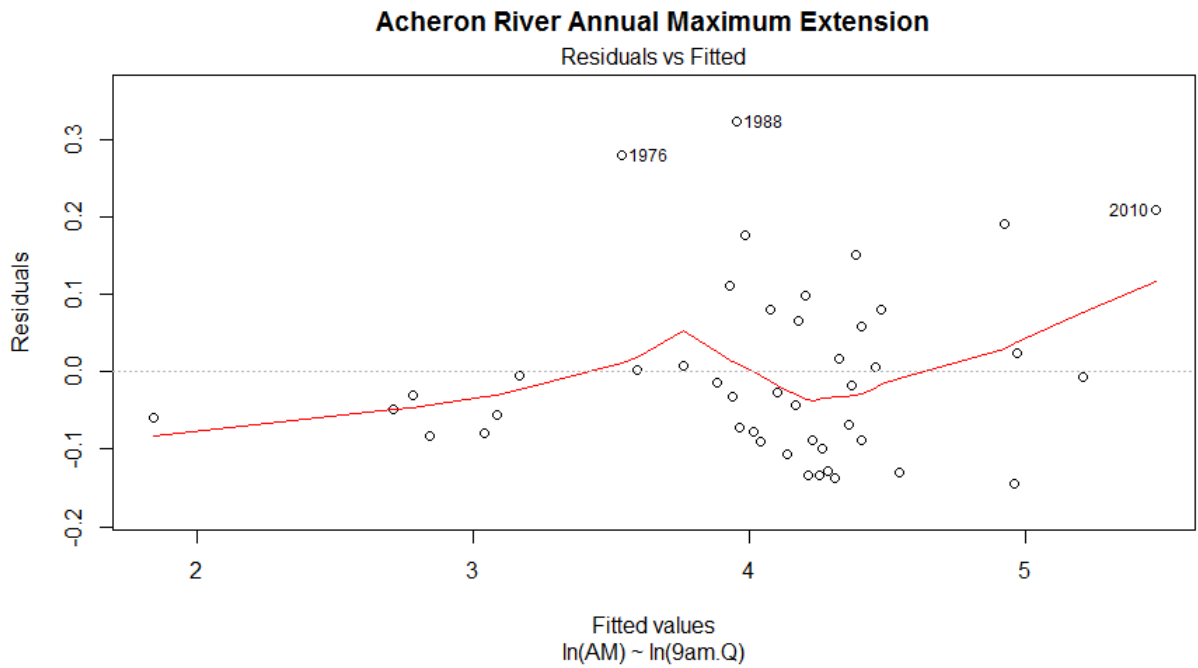


Figure 10-3 Acheron River Annual Maximum Extension: Residuals Plot

Homoscedasticity

The constancy of variance was examined using the Scale – Location plot (Figure 10-4). In this plot if points are distributed evenly around a horizontal line then the assumption of homoscedasticity is met. This behaviour is broadly met in Figure 10-4.

