Regional Flood Mapping Lower Wimmera – Hydrology (R02)

January 2017

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1. INTRODUCTION

Water Technology was commissioned by the Wimmera CMA to undertake the Lower Wimmera Regional Flood Investigation.

The overall objective of the study is to develop regional scale flood mapping for the Lower Wimmera River between Quantong and Jeparit. This mapping will be used to satisfy a range of business requirements from planning and emergency response to community awareness and insurance. The study area was extended upstream by Water Technology to the Wimmera River at Horsham (Walmer) gauge location in order to utilise the long period of record at the gauge as an inflow boundary and link the mapping to the gauge for flood response purposes.

This report details the hydrological analysis undertaken for the project, and should be read in conjunction with the previous Data Review Report (R01).

2. STUDY AREA

The Wimmera River originates in the Pyrenees Ranges, near the township of Elmhurst, and flows generally westward, toward Horsham, and then northwards to Lake Hindmarsh. Downstream of Glenorchy, the river has very little catchment north of the river as the catchment slopes away from the river with a number of distributary systems flowing between ancient sand dunes which are roughly aligned north-south. This is clearly shown in Figure 2-1 and Figure 2-3.

The catchment of the Wimmera River upstream of the Horsham (Walmer) streamflow gauge, located just downstream of Horsham is approximately 4,000 km². The Mackenzie River catchment which flows into the Wimmera River immediately downstream of the Horsham (Walmer) streamflow gauge is approximately 400 km², with Norton, Sandy and Darragan Creeks having smaller catchments again. The Wimmera River catchment downstream of Quantong has limited tributary inflows with the river flowing between the ancient sand dunes of the Wimmera-Mallee. The contributing catchment downstream of Quantong is approximately 1,500 km² but much of this is likely to be ineffective as a series of terminal lakes and depressions in the ancient sand dunes store local rainfall.

The Lower Wimmera River study area as shown in Figure 2-4, extends downstream from Horsham to Lake Hindmarsh. It is characterised by a lower gradient than the upper catchment. The study area is dominated by agricultural land with floodplains of the Wimmera River and its tributaries containing agricultural assets that are likely to be subject to inundation during large rainfall events. Various residential areas are at risk also, including properties on the outskirts of Horsham, Quantong, Dimboola and Jeparit, as well as rural properties at Duchembegarra, Arkona, Antwerp and Tarranyurk.

Rainfall across the Wimmera Catchment varies considerably, with the upper catchment generally receiving 500-600 mm/year (but increasing to 800-900 mm/year at the top of the Grampians), and the lower catchment generally receiving 350-400 mm/year. Months with the highest average rainfall are typically June to August. Although the region north of Horsham does experience significant storms similar to the catchment south of Horsham, the confined nature of the catchment is such that the runoff generated downstream of Horsham is much less and what little runoff is generated is often through the system well before the upper catchment peak arrives from the Wimmera River and Mackenzie River.

Historical records indicate that peak flow rates experienced in the lower section of the river are lower than those in the upstream/middle sections. This is due to attenuation and the presence of distributary waterways upstream (Swedes Cutting, Dunmunkle Creek and Yarriambiack Creek). These distributary waterways allow flow to exit the Wimmera River catchment, with Swedes Cutting transferring flow into the Richardson River catchment. The Mackenzie River and other tributaries, namely Norton, Sandy and Darragan Creeks provide inflow to the Wimmera River downstream of

Horsham as shown in Figure 2-2 . Often these tributary inflows peak prior to the Wimmera River, passing through the system before the Wimmera River peak arrives. The dominant flood causing mechanism in the lower Wimmera River is the upper Wimmera River catchment flood flows.

There are a number of irrigation channels within the lower Wimmera River catchment, formerly used for stock and domestic supply. The construction of the Northern Mallee and Wimmera Mallee Pipelines has superseded these channels and a number of domestic water storages. These pipelines have increased water availability by reducing water losses in the supply system and have also increased the control of environmental flow releases.

