Avon River Regional Flood Mapping – Hydrology Report

June 2015

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1. INTRODUCTION

Water Technology was commissioned by the Department of Environment, Land, Water and Planning (DELWP) to undertake regional flood mapping for the Avon River. This project includes detailed hydrological and hydraulic modelling of the Avon River and its tributaries including Freestone Creek, Valencia Creek and Blackall Creek, and will take into account the downstream influences of Lake Wellington. This mapping will be used to satisfy a range of business requirements from planning, emergency response, to community awareness and for insurance purposes.

This report details the hydrological analysis undertaken for the project, and should be read in conjunction with the previous Preliminary Report (Water Technology, 2015).

2. STUDY AREA

The Avon River rises on the slopes of Mount Wellington in the eastern highlands of the Great Dividing Range and flows south to Lake Wellington and the Gippsland Lakes. The mountainous upper catchment is largely forested, while the lower catchment downstream of the confluence with Valencia Creek is generally flatter, with agriculture the primary land use (Earth Tech, 2007). The floodplain in the lower reaches is traversed by watercourses, swamps and lagoons. Overall, the river descends some 664 m over its 122 km length.

Regional mapping will include approximately 40 km of the downstream floodplain of the Avon River catchment, as well as large portions of Freestone Creek, Valencia Creek and Blackall Creek. Key towns within this catchment area include Stratford, Boisdale and Briagolong. The study area and significant watercourses are shown in Figure 2-1.

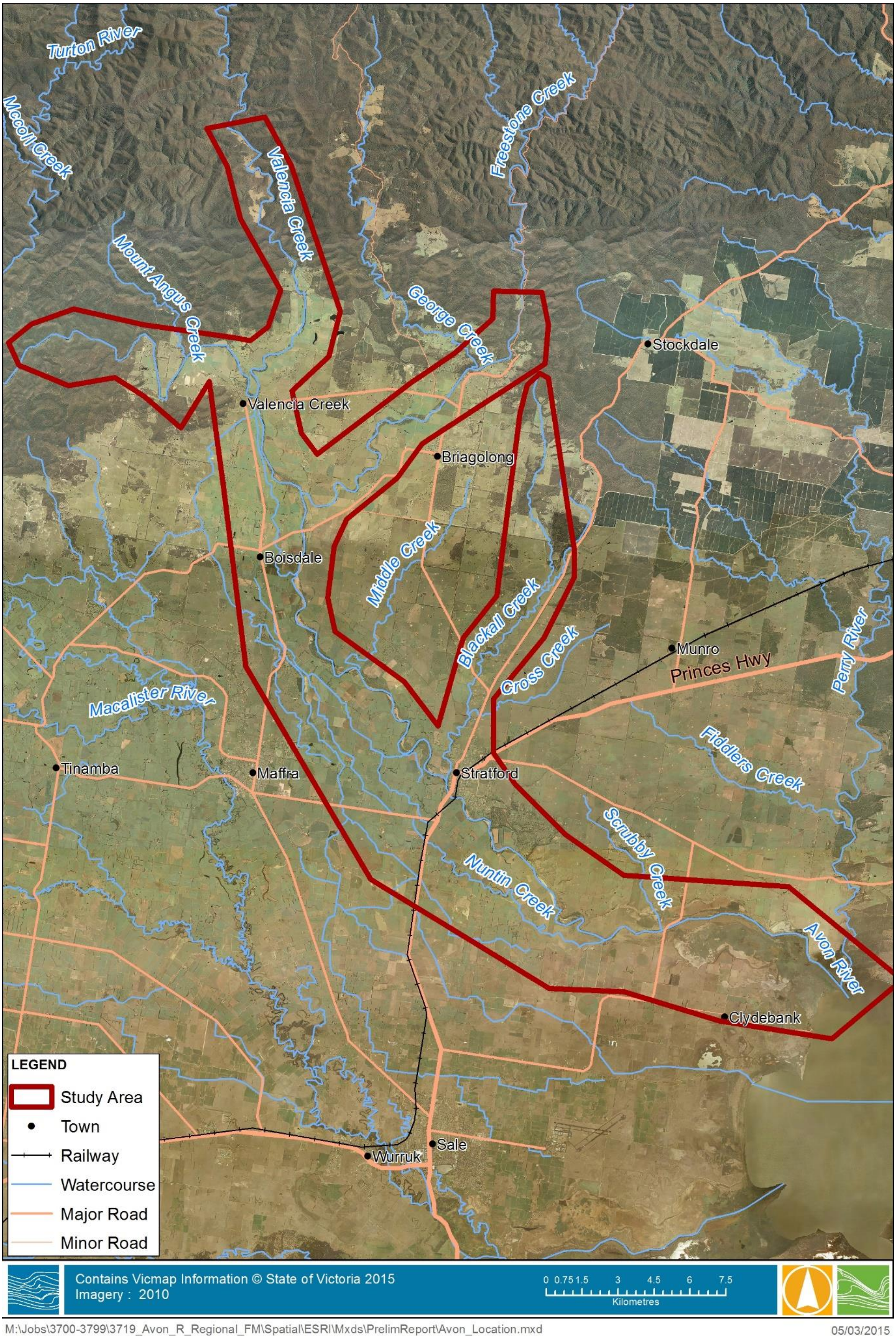

Figure 2-1 Avon River study area

3. HYDROLOGY

3.1 Overview

The hydrological analysis for the Avon River consisted of a review of the hydrological context of the study area followed by hydrologic modelling using RORB and flood frequency analysis on gauges with a good period of record. The RORB model was calibrated to three gauged events and parameter sets for design were validated against flood frequency analysis and regional flow estimates.

3.2 Catchment Description

The Avon River catchment has an area of 1,650 km^2 extending 72 km northward from Lake Wellington to a maximum elevation of 1,615 m AHD at Mount Wellington (Figure 3-1). The river has two main tributaries, Freestone Creek and Valencia Creek. A number of other minor streams feed into the River throughout its course. The Macalister River to the west and Perry River to the east have clearly defined catchments and are unlikely to exchange flows with the Avon River until they reach the downstream outlet at Lake Wellington.

The main stream length from the catchment divide to the mouth is 113 km with an equal area slope of 2.2 m/km. Equal area slope is the averaged slope of a river, and if plotted as a straight line against the real topography will have an equal weighting of topographic error above and below the approximated line. It is commonly used in hydraulic and hydrological formulae. The catchment is much steeper in the ranges upstream of Valencia Creek than in the floodplain.

A steep rainfall gradient exists over the catchment with average annual rainfall reaching 1,910 mm in the headwaters, while at the catchment centroid the average annual rainfall is around 670 mm. Effectively the lower catchment is within the rain shadow of the Australian Alps, part of the Great Dividing Range.

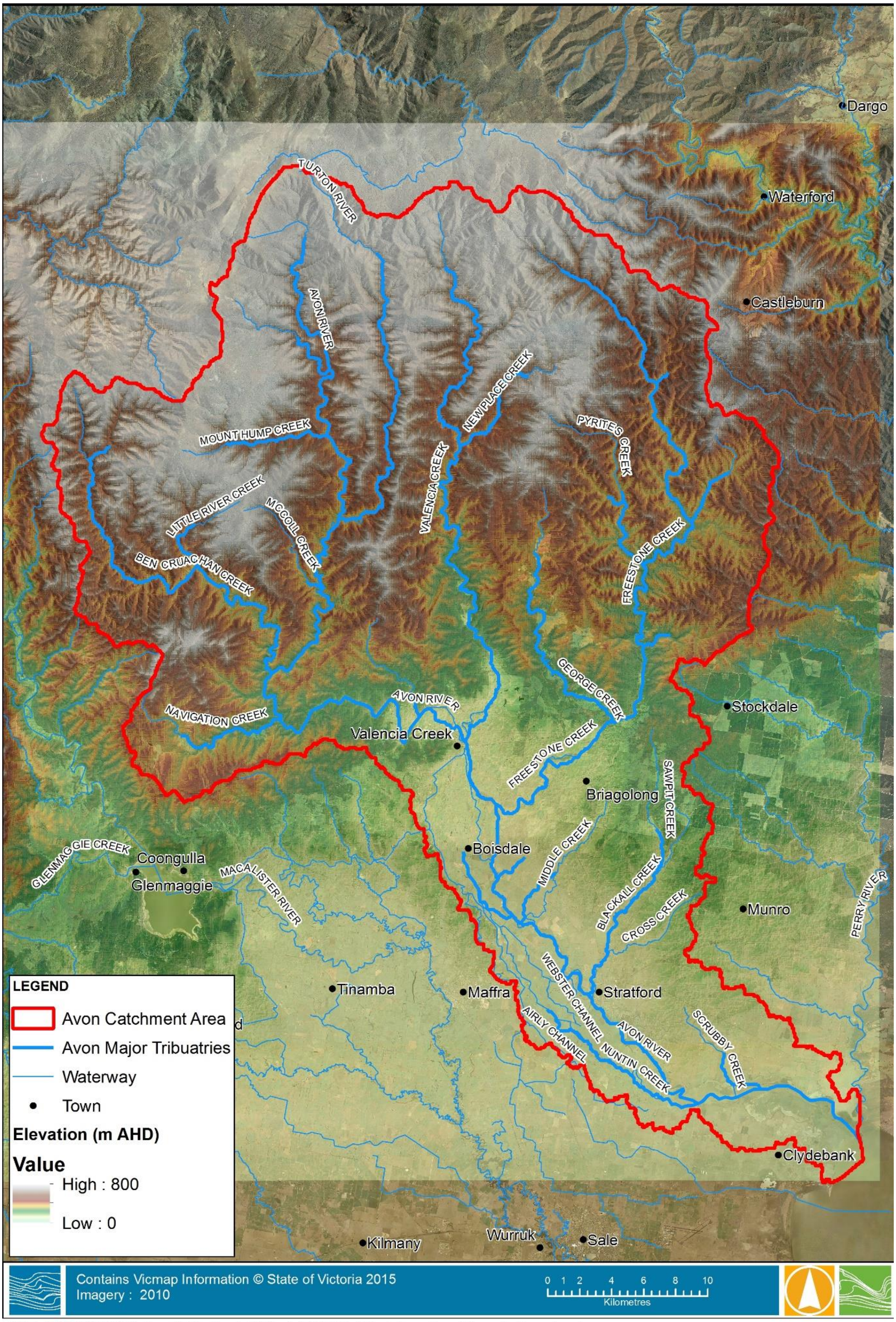

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Figure 3-1 Avon River Catchment

3.3 Design Rainfall Estimates

Design rainfalls were calculated for the 20%, 10%, 5%, 2% and 1% AEP events using the Intensity-Frequency-Duration analysis from Australian Rainfall and Runoff (ARR) (1987). The IFD parameters (Table 3-1) were obtained from the Bureau of Meteorology's IFD program website (www.bom.gov.au/water/designRainfalls/ifd) for the catchment centroid.

Table 3-1 IFD parameters

2yr (50% AEP) 1hr rainfall intensity (mm/hr)	21.87
2yr (50% AEP) 12hr rainfall intensity (mm/hr)	5.48
2yr (50% AEP) 72hr rainfall intensity (mm/hr)	1.7
50yr (2% AEP) 1hr rainfall intensity (mm/hr)	45.47
50yr (2% AEP) 12hr rainfall intensity (mm/hr)	10.07
50yr (2% AEP) 72hr rainfall intensity (mm/hr)	3.24
Skew	0.31
F2	4.24
F50	15.25

Comparisons were made with the new IFDs developed for Project 1 of the ARR Revision Project (http://www.bom.gov.au/water/designRainfalls/revised-ifd/). On average the new IFD parameters were around 5% lower than AR&R (1987) (for 1%-10% AEP events), with some AEP/Duration values up to 22% lower.

The 1987 IFD parameters were adopted to be consistent with existing methods for determining areal reduction factors, design losses and hydrologic parameter estimates, which were developed with the older IFD information.

Unfiltered temporal patterns from ARR (1987) for Zone 1 were applied for the design events, as recommended in Hill et al. (1998) for use with their design losses. Rainfall depths were applied uniformly across the catchment.

Areal reduction factors from Siriwardena and Weinmann (1996) were applied to the point design rainfall estimates. These areal reduction factors are recommended for use in Victoria instead of the original ARR values (Hill et al. 1998). These have now been recommended for adoption in the ARR Project 2 Stage 2 report (2013).

3.4 Gauge Review

Five streamflow gauges currently operate in the catchment, while historic data is also available for four other gauges (Table 3-2). Of the currently operating gauges, Valencia Creek at Gillio Road, Avon River at The Channel and Freestone Creek at Briagolong gauges record streamflow at the three largest upstream tributaries that are to be mapped. Downstream gauges at Stratford and Clydebank include 90% and 96% of the Avon River catchment, respectively. The Avon River at Stratford gauge is located in the best location for model calibration, as it is downstream of all large tributaries and has a high quality gauging record. The gauge is also situated adjacent to the township of Stratford, a critical location with respect to flood mapping. The Avon River at The Channel, Valencia Creek at Gillio Road and Freestone Creek at Briagolong gauges were also used to calibrate the hydrologic model. A flood frequency analysis was undertaken at all four of these gauges to verify the design flows generated by the hydrologic model. The hydrologic model is not limited by issues with the stage-discharge relationship at the downstream gauge at Clydebank, which hindered the effectiveness of flood frequency analysis at the gauge, discussed further in Section 3.5.

Table 3-2 Streamflow gauges in Avon River catchment

Gauge No.	Location	Period	Years	Catchment Area (km^2)
225223	Valencia Creek @ Gillio Road	1971 - 2015	35	195
225224	Avon River @ The Channel	1972 - 2015	34	554
225201	Avon River @ Stratford	1976 - 2015	38	1485
225218	Freestone Creek @ Briagalong	1967 - 2015	49	309
225234	Avon River @ Clydebank	1977 - 2015	39	1584
225255	Avon River U/S of Valencia Creek Junction	2004 - 2012	9	-
225211	Avon River @ Buxton	1953 - 1972	20	580
225220	Valencia Creek @ Radettis	1967 - 1971	5	233
225205	Avon River @ Valencia Creek	1919 - 1964	46	862

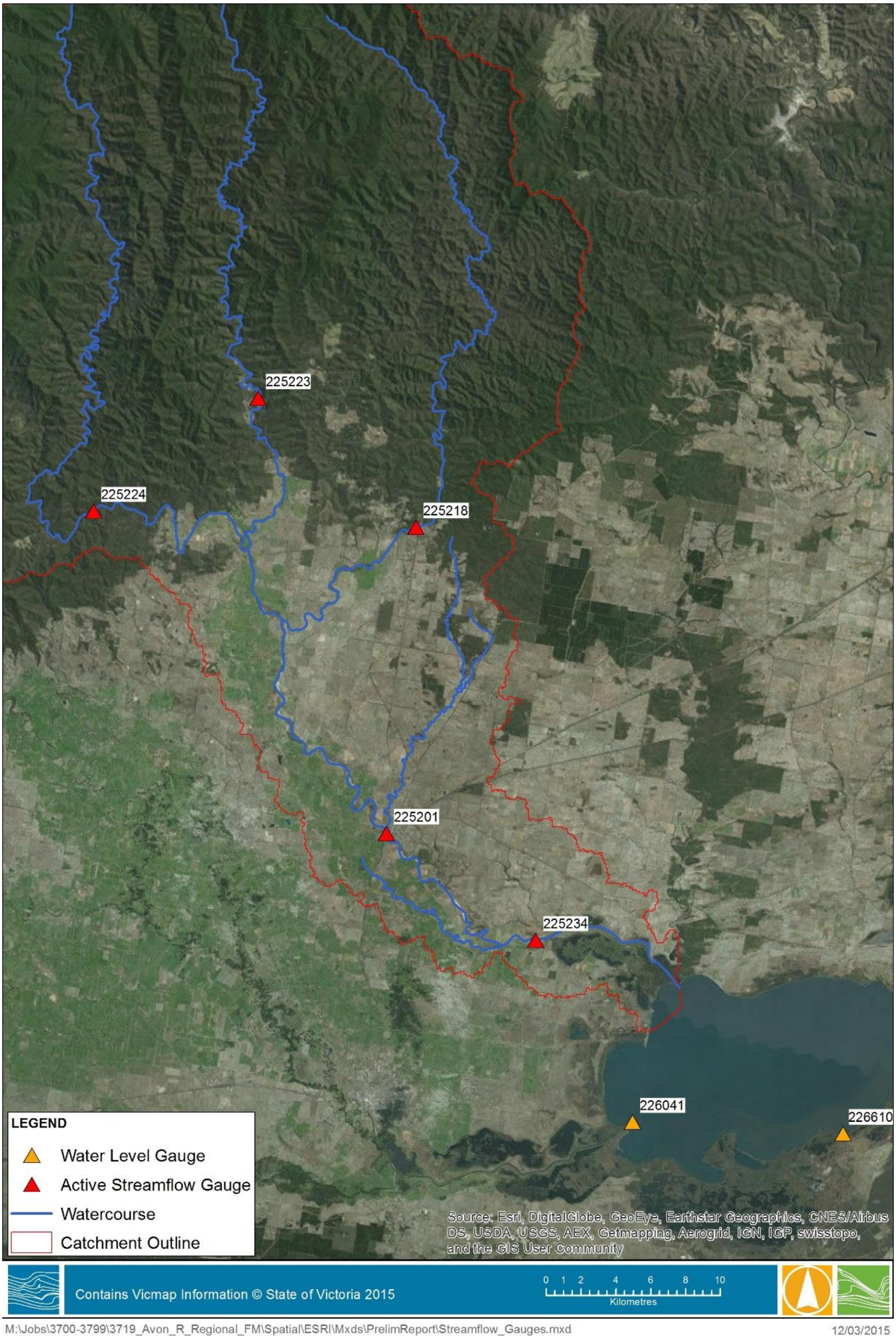

Figure 3-2 Streamflow and water level gauges in the Avon River catchment

3.4.1 Avon River at Stratford

The Avon River at Stratford gauge (225201) has 38 years of instantaneous flow data. The rating for the current gauge is officially considered reliable up to flows of 2,500 m^3/s, with a large number of physical gauging measurements showing low scatter for high flow events (greater than 10 m^3/s), as shown in Figure 3-3, and the gauged flows are generally lower than the equivalent rating curve estimates. Low flow estimates (less than 10 m^3/s) show considerable scatter, likely due to the influence of Lake Wellington and the geomorphologic change of the river since the first gauging in 1908.

Consultations with the current hydrographer of the Avon basin suggest the gauging relationship at Stratford has been evolving for quite some time, likely due to channel change, however this has progressed in a discrete manner and is reflected in the flow estimates for the gauge (Wayne Ross pers. comm., 2015).

The long term water level record (Figure 3-5) was also reviewed and it was found that following the 1990 event, gauged levels were elevated, even during low flow periods, for a number of years. The low flow water level, after suddenly increasing in 1990, showed signs of settling back to pre-1990 levels until 1998 where the low flow level again increased after a major flood. The same trend continued after the 2007 flood. This is indicative of sand accretion in the channel after the 1990 event. The 1990 rating curve had a lower predicted flow for a given water level than the rating curve used in 1998, and the same trend continues between 1998 and later years gauging.

Based on this review, it is considered the flow estimates at the Stratford gauge have a low reliability for low flow conditions, and moderate reliability for high flows.

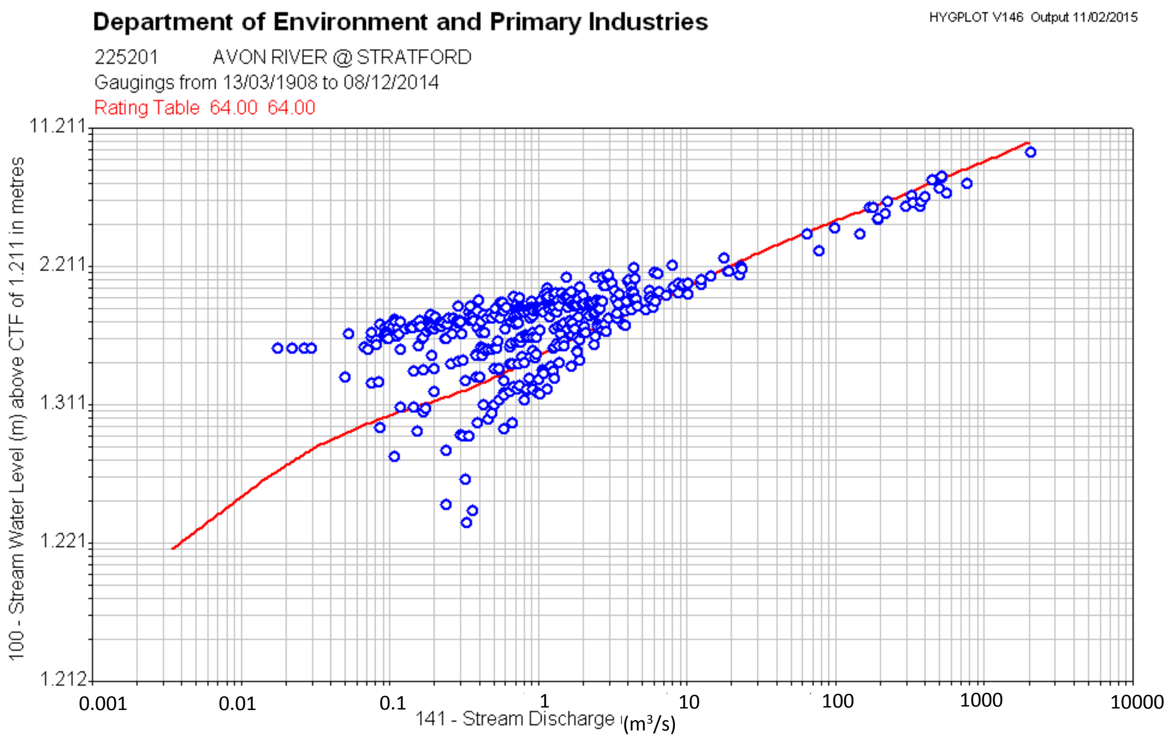

Figure 3-3 Rating Curve for Avon River @ Stratford (225201)