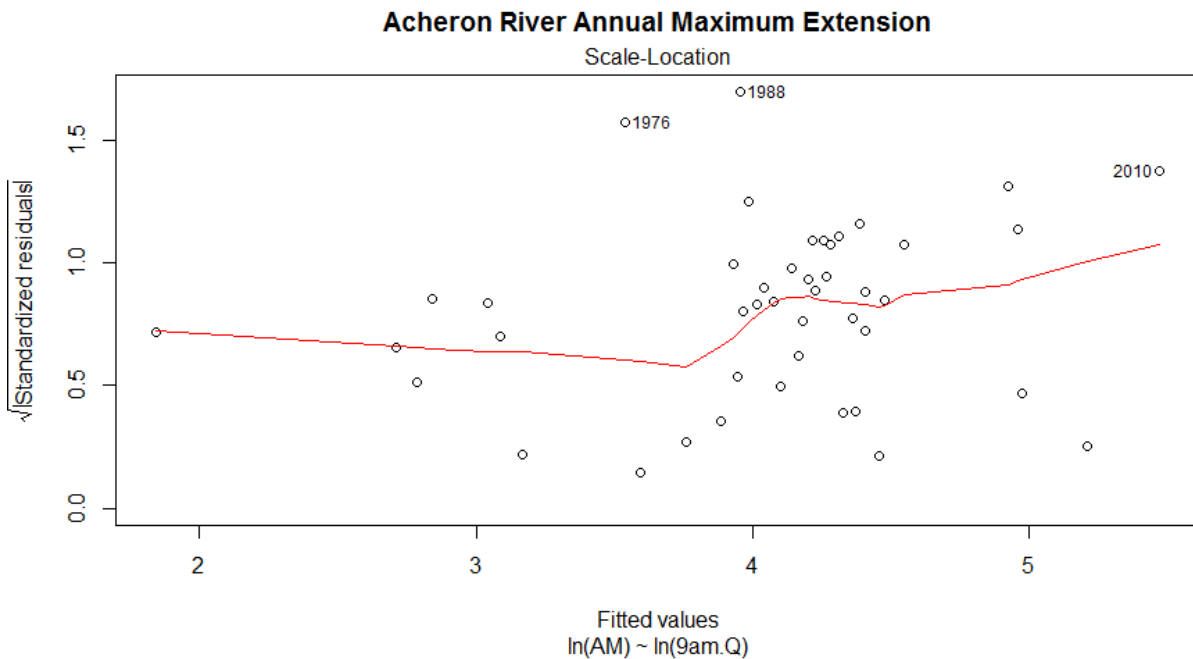


Figure 10-4: Acheron River Annual Maximum Extension: Scale – Location Plot

Outliers, High Leverage Points and Influential Observations

The data and model results were checked for outliers, high leverage points and influential observations. Other than the 1973 and 2014 records no other records were removed.

High leverage points were investigated and are shown in Figure 10-5. This plot shows that the Leverage values for 1974, 1996 and 2010 are high; however, inspection of these records does not provide any reason for their removal (see discussion about large residuals).

Influential observations were evaluated using Cook's distance as shown in Figure 10-5. This figure shows that all values fall within a Cook's distance of 0.25. A typical cut-off is 0.5 emphasising there are no significant outliers, leverage points or influential observations.

Summary

Overall, the model diagnostics indicate that the OLS regression assumptions are met with the exception of normality. This suggests that there is some structure within the model residuals that is not accounted for by the linear model. Log-log and power transforms were investigated to assist with the normality assumptions; however, these transforms did not improve the predicative ability of the model. Furthermore, the resulting model form of these transformed models is significantly more complex. For these reasons, and the fact that the resulting linear model provided an excellent fit to the data (see Figure 5-2) and a high coefficient of variation the original model was accepted.

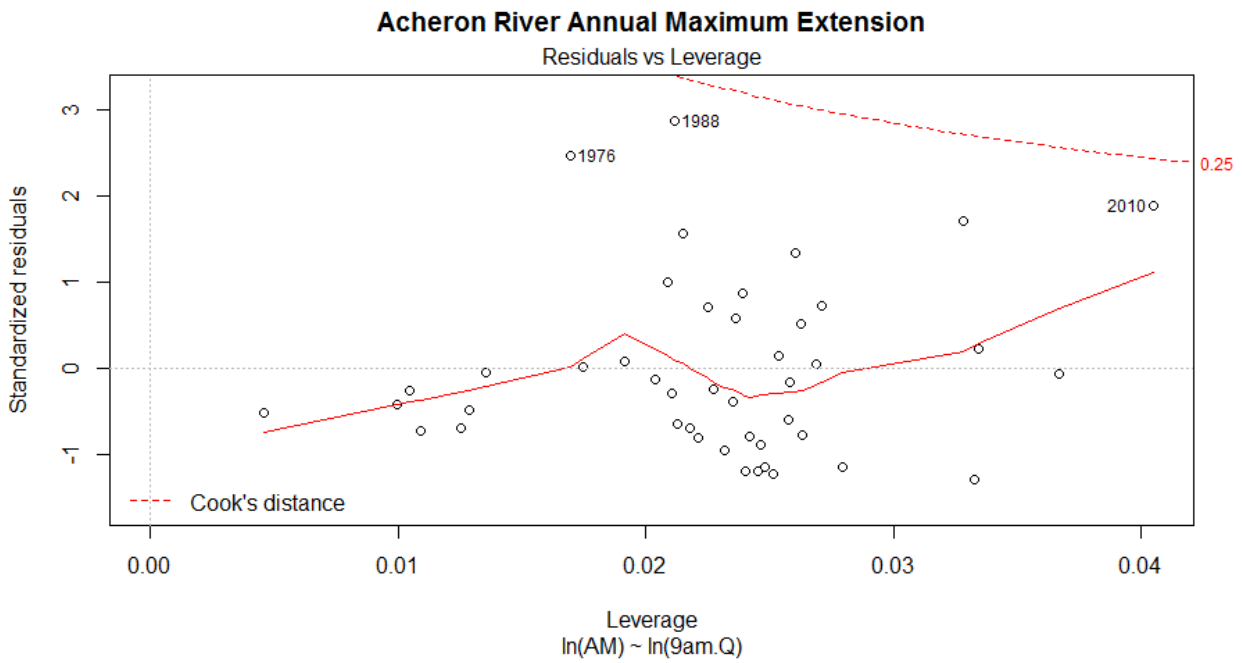


Figure 10-5:Acheron River Annual Maximum Extension: Residuals versus Leverage Plot