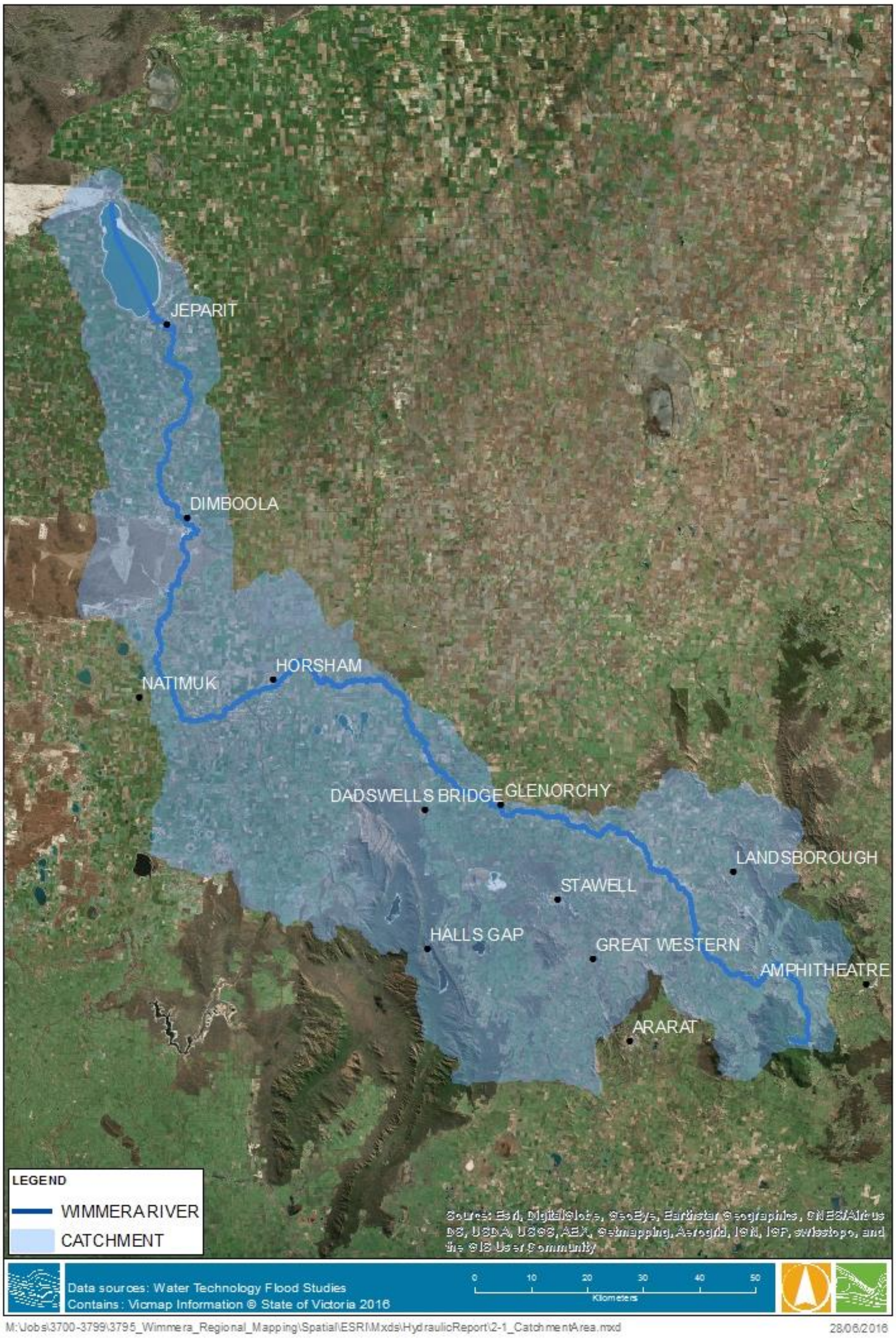

Figure 2-1 Catchment Area of the Wimmera River

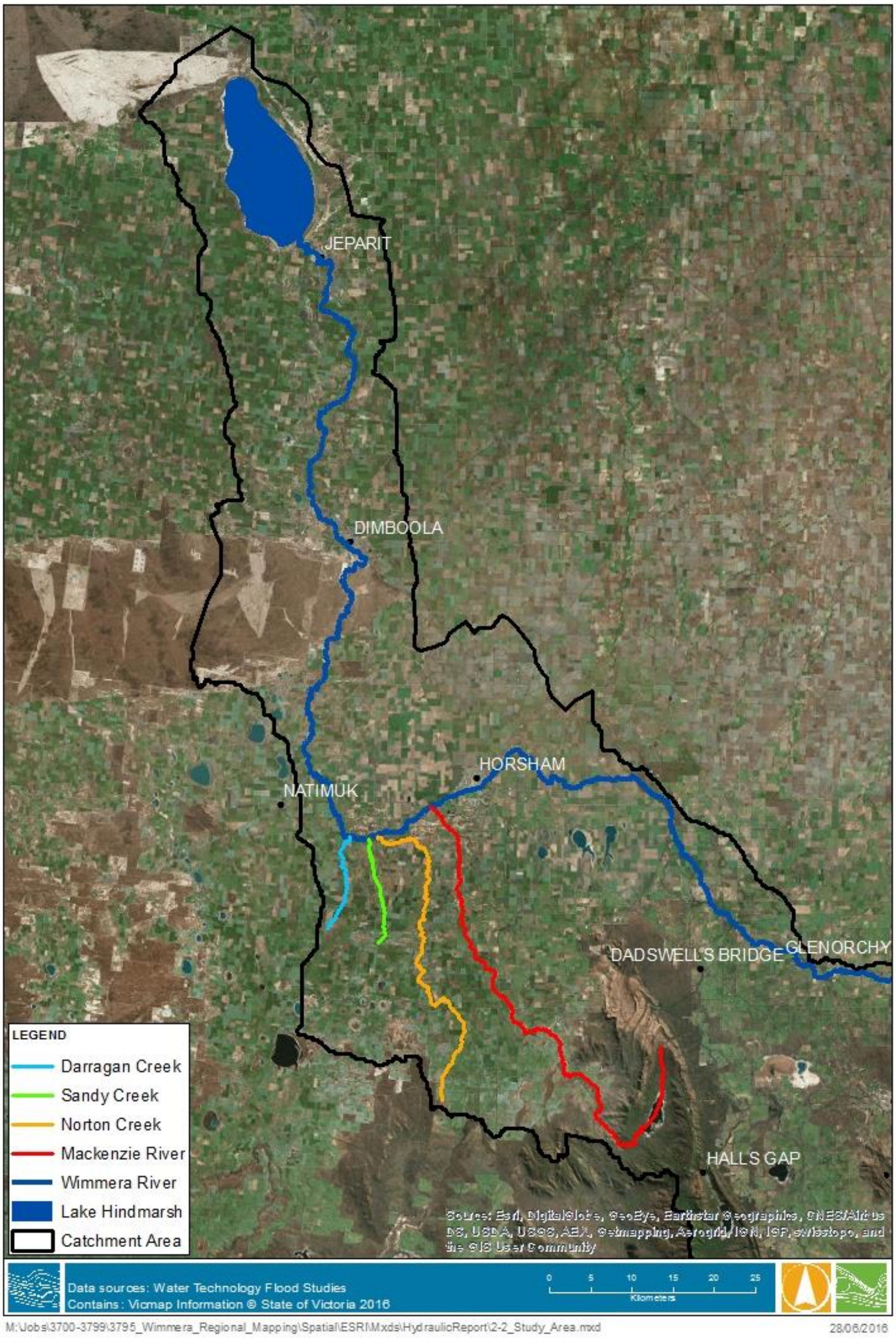

Figure 2-2 Lower Wimmera Study Area and Major Tributaries

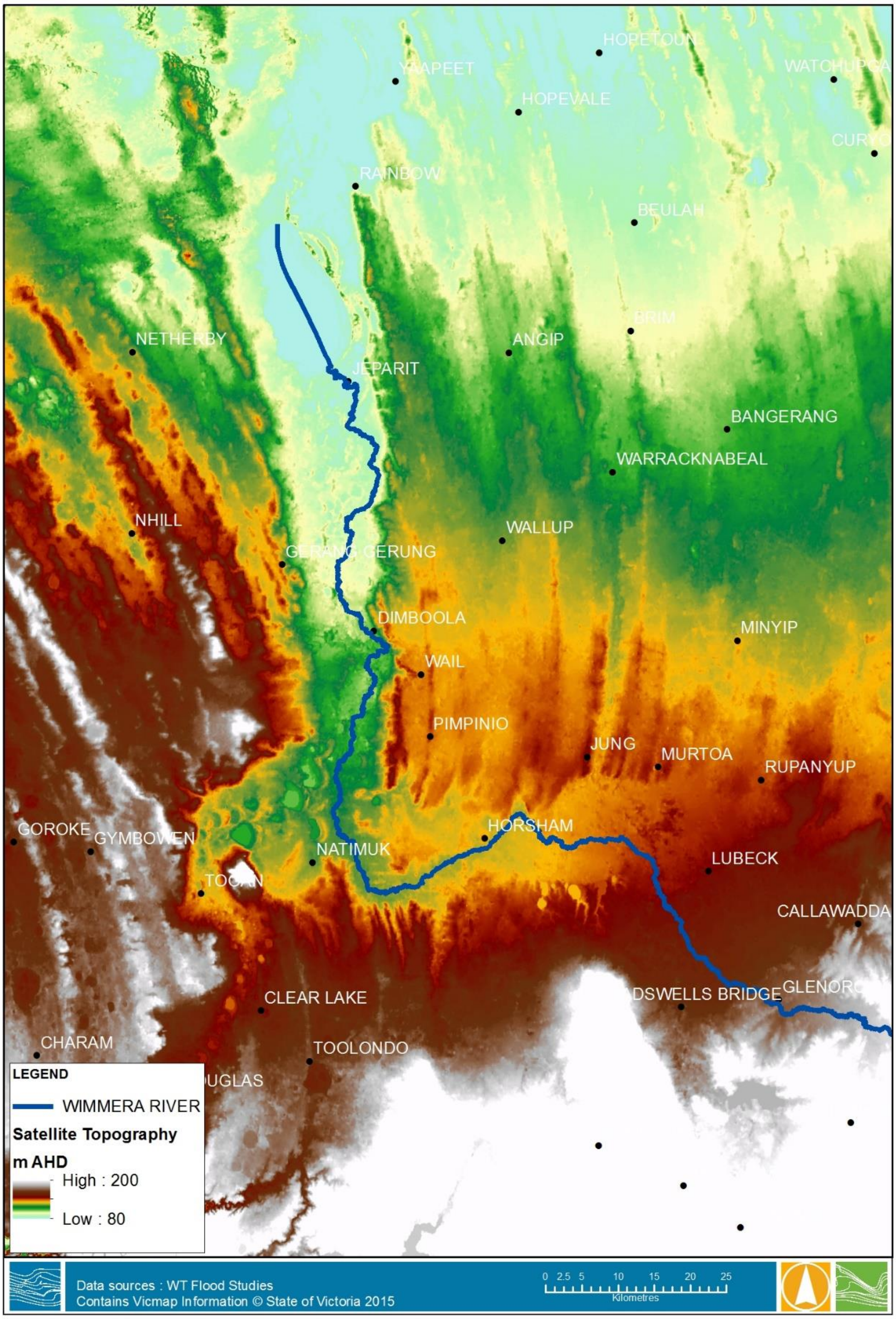

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Figure 2-3 Topography of the Lower Wimmera River

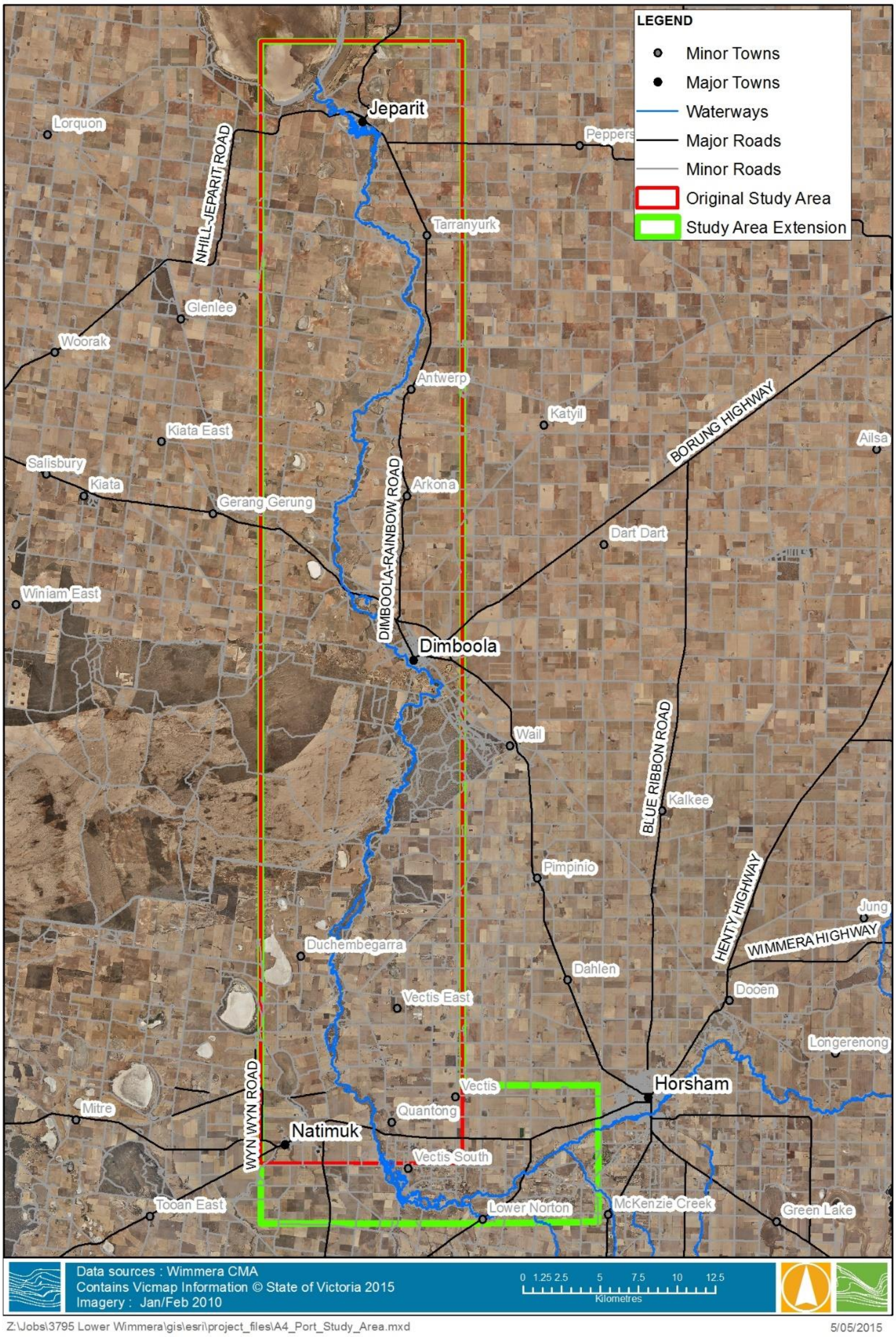

Figure 2-4 Lower Wimmera Study Area

3. HYDROLOGY

3.1 Overview

The hydrological analysis for the lower Wimmera River downstream of Horsham consisted of a review of the hydrological context of the study area followed by flood frequency analysis. Due to uncertainty in gauged peak flow estimates and the January 2011 peak flow (personal communication with Wimmera CMA), a review was undertaken of the rating curve for the Wimmera River at Horsham gauge (415200).