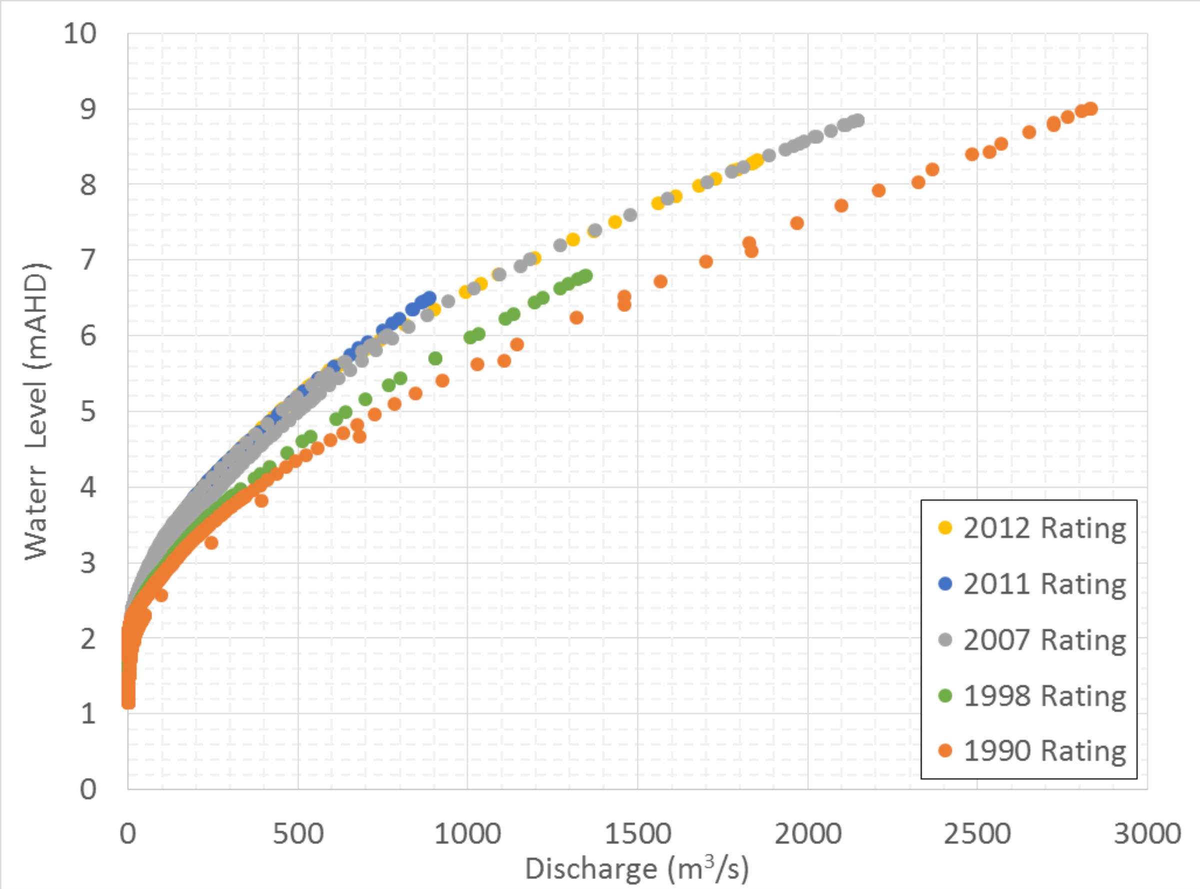

Figure 3-4 **Water Level vs. Discharge Plot for Avon River @ Stratford (225201) showing variation in rating curves for selected periods of record**

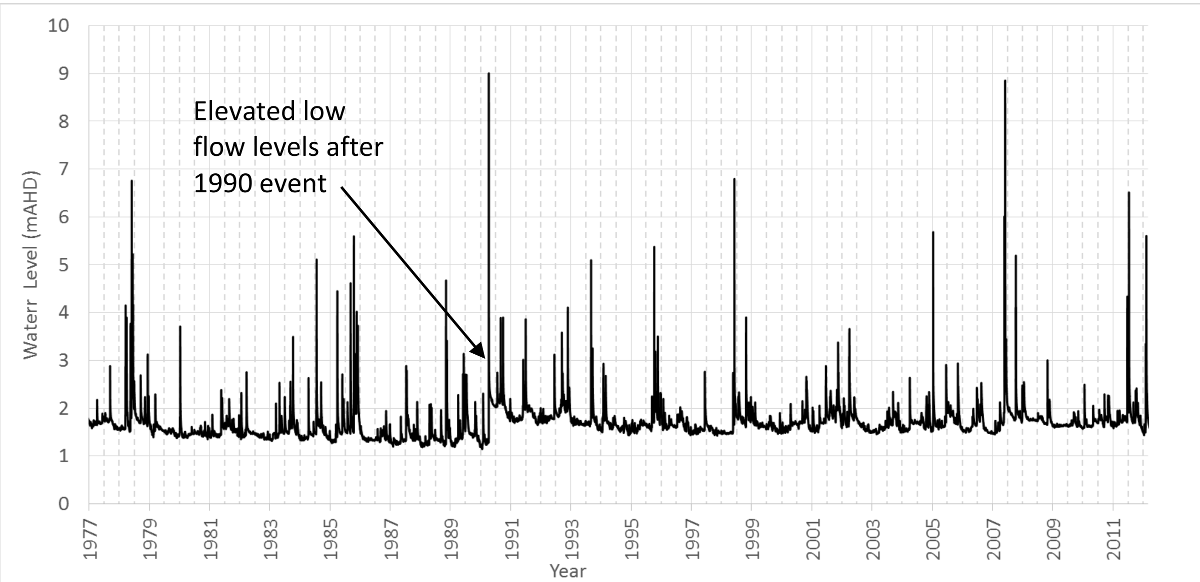

Figure 3-5 **Avon River at Stratford Gauge Levels**

3.4.2 Avon River at The Channel

The Avon River at The Channel gauge (225224) has 34 years of flow data from 1972-2015. The rating curve at the upper end is based on a small number of high and low flow gauging measurements with low scatter (Figure 3-6), and is therefore expected to be reliable for estimating flows in the upper Avon.

The rating for the current gauge is officially considered reliable up to flows of 360 m^3/s, with larger values being extrapolated. However, this extrapolation appears to follow a consistent trend and is considered reliable for calibration, where flows reach up to approximately 1000 m^3/s. Without gaugings in this extrapolated region the rating curve was used with caution.

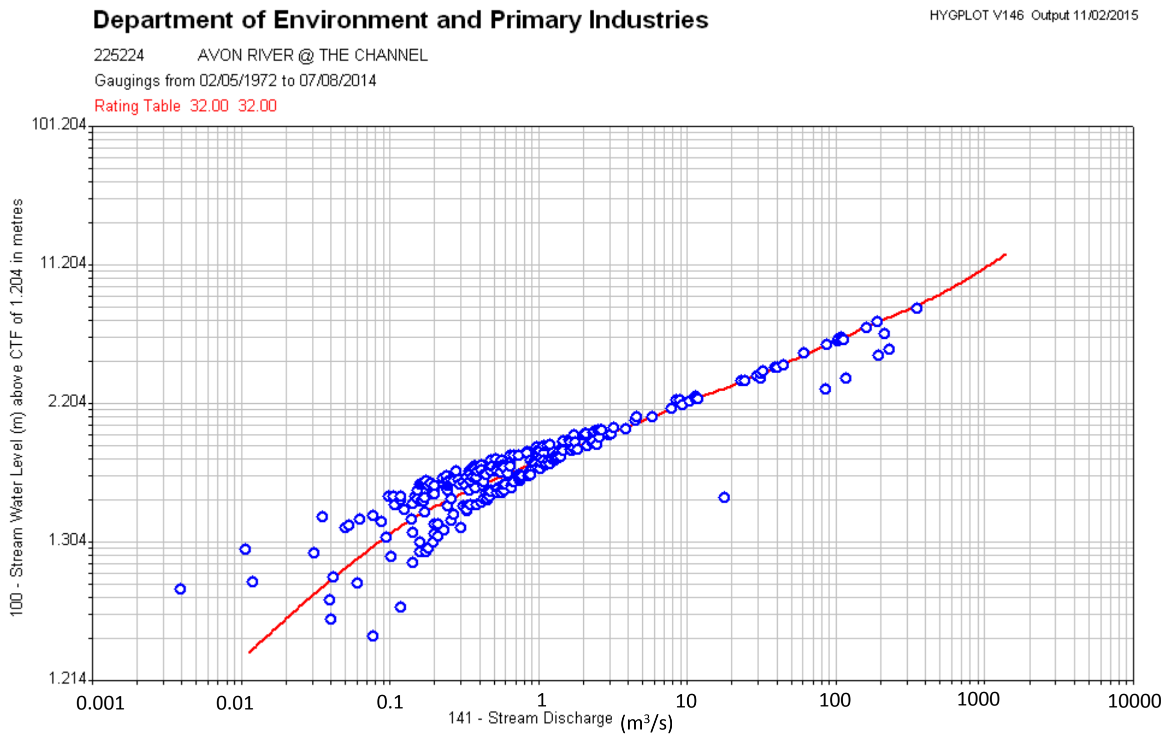

Figure 3-6 Rating Curve for Avon River at The Channel (225224)

3.4.3 Valencia Creek at Gillio Road

The Valencia Creek at Gillio Road gauge (225223) has 35 years of flow data from 1971-2015. The rating curve at the upper end is based on a small number of flow gauging measurements with very little scatter (Figure 3-7), and is therefore expected to be reliable for estimating flows in in the Valencia Creek catchment.

The rating for the current gauge is officially considered reliable up to flows of 210 m^3/s, with larger values being extrapolated. However, this extrapolation appears to follow a consistent trend and is considered reliable for calibration, where flows reach up to approximately 350 m^3/s. Without gaugings in this extrapolated region the rating curve was used with caution.

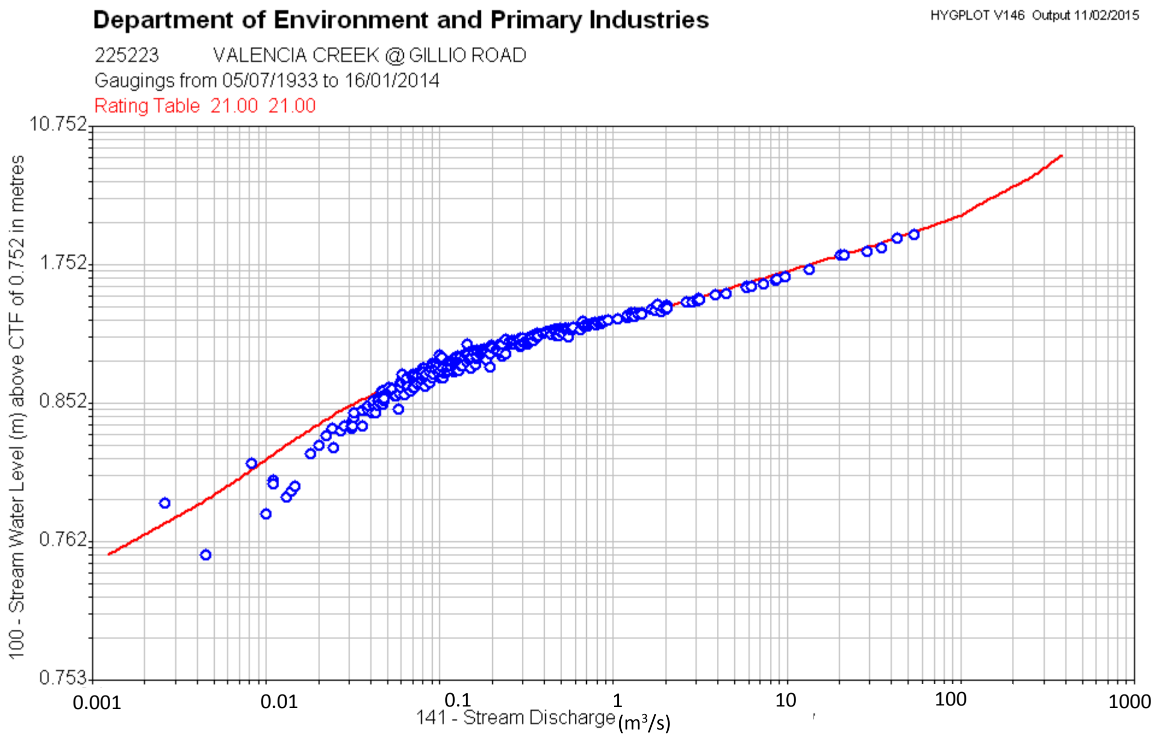

Figure 3-7 Rating Curve for Valencia Creek at Gillio Road (225223)

3.4.4 Freestone Creek at Briagolong

The Freestone Creek at Briagolong gauge (225223) has 49 years of flow data from 1967-2015. The rating curve at the upper end is based on a small number of flow gauging measurements with very little scatter (Figure 3-8), and is therefore expected to be reliable for estimating flows in in the Freestone Creek catchment.

The rating for the current gauge is officially considered reliable up to flows of 125 m^3/s, with larger values being extrapolated. However, this extrapolation appears to follow a consistent trend and is considered reliable for calibration, where flows reach up to approximately 650 m^3/s. Without gaugings in this extrapolated region the rating curve was used with caution.

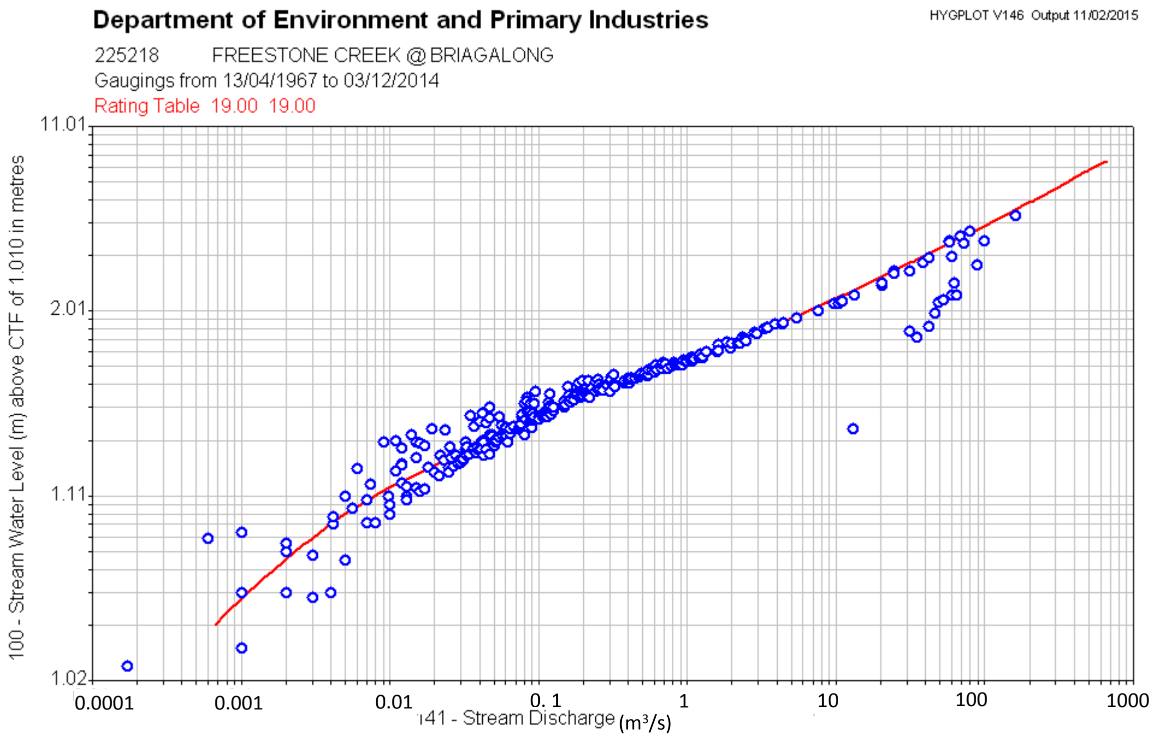

Figure 3-8 Rating Curve for Freestone Creek at Briagolong (225218)

3.4.5 Avon River at Clydebank

The Avon River at Clydebank gauge (225234) has 39 years of flow data from 1977-2015. The rating curve is based on many low flow gauging measurements with considerable scatter (Figure 3-9).

Clydebank does not have high flow readings within the calibration flow range (up to approximately 2000m^3/s). The rating curve for Avon River at Clydebank has a highest gauging of 1.725 m (approximately 13m^3/s). There are a number of issues associated with stage-discharge relationships at Clydebank. Whilst the gauge is on the Avon River, during high flow events wetlands on either side of the river are activated, causing multiple flow paths across the floodplain separate to the Avon River flow path. Clydebank is also close to the Avon River outlet at Lake Wellington, which has been shown to vary with a number of factors including atmospheric conditions, wind conditions, tides and recent amount of discharge into the lake (Brizga et al., 2013). Due to the uncertainty in the stage-discharge relationship for high flows at Clydebank, the flow values will not be used for calibration. However, downstream water levels will be able to be validated in the hydraulic model based on the recorded Clydebank water levels.

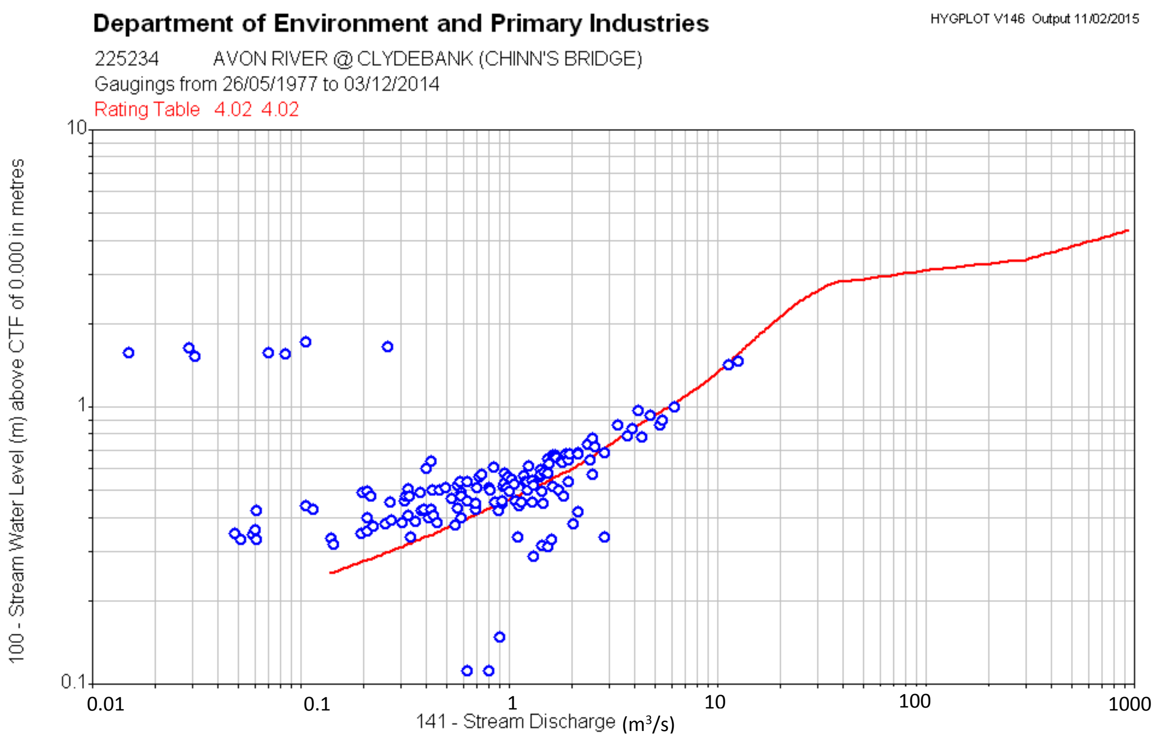

Figure 3-9 Rating Curve for the Avon River at Clydebank (225234)

3.4.6 Lake Wellington at Bull Bay

Water levels in Lake Wellington are recorded at the Bull Bay gauge site (226041), with data available from 1975 to present, with a number of data gaps. As detailed in Brizga et al (2013) the data between 1975 and 1988 was collected by Latrobe Valley Water over the period 1975 to 1988 and was digitised for the Latrobe Environmental Flows project (Brizga et al, 2013). The resolution of the digitised additional data was typically 1-2 hours, with a level resolution of 0.01 m or better. The more recent data is available at 15 minute intervals with a similar level of resolution.

The water level in Lake Wellington is comprised of both tidal and non-tidal components, with the dominant forcing factor being the effect of changes in atmospheric pressure and wind. An example from Brizga et al (2013) of the relative impacts of weather and tides on water levels in Lake Wellington is shown in Figure 3-10.

The observed water level in Lake Wellington has a range of around 0.5 m over the 6 month period shown (Aug 2010 – Jan 2011). The tidal component is at most only ±0.03 m whereas storm surge is the dominant water level control, raising water levels for extended periods. Over the period shown, the change in water level due to atmospheric changes associated with low pressure weather systems is in the order of 0.5 m. The effect of wind set-up (and set-down) is less pronounced (around ±0.1 m) and occurs over shorter, daily time scales but has an important role in internal circulation processes such as the mixing and transport of saline water, particularly for shallow areas such as Lake Wellington. Variations in water levels also occur on a seasonal basis, and levels are also affected by the strength of the southern oscillation index.

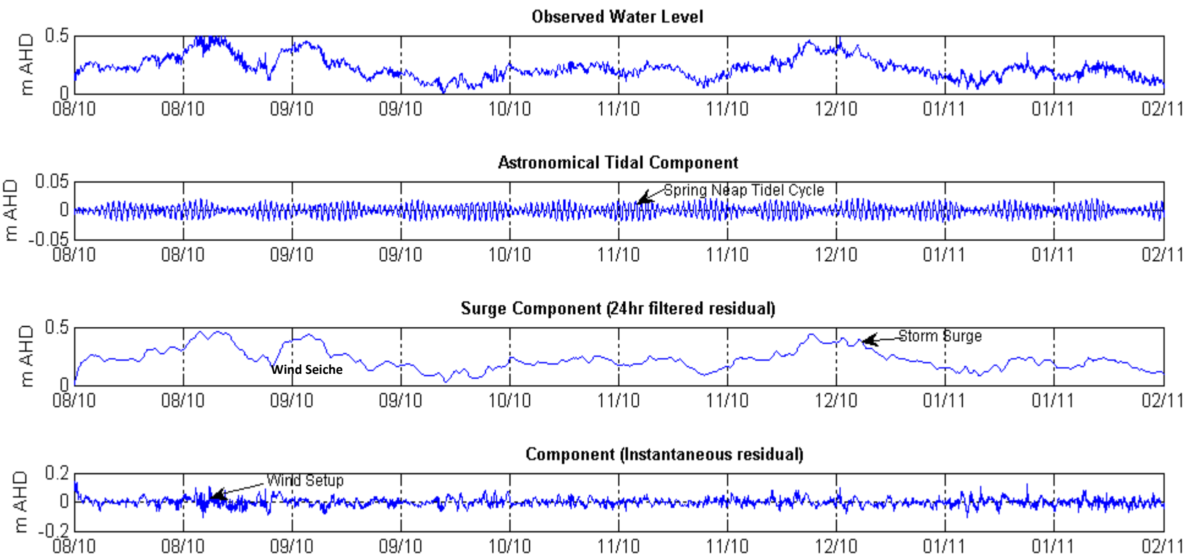

Figure 3-10 Example of relative impacts of weather and tide on water levels in Lake Wellington

3.4.7 Flood Class Levels

The Bureau of Meteorology provides flood forecasting and flood warning services for the Avon River. Flood watches are issued when the combination of forecast rainfall and other hydrological conditions indicate there is a potential risk of flooding. Flood warnings are then issued to advise that flooding is occurring or is expected to occur based on defined criteria. These criteria are the flood classes defined as minor, moderate, or major at specific gauging station locations along the river. On the Avon, flood classes are defined at The Channel and at the Stratford gauge sites.