Appendix C Timing of annual maximum discharge for the rivers of the upper Goulburn

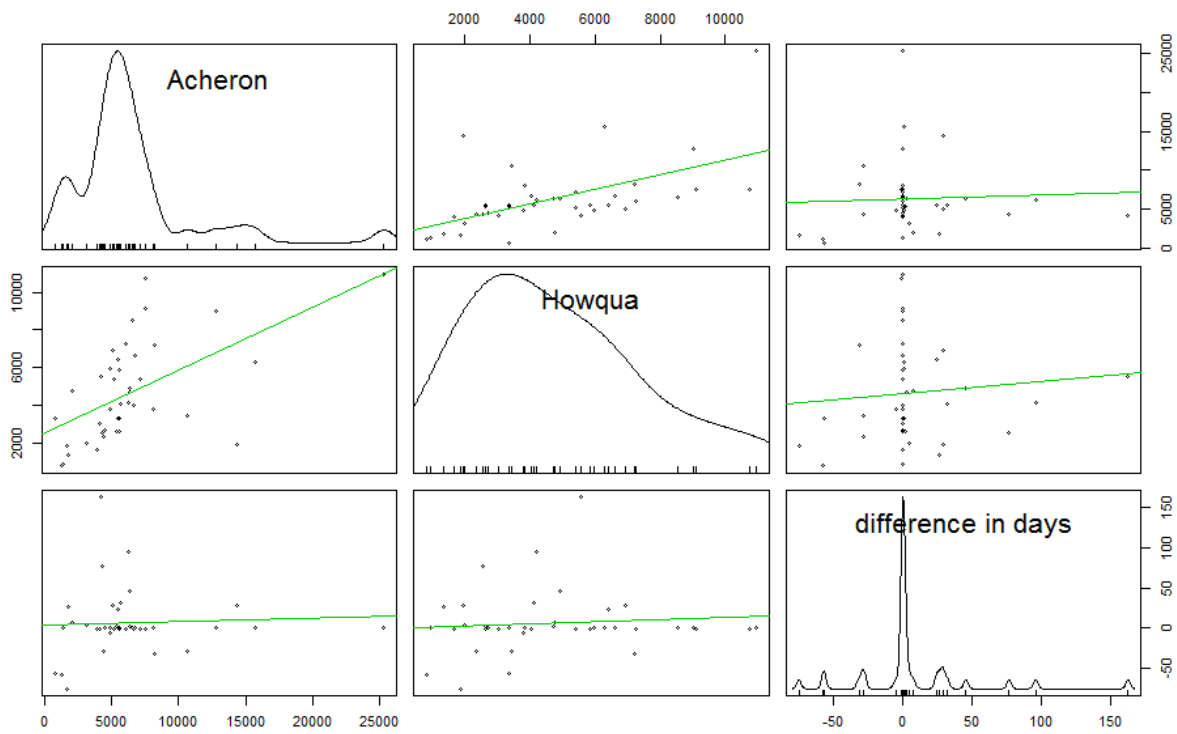


Figure 10-6 Timing of annual maximum discharge on the Acheron and Howqua Rivers