The lower Wimmera River catchment receives inflows from the Wimmera River and Burnt Creek which flows into the river upstream of the Western Highway at Riverside. Mackenzie River, Norton Creek and Darragan Creek all flow into the Wimmera River off the southern catchment between Horsham and Quantong.

Flooding of the lower Wimmera River downstream of Horsham is dominated by incoming flows from the upper Wimmera River catchment. The East Horsham Flood Intelligence Report (Water Technology, 2013) provides a description of typical flood timing. From the start of intense rainfall to the peak of flooding in Glenorchy takes approximately 45 to 60 hours. The time between flood peaks between Glenorchy and Horsham is then between 3 to 4 days. From Horsham to Dimboola the travel time between peaks is 3 days or more, with another 2 days to Tarrenyurk.

The Mackenzie River peak at Horsham generally arrives well before the Wimmera River peak. An analysis of streamflow gauge data revealed that the Mackenzie River has peaked between 2.5 and 3.5 days earlier than the Wimmera River at Horsham on all significant flood events where concurrent record is available (Sep 1988, Oct 1992, Oct 1996, Sep 2010 and Jan 2011). During those events the Mackenzie River flows had receded by the time the Wimmera River peak arrived, with Mackenzie River flows between 200 to 630 ML/d at the time of the Wimmera River peak flow. These Mackenzie River flow rates are for the gauge located downstream of the Old Hamilton Road which does not capture the Bungalally Creek flows which enter Mackenzie River downstream of the gauge. However these Bungalally Creek flows are likely to be relatively minor, days after it has peaked.

The smaller tributary flood flows will only impact on peak flood levels in the Wimmera River if they occur concurrently with the Wimmera River. Given the large difference in catchment size between the Wimmera River upstream of Horsham and the tributaries downstream of Horsham, the tributaries generally peak well before the Wimmera River peak arrives at Horsham. The impact of tributary inflows will be assessed through the hydraulic modelling and will be documented in a subsequent report. Wimmera River design flows will be modelled with and without appropriate tributary inflows to test the influence they may have on flood levels downstream of Horsham. Additional tributary inflow of between 200 and 1,000 ML/d will be tested in the hydraulic modelling. Given the likely minor impact on flood levels a rigorous joint probability assessment is not warranted.

3.2 Existing Hydrology

A number of relevant studies have been completed in the Wimmera River catchment previously. These were all outlined in the earlier Data Collation report, with the design hydrology summarised below.

Table 3-1 Previous Lower Wimmera River Design Hydrology

AEP (%)	Wimmera River at Horsham (Walmer) Peak Design Flow (ML/d)		
	Horsham Flood Study (2003) [1]	Wimmera River and Yarriambiack Creek Flows Study (2009) [2]	Jeparit Flood Study (2008)
20	12,900	10,100	10,200
10	18,100	10,500	14,900
5	23,700	22,300	20,000
2	31,200	30,300	26,600
1	37,000	34,600	33,400
0.5	43,000	42,900	37,100

[1] Dimboola Flood Study (2003) adopted same hydrology.

[2] The Horsham Bypass Hydrology and Hydraulics Investigation (2012), East Horsham Flood Plan (2013) adopted same hydrology.

3.3 Streamflow Gauge Review

There are several streamflow gauges that provide information on flood heights and flows along the Lower Wimmera River. These were described in detail in the Data Collation report. A summary of streamflow and flood height gauges within the study area is included in Table 3-2 and Figure 3-1 below.

The Walmer gauge is the critical gauge for assessment within this study as it will be used to provide flows into the hydraulic model. A detailed Flood Frequency Analysis (FFA) has been undertaken to determine design flows into the hydraulic model. Additional gauges within the study area will be used to verify and calibrate the hydraulic model. The impact of flows from the tributaries on design flood levels in the Wimmera River downstream of Horsham will be tested, with tributary gauging assisting to provide the range of flows for sensitivity testing.

Table 3-2 Streamflow Gauge Summary in the Lower Wimmera River Study Area

Gauge Name	Gauge Number	Gauge Record	Flood Height	Flow
Wimmera River at Horsham (Walmer)	415200	1910 - Current	X	X[1]
Mackenzie River at McKenzie Creek	415251	1988 - Current	X	X
Norton Creek at Lower Norton	415273	2008 - Current	X	X[2]
Wimmera River at Quantong	415261	2009 - Current	X	
Wimmera River US Dimboola	415256	1989 - Current	X	X
Wimmera River at Lochiel Railway Bridge	415246	1987 - Current	X	X
Wimmera River at Tarranyurk	415247	1987 - Current	X	X[3]
Wimmera River at Jeparit	415212	May – July 1998	X	

[1] Walmer gauge can be impacted by backwater from Mackenzie River, this is investigated later in this report.

[2] Norton Creek flow gauge is drowned out from the Wimmera River in large floods, a rating curve exists but is not reliable even in small flows

[3] Flow gauging was discontinued in 2010, so there is a flow record prior to that.

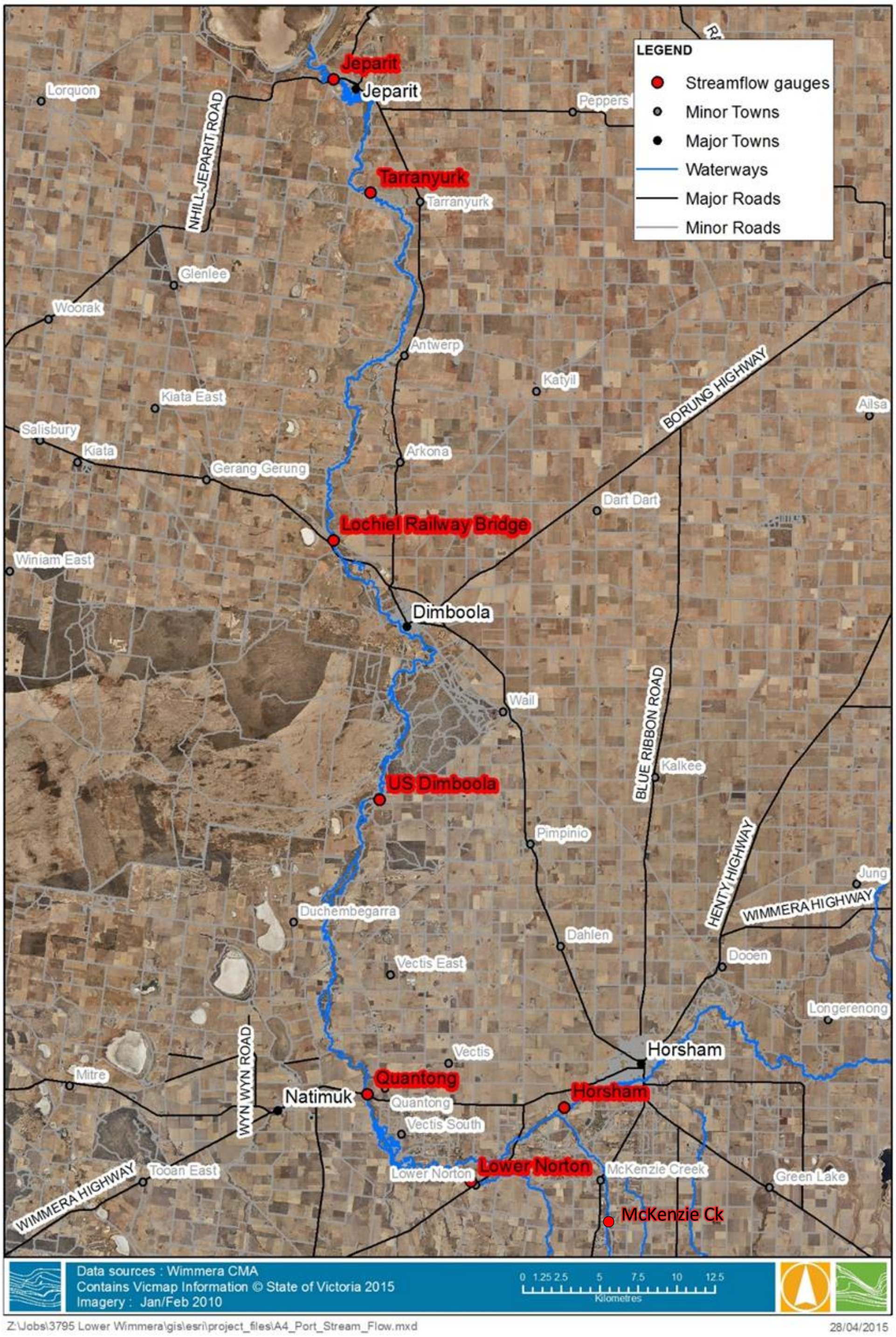

Figure 3-1 Lower Wimmera River Streamflow Gauges

3.4 Inflows Downstream of Horsham

As the study area extends along the Wimmera River all the way from Horsham to Jeparit, the hydrology analysis has considered whether to include inflows downstream of Horsham. To better understand the lower Wimmera River hydrology a comparison of the gauge flows from 1987 to current was undertaken for the Horsham, U/S Dimboola and Lochiel Bridge streamflow gauges. This analysis has identified 5 events (1988, 1992, 1996, 2010 and 2011), with flows at the Horsham gauge larger than 10,000 ML/d (approximately 20% AEP event). For each of these events the gauged flow hydrographs at Horsham, U/S Dimboola and Lochiel Railway Bridge were compared.