The definition for different flood classes is summarized in Table 3-3, while the flood class values on the Avon River are detailed in Table 3-4. The height shown for each flood class level is based on the gauge data and is the water level above the gauge zero. At Stratford the gauge zero is 0 m AHD, while at The Channel the gauge zero is 72 m AHD. The flow magnitude associated with the flood class level has been estimated for each site based on the current gauge rating curve.

Table 3-3 Bureau of Meteorology Flood Class Definitions

Flood Class	Definition
Minor	Causes inconvenience. Low-lying areas next to water courses are inundated. Minor roads may be closed and low-level bridges submerged. In urban areas inundation may affect some backyards and buildings below the floor level as well as bicycle and pedestrian paths. In rural areas removal of stock and equipment may be required.
Moderate	In addition to the above, the area of inundation is more substantial. Main traffic routes may be affected. Some buildings may be affected above the floor level. Evacuation of flood affected areas may be required. In rural areas removal of stock is required
Major	In addition to the above, extensive rural areas and/or urban areas are inundated. Many buildings may be affected above the floor level. Properties and towns are likely to be isolated and major rail and traffic routes closed. Evacuation of flood affected areas may be required. Utility services may be impacted

Table 3-4 Flood Classes on the Avon River

Gauge Station	Minor		Moderate		Major	
	Height (m)	Flow (m^3/s)	Height (m)	Flow (m^3/s)	Height (m)	Flow (m^3/s)
Avon River at the Channel	5.00	213	6.90	507*	7.50	604*
Avon River at Stratford	4.50	332	6.00	761	6.50	962

* Flow values for heights above 6.0 m have been extrapolated

3.5 Flood Frequency Analysis

3.5.1 Overview

Flood frequency analysis (FFA) allows the estimation of peak flows of selected Annual Exceedance Probability (AEP) events based on a statistical analysis. FFA was undertaken for the Avon River at The Channel, Avon River at Stratford, Valencia Creek at Gillio Road and Freestone Creek at Briagolong gauges.

Hydrographs extracted from the hydrologic model at the Avon River at The Channel, Freestone Creek at Briagolong and Valencia Creek at Gillio Rd gauges are to be used as direct inflows to the hydraulic model. It was therefore considered Important to validate calibrated losses at these gauges with flood frequency analysis.

The FFA was undertaken on the annual flow series from the gauge records using the analysis program FLIKE, as recommended in the updated ARR guidelines. FLIKE uses a Bayesian approach to parameter fitting (either the Global Probabilistic or Quasi-Newton fitting algorithms) to the records in order to assess the return period of different magnitude flows. There are a number of probability distributions which can be used to undertake an FFA, including the Log Pearson III, Log-Normal, Generalised Pareto, Generalised Extreme Value and Gumbel distributions and a selection of these are applied in the analysis, with the 'best fit' distribution adopted in the final assessment.

The Avon River flow series showed that highest flows have previously occurred in winter and spring (June – October). The flow series analysis therefore assumed that the flow year started in March.

3.5.2 Gauge Relationships

Gauge relationships between each upstream gauge (Avon River at The Channel, Valencia Creek at Gillio Rd and Freestone Creek at Briagolong) and the Stratford Gauge have been developed in order to extend the length of records available for the flood frequency analysis at each site. Generally the Stratford gauge has a reliable historic data, although data was missing for the 1971 flood. The water level at the Stratford gauge is also directly affected by all upstream inflows, and is therefore likely to have a more direct relationship with the upstream gauges than the upstream gauges have with each other. By using the relationship between each upstream gauge and the Stratford gauge, peak flows at the upstream site outside the available gauged record can be estimated and therefore improve the flood frequency analysis estimates.

Figure 3-11, Figure 3-12, and Figure 3-13 shows the relationship between the different upstream sites and the Avon River at Stratford. There is a strong correlation ($R^2 > 0.8$) between each upstream location and the flows at Stratford which is expected given the majority of runoff is generated in the upper catchment.

Annual maximums were used for these relationships under the assumption that large floods in each gauged tributary correlate with large floods at Stratford. Based on hydrologic calibration it has been noted that this is a general trend within the system.

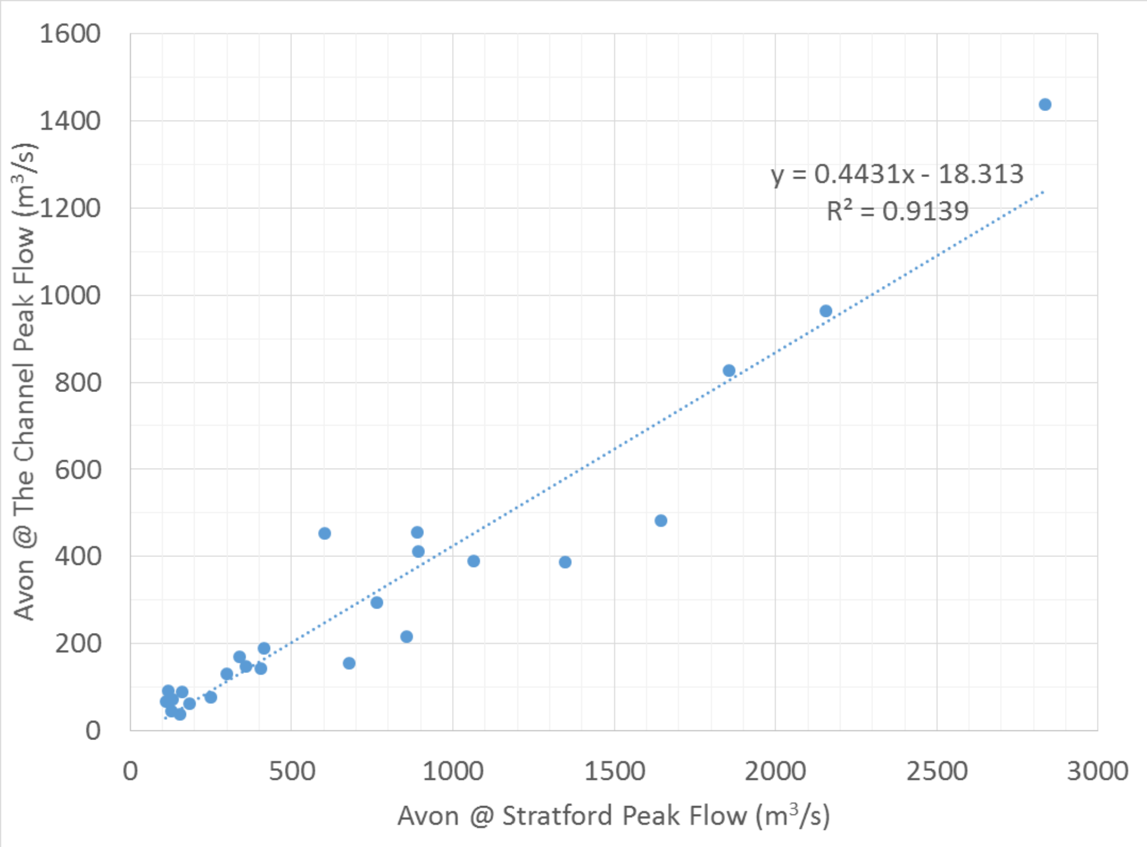

Figure 3-11 **Relationship between Avon River at The Channel at Stratford**

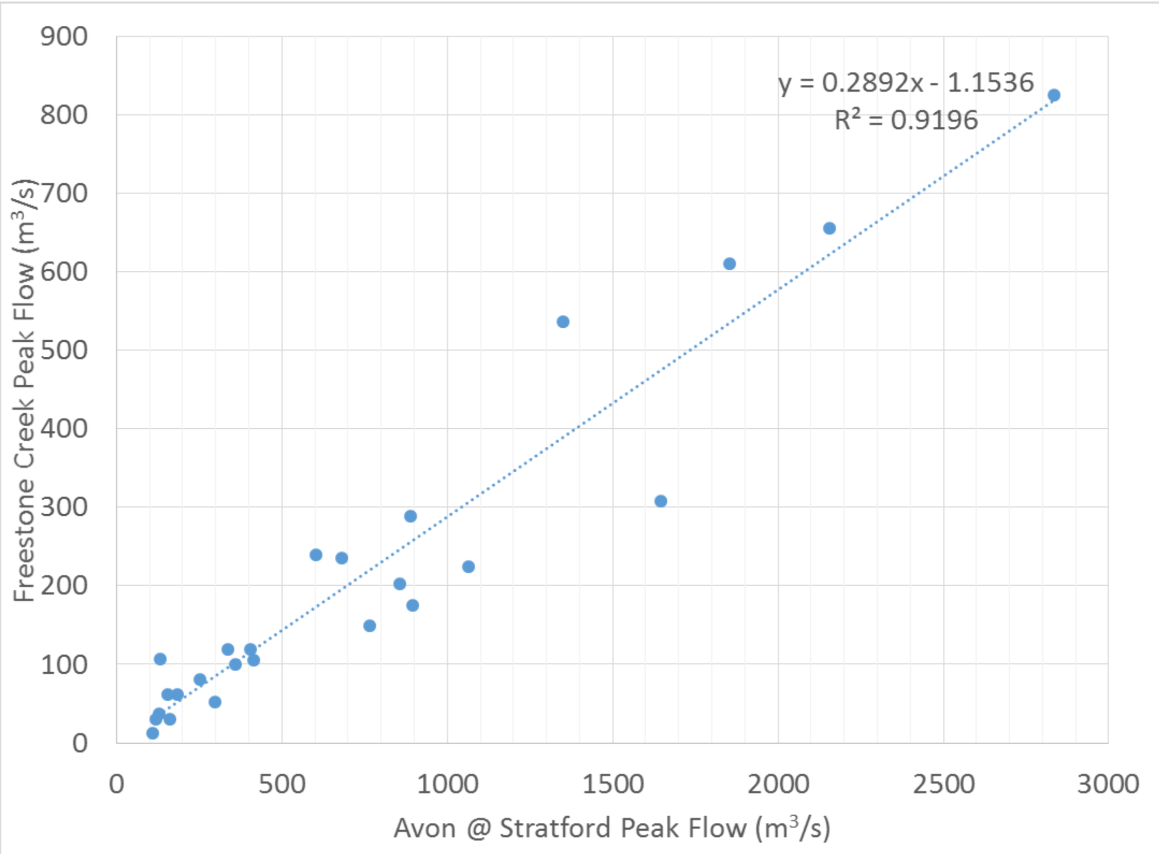

Figure 3-12 **Relationship between Freestone Creek at Briagolong and Avon River at Stratford**

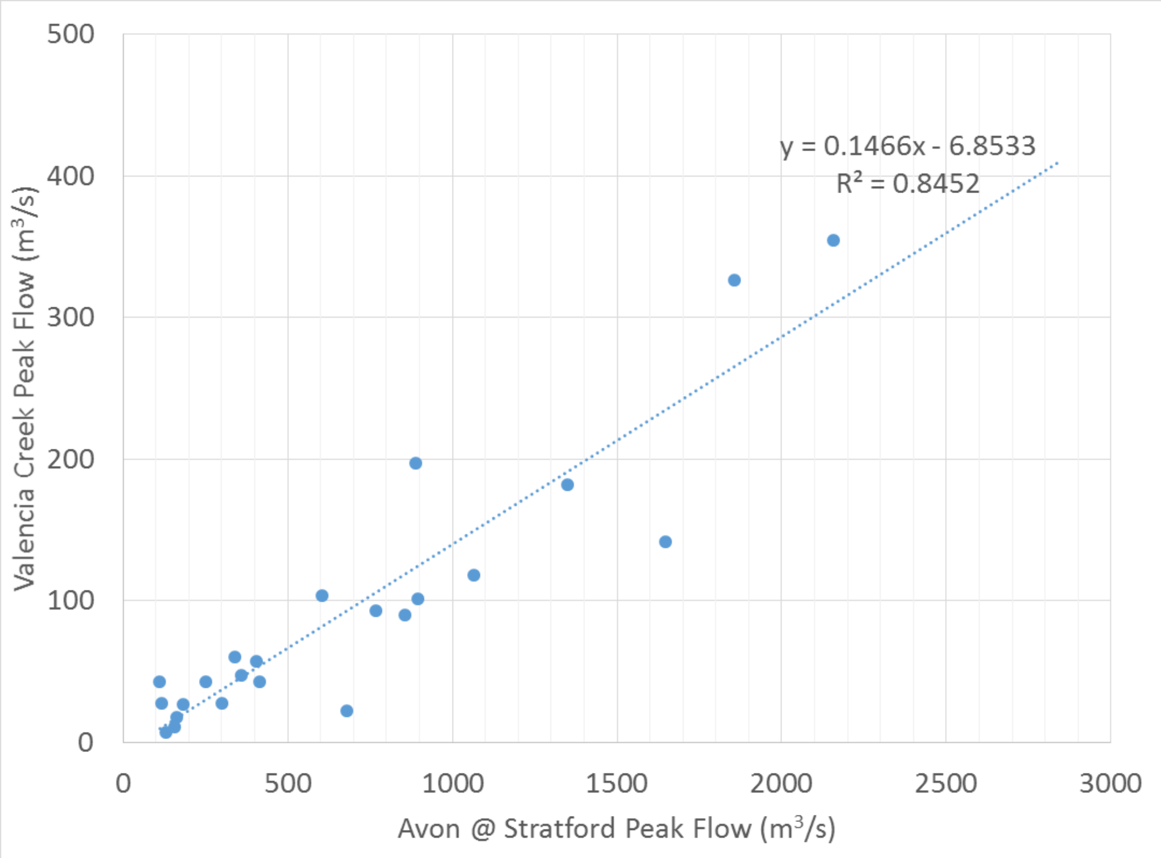

Figure 3-13 Relationship between Valencia Creek at Gillio Rd and Avon River at Stratford

3.5.3 Avon River at Stratford

Annual maximum flows were extracted from the gauge record for Avon River at Stratford (225201) and are listed in Table 3-5. The 1936 and 1950 flood peaks were recovered from historic documents whilst the 1971 flood was estimated based on scaling from Freestone Creek as described in Section 3.5.2.

Table 3-5 Summary of annual peak flows for Avon River at Stratford

Year	Max Flow (m^3/s)	Year	Max Flow (m^3/s)	Year	Max Flow (m^3/s)
1936	2000*	1988	679.9	2002	250.9
1950	1650**	1989	118.5	2003	20.8
1971	2080***	1990	2834.5	2004	27.5
1977	155.1	1991	338.0	2005	603.5
1978	1645.5	1992	413.7	2006	22.4
1979	40.8	1993	766.2	2007	2156.0
1980	358.3	1994	110.9	2008	94.0
1981	54.9	1995	894.6	2009	3.7
1982	129.4	1996	29.5	2010	30.6
1983	298.9	1997	82.4	2011	889.4
1984	856.4	1998	1349.2	2012	1854.8
1985	1064.8	1999	12.3	2013	404.6
1986	13.3	2000	58.6	2014	132.4
1987	161.5	2001	183.7		

**From Strom, 1937*
*** From Macintyre & Grant, 1950*
**** Estimated based on Freestone Creek @ Briagolong Gauge Value*

A number of reports of historic flooding were found, however they lacked sufficient quantitative evidence to include in the flood frequency analysis. A censored flood peak threshold was included in the flood frequency analysis based on anecdotal information as summarised in Table 3-6.

Table 3-6 Treatment of historic flood peak threshold (Avon River at Stratford)

Threshold (m^3/s)	Peaks above threshold	Peaks below threshold
2000	1	111 (1936 flood largest between settlement in 1865 and start of gauging in 1977)

'Censored flood peaks' allow indirect flow estimates to be included as quantitative values in flood frequency estimation. The censored flood peak in Table 3-6 refers to the fact that while we don't know the exact magnitude of the 1936 flood, we do know it was greater than 2000m^3/s. We also know that there were no floods bigger than this one between 1865 and 1977, so there is 111 years of unrecorded flows that there was less than 2000m^3/s peak flow for the year. The inclusion of this unrecorded data increases the statistical accuracy of flow estimates.

The results of the FFA are shown in Figure 3-14 and Table 3-7. They show a 1% AEP flow estimate of 2,798 m^3/s with 5-95% confidence limits of 2,181 to 4,184 m^3/s. These confidence limits are considered reasonable based on experience with other FLIKE analyses.

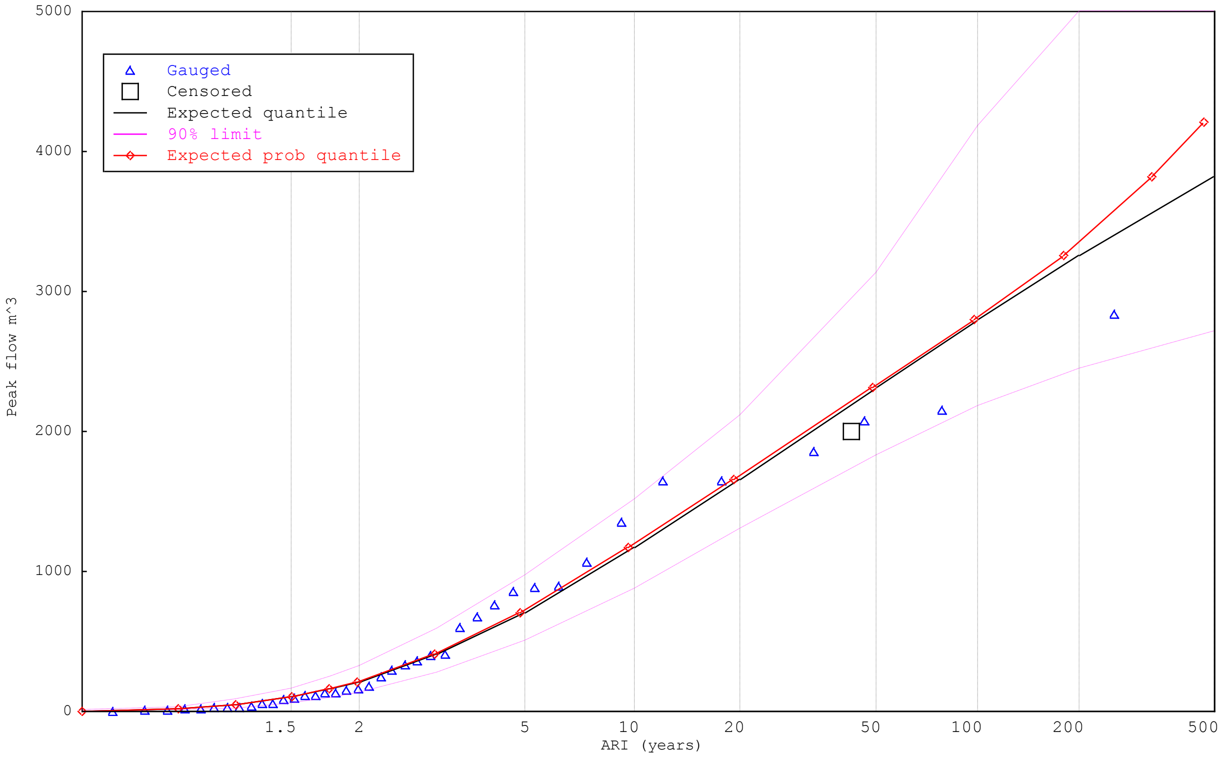

Figure 3-14 Log Pearson III distribution fitted to annual series for Avon River at Stratford (with historic information included)

Table 3-7 FFA Peak Flow Estimates for Avon River at Stratford

AEP	Peak Flow Estimate (m^3/s)	
	Log Pearson III	5-95% Confidence Limits
20%	709	(501 – 972)
10%	1168	(878 – 1514)
5%	1658	(1301 – 2114)
2%	2316	(1832 – 3132)
1%	2799	(2181 – 4184)
0.5%	3258	(2452 – 5488)
0.2%	3820	(2719 – 7453)

Comparison to Previous Estimates

Estimates of peak flows from previous studies by SKM (2003) and Alluvium (2013) are shown in Figure 3-15.

The SKM (2003) estimate aligns well within the 5% confidence limits of the FFA, with design flow values approximately 20% higher on average. SKM's (2003) flood frequency analysis used a partial series focussing on small (10% AEP and smaller) events. As the partial series does not have historic information included, has 11 less years of data, and uses older flood frequency techniques, the current analysis is considered more appropriate.

Alluvium's (2013) estimate is also within the 5% confidence limits for the FFA. Alluvium's design flow estimate included a partial and annual series based on flow data between 1976 and 2012. Almost identical flow data is being used between the two analyses, however the FFA has included historic floods. This higher degree of certainty has allowed for lower flow estimates in the larger events.

The current FFA with historic information included is broadly consistent with previous work, however it provides more credible estimates than the previous analyses, as it includes much more gauged data than the 2003 analysis, as well as historical information on flooding prior to gauge records (which was not included in the 2012 analysis). The current analysis also makes use of improved flood frequency methods within FLIKE as recommended by the current Australian Rainfall and Runoff review (Kuzcera, 2014).

The current Australian Rainfall and Runoff review has developed a new regional flood frequency estimate (RFFE) which was used to compare Avon River flows to regional methods, called the Australian Regional Flood Frequency Model (ARFF). The ARFF estimates for peak flows were considerably lower than that which was estimated using FLIKE. In this data rich catchment, the FLIKE analysis is considered much more reliable than methods based on regional parameters.