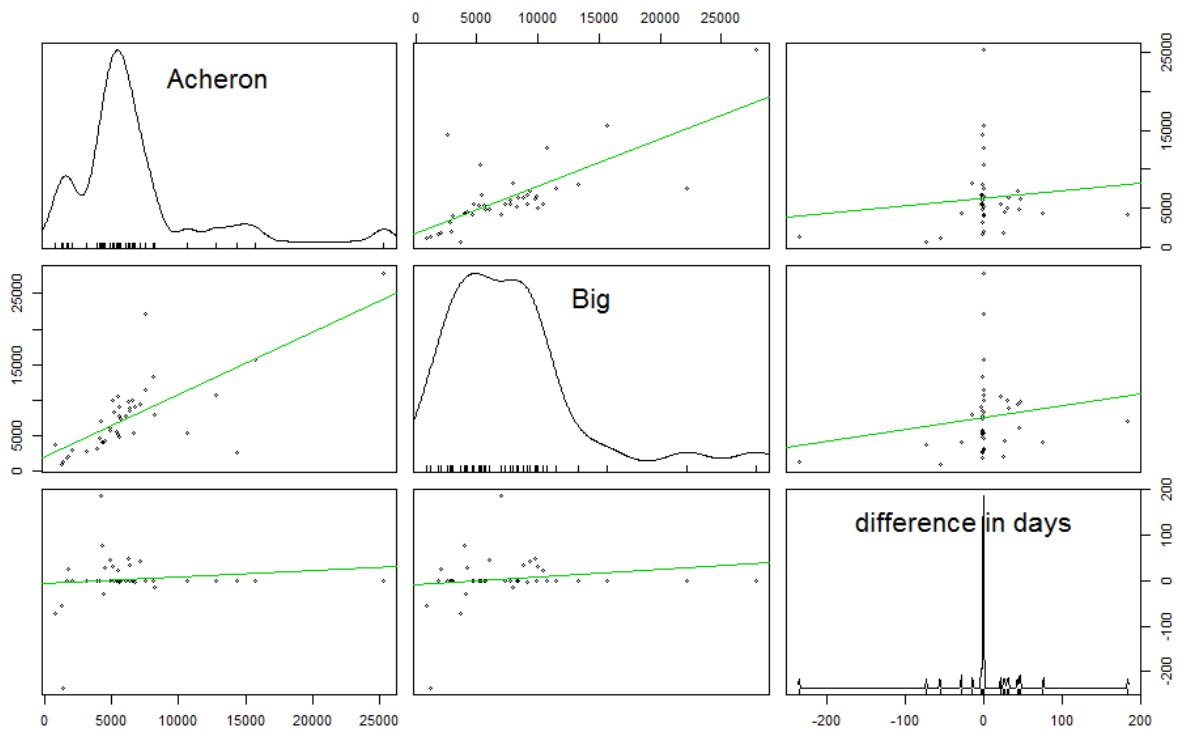


Figure 10-7 Timing of annual maximum discharge on the Acheron and Big Rivers

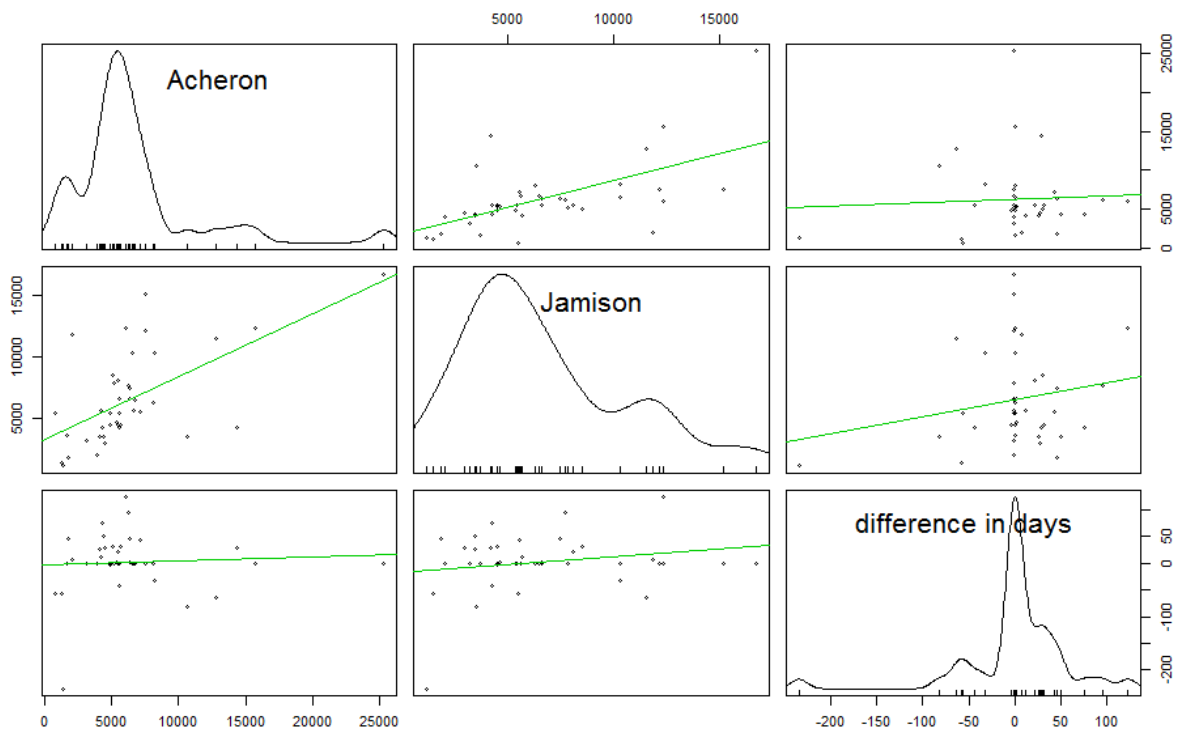


Figure 10-8 Timing of annual maximum discharge