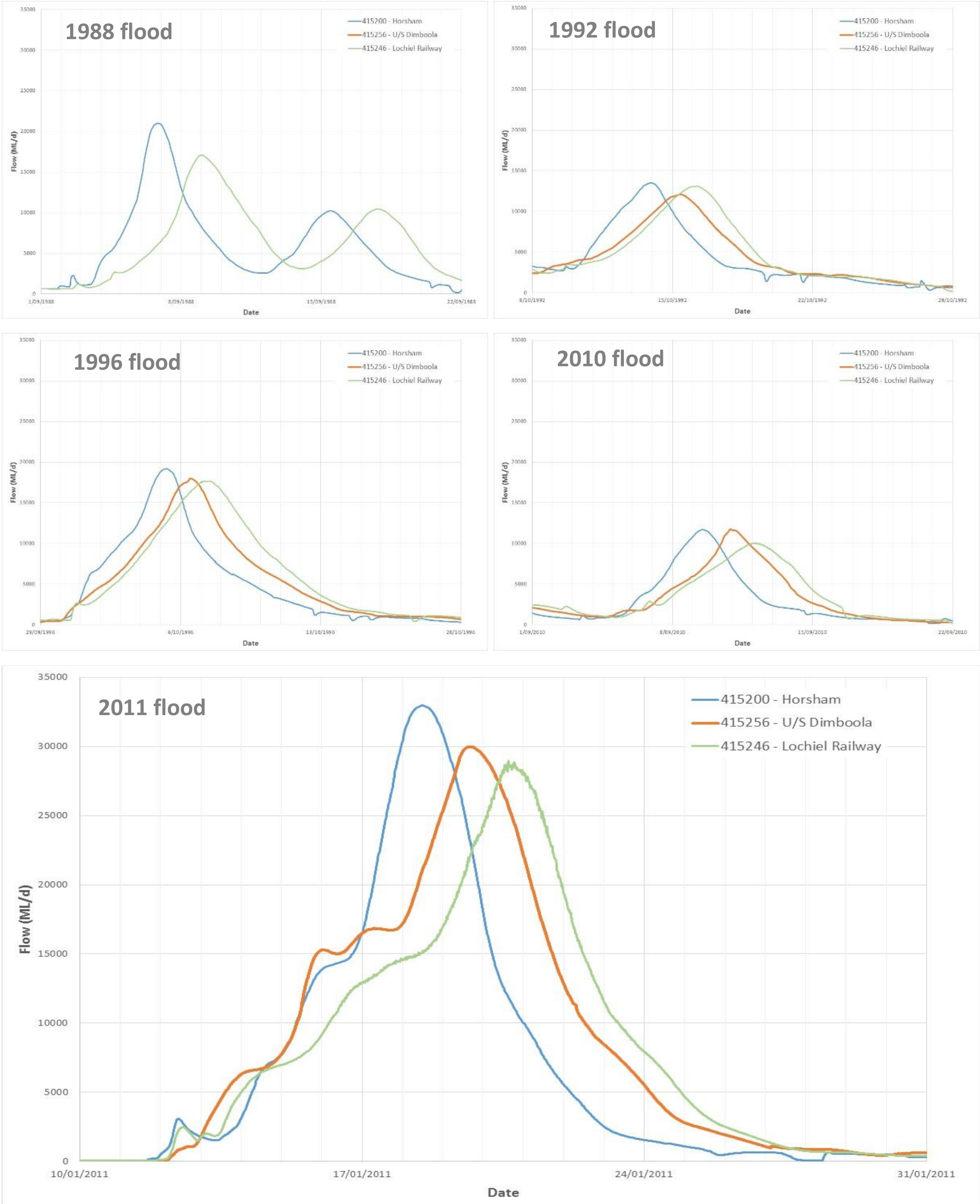

Figure 3-2 Historic Streamflow Gauge Flow Comparison

The historic hydrographs displayed above show that during the last 5 significant flood events on the lower Wimmera River a very similar behaviour in the hydrology is observed. The flow in the river at Horsham is slightly attenuated as the flood wave moves down the river system. The attenuation is relatively minor, explained by the confined nature of the floodplain downstream of Horsham. This trend of gradual attenuation downstream of Horsham suggests that there are no major inflows along the river that influence the flow and the peak flood levels along the river.

The 1992 hydrographs show the Lochiel Bridge gauge with a higher peak flow than Dimboola. At first glance this would suggest a significant local inflow between the gauges, however these hydrographs may be misleading. The Dimboola and Lochiel Bridge gauges had only been in operation for 3 years prior to the 1992 flood event. The rating curves were most likely significantly revised as a result of the 1992 and 1996 flood events. The rating curve at the time of gauging may have a bearing on the relationship observed. Another piece of information that is peculiar is that in the 1996 event the water levels at Horsham and Lochiel Bridge gauges were 0.17 to 0.18 m higher than in the 1992 event, however for the Dimboola gauge the 1996 water level was 0.39 m higher than the 1992 water level. During the 1992 event the area around Dimboola received between 20-30 mm of rainfall. This may have led to minor inflows but there is no evidence on the rising limb of the gauged hydrographs of a significant inflow, just a gradual smooth rise characteristic of the Wimmera River flood wave propagating down the catchment. Although the reason for the 1992 discrepancy between Dimboola and Lochiel Bridge hydrographs is uncertain, it is considered more likely that it is due to gauge uncertainty and not a local source of inflows between Dimboola and Lochiel Bridge.

The Mackenzie River, Norton Creek and Darragan Creek are the only major waterways that may contribute significant flow to the Wimmera River downstream of Horsham. All of these waterways enter the river between Horsham and Quantong.

The Norton Creek gauge is situated within the backwater of the Wimmera River, and for relatively minor flows in the Wimmera River (greater than 1,500 ML/d), the Norton Creek gauge appears to respond in unison with the Wimmera River gauge at Horsham, suggesting it is indeed backwatered from the river. Norton Creek has a relatively small catchment compared to that of the Wimmera River, with the flows generated from this small catchment low in comparison. In addition, the comparatively small flows from Norton Creek will enter the Wimmera River early in an event, well before the peak of the Wimmera River.

The Darragan Creek is ungauged, and has a catchment significantly smaller than Norton Creek. Although there is no gauge data to verify the assumption, it can be safely assumed that the peak flow generated from this catchment will be insignificant in comparison to a peak flow generated by the Wimmera River catchment and it will peak well before the Wimmera River.

The Mackenzie River is a much larger waterway than Norton and Darragan Creeks, with a large catchment that extends up into the Grampians. With much of the runoff generated in the headwaters of the Grampians, the level of Wartook Reservoir is critical to the peak flow generated in Mackenzie River. The Mackenzie River at Mckenzie Creek streamflow gauge rating table is reliable only up to 1,000 ML/d. The recorded January 2011 flow of 4,270 ML/d is well beyond the reliable section of the rating curve. Preliminary design hydrology for the Mackenzie River downstream of Wartook currently being undertaken by Water Technology (pers. com. with Alison Miller of Water Technology), suggests a 1% AEP flow of around 3,570 ML/d with a January 2011 flow of 3,780 ML/d (as estimated by GWMWater). With the Wimmera River at Horsham 1% AEP flow and January 2011 flow upwards of 30,000 ML/d, the Mackenzie River flow is potentially a significant contribution when considering peak flow. As discussed earlier in Section 3.1, the Mackenzie River peak flow generally arrives at Horsham 2.5 to 3.5 days prior to the larger Wimmera River peak. Analysis of the timing of the Mackenzie River flow in relation to the Wimmera River flow at Horsham, Figure 3-3, shows the influence of the Mackenzie River inflow on the rising limb, days before the peak. In January 2011, after the Mackenzie River had peaked and started to recede, the Wimmera River at Horsham flow doubled as the flows from the upper Wimmera River catchment came through. The Mackenzie River flow at the time of the January 2011 Wimmera River peak was around 550-600 ML/d. An analysis of past flood events (discussed in Section 3.1) showed that the Mackenzie River flow at the time of Wimmera River peak flow can be within the range of 200-630 ML/d.

The Mackenzie River inflows will provide volume to the Wimmera River on the rising limb, but for design flood considerations, the impact of Mackenzie River flow will be insignificant on flood levels along the Wimmera River downstream of Horsham. This however will be tested by adding typical tributary flows to the hydraulic model to assess the likely impact on water level along the Wimmera

River downstream of Horsham. It is possible that the tributary volume may have an impact further down the system as the peak flow is attenuated and the flood volume in the hydrograph filling the floodplain continues to be diminished.