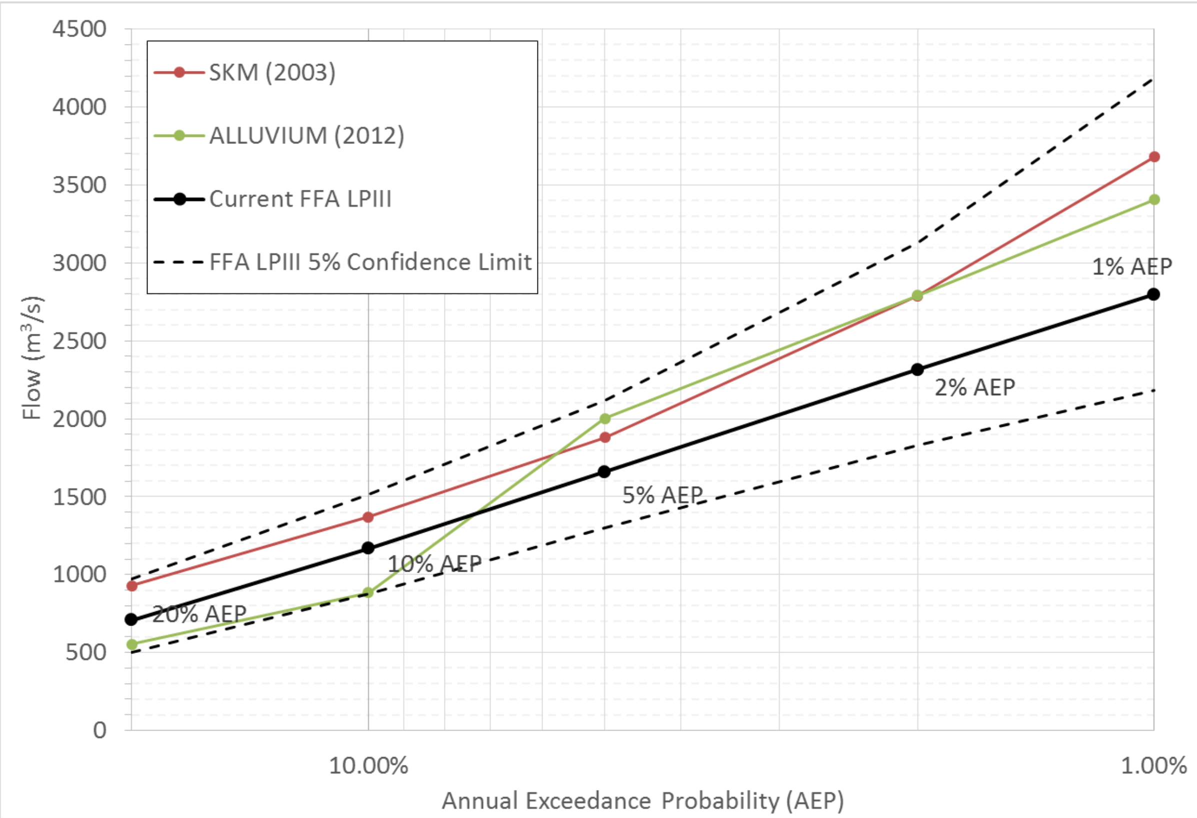

Figure 3-15 Comparison of Peak Flow Estimates

Table 3-8 RFFE Flow Estimates and previous Flood Frequency Estimates for Stratford gauge

AEP	Peak Design Flow (m^3/s) (SKM, 2003)*	Peak Design Flow (m^3/s) (Alluvium, 2013)	ARFF Design Flow Estimate		
			Design Estimate (m^3/s)	Upper Confidence Limit (m^3/s)	Lower Confidence Limit (m^3/s)
20%	930	552	241	539	109
10%	1370	884	337	761	150
5%	1880	2001	434	994	189
2%	2790	2793	566	1321	242
1%	3680	3407	666	1565	280

*Results were estimated from the graph provided as a data table was not supplied in report

3.5.4 Avon River at The Channel

Annual maximum flows were extracted from the gauge record for Avon River at The Channel (225224) and are listed in Table 3-9. The 1936, 1950 and 1971 flood peaks were estimated based on scaling from Stratford as described in 3.5.2.

Table 3-9 Summary of annual peak flows for Avon River at The Channel

Year	Max Flow (m^3/s)	Year	Max Flow (m^3/s)	Year	Max Flow (m^3/s)
1936	868*	1985	389.8	2000	30.8
1950	715*	1986	6.4	2001	63.1
1971	905*	1987	90.3	2002	76.7
1973	25.7	1988	155.5	2003	13.8
1974	284.6	1989	91.4	2004	7.3
1975	242.8	1990	1437.7	2005	453.1
1976	263.7	1991	170.7	2006	17.2
1977	38.9	1992	190.9	2007	962.5
1978	483.7	1993	294.0	2008	42.9
1979	34.5	1994	67.6	2009	7.2
1980	147.1	1995	411.6	2010	30.1
1981	18.6	1996	17.8	2011	455.0
1982	46.4	1997	70.3	2012	827.8
1983	131.9	1998	387.0	2013	143.2
1984	217.7	1999	5.3	2014	72.8

** Estimated based on Avon River @ Stratford Flow*

A censored flood peak was included in the flood frequency analysis based on anecdotal information as summarised in Table 3-10.

Table 3-10 Treatment of historic flood peak threshold (Avon River at The Channel)

Threshold (m^3/s)	Peaks above threshold	Peaks below threshold
870	1	105 (1936 flood largest between settlement in 1865 and start of gauging in 1973)

The results of the FFA are shown in Figure 3-16 and Table 3-11. They show a 1% AEP flow estimate of 1,309 m^3/s with 5-95% confidence limits of 959 to 2,089 m^3/s. These confidence limits are considered reasonable based on experience with other FLIKE analyses.

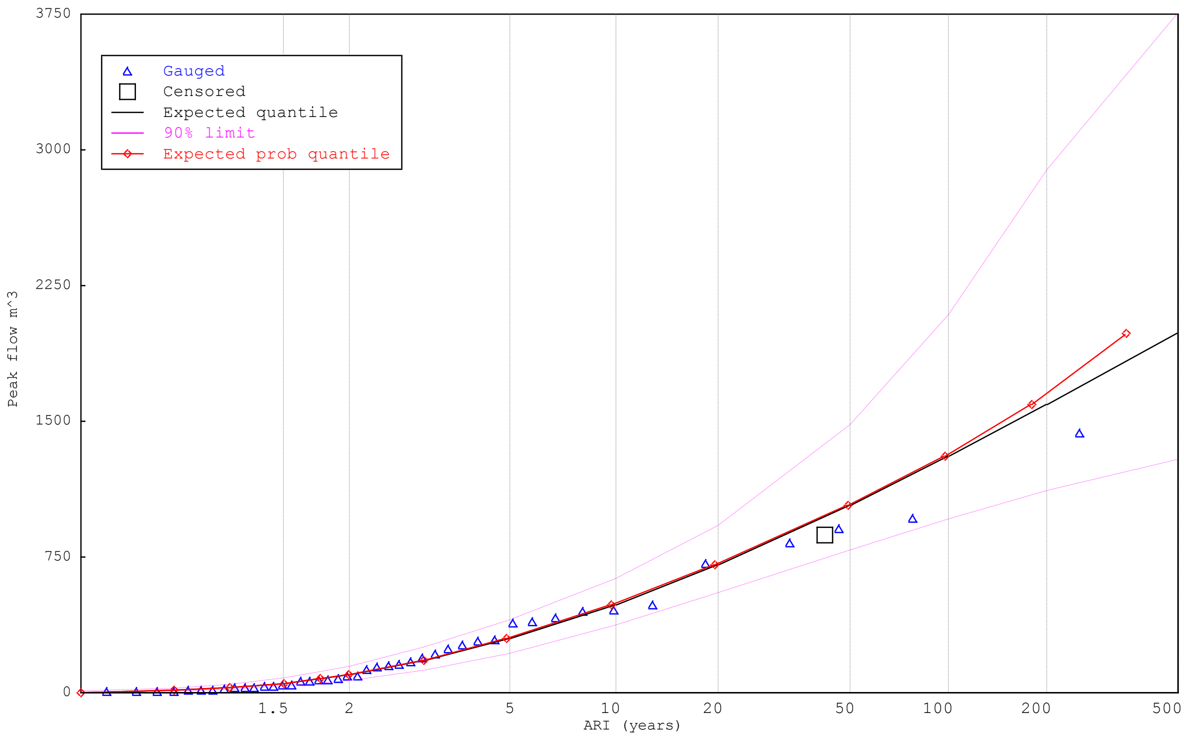

Figure 3-16 Log Pearson III distribution fitted to annual series for Avon River at The Channel (with historic information included)

Table 3-11 FFA Peak Flow Estimates for the Avon River at The Channel

AEP	Peak Flow Estimate (m^3/s)	
	Log Pearson III	5-95% Confidence Limits
20%	297	(215 – 398)
10%	488	(370 – 631)
5%	709	(549 – 924)
2%	1038	(788 – 1479)
1%	1309	(959 – 2089)
0.5%	1593	(1113 – 2886)
0.2%	1986	(1283 – 4313)

3.5.5 Valencia Creek at Gillio Road

Annual maximum flows were extracted from the gauge record for Valencia Creek at Gillio Road (225223) and are listed in Table 3-12. The 1936, 1950, 1971 and 1990 flood peaks were estimated based on scaling from Stratford as described in Section 3.5.2.

Table 3-12 Summary of annual peak flows Valencia Creek at Gillio Road

Year	Max Flow (m^3/s)	Year	Max Flow (m^3/s)	Year	Max Flow (m^3/s)
1936	286*	1985	117.8	2001	27.0
1950	235*	1986	2.4	2002	43.0
1971	298*	1987	17.9	2003	0.8
1972	0.4	1988	22.5	2004	2.5
1973	6.1	1989	27.5	2005	103.8
1974	122.7	1990	409**	2006	5.9
1975	16.2	1991	60.0	2007	354.7
1976	98.4	1992	42.8	2008	9.0
1977	10.6	1993	93.0	2009	1.3
1978	141.7	1994	43.0	2010	14.9
1979	5.6	1995	101.0	2011	197.1
1980	47.5	1996	2.5	2012	326.7
1981	5.6	1997	9.4	2013	57.3
1982	7.4	1998	181.8	2014	N/A***
1983	27.9	1999	1.4		
1984	90.0	2000	4.5		

** Estimated based on Avon River @ Stratford Flow*
*** Gauge washed away - estimated based on Avon River @ Stratford Flow*
****Not enough data recorded in 2014.*

A censored flood peak was included in the flood frequency analysis based on anecdotal information as summarised in Table 3-13.

Table 3-13 Treatment of historic flood peak threshold (Valencia Creek at Gillio Road)

Threshold (m^3/s)	Peaks above threshold	Peaks below threshold
286	1	104 (1936 flood largest between settlement in 1865 and start of gauging in 1972)

The results of the FFA are shown in Figure 3-18 and Table 3-14. They show a 1% AEP flow estimate of 419 m^3/s with 5-95% confidence limits of 316 to 670 m^3/s. These confidence limits are considered reasonable based on experience with other FLIKE analyses.

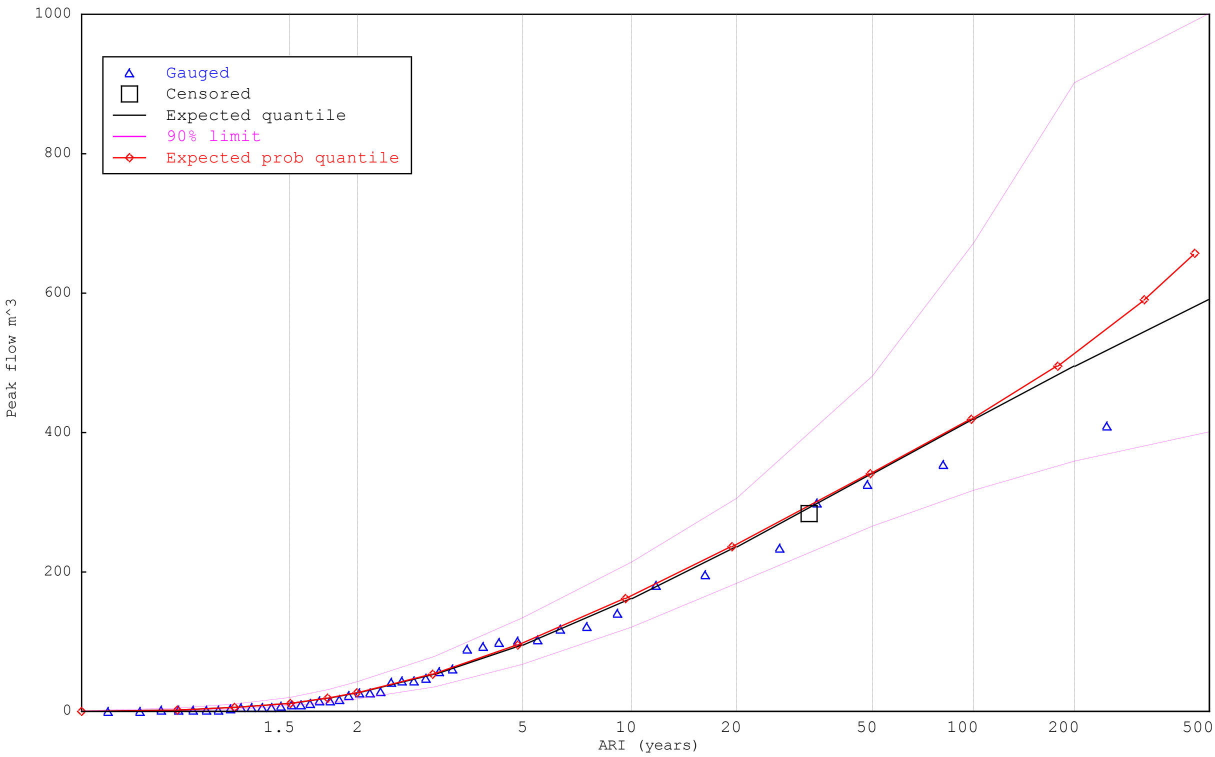

Figure 3-17 **Log Pearson III distribution fitted to annual series for Valencia Creek at Gillio Road (with historic information included)**

Table 3-14 **FFA Peak Flow Estimates for Valencia Creek at Gillio Road**

AEP	Peak Flow Estimate (m^3/s)	
	Log Pearson III	5-95% Confidence Limits
20%	95	(66 – 133)
10%	162	(121 – 213)
5%	237	(184 – 305)
2%	340	(264 – 481)
1%	419	(316 – 670)
0.5%	495	(359 – 902)
0.2%	590	(400 – 1271)

3.5.6 Freestone Creek at Briagolong

Annual maximum flows were extracted from the gauge record for Freestone Creek at Briagolong (225218) and are listed in Table 3-15. The 1936 and 1950 flood peaks were estimated based on scaling from Stratford as described in Section 3.5.2.

Table 3-15 Summary of annual peak flows for Freestone Creek at Briagolong

Year	Max Flow (m^3/s)	Year	Max Flow (m^3/s)	Year	Max Flow (m^3/s)
1936	577*	1983	51.7	2000	29.3
1950	475*	1984	203.2	2001	61.9
1968	54.4	1985	224.9	2002	80.8
1969	212.9	1986	11.3	2003	2.6
1970	337.5	1987	29.8	2004	50.4
1971	600.2	1988	234.9	2005	239.7
1972	0.6	1989	30.6	2006	7.5
1973	14.9	1990	824.9	2007	655.9
1974	169.7	1991	118.6	2008	93.4
1975	78.6	1992	104.8	2009	1.1
1976	108.0	1993	148.7	2010	17.1
1977	61.5	1994	13.0	2011	288.5
1978	308.5	1995	175.6	2012	610.8
1979	3.5	1996	4.9	2013	118.5
1980	99.6	1997	12.3	2014	107.2
1981	23.5	1998	535.8		
1982	36.5	1999	4.8		

** Estimated based on Avon River @ Stratford Flow*

A censored flood peak was included in the flood frequency analysis based on anecdotal information as summarised in Table 3-16.

Table 3-16 Treatment of historic flood peak threshold (Freestone Creek at Briagolong)

Threshold (m^3/s)	Peaks above threshold	Peaks below threshold
577	1	101 (1936 flood largest between settlement in 1865 and start of gauging in 1968)

The results of the FFA are shown in Figure 3-18 and Table 3-17. They show a 1% AEP flow estimate of 781 m^3/s with 5-95% confidence limits of 633 to 1,085 m^3/s. These confidence limits are considered reasonable based on experience with other FLIKE analyses.

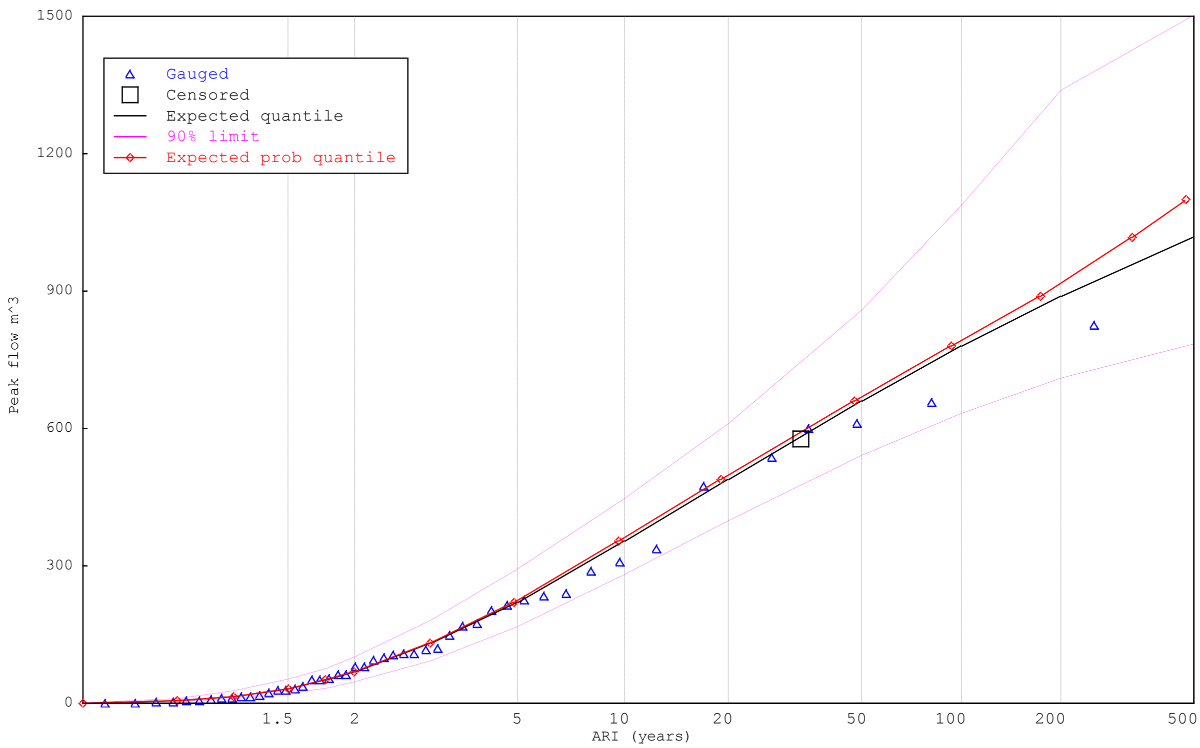

Figure 3-18 Log Pearson III distribution fitted to annual series for Freestone Creek at Briagolong (with historic information included)

Table 3-17 FFA Peak Flow Estimates for Freestone Creek at Briagolong

AEP	Peak Flow Estimate (m^3/s)	
	Log Pearson III	5-95% Confidence Limits
20%	221	(166 – 291)
10%	354	(279 – 446)
5%	489	(397 – 608)
2%	661	(541 – 857)
1%	781	(633 – 1085)
0.5%	890	(707 – 1338)
0.2%	1016	(783 – 1698)

3.6 Hydrologic Modelling

3.6.1 Overview

A hydrological model of the catchment was developed for the purpose of extracting design flows to be used as boundary conditions in the Avon River hydraulic model. The rainfall-runoff program, RORB (Version 6) was used for this study.

RORB is a non-linear rainfall runoff and streamflow routing model which is used for calculation of flow hydrographs in drainage and stream networks. The model requires catchments to be divided into subareas, connected by a series of conceptual reach storages. Design storm rainfall is input to the centroid of each subarea. Specified losses are then deducted, and the excess routed through the reach network.

There are four streamflow gauges within the catchment which were used to calibrate the RORB model. The Avon River gauge at Stratford has 38 years of flow records from 1976-2015, covering the 2007, 2011 and 2012 floods and other smaller floods. The Avon River at The Channel, Freestone Creek at Briagolong and Valencia Creek at Gillio Road all have a similar period of record, and rating curves with a similar level of confidence. Parameter selection was based on calibration to all four gauges and comparison to accepted regional methods, and the design flows were validated against the flood frequency analysis. The approach for the selection of routing and loss parameters is outlined in the following sections

3.6.2 RORB Model Development

The ArcHydro tool was used to determine the initial delineation of catchments, sub-catchments and drainage paths of the Avon River for input to the hydrologic model (Figure 3-19). The catchment was split into 82 sub-catchments with areas ranging from 1.6 to 70.4 km^2. A RORB model was then constructed of the catchment using miRORB (MapInfo RORB tools).

The RORB model was at a resolution adequate to resolve the main drainage paths and sub-catchments, and to provide smooth hydrographs for the hydraulic model. This meant the relatively minor catchments of Blackall Creek and Nuntin Creek generally required much smaller subcatchments than the main streams to be adequately resolved for the hydraulic model. The large variance in subarea size meant that catchment routing parameters could not be expected to remain uniform as in traditional RORB models. 'Interstation areas' were therefore introduced at the downstream end of Blackall Creek, and at Boisdale near Nuntin Creek drain, which allow for scaled catchment routing parameters to be adopted in these catchments with small sub-catchment areas. These areas have adopted the same losses as the calibrated upstream areas.

Interstation areas are also included at each gauge. This allows independent calibration of each gauge.

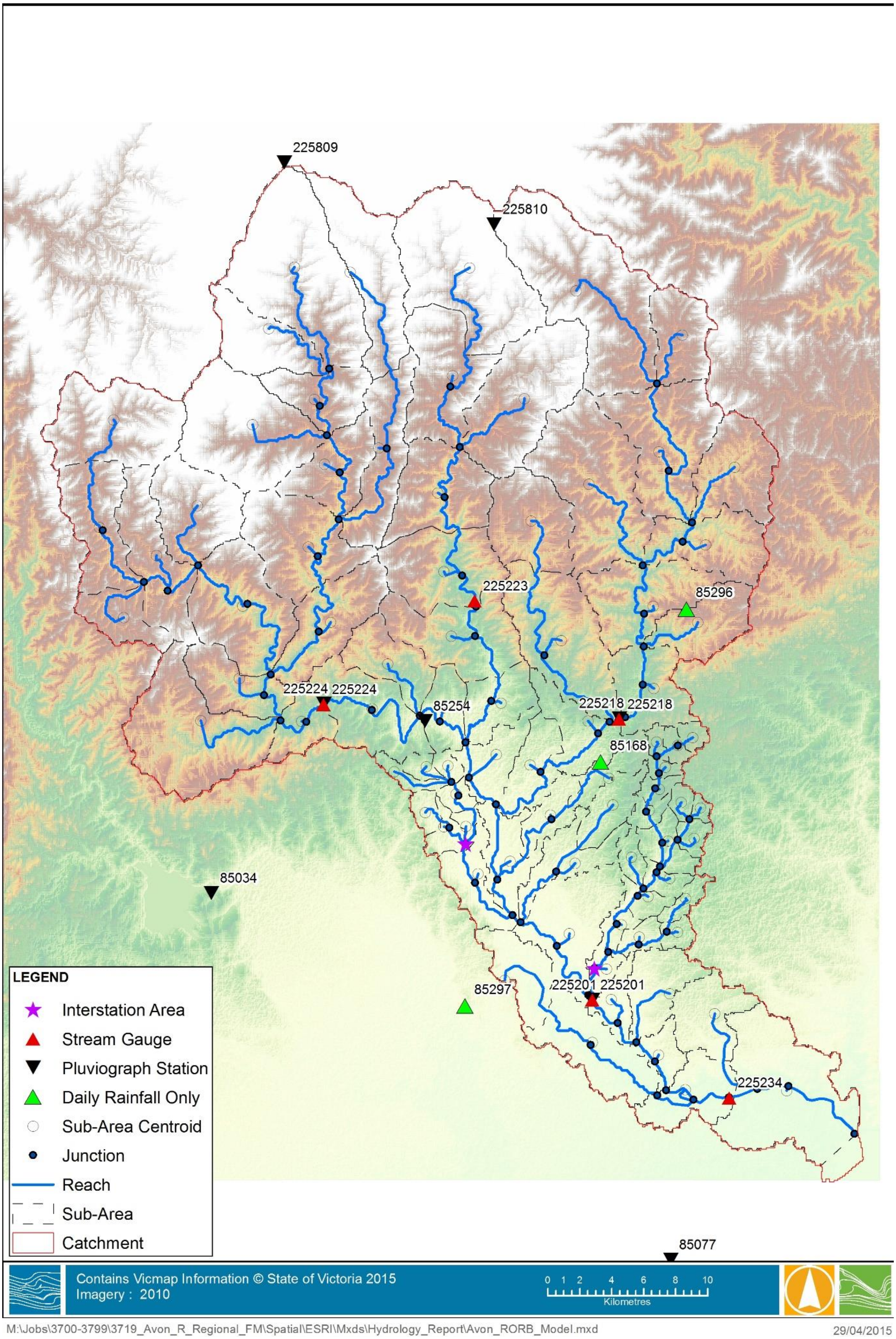

Figure 3-19 RORB Model Structure

3.6.3 Fraction Impervious

The fraction impervious (FI) was included in the hydrologic model by applying a representative FI for each subarea. Aerial imagery suggests that the Avon River catchment has very limited impervious areas. For the RORB model, the upper forested catchment was assumed to have a fraction impervious of 0. The downstream agricultural areas were all assumed to have a fraction impervious of 0.1 and the key townships of Stratford, Briagolong and Boisdale were all assumed to have a fraction impervious of 0.5, as described by Table 3-18.