on the Acheron and Jamison Rivers

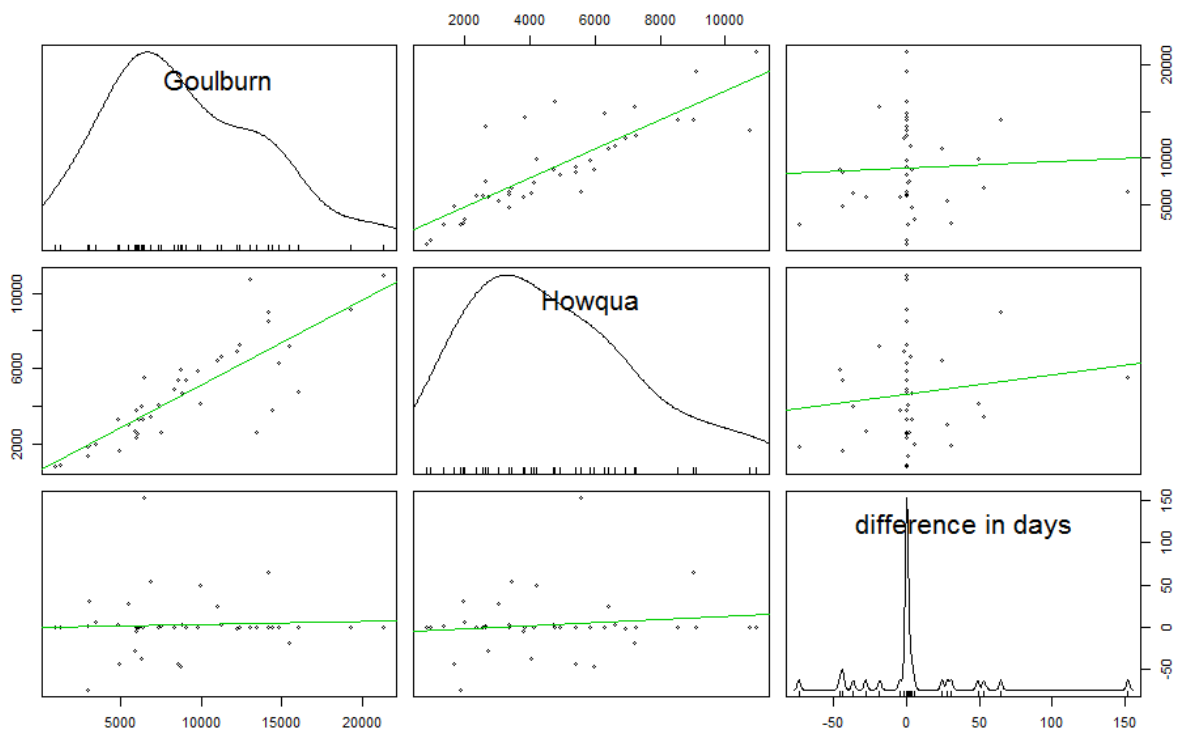


Figure 10-9 Timing of annual maximum discharge on the Goulburn and Howqua Rivers

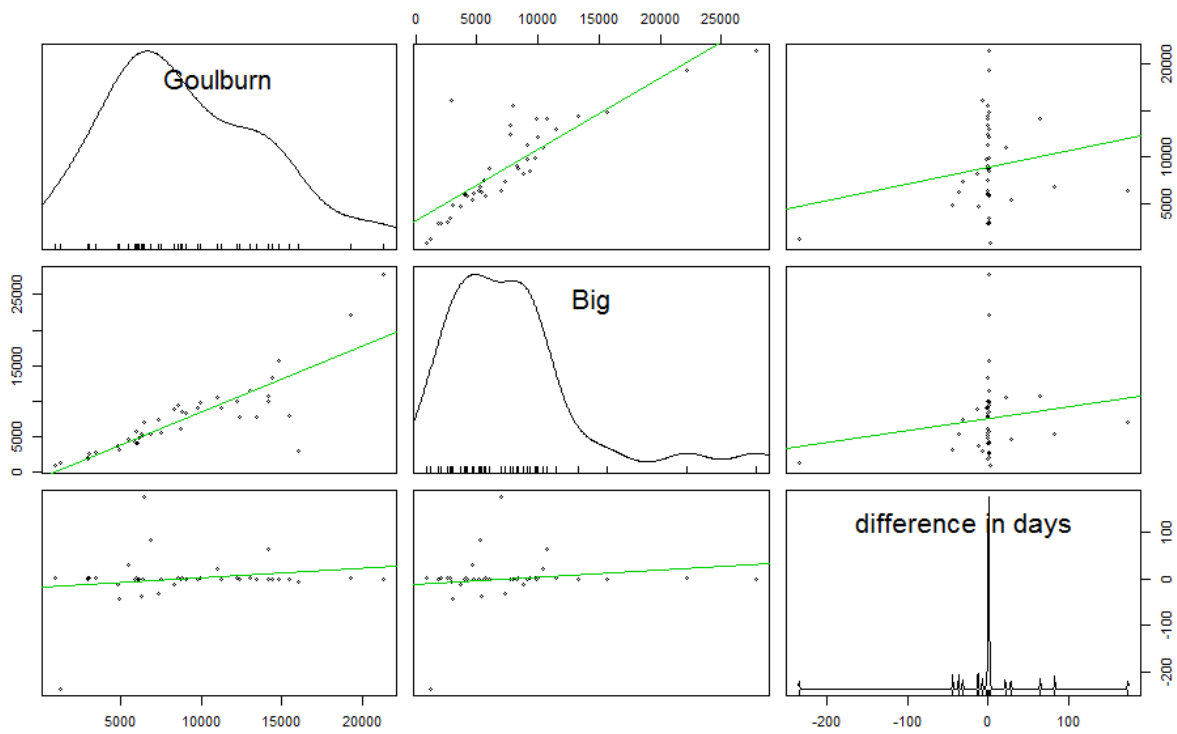