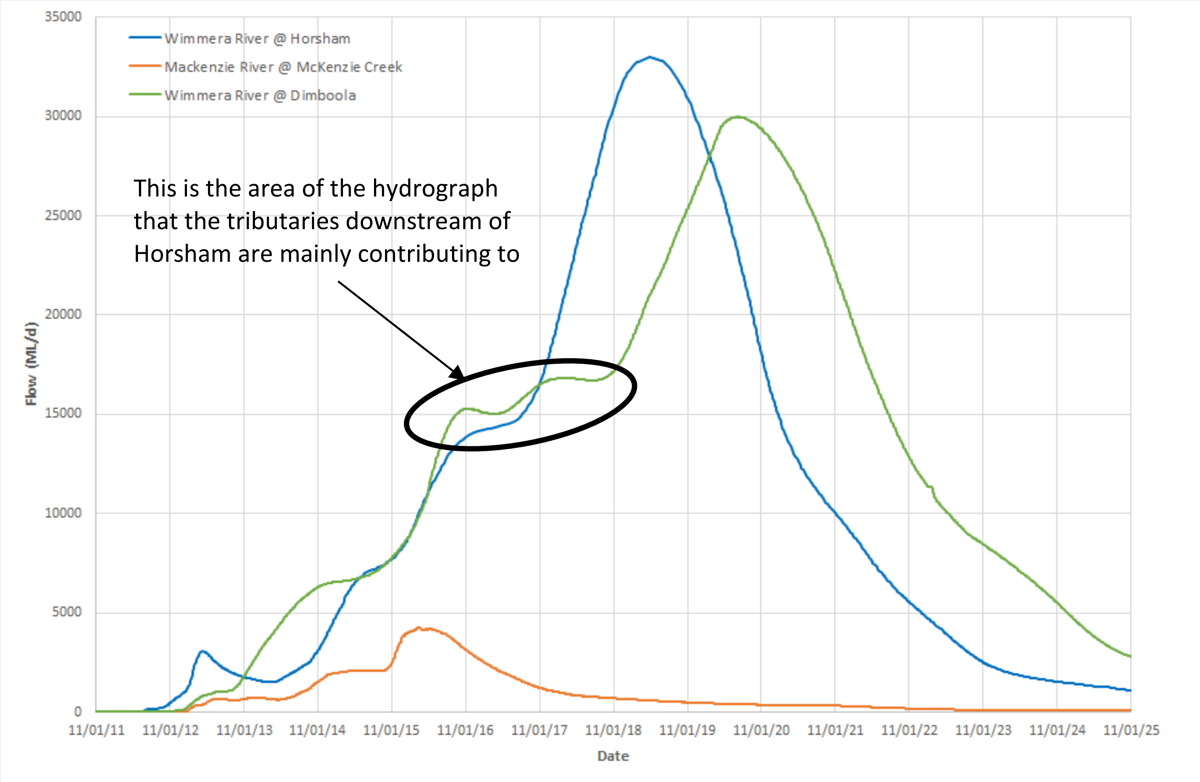

Figure 3-3 January 2011 Wimmera River and Mackenzie River flow contributions

3.5 Wimmera River @ Horsham Streamflow Gauge

3.5.1 Desktop Gauge Review

The Data Collation report reviewed the Horsham gauge in detail, this has been reproduced below as this analysis is critical in understanding the gauge and thus the hydrology used in the flood modelling.

The Wimmera River streamflow gauge at Horsham (Walmer) has a long period of record with daily flow records from 1889 to 1910 and daily gauge height and flow from 1910 to 1963. From 1963 to current, instantaneous gauge recordings of level and flow is available. Together, these periods of gauging provide 124 years of complete record to develop an annual series for flood frequency analysis (FFA).

Figure 3-4 shows the length of gauge record and the recorded Quality Codes. Several high flow events have been recorded by the gauge, the highest recorded flows and their respective years are shown in Table 3-3 along with a number of other historical events with less certainty in the flow estimates, but which have been ranked in order of magnitude using a number of historical sources.

The largest event within the instantaneous record occurred during January 2011. The 1909 and 1894 events are attributed with significantly higher peak flows than January 2011 in the DELWP gauge, but there is significant uncertainty in these estimates. The January 2011 hydrograph is clearly the highest recorded event in recent history, a hydrograph of the event is shown in Figure 3-6, along with the recorded Quality Codes.

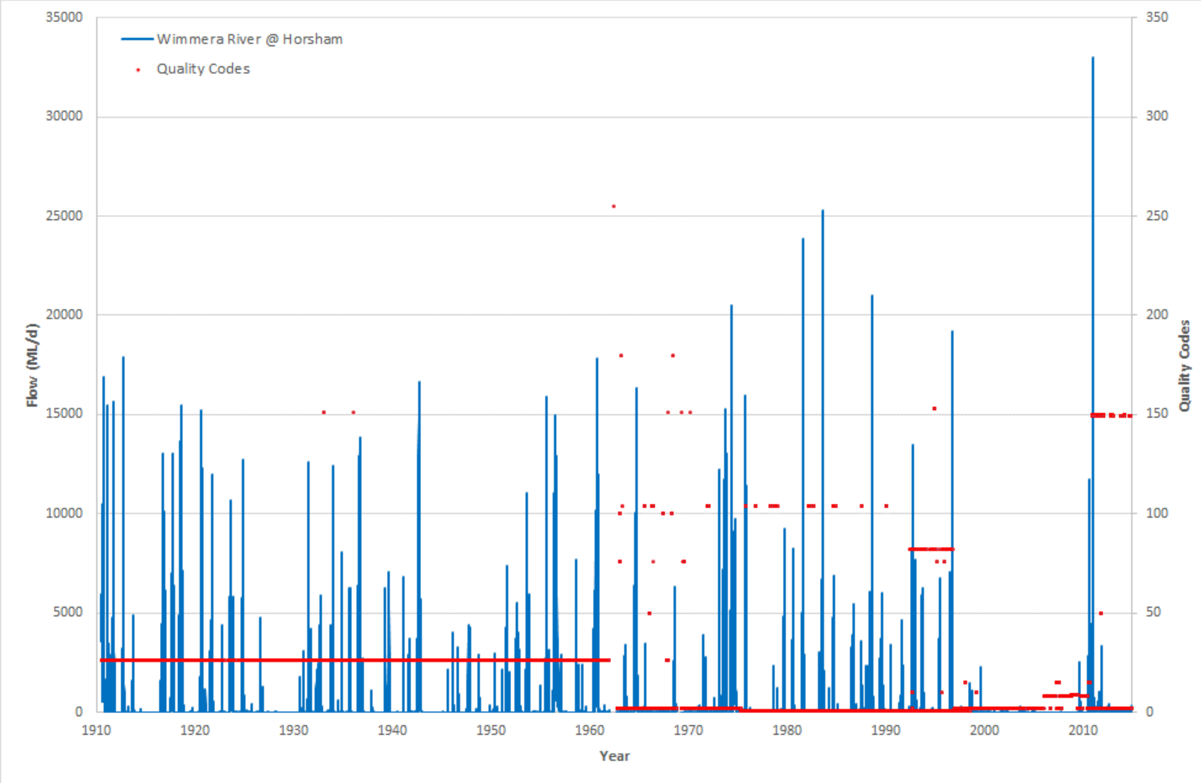

Figure 3-4 Gauge record at Wimmera River at Horsham (Walmer) showing flow and the Quality Codes[1]

Abdul Aziz of the Wimmera CMA sourced a number of highly valuable documents from the Horsham Historical Society and the State archives. These combined with the gauge record has allowed us to recreate a detailed historical record of Wimmera River streamflow at Horsham.

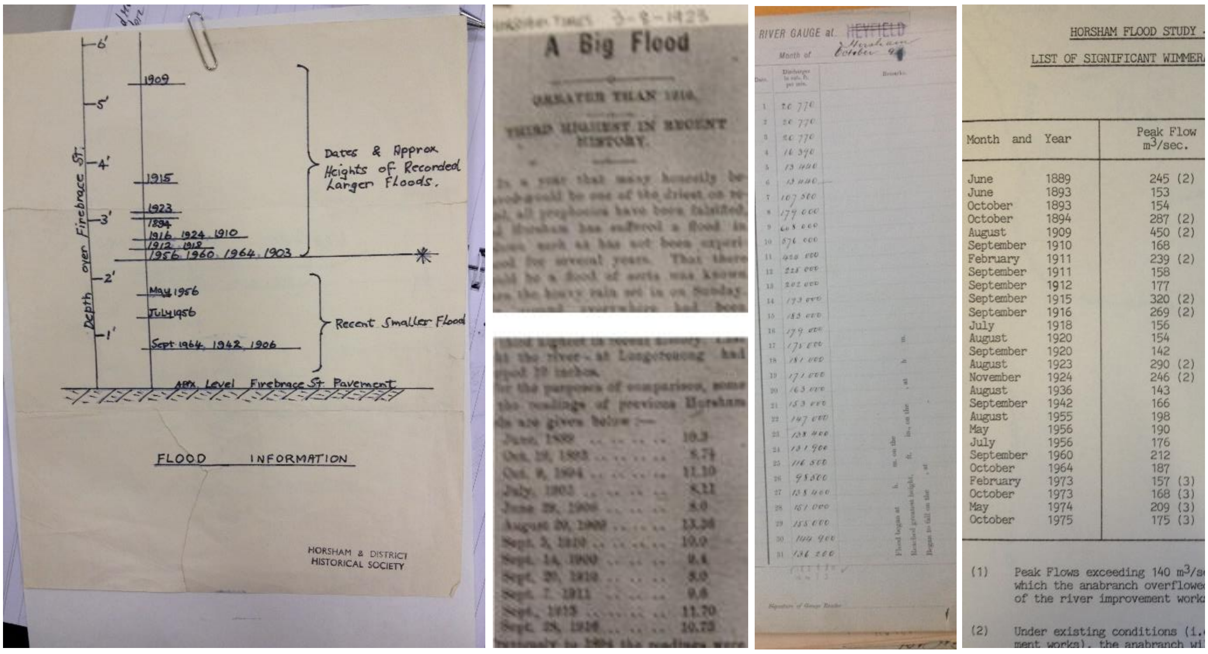

Figure 3-5 Example of historical information sourced for Wimmera River at Horsham

[1] Data downloaded from http://data.water.vic.gov.au/monitoring.htm, quality codes greater than 50 should be used with caution.