Table 3-18 Fraction Impervious Designation for Planning Zones

Description	Fraction Impervious (FI)
Agriculture / Floodplain Area	0.1
Forest	0
Township Zone	0.5

3.6.4 Baseflow

Baseflow has been extracted from instantaneous streamflow data at the Stratford gauge using Basejumper (SKM, 2007). Basejumper uses the Lyne and Hollick digital filter to separate a flow series into quick and slow response components. The separated baseflow hydrographs were then compared for all calibration events, as shown below. A baseflow separation parameter of 0.925 was adopted. The baseflow hydrograph for the Avon River at Stratford tends to peak much later then the total flood hydrograph and as such has little impact on the flood peak. The largest difference was seen in the smaller 2011 event where a difference in peak of 1.3% was observed when baseflow was extracted. It is also noted that the baseflow hydrograph has little impact on the hydrograph shape, especially at the start and peak of events. Since it makes such a limited contribution, baseflow was not extracted from the hydrographs for calibration, or added to the design hydrographs.

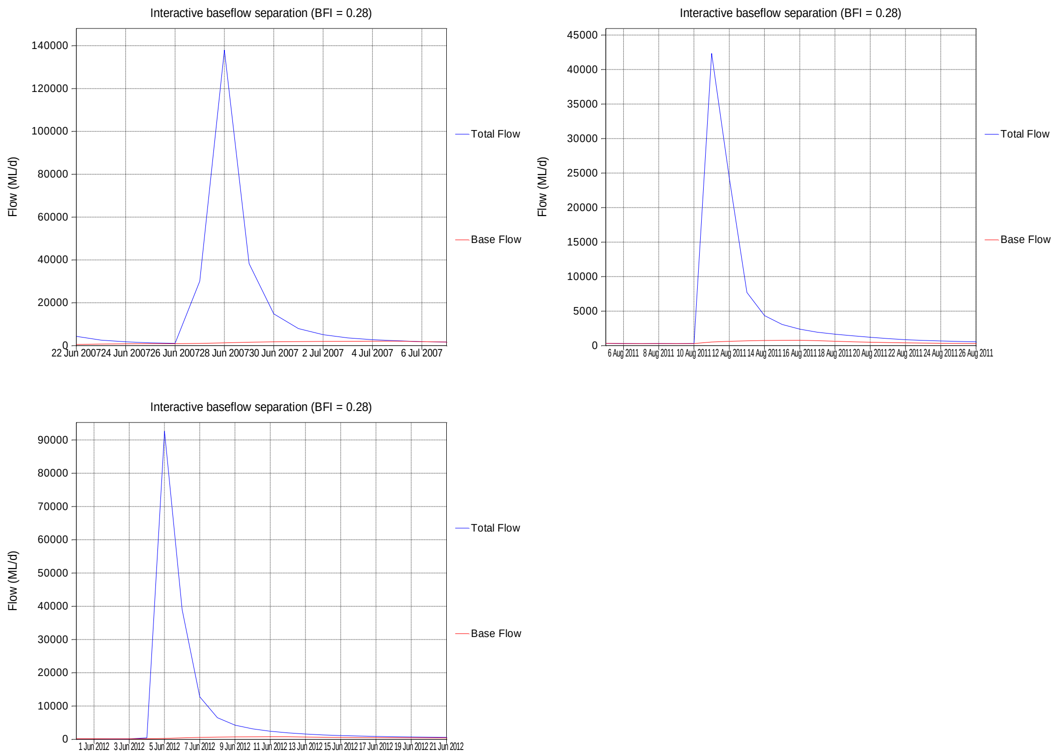

Figure 3-20 Baseflow separation for June 2007, August 2011 and June 2012 calibration events for the Avon River at the Stratford gauge.

3.6.5 Calibration Events

Three recorded events were used for the calibration of the RORB hydrologic model; namely the June 2007, August 2011, and June 2012 floods. Each of these events was represented with a unique temporal and aerial rainfall pattern generated from local rainfall gauge records. The outflow hydrographs from the RORB model were then compared to stream gauges at four locations; Avon River at Stratford, Avon River at The Channel, Valencia Creek at Gillio Road, and Freestone Creek at Briagolong.

The 2007 and 2012 events were moderate to large, with estimated AEPs of approximately 2.5% and 4%, respectively, while the 2011 was a smaller event with an AEP of around 20%. The 2007 event exhibited slightly different behaviour to the other two, with a double peak shaped hydrograph at the gauges and the peak occurring in the Avon comparatively later than at Valencia and Freestone Creeks.

Figure 3-21, Figure 3-23, and Figure 3-25 illustrate the aerial rainfall patterns used in each of the calibration runs. Figure 3-22, Figure 3-24, and Figure 3-26 show the rainfall hyetographs and recorded flows at the four gauges.

The 1990 flood event was not included in the calibration as the river system experienced significant channel change during the event and the Valencia Creek gauge was washed away during this event.

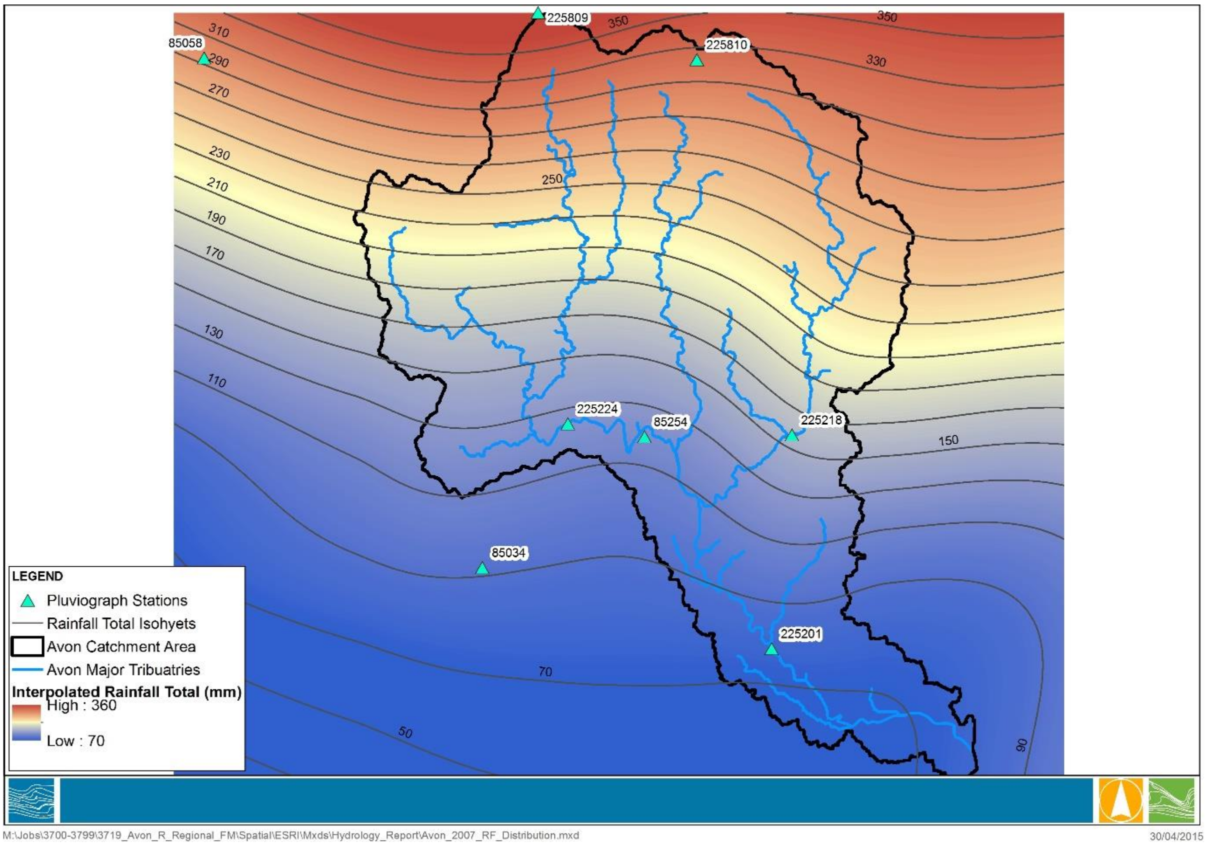

Figure 3-21 Total rainfall across the catchment for the June 2007 calibration event

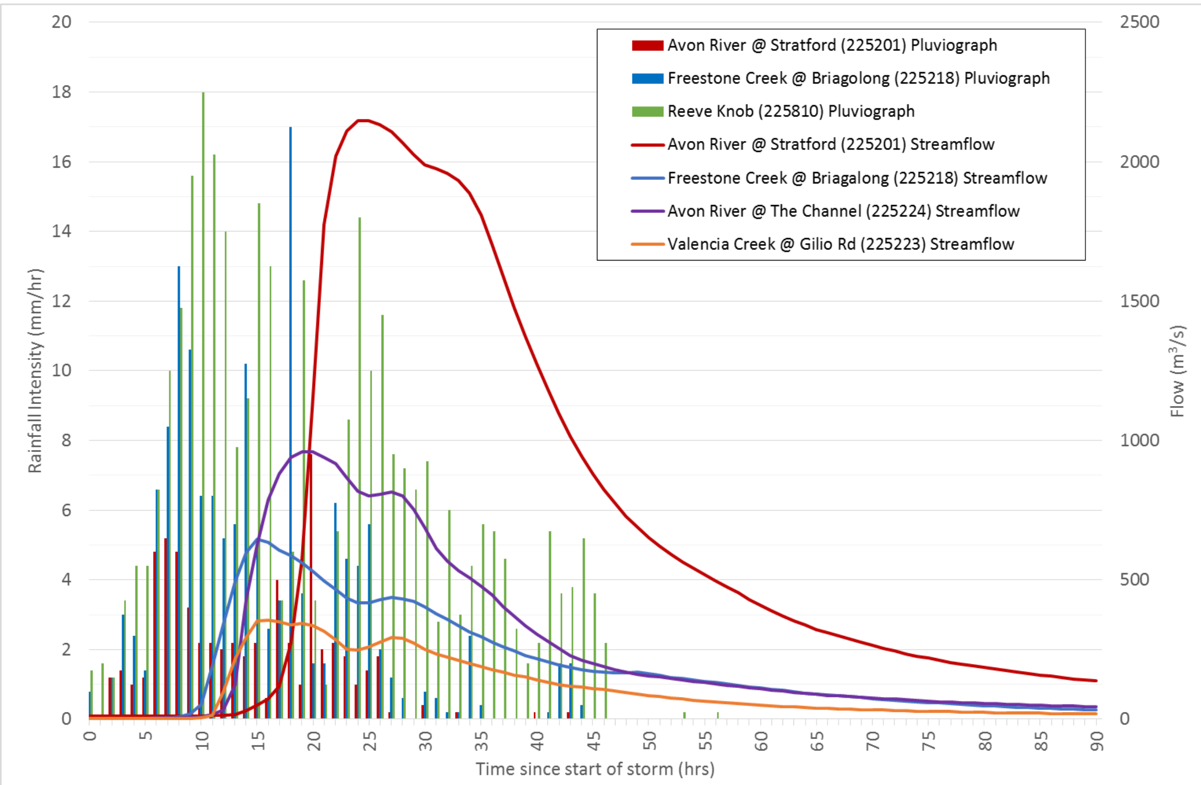

Figure 3-22 Calibration event hyetographs and instantaneous flow hydrographs for the June 2007 calibration event

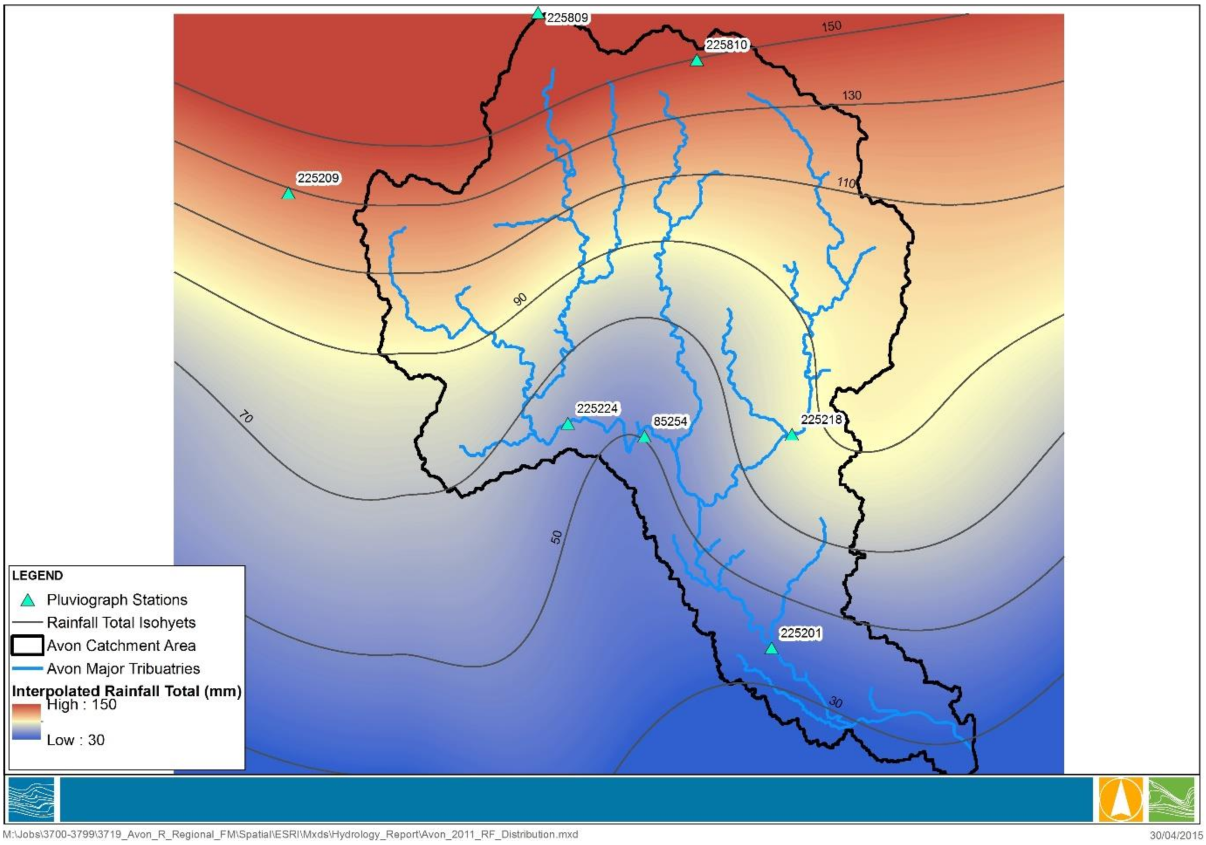

Figure 3-23 Total rainfall across the catchment for the August 2011 calibration event

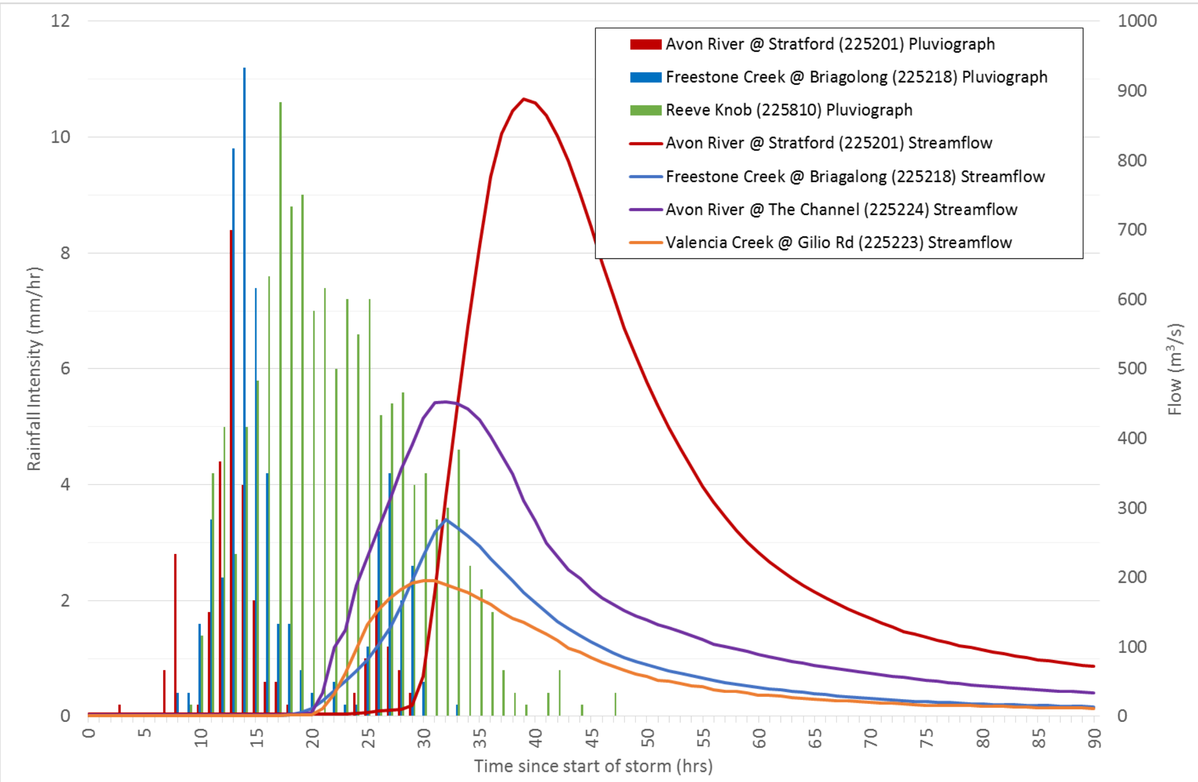

Figure 3-24 Calibration event hyetographs and instantaneous flow hydrographs for the August 2011 calibration event

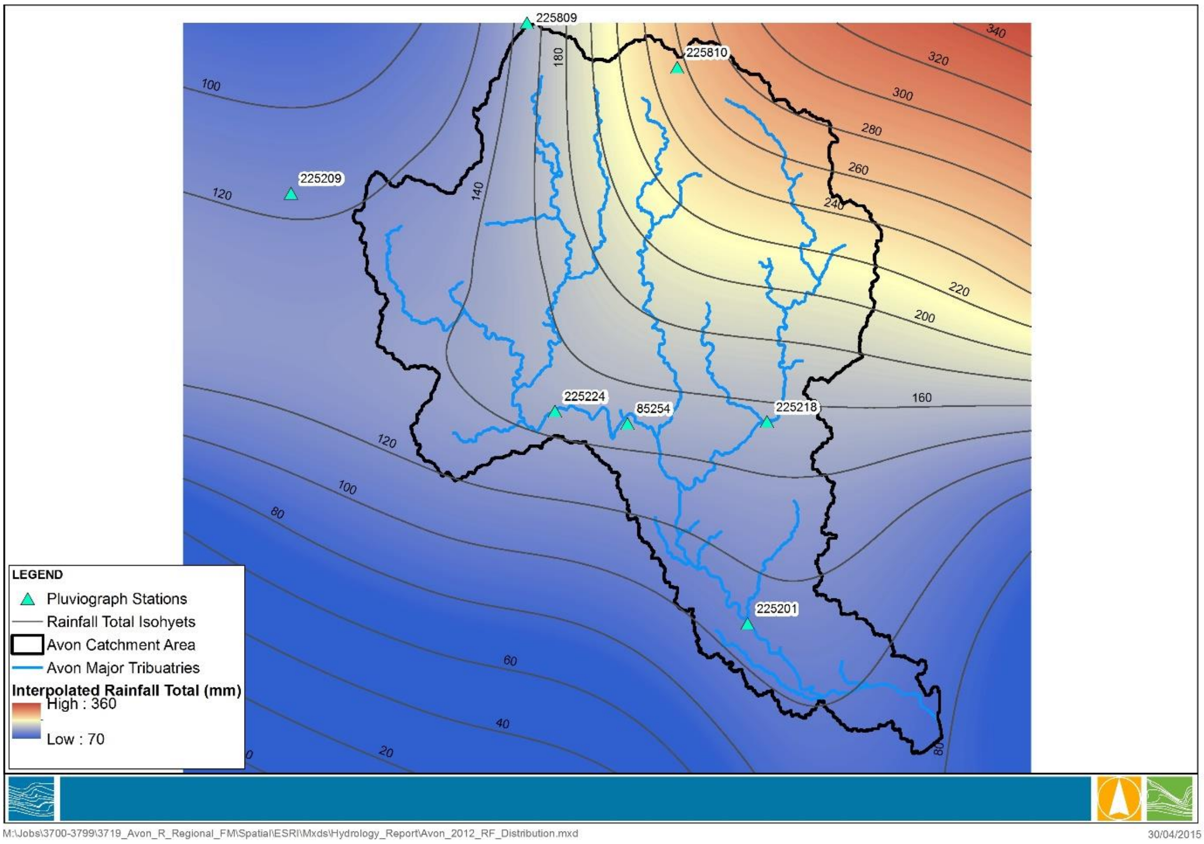

Figure 3-25 Total rainfall across the catchment for the June 2012 calibration event