Figure 10-10 Timing of annual maximum discharge on the Goulburn and Big Rivers

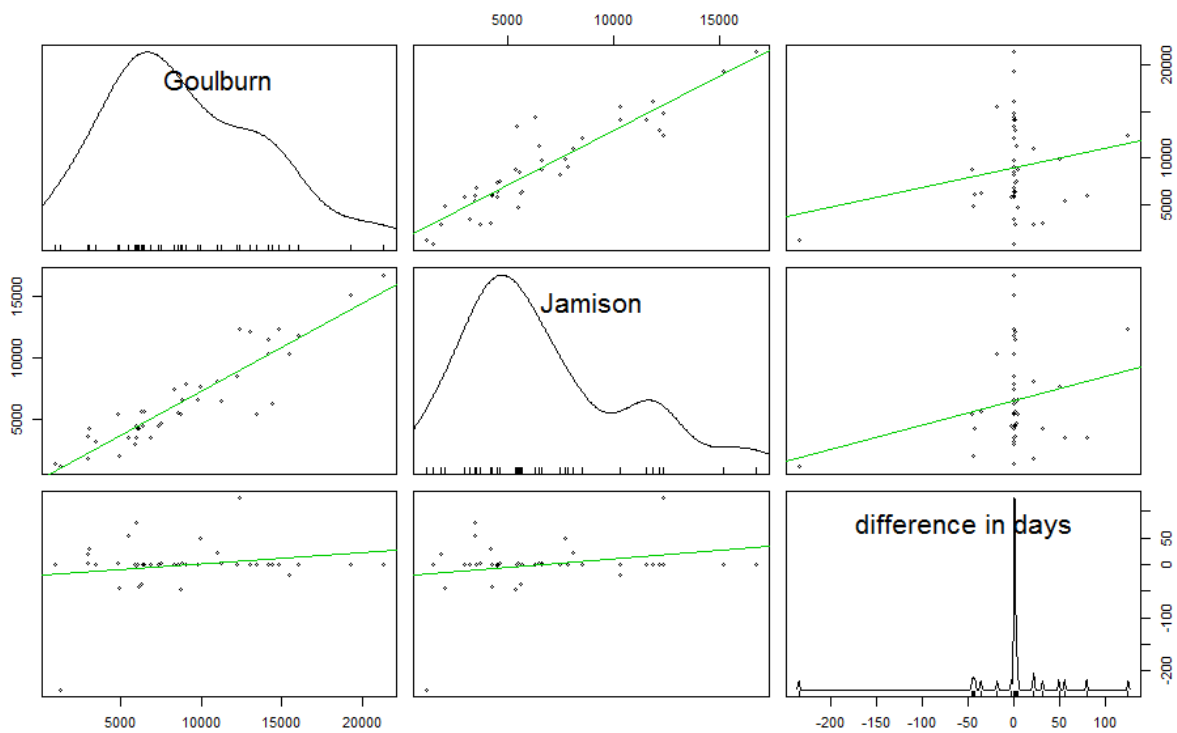


Figure 10-11 Timing of annual maximum discharge on the Goulburn and Jamison Rivers