Table 3-3 Wimmera River at Horsham largest recorded peak flows

Year	Source and comments	Peak Flow	
		ML/d	m^3/s
1889	Horsham Flood Study (1979)	21,168	245
1893	Horsham Flood Study (1979)	13,306	154
1894	Significant uncertainty, the DELWP gauge records 44,249 ML/d but is most likely incorrect, adopted flow from Horsham Flood Study (1979) and written gauge book records (sourced by Abdul Aziz of Wimmera CMA).	24,792	287
1903	Historical society document showing 1903 having similar level on Firebrace Street as 1956, 1960 and 1964, adopted average of the three other flows.	16,848	195
1906	Historical society document showing 1906 having similar level on Firebrace Street as 1942	14,342	166
1909	Significant uncertainty, the DELWP gauge records 43,860 ML/d but is most likely incorrect, adopted flow from Horsham Flood Study (1979).	38,880	450
1910	Horsham Flood Study (1979)	14,515	168
1911	Horsham Flood Study (1979)	20,650	239
1912	Horsham Flood Study (1979)	15,293	177
1915	Horsham Flood Study (1979)	27,648	320
1916	Horsham Flood Study (1979)	23,242	269
1918	Horsham Flood Study (1979)	13,478	156
1920	Horsham Flood Study (1979)	13,306	154
1923	Horsham Flood Study (1979)	25,056	290
1924	Horsham Flood Study (1979)	21,254	246
1936	Horsham Flood Study (1979)	12,355	143
1942	Horsham Flood Study (1979)	14,342	166
1955	Horsham Flood Study (1979)	17,107	198
1956	Horsham Flood Study (1979)	16,416	190
1960	DELWP gauge	17,802	206
1964	DELWP gauge	16,325	189
1973	DELWP gauge	15,266	177
1974	DELWP gauge	20,466	237
1975	DELWP gauge	15,951	185
1981	DELWP gauge	23,879	276
1983	DELWP gauge	25,312	293
1988	DELWP gauge	21,005	243
1992	DELWP gauge	13,480	156
1996	DELWP gauge	19,198	222
2010	DELWP gauge	11,723	136
2011	Gauging was undertaken at Western Highway at the peak of the event, this is described in Section 3.5.2. The remainder of Section 3 discusses the peak flow for January 2011, justifying the adopted 33,000 ML/d.	33,000	382

The above historic peak flows along with other smaller flow years were included in the flood frequency analysis presented later in this report in Section 3.6.

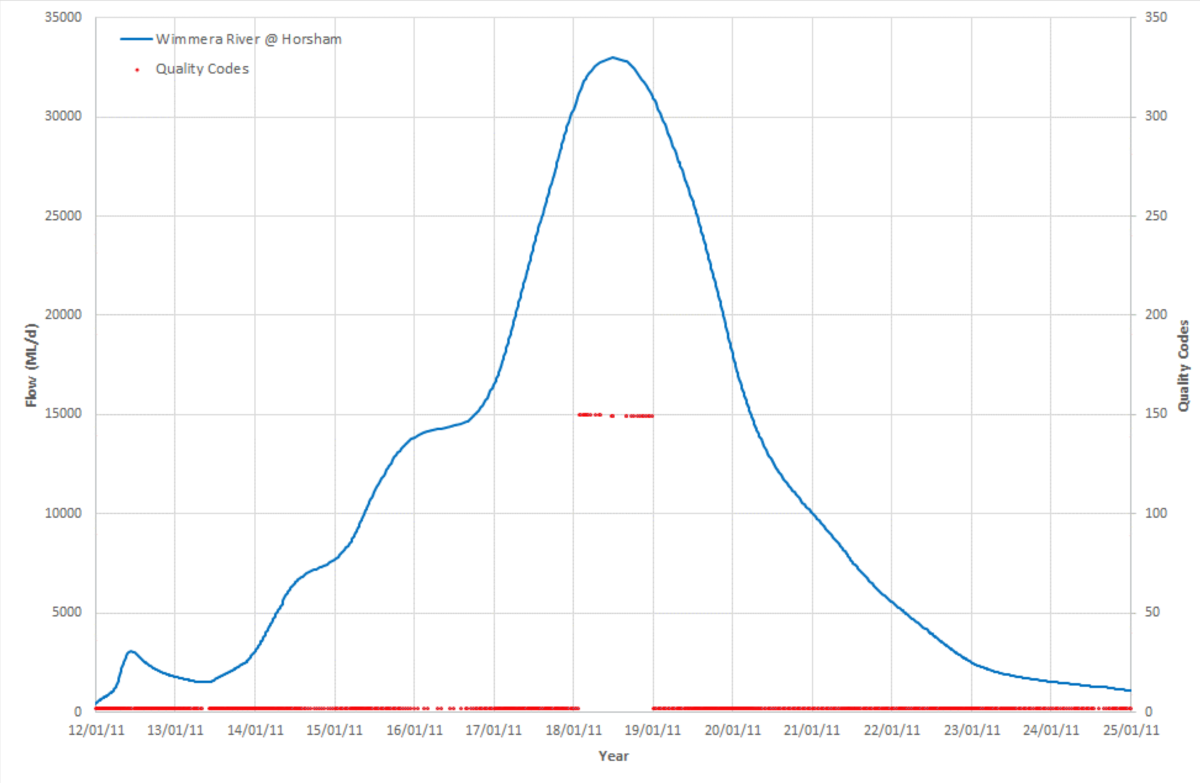

Figure 3-6 January 2011 hydrograph recorded at the Wimmera River at Horsham (Walmer) streamflow gauge

During January 2011, the Wimmera River flowrate was measured at the Western Highway Bridge 6 km upstream by Thiess Environmental[2], the gauging was completed at this location due to the Horsham gauge being too dangerous for Thiess staff to access. The location of the Horsham gauge (Walmer) and the Western Highway Bridge are shown in Figure 3-7. The Horsham gauge (Walmer) is located near the Horsham Rifle Range, immediately upstream of the Mackenzie River confluence. The gauge is located in a meandering section of river with high flow anabranches on either side of the river. The gauge is impacted by Mackenzie River flows, the degree of which is discussed further in Section 3.5.6. The gauge is in a poor location for measuring high Wimmera River flows and also low Wimmera River flows when impacted by Mackenzie River backwater.

After the January 2011 event the gauged water levels at the Horsham (Walmer) gauge and the recorded flow at the Western Highway Bridge were used to revise the Wimmera River at Horsham (Walmer) gauge rating curve.

The current Wimmera River at Horsham (Walmer) gauge streamflow rating curve and historic gauging measurements are shown in Figure 3-8, with the previous (v15) and current (v17) rating curves shown in Figure 3-9.

The change between the current rating curve and the rating curve in use prior to the January 2011 gauging is significant, especially at high flows. At the maximum level reached during the January 2011 event (4.277 m), the current rating table estimates a flow of 382 m^3/s (33,000 ML/d), whereas the previous rating was exceeded at 3.65 m but from extrapolation the flows estimated by this previous rating curve would have been significantly higher. For all levels above 1 m on the gauge (around 1,000 ML/d), the current rating curve produces lower flow estimates than the previous rating curve, with significantly lower flows at high water levels.