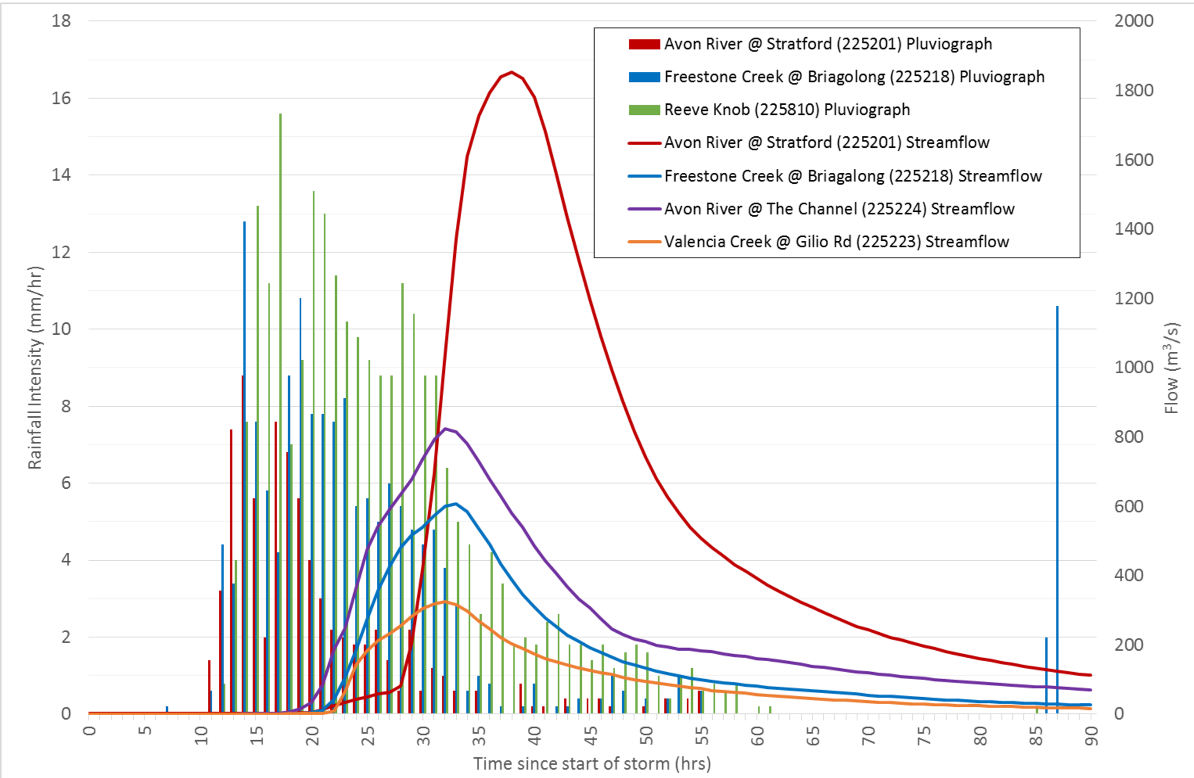

Figure 3-26 Calibration event hyetographs and instantaneous flow hydrographs for the June 2012 calibration event

3.6.6 Calibration of RORB Parameters

The RORB model was run using the initial loss/continuing loss model. The RORB storage and loss parameters – k_c, m, initial loss (IL) and continuing loss (CL) – were fitted for each calibration event to give the best fit to the observed hydrographs. Priority was given to fitting the hydrograph peak and shape, with the volume and timing the secondary priority. The routing parameter k_c was set using a combination of calibration and regional equations. The exponent m was set to 0.8 as per RORB default.

A number of regional equations for the calculation of k_c that are recommended in ARR87 and the RORB manual were used to guide the selection of this parameter (Table 3-19).

Table 3-19 Regional equations for the calculation of k_c

Source	k_c Value					
	Avon River (US of The Channel)	Avon River (US of Stratford)	Valencia Creek	Freestone Creek	Blackall Creek	Nuntin Channel (US of Boisdale)
Aust wide Yu (1989) (Pearse et al 2002)	66					
Vic MAR>800 mm - Eq 3.21 ARR87 (Book V)	44	35	28	38	17	11
Vic MAR<800 mm - Eq 3.22 ARR87 (Book V)	30	21	15	20	8	4
Aust wide Dyer (1994) (Pearse et al 2002)	79					
Victoria data (Pearse et al, 2002)	86					
Default RORB	52	40	31	38	18	11
Scaling from Seaspray Flood Study (Water Technology, in progress)	38					
Scaling from Traralgon Flood Study (Water Technology, in progress)	34					

The final calibrated model parameters for each event are summarised in the following tables. The fit of the RORB modelled hydrographs to the gauged hydrographs for each calibration is shown in Figure 3-27, Figure 3-28, and Figure 3-29.

Table 3-20 RORB Calibration Parameters – Avon River at Stratford

Event	k_c	m	IL (mm)	CL (mm/hr)
2007	20	0.8	50	0.5
2011	20	0.8	40	1.5
2012	25	0.8	50	2

Table 3-21 RORB Calibration Parameters – Avon River at the Channel

Event	k_c	m	IL (mm)	CL (mm/hr)
2007	22	0.8	20	2.2
2011	24	0.8	40	0.8
2012	30	0.8	30	0.1

Table 3-22 RORB Calibration Parameters – Valencia Creek at Gillio Road

Event	k_c	m	IL (mm)	CL (mm/hr)
2007	16	0.8	40	2.0
2011	20	0.8	40	0.0
2012	26	0.8	35	1.9

Table 3-23 RORB Calibration Parameters – Freestone Creek at Briagolong

Event	k_c	m	IL (mm)	CL (mm/hr)
2007	18	0.8	20	2.0
2011	25	0.8	35	0.2
2012	24	0.8	50	0.4

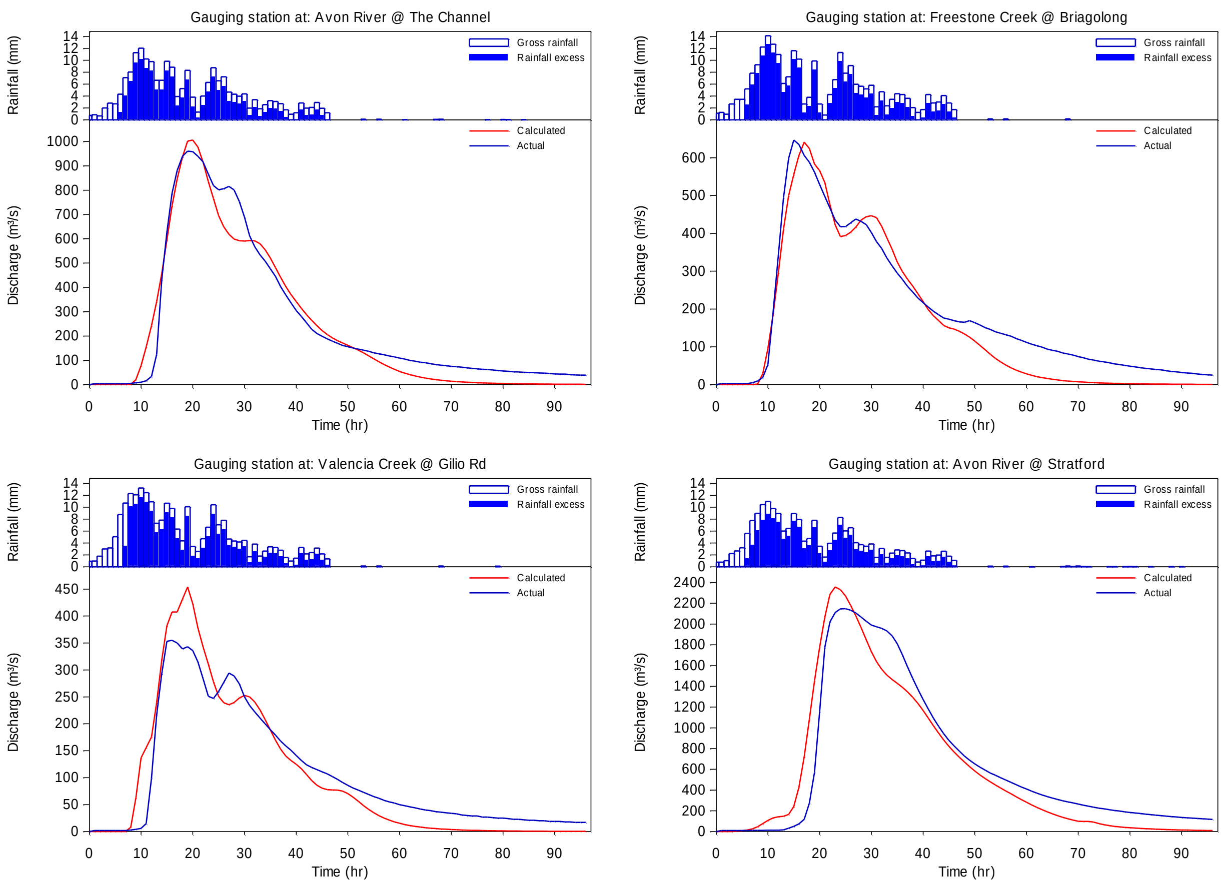

Figure 3-27 Calibration plots for June 2007

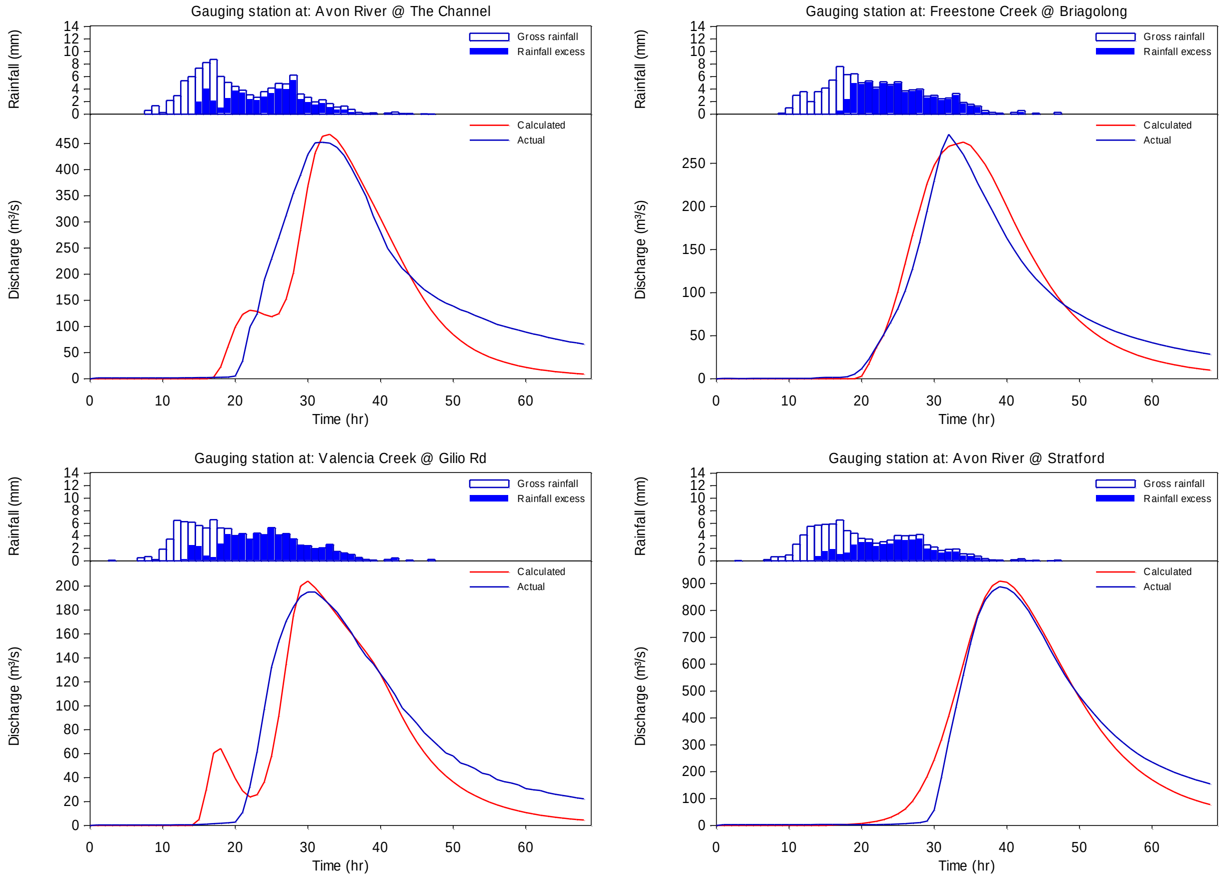

Figure 3-28 Calibration plots for August 2011

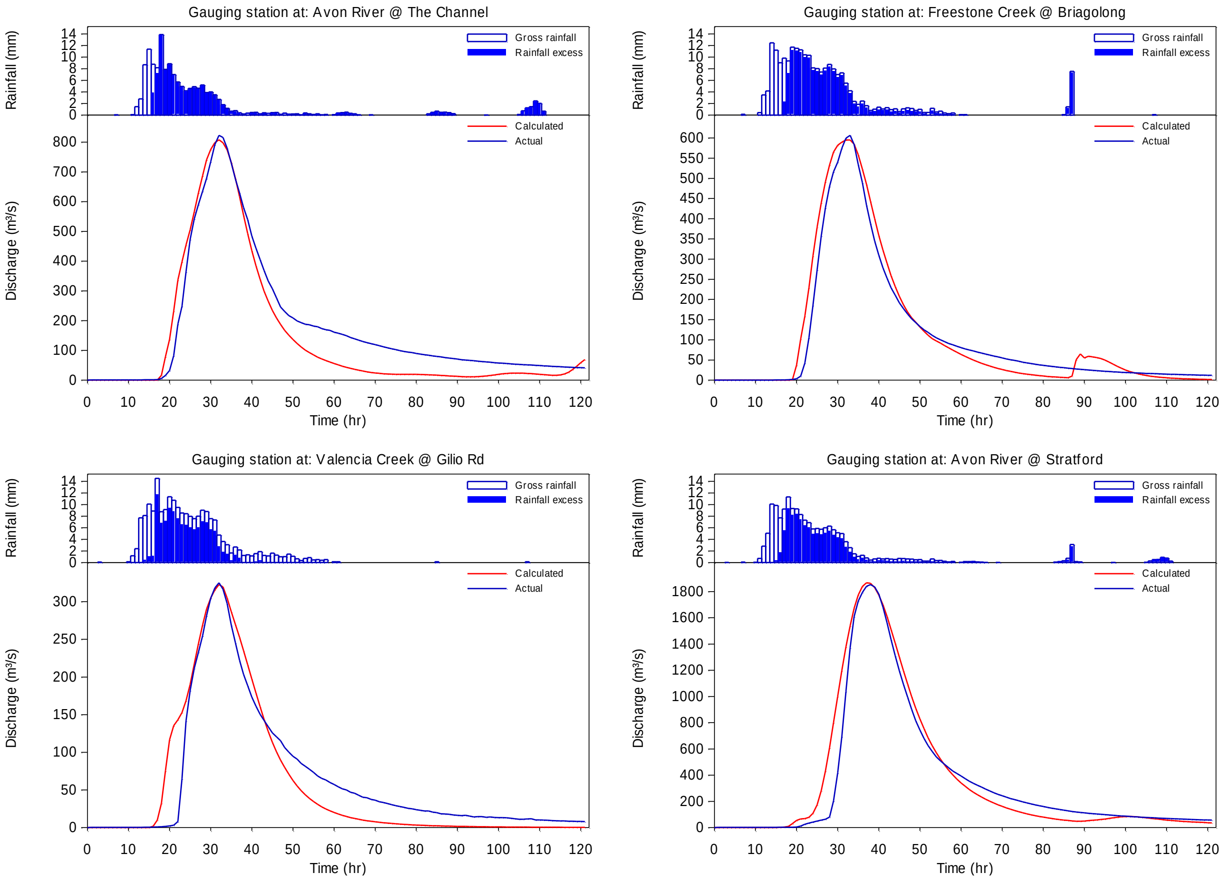

Figure 3-29 Calibration plots for June 2012

The shape and volume of the fitted hydrographs at all four gauges agree well with gauged data. The 2012 and 2011 events were particularly well-matched in shape, timing and volume. The RORB model for these events were able to accurately reproduce flows at all major gauging stations.

In the 2007 event the RORB model predicted the peak of the hydrograph reasonably, with the timing and total flow volume matching well. The modelled peak flow was slightly higher than recorded at the Avon River and Valencia Creek gauges. The shape of the hydrograph at Stratford is also slightly different, with the recorded data showing a pronounced double peak type hydrograph, whereas the RORB model produces a hydrograph with a single main peak and a much smaller secondary peak. Possible reasons for variation in peak flow and hydrograph shape is the routing of the upstream hydrographs. Slight variations on when the Freestone Creek, Valencia Creek and Avon River converge could cause significant differences in peak flows. The peak of Freestone Creek coincided with the Avon peak in the RORB model, however the peaks were slightly different during the real event, which would explain the difference in peak flows. Another explanation could be in the temporal variation of rainfall, as the Avon catchment appears to not register the second peak in rainfall compared to the recorded data.

The k_c values fitted for the calibration events are within the range of those provided by regional equations in Table 3-19. The initial losses tend to be higher than design values and continuing losses tend to be on the low side for the 2011 and 2012 events but reasonable for the 2007 event.

3.6.7 Design Loss Estimates

Design losses were estimated by the design loss prediction equations developed by Hill et al (1998) and (Hill et al. 2014). The losses recommended in AR&R (1987) consistently overestimated peak flows. The Hill et al (1998) losses, in combination with areal reduction factors from Siriwardena and Weinmann (1996), produced peaks that were more consistent with the results of flood frequency analysis.

Hill, et al (1998) calculate initial loss by first calculating the storm initial loss using Equation 1, then the burst initial loss (Equation 2). The burst initial loss varies with storm duration and accounts for the embedded nature of AR&R design rainfalls (Hill et al 1998). The continuing loss is estimated using Equation 3.

Storm initial loss:

$$IL_s = -25.8BFI + 33.8 \qquad (1)$$

Burst initial loss:

$$IL_b = IL_s\left\{1 - \frac{1}{1+142\frac{\sqrt{duration}}{MAR}}\right\} \qquad (2)$$

Continuing loss:

$$CL = 7.97BFI + 0.00659PET - 6.00 \qquad (3)$$

The AR&R Project 6 Stage 3 report (Hill et al. 2014) contains new recommended initial and continuing loss equations, as shown below. No recommendation has been made for the conversion of storm initial loss to burst initial loss.

Storm initial loss:

$$IL_s = 16.7 + 0.141P_{24h}^{2\%} - 0.291MedianAPI \qquad (4)$$

Continuing loss:

$$CL = 3.0\ mm/hr \qquad (5)$$

The values of the input parameters to the previous equations are as follows:

- Median API 29 mm
- BFI 0.21
- PET 1,068 mm
- MAR 651 mm
- $P_{24h}^{2\%}$ 167 mm

The design loss estimates produced by both methods are given in Table 3-24. The two methods were found to produce very similar estimates. The Project 6 losses (Hill et al. 2014) are the most consistent with the losses applied to the calibration events. The equations were applied for the whole catchment. Values of initial loss for the upper catchment interstation areas may be higher.

Table 3-24 Design loss parameter estimates

Source	IL_s (mm)	IL_b (mm)	CL (mm/hr)
Hill et al (1996)	28	11-18 (for 9-72 hour events)	2.7
Project 6 Stage 3 Report (Hill et al. 2014)	32	-	3

3.6.8 Design Flood Validation

Various k_c and loss values were compared to the FFA at Stratford (including historical events) to determine the best fit for the design hydrology. The ARR Project 6 Stage 3 Report (Hill et al. 2014) did not find evidence of variation of loss values with AEP, a finding which is consistent with a range of previous studies. Therefore, rather than varying losses to fit the design flows exactly to the FFA, the validation process was aimed at selecting a single set of loss parameters which provided a reasonable fit across the whole range. This approach was justified given the FFA was based on a dataset with 38 years of historical gauged data and historic floods at Stratford.

RORB parameters were tested using k_c and loss values which were output for each calibration event. These were then compared to design loss estimation based on Hill et al (1996, 2014). After comparison, a parameter set was chosen that best matched the flood frequency analysis at each gauge across all events. The selected parameters are displayed in Table 3-25.

In general, design initial losses were required to be high when compared to calibration and other estimates to get the best fit to flood frequency analysis peak flows. These higher design losses are required for accurate validation in this hydrologic analysis, however, the additional floodplain delineation that occurs in two-dimensional hydraulic analysis may show that losses have been overestimated, and if this is the case the hydrologic inflows will be revisited.

Table 3-25 Adopted Design RORB parameters

Location	k_c	Initial Loss (mm)	Continuing Loss (mm/h)
Avon River at Stratford	20	50	1
Avon River at The Channel	22	50	2
Freestone Creek at Briagolong	19	50	1
Valencia Creek at Gillio Rd	18	50	3

Avon River at Stratford

The chosen Avon River k_c of 20 was the same as two calibration events of 2007 and 2011, and marginally lower than 2012 (k_c value of 25). This value is also broadly consistent with regional estimates of k_c values from ARR (1987), which suggest a value of between 21 and 35. Loss parameters are also consistent with calibration values rather than calculated estimates, with the initial loss of 50 mm equivalent to the calibrated 2007 and 2012 values, whilst 2011 had 40 mm. The continuing loss value of 1 mm/hr is slightly lower than 2011 (1.5 mm/hr) and 2012 (2 mm/hr) and slightly higher than that used for 2007 calibration (0.5 mm/hr). The continuing loss values are also lower than that recommended in AR&R (1987). The fit to flood frequency when using these parameters is shown in Figure 3-30 below. These parameter values provide a very close fit to both high and low frequency events. Other tested parameter sets are also displayed in Figure 3-30.

The shape of the hydrographs for selected parameter sets was compared to the 2012 gauged hydrograph to check that the selected k_c value matched hydrograph shape consistent with actual events (Figure 3-31). The comparison shows that the adopted parameters provide a better fit to the hydrograph shape than that of the 2007 calibration event or using ARR loss values.