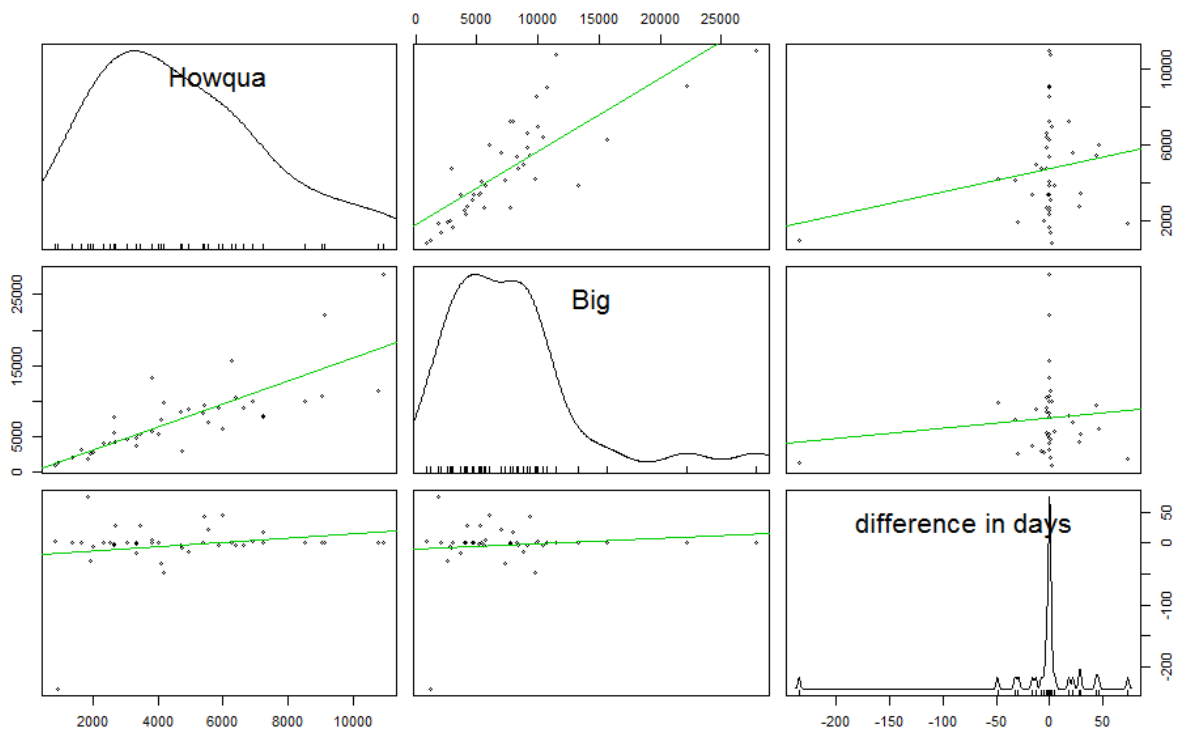


Figure 10-12 Timing of annual maximum discharge on the Howqua and Big Rivers

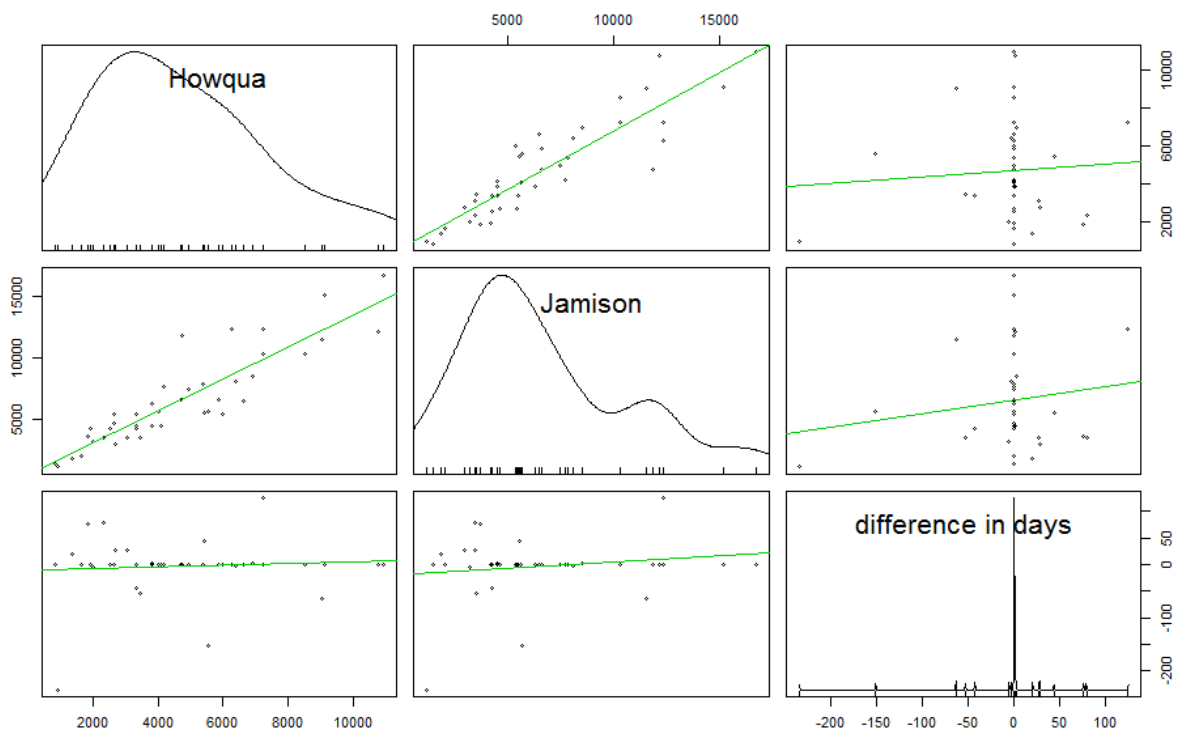


Figure 10-13 Timing of annual maximum discharge