[2] Pers. Comm. - Thiess Environmental (Rebekah Webb)

Given the large differences in estimated flow with the two latest rating curves, a detailed investigation into the rating curve using a hydraulic model was undertaken and is described in the next section. In addition

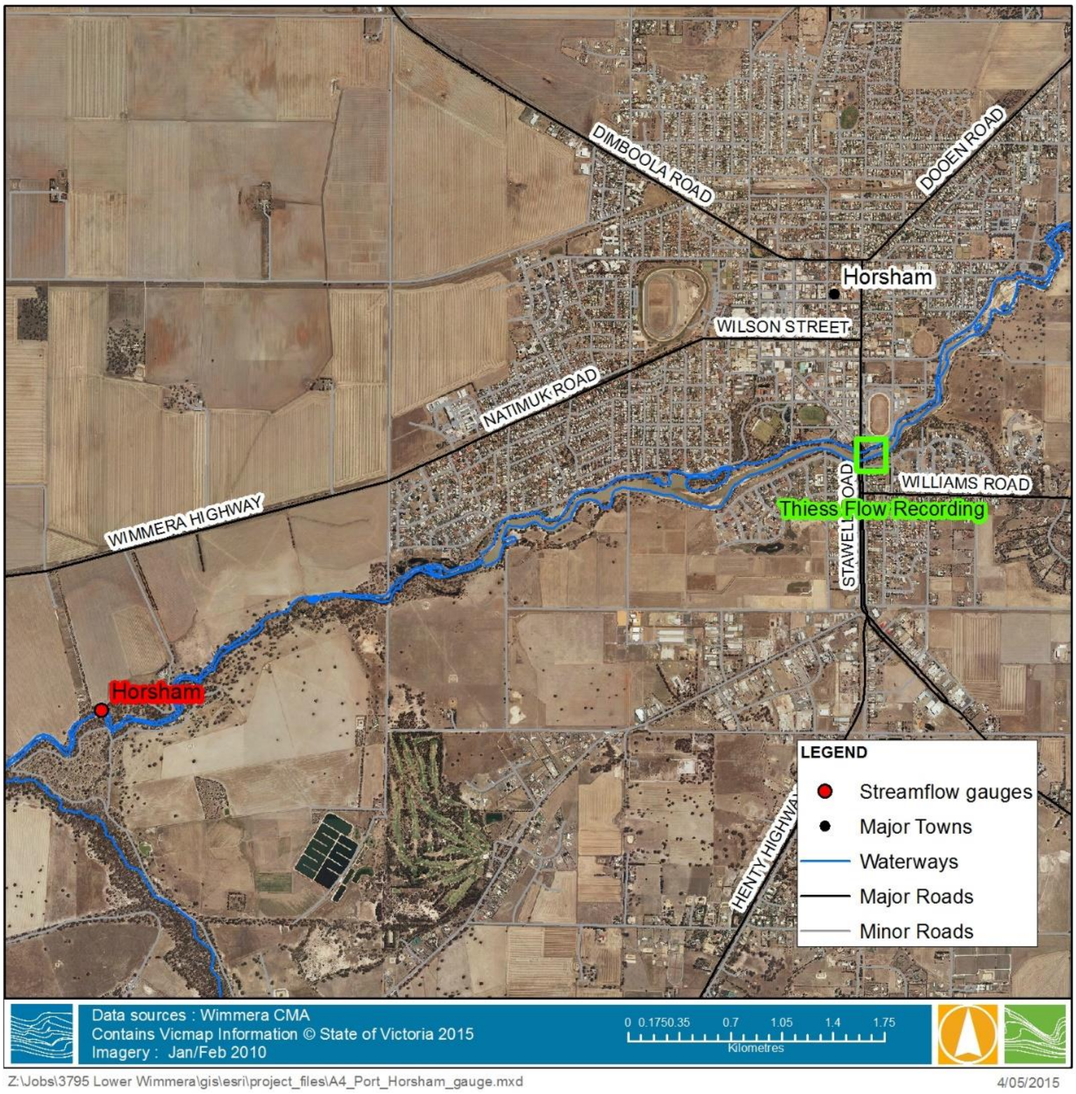

Figure 3-7 Wimmera River at Horsham (Walmer) gauge and Western Highway January 2011 measurement locations

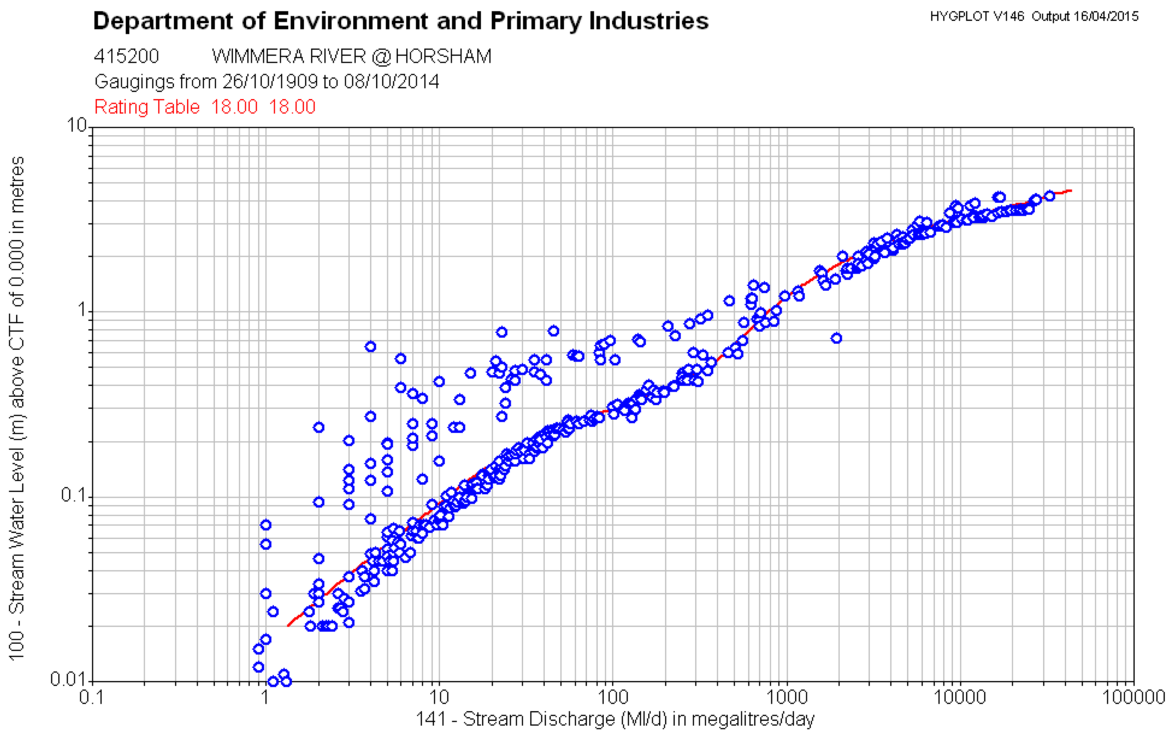

Figure 3-8 Wimmera River at Horsham streamflow gauge rating curve and measurements[3]

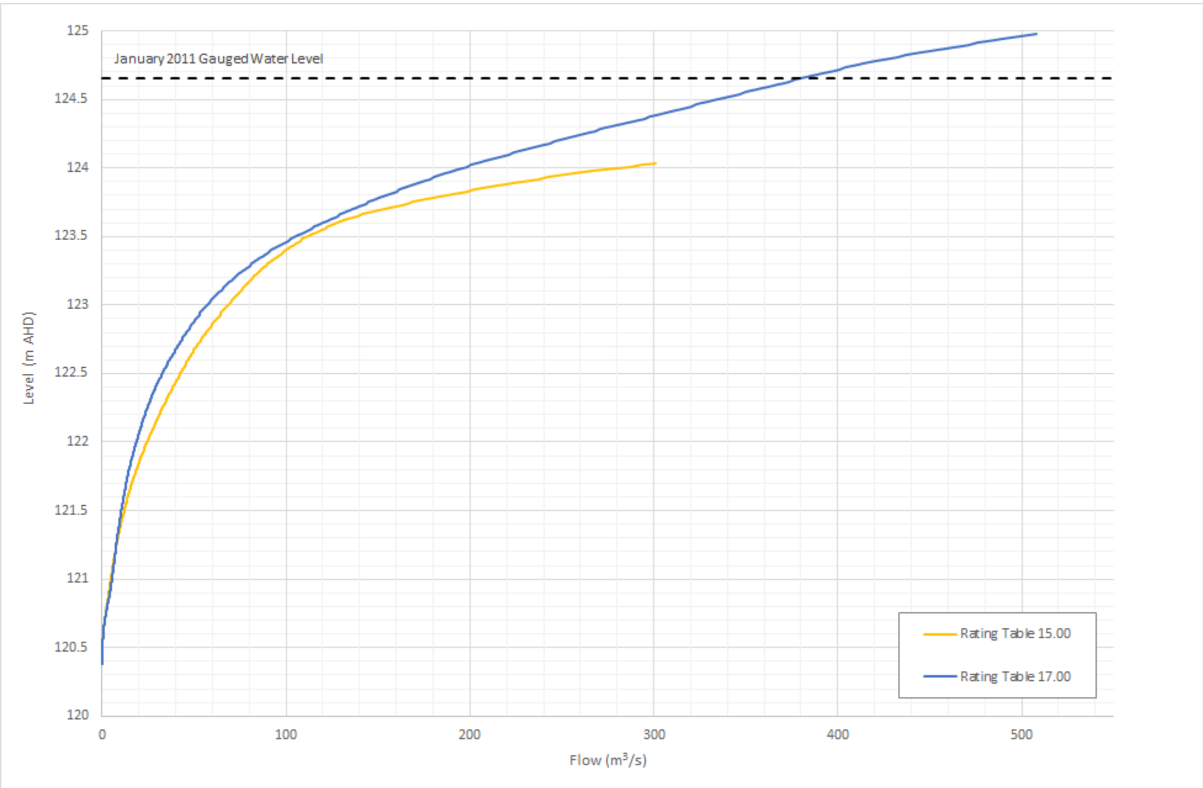

Figure 3-9 Wimmera River at Horsham current and previous rating curves

[3] Plot downloaded from http://data.water.vic.gov.au/monitoring.htm (Accessed 27/10/2014), gauge datum 120.381 m AHD

3.5.2 Meeting with Hydrographers

Water Technology was supplied with an email from a Wimmera CMA staff member shortly after the January 2011 event, quoting a preliminary flow rate for the peak gauging undertaken at the Western Highway. This flow of 37,747 ML/d did not match with the gauge record or the current rating curve.