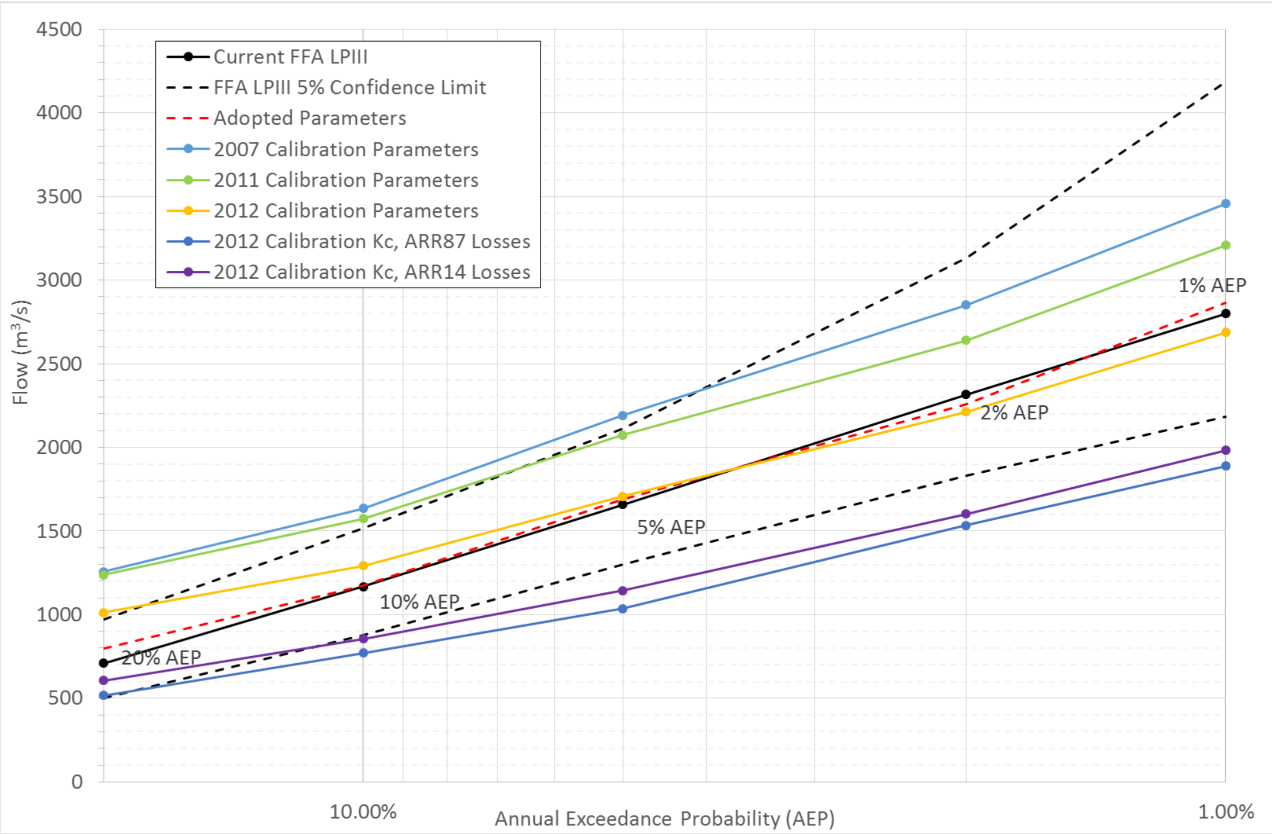

Figure 3-30 RORB peak flow results for various k_c and IL values at Stratford

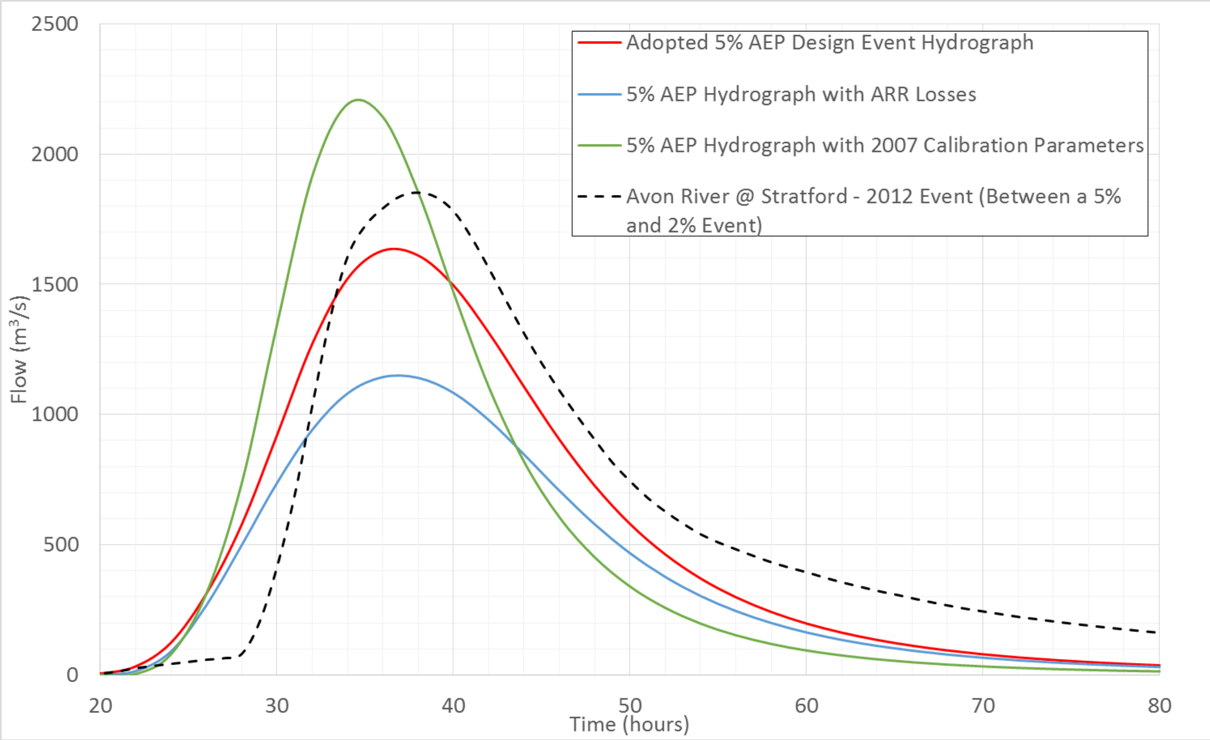

Figure 3-31 Comparison of shape of design hydrographs for selected parameter sets at Stratford

Avon River at The Channel

The chosen Avon River at the Channel k_c of 22 was the same as the 2007 calibration event, and lower than the calibrated 2011 and 2012 events (k_c values of 24 and 30, respectively). This value is also lower than regional estimates of k_c values from AR&R (1987), which suggest a value of between 30 and 44. Loss parameters are also more consistent with calibration values rather than calculated design estimates, with the initial loss of 50 mm higher than the calibrated values (20 mm, 40 mm and 30 mm). The continuing loss value of 2 mm/hr is slightly lower than 2007 value (2.2 mm/hr) and higher than the 2012 and 2011 values (0.8 mm/hr and 0.1 mm/hr). The continuing loss values are lower than that recommended in AR&R (1987). The fit to flood frequency when using these parameters is shown in Figure 3-32 below. These parameter values provide a very close fit to both high and low frequency events. Other tested parameter sets are also displayed in Figure 3-32.

The shape of the hydrographs for selected parameter sets was compared to the 2012 gauged hydrograph to check that the selected k_c value matched produced a hydrograph shape consistent with actual events (Figure 3-33). The comparison shows that the adopted parameters provide a better fit to the hydrograph shape than that of the 2007 calibration event or using AR&R (1987) loss values.

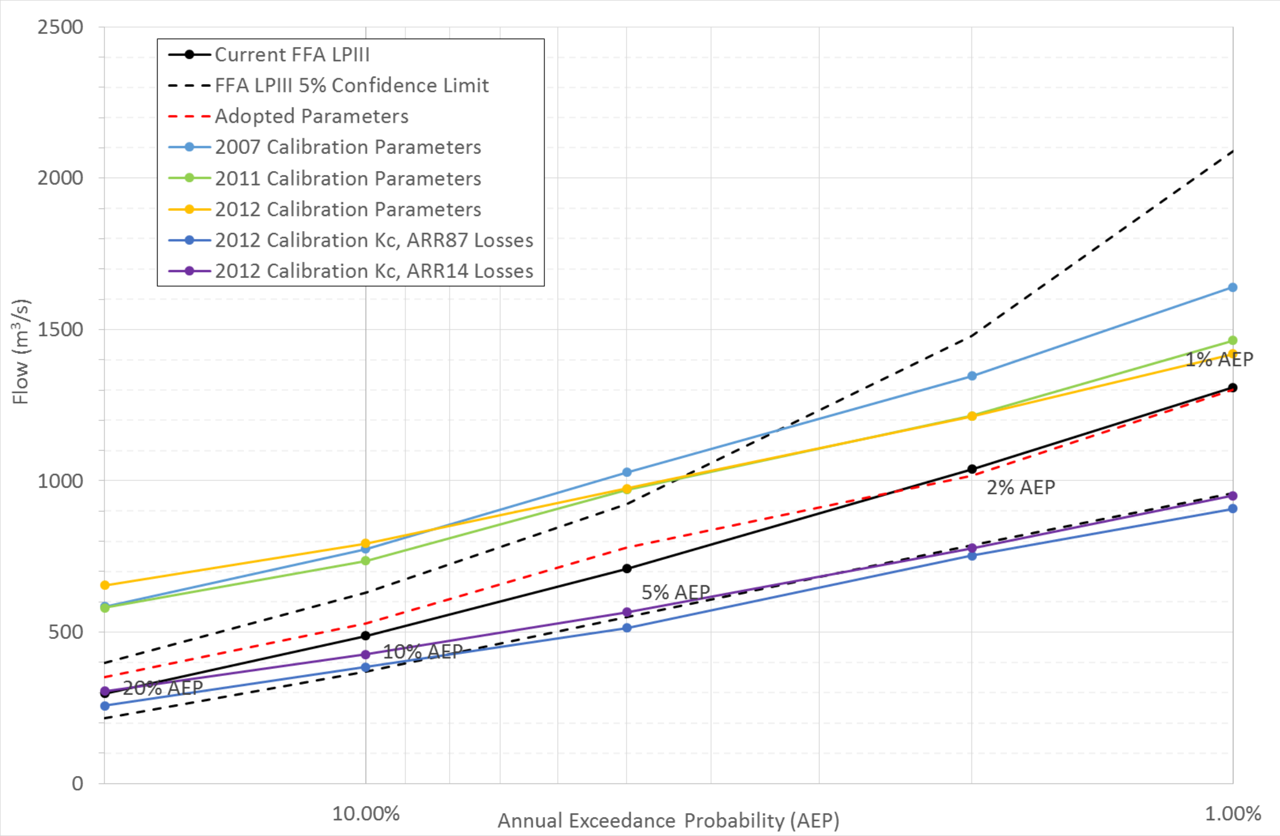

Figure 3-32 **RORB peak flow results for various k_c and IL values at The Channel**

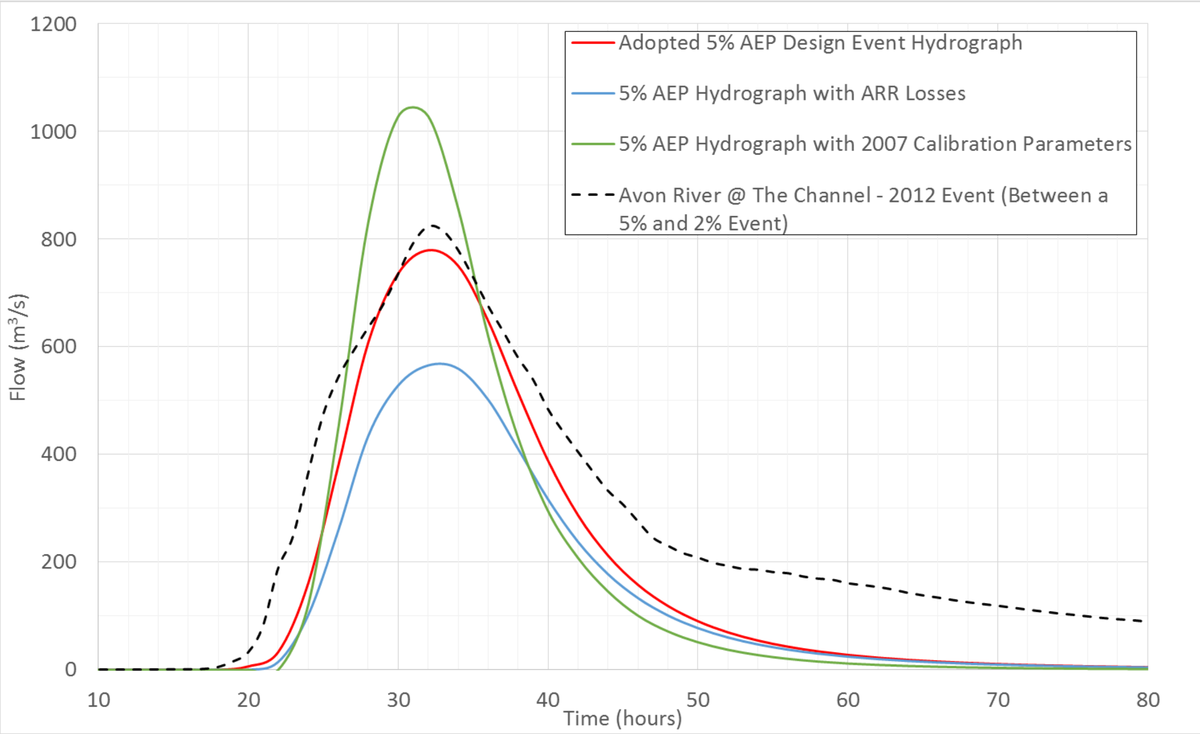

Figure 3-33 **Comparison of shape of design hydrographs for selected parameter sets at The Channel**

Freestone Creek at Briagolong

The chosen Freestone Creek k_c of 19 is a value in between the calibration event values, which range from 18 to 25. This value is also broadly consistent with regional estimates of k_c values from AR&R (1987), which suggest a value of between 20 and 38. Loss parameters are also consistent with calibration values rather than calculated estimates, with the initial loss of 50 mm equivalent to the calibrated 2012 values, whilst 2011 used 35 mm and 2007 used 20 mm. The continuing loss value of 1 mm/hr is in between the calibrated parameters which range from 0.2 mm/hr to 2 mm/hr. The continuing loss values are also lower than that recommended in AR&R (1987). The fit to flood frequency when using these parameters is shown in Figure 3-34 below. These parameter values provide a very close fit to both high and low frequency events. Other tested parameter sets are also displayed in Figure 3-34.

The shape of the hydrographs for selected parameter sets was compared to the 2012 gauged hydrograph to check that the selected k_c value matched produced a hydrograph shape consistent with actual events (Figure 3-35). The comparison shows that the adopted parameters provide a reasonable fit to hydrograph shape.

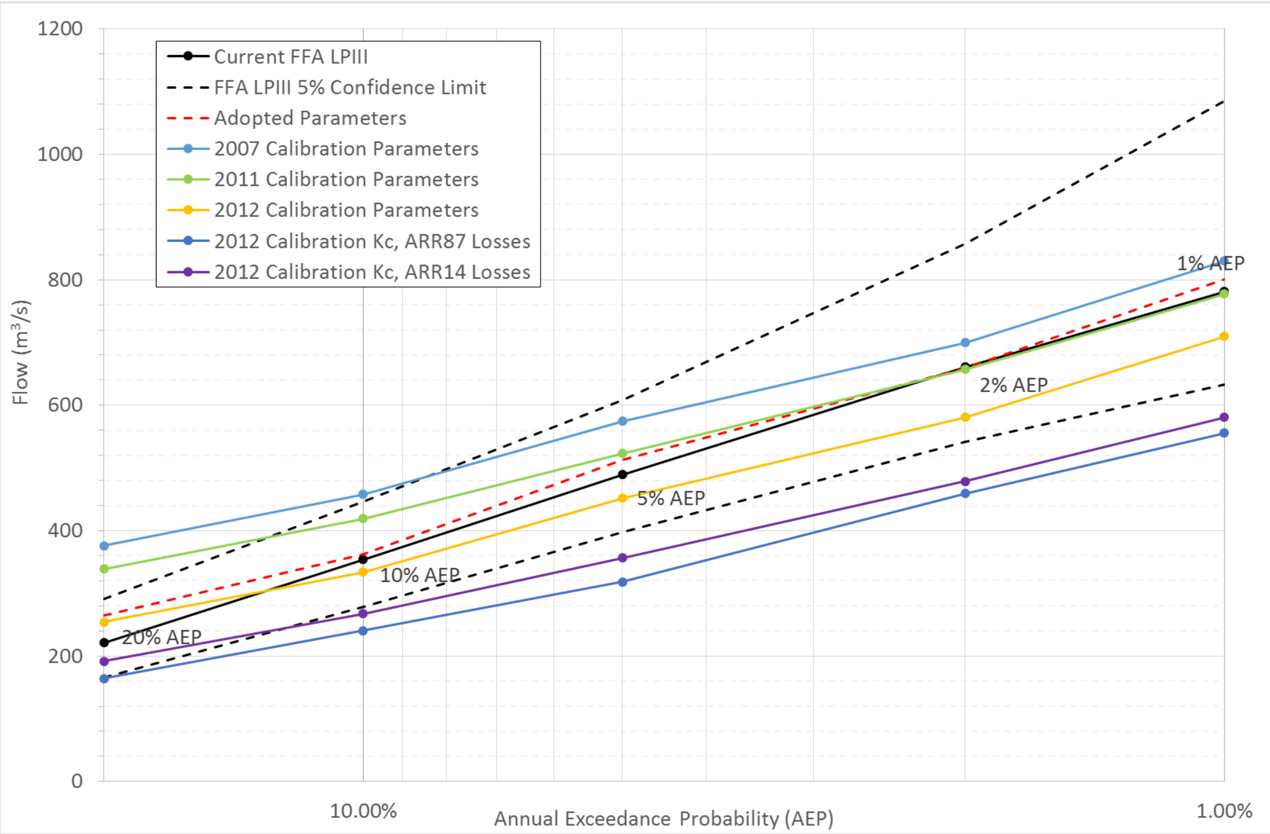

Figure 3-34 RORB peak flow results for various k_c and IL values at Freestone Creek

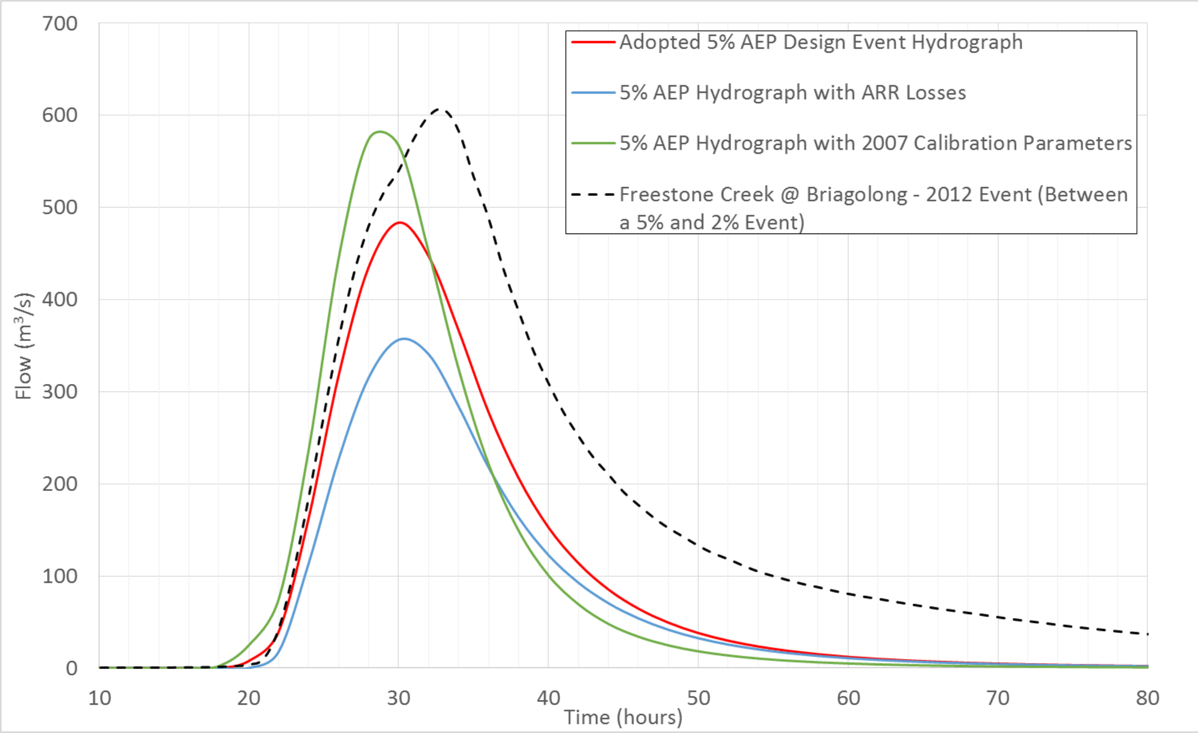

Figure 3-35 Comparison of shape of design hydrographs for selected parameter sets at Freestone Creek

Valencia Creek at Gillio Road

The chosen Valencia Creek k_c of 18 was within the range of 16 to 26 estimated during the calibration events. This value is also consistent with regional estimates of k_c values from ARR (1987), which suggest a value of between 15 and 28. Loss parameters are higher than calibrated values with an intital loss of 50 mm (calibrated values range from 35 to 40 mm) and a continuing loss of 3 mm/hr (calibrated values range from 0 to 2 mm/hr). The fit to flood frequency when using these parameters is shown in Figure 3-36 below. These parameter values provide a very close fit to both high and low frequency events. Other tested parameter sets are also displayed in Figure 3-36.

The shape of the hydrographs for selected parameter sets was compared to the 2012 gauged hydrograph to check that the selected k_c value matched produced a hydrograph shape consistent with actual events (Figure 3-37). The comparison shows that the adopted parameters provide a reasonable better fit to hydrograph shape than other parameter sets.