on the Howqua and Jamison Rivers

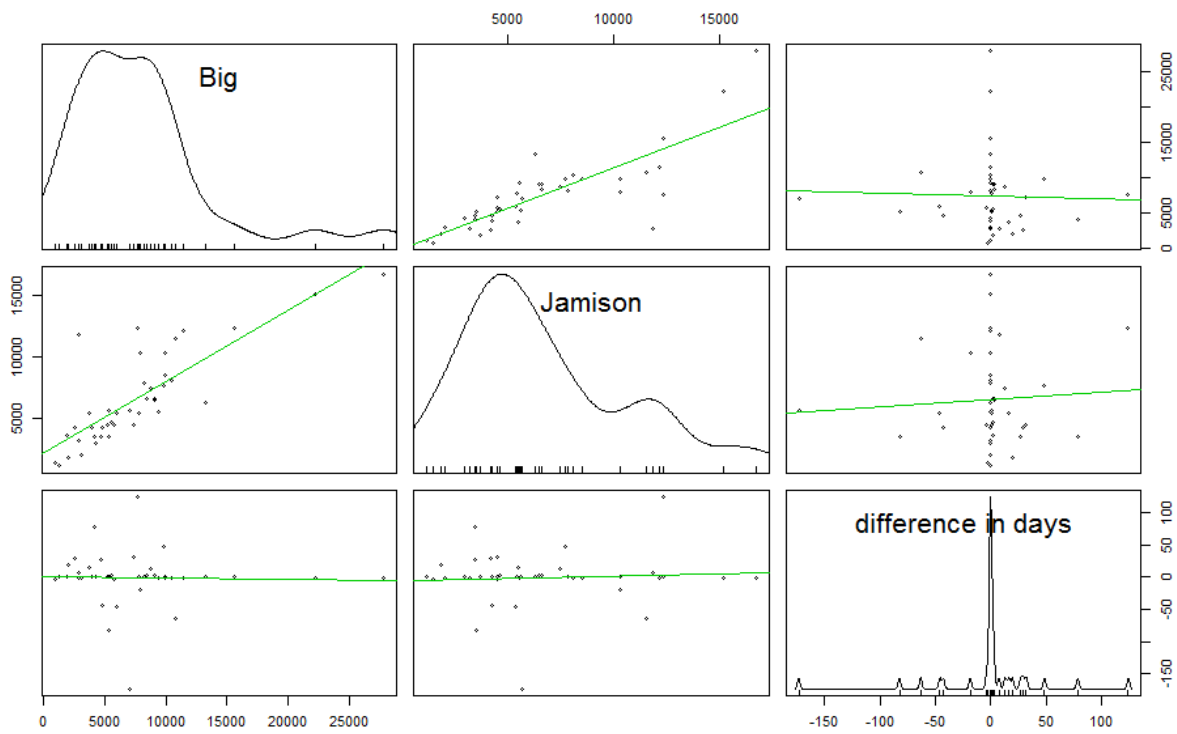


Figure 10-14 Timing of annual maximum discharge on the Big and Jamison Rivers



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