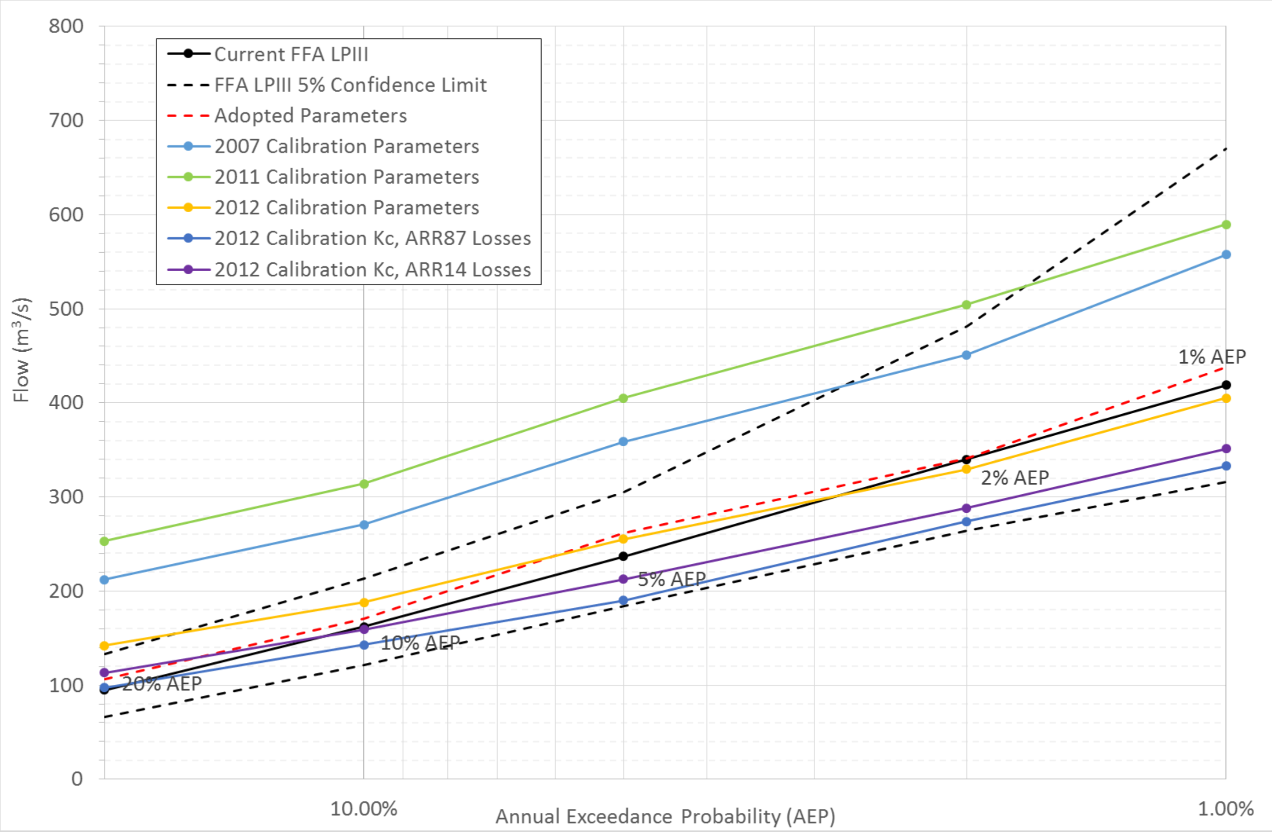

Figure 3-36 **RORB peak flow results for various k_c and IL values for Valencia Creek**

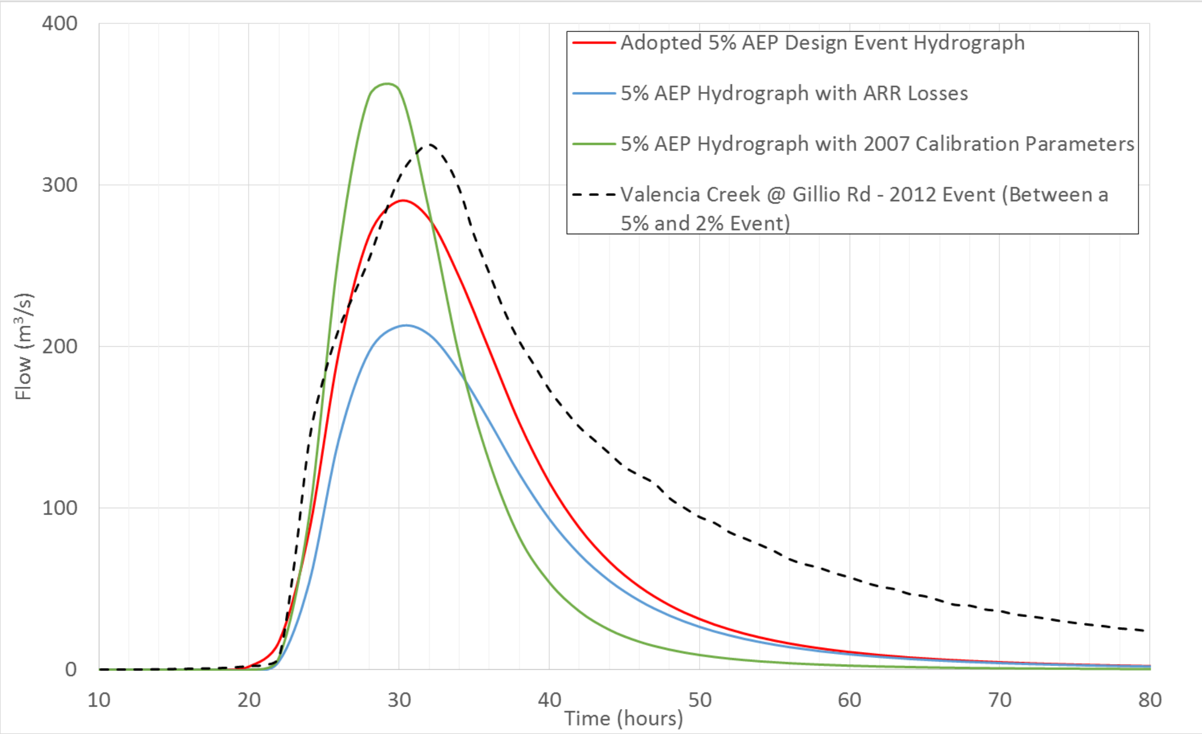

Figure 3-37 **Comparison of shape of design hydrographs for selected parameter sets for Valencia Creek**

3.7 Design Flows and Hydrographs

The adopted RORB routing and loss parameters summarised in Table 3-25 were found to produce peak flows that were a reasonable match with flood frequency analysis peak flows. The adopted RORB parameters were generally within the range of calibration values. The resulting hydrographs for Avon River at Stratford are shown in Figure 3-38, with peak flows for each of the major tributaries described in Table 3-26.

Table 3-26 Recommended design peak flows

AEP	Design Flow - Stratford (m^3/s)	Design Flow – The Channel (m^3/s)	Design Flow – Freestone Creek (m^3/s)	Design Flow – Valencia Creek (m^3/s)	Critical Duration (Stratford)
20%	808	350	264	107	36hr
10%	1184	530	363	170	36hr
5%	1703	779	512	262	36hr
2%	2277	1017	659	341	36hr
1%	2883	1301	800	434	36hr
0.5%	3495	1544	919	524	48hr
0.2%	4272	1884	1106	661	48hr

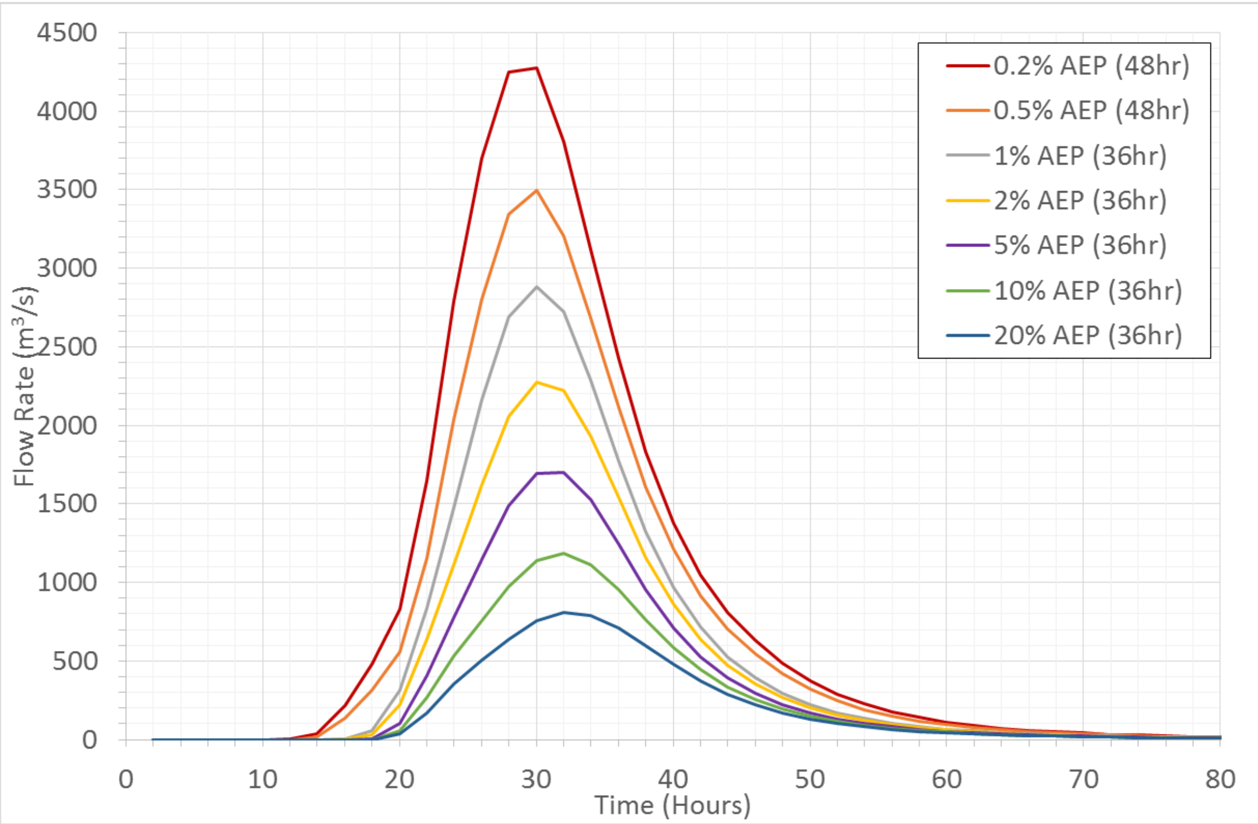

Figure 3-38 Avon River at Stratford design flood hydrographs

3.7.1 Flood Classes

For this study the minor, moderate, and major flood class events will be analysed in the hydraulic model. Details of the flow magnitude associated with these events was summarised previously in Table 3-4. Using the recommended design peak flow estimates, an AEP has been estimated for each flood class event, Table 3-27.

Table 3-27 Estimated AEP of the Flood Class Events

Gauge Station	Minor		Moderate		Major	
	Flow (m^3/s)	Approximate AEP (%)	Flow (m^3/s)	Approximate AEP (%)	Flow (m^3/s)	Approximate AEP (%)
Avon River at the Channel	213	50 – 20%	507	10%	604*	10 – 5%
Avon River at Stratford	332	50 – 20%	761	20%	962	20 – 10%

* Flow values for heights above 6.0 m have been extrapolated

As all AEP events specified in Table 3-27 are being simulated in the hydraulic model, it is proposed that flood class levels will be analysed based on hydraulic modelling undertaken for design events. If major differences are noted between design events when flood class levels lie between these events, additional runs will be undertaken to more accurately approximate the flood class events.

3.8 PMF Estimation

The Probable Maximum Flood (PMF) is the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in a particular drainage area. The PMF was estimated through estimation of the Probable Maximum Precipitation (PMP), then application of the PMP to the RORB model to generate PMF flood hydrographs.

3.8.1 Probable Maximum Precipitation Method

The Probable Maximum Precipitation (PMP) is defined by the *Manual for Estimation of Probable Maximum Precipitation* (WMO,1986) as:

> *"...the greatest depth of precipitation for a given duration meteorologically possible for a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends."*

Australian Rainfall and Runoff (AR&R) Book VI recommends the use of generalised methods for estimating the PMP, as recommended by the World Meteorological Organisation (1986). These methods use data from a large number of storms over a wide area and make adjustments for moisture availability and topographic effects. The Generalised Southeast Australia Method (GSAM) is suitable for long duration storms (greater than 24 hours) over catchments of any size in southeast Australia.

3.8.2 Generalised Southeast Australian Method (GSAM)

The Avon River is located in the GSAM coastal zone. PMP rainfall depths were calculated based on the methods outlined in the *Guidebook to the Estimation of Probable Maximum Precipitation: Generalised*

Southeast Australia Method (Bureau of Methodology, 2006). For catchment areas between 1,000 and 40,000 km^2 in the coastal zone of Victoria the method is valid for durations from 24 to 72 hours.

The GSAM method requires the input of three spatially varying factors. These are the Topographic Adjustment Factor (TAF), the Moisture Adjustment Factor (MAF) and Extreme Precipitable Water (EPW). The MAF is calculated by dividing the seasonal catchment average EPW by the seasonal standard EPW, and has separate values for summer and autumn. The values of these factors for the Avon River study area are:

- Topographic Adjustment Factor (TAF) = 1.575
- Moisture Adjustment Factor (MAF) Summer (Annual) = 0.72
- Moisture Adjustment Factor (MAF) Autumn = 0.67

The area of each catchment was then used to calculate an initial depth for both summer and autumn for a range of durations. These depths were then multiplied by the TAF and MAF to give the final GSAM PMP estimate.

The resulting PMP estimates are given in Table 3-28 below.

Table 3-28 PMP depth estimates (GSAM)

Duration (hours)	Final PMP Estimate (mm)
24	690
36	780
48	840
72	920

The design temporal distributions given in BOM (2006) were adopted.

3.8.3 PMP Spatial Patterns

A uniform spatial pattern was adopted, instead of that given in BOM (2003) and BOM (2006) for both the GSDM and GSAM PMP rainfall. This was because the PMF estimation aims to give a broad-scale map of PMF across the catchment, rather than in a particular location. The GSDM and GSAM spatial pattern aims to give the highest possible flow at a particular point within reason, rather than across the catchment. It is acknowledged that by running only a limited number of durations with a uniform spatial pattern we cannot truly estimate the PMF at every point in the catchment; however it is understood that other factors in the PMP and PMF estimation process provide a conservative PMF that is suitable for planning purposes. The PMF should be reassessed if it is required for dam design or any other design purpose at a particular point in the catchment.

3.8.4 Probable Maximum Flood Estimation

The Probable Maximum Flood (PMF) was modelled by applying the PMP in RORB. The rainfall depth estimates and temporal and spatial patterns calculated above from the GSAM method were adopted.

Since baseflow was found to be a negligible proportion of the calibration events, it was not considered necessary to include baseflow in the PMF modelling.

The PMP rainfall totals, spatial and temporal patterns were input into the RORB model, with the calibrated routing parameters. An initial loss of 0 mm and a continuing loss of 1 mm/hr were adopted as recommended in Australian Rainfall and Runoff Book VI (1998). The resulting PMF peak flows are given in Table 3-29, and the hydrographs are shown in Figure 3-39.

Table 3-29 PMF peak flow estimates

	Design Flow - Stratford (m^3/s)	Design Flow – The Channel (m^3/s)	Design Flow – Freestone Creek (m^3/s)	Design Flow – Valencia Creek (m^3/s)	Critical Duration (Stratford)
PMF	14,810	5,870	3,164	2,101	24hr

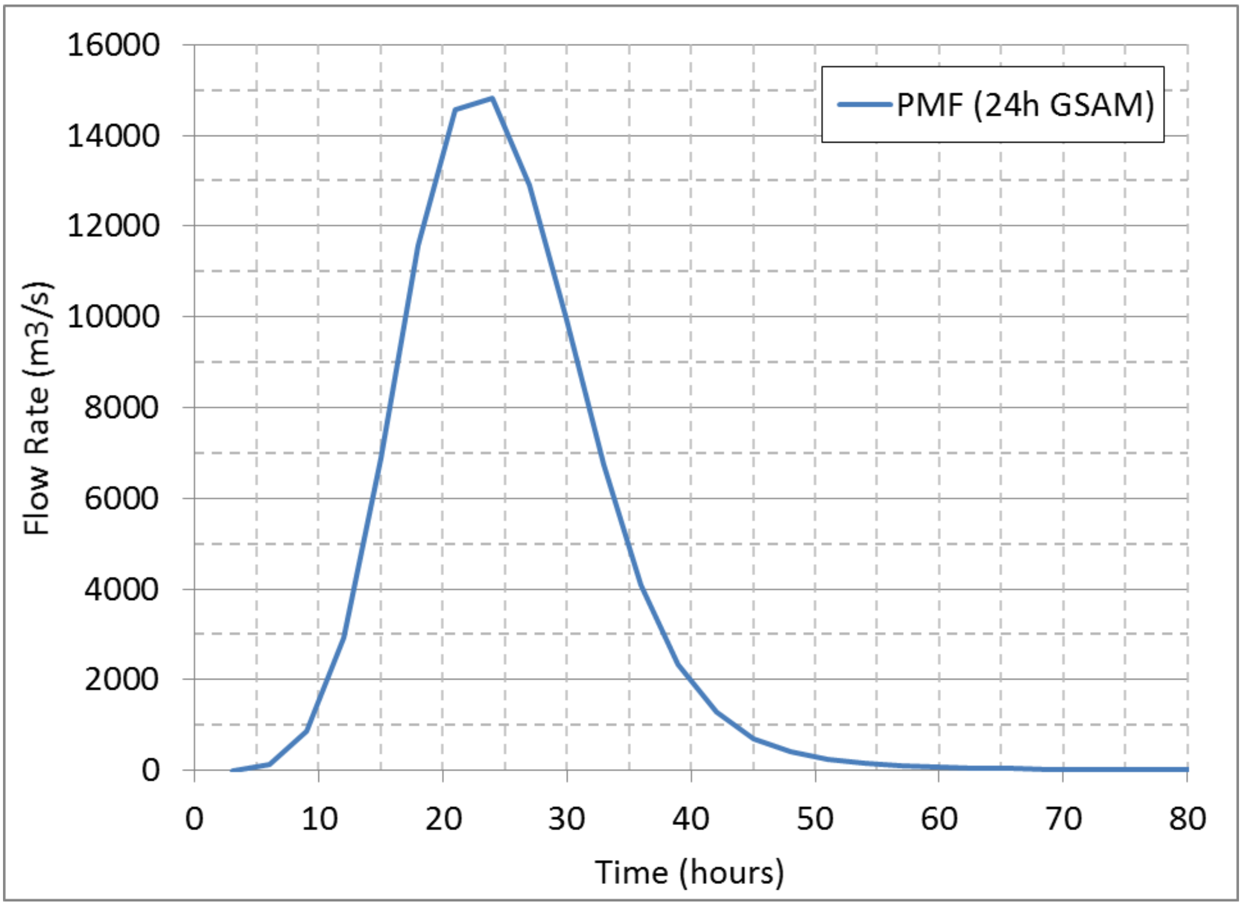

Figure 3-39 Avon River at Stratford PMF hydrograph

3.8.5 Validation

A PMF Estimate for Avon River at Stratford was prepared using the Quick Method of Nathan et al. (1994) to validate the GSAM estimate. This method applies a set of empirical equations to compute a triangular PMF hydrograph. The equations are:

$Q_p = 129.1\ A^{0.616}$
$V = 497.7\ A^{0.984}$
$T_p = 0.0001062\ A^{-1.057}\ V^{1.446}$
$T_r = V / (1.8\ Q_p)$

Where:

Q_p is peak flow (m^3/s)
A is catchment area (km^2)
V is hydrograph volume (ML)
T_p is time to peak of hydrograph (h)
And T_r is base length of hydrograph (h)

The equations are applicable to southeast Australian catchments from 1 to 10,000 km^2 that do not have large lakes or storages. The resulting PMF peak flow, volume, time to peak and hydrograph length are:

A	1,485 km^2
Q_p	11,607 m^3/s
V	657,577 ML
T_p	12.2 h
T_r	31.5 h

The quick PMF peak flow is within 22% and volume is within 33% of the RORB PMF results, providing validation that the RORB PMF estimate is appropriate. The RORB PMF estimate is higher, providing a more conservative estimate.

4. CONCLUSION AND NEXT STEPS

Through a process of flood frequency analysis, hydrologic modelling and application of various regional methods, a set of design flood hydrographs have been developed for the Avon River and its tributaries. The hydrological analysis has been based on robust methods and extensive cross-validation due to the relatively high gauge density within the catchment. Validation of the design peak flows against flood frequency analysis and comparison of the design hydrographs against gauged hydrographs gives confidence that they are representative of actual flood risk and appropriate for design.

The next steps in the analysis are:

- Further development and calibration of the hydraulic model
- Sensitivity testing of hydraulic model

5. REFERENCES

Alluvium (2013). Avon and Macalister Flood Recovery Investigation and Design: Assessment and Recommendations for Gravel Bar Management. Report R01 by Alluvium Consulting Australia for West Gippsland Catchment Management Authority, Traralgon.

Australian Rainfall and Runoff (ARR). (1987). *A Guide to Flood Estimation,* Institution of Engineers Australia.

Australian Rainfall and Runoff (ARR). (2013). *Project 2 Stage 2: Spatial Patterns of Rainfall*, Institution of Engineers Australia.

Brizga, S.O., Lauchlan Arrowsmith, C., Tilleard, J., Boon, P., McMahan, A., O'Connor, N., Quin, D., Pope, A. (2013). *Latrobe Estuary: Environmental Water Requirements Report.* Water Technology Pty Ltd report to West Gippsland Catchment Management Authority.

Bureau of Meteorology (2003) *The Estimation of Probable Maximum Precipitation in Australia: Generalised Short-Duration Method,* Bureau of Meteorology, Melbourne, Australia.

Bureau of Meteorology (2006) Estimation of Probable Maximum Precipitation: Generalised Southeast Australia Method. Australian Government Bureau of Meteorology.

Earth Tech (2007). Environmental Flow Determination for the Avon River – Flow Recommendations Paper. *West Gippsland Catchment Management Authority.*

Engineers Australia (2013). *Collation and Review of Areal Reduction Factors from Applications of the CRC-Forge Method in Australia.* Australian Rainfall and Runoff Revision Project 2: Spatial Patterns of Rainfall. Final Report P2/S2/012.

Hill, P., Mein, R., Siriwardena, L. (1998). *How Much Rainfall Becomes Runoff? Loss Modelling for Flood Estimation.* CRC for Catchment Hydrology Industry Report 98/5.

Hill, P., Graszkiewicz, Z., Taylor, M., Nathan, R. (2014) *Australian Rainfall and Runoff: Revision Project 6: Loss Models for Catchment Simulation*. Institute of Engineers Australia.

Kuzcera, G. (2014). ARR Revision: Flood Frequency Analysis (presentation). Institute of Engineers Australia and Australian Rainfall and Runoff.

Nathan, R.J., Weinmann, P.E. and Gato, S.A. (1994) A Quick Method for Estimating the Probable Maximum Flood in South Eastern Australia. In: *Water Down Under 94: Surface Hydrology and Water Resources Papers; Preprints of Papers*. Barton, ACT: Institution of Engineers, Australia, 1994: 229-234.

Siriwardena, L., Weinmann, P. (1996) *Derivation of Areal Reduction Factors for Design Rainfalls in Victoria,* Report No. 96/4, CRC for Catchment Hydrology.

SKM (2003). Lake Wellington Catchment Salinity Management Plan – Clydebank Morass Salt and Water Balance Study Final 3. *Victorian Department of Sustainability and Environment.*

SKM (2007). *Basejumper: A Tool for Analysing Time Trends in Baseflow.*

Water Technology. (2015). *Avon River Regional Flood Mapping – Preliminary Report*, Report prepared for Department of Environment, Land, Water and Planning (DELWP).

World Meteorological Organization (WMO). (2009). *Manual for Estimation of Probable Maximum Precipitation*, 3rd Ed, WMO – No. 1045, Geneva, ISN 978-92-63-11045-9