Given the level of uncertainty in the gauged January 2011 flow and the re-rating at the Horsham gauge, the study team, Wimmera CMA and the contracted hydrographers met to discuss the specifics of the gauge site. As mentioned previously, given the difficulty accessing the site and the nature of the floodplain making it difficult to gauge at high flows, the gauging was performed immediately upstream of the Western Highway bridge.

The Horsham streamflow gauge (6 km downstream of the Western Highway gauging site), peaked at 4.277 m from 11:30am to 12noon on the 18th January. Gaugings at the Western Highway were completed at 7:05am and 7:50am on the 18th January and again the following day at 6:35am and 7:15am. The gauged flows are summarised below in Table 3-4.

Table 3-4 Western Highway flow gauging

Date and Time of Gauging	Flow at Highway (ML/d)	River Status at d/s Gauge
4:55pm 17th January 2011	27,690	Rising
7:05am 18th January 2011	32,270	Peaking
7:50am 18th January 2011	32,500	Peaking
6:35am 19th January 2011	26,400	Falling
7:15am 19th January 2011	26,470	Falling

The flow gaugings at the highway used an acoustic doppler which produced velocity distributions across the river profile. In consideration of the velocity profiles and site conditions, the hydrographers attributed these gaugings with a level of accuracy of 3.4%. The hydrographers made it very clear that the preliminary flow rate was taken directly from the field prior to any quality assurance being carried out, this preliminary estimate of 37,747 ML/d should not be used for any future work. They are very confident with the current estimate of 32,500 ML/d.

The 2010-11 Victorian floods produced record streamflows at many gauges in the north-west of Victoria. The Department of Sustainability and Environment commissioned Thiess Services to undertake a large program of rating table extrapolations across many basins. The hydrographers supplied a report that detailed the rating curve extrapolations and checks performed in the Avoca and Wimmera River catchments[4]. The report states "*The rating table was extrapolated using the Manning Equation method, historical high flow measurements, the flood measurements undertaken on January 17th, 18th and 19th 2011 and a cross sectional survey.*"

Water Technology is of the view that the gaugings completed by the hydrographers at the Western Highway bridge are likely to be of sufficient accuracy for adoption in this study.

3.5.3 Additional Considerations

The Quantong gauge is located 18 km downstream of the Horsham gauge, and the time from peak to peak during the January 2011 event was roughly 12 hours. This indicates that the peak of the flood was moving down the system at approximately 1.5 km/hr (0.42 m/s). The distance between the Western Highway and the Horsham gauge is approximately 6 km. By applying the same travel speed

[4] Thiess Services (2012), Rating Table Extrapolations for the Wimmera and Avoca Catchments.

for the flood peak, this would suggest that the flood peak took 4 hrs to travel between the Western Highway and the Horsham gauge. This indicates that the flood may have peaked at the Western Highway around 8 am, almost exactly when the peak gauging was completed at the Wimmera Highway.

Previous modelling of Horsham and aerial imagery of the January 2011 event shows that some flow bypasses the highway, breaking out of the river between Bailie and Mcbryde Streets, travelling west along Hamilton Street, across Firebrace St, then heading south back to the river. Previous modelling shows this flow rate was likely to be between 100 to 1000 ML/d based on the previous 2% and 1% AEP modelling results respectively.

Assuming the flow bypassing the highway may be somewhere between the two above estimates, it was concluded that the peak January 2011 flow was approximately 33,000 ML/d (382 m^3/s).

3.5.4 Hydraulic Model Rating Curve Review

Given the importance of the estimated Wimmera River flows at the Horsham gauge to the outcomes of this study, a detailed review of the rating curve using a hydraulic model was completed.

A detailed 4 m grid TUFLOW model was constructed of the Wimmera River floodplain from the Western Highway to approximately 2 km downstream of the Mackenzie River. The detailed model was validated to previous hydraulic modelling of the 1% AEP design flood from the Horsham Bypass Hydrology and Hydraulics Investigation (Water Technology, 2012). The model was comprised of an upstream inflow boundary at the Western Highway and a H-Q boundary at the downstream end of the model.

A series of steady state flows were run through the model and the modelled rating curve was compared to the current and previous rating curves, Figure 3-10. The flow increments ran through to a maximum flow of 500 m^3/s. Three roughness parameters of 0.05, 0.075 and 0.1, representing possible roughness of the river corridor were tested.

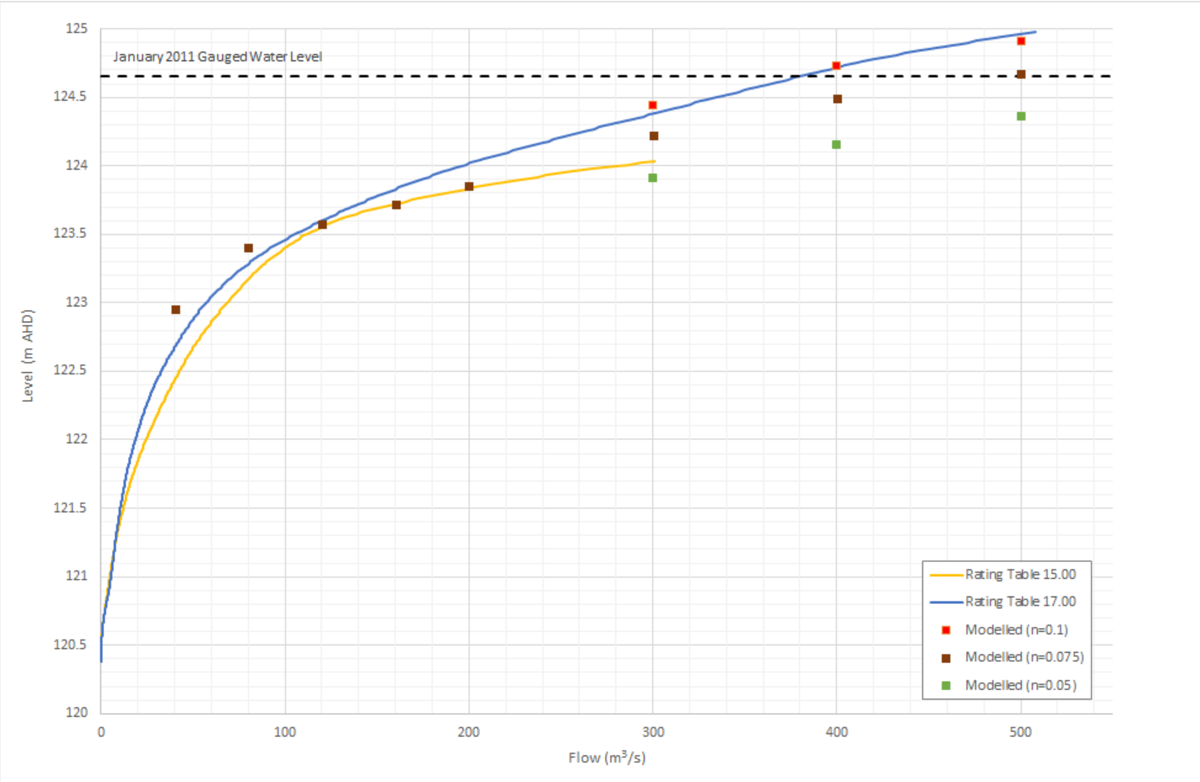

Figure 3-10 Comparison of current and previous rating curves with modelled rating curve

As shown above, using a roughness of 0.1 in the river corridor closely reproduced the current rating curve (version 17) for high flows. The previous rating curve (version 15) was replicated with a roughness between 0.05 and 0.075. The lower roughness of 0.05 resulted in a water level at the gauge 0.3 m lower than the observed January 2011 level with a flow of 500 m^3/s. To achieve the January 2011 water level a flow outside the bounds of expected flow considering upstream and downstream gauges would be required. The roughness value of 0.05 was therefore discounted for the rating curve model as it produced water levels that were too low.

3.5.5 Verification of Flows with Lower Wimmera River Model

To further investigate the suitability of the gauge rating curves at high flows, the January 2011 flow hydrograph was modelled in a preliminary version of the MIKE Flexible Mesh model from Horsham to Lake Hindmarsh. Both the gauged hydrograph and the adjusted January 2011 hydrograph using the modelled rating curve assuming a roughness of 0.075 was modelled. The peak flows for the two scenarios differed significantly, with a peak of 381 m^3/s using the current gauge rating and a peak flow of 492 m^3/s using the modelled rating curve with roughness 0.075.

For the Horsham to Lake Hindmarsh flexible mesh model a constant roughness of 0.05 was adopted for this preliminary run. Note that the roughness values between the 4 m grid rating curve model and the preliminary flexible mesh model should not be directly compared. The roughness values should be based on the physical attributes of the waterway, but in modelling will differ dependant on grid sizes and model schematisation. On the site inspection carried out on 23rd March 2015, a number of locations along the river were visited. The section of river downstream of Horsham (see photos in Figure 3-11), did seem to be more densely vegetated and considered rougher than other sections of the river visited at Quantong, Dimboola and Jeparit. The roughness in this stretch of river downstream of Horsham is quite high, values of 0.075 and 0.1 are realistic. Chow (1959) recommends that for *"floodways with heavy stand of timber and underbrush"*, roughness values in the range from 0.075 (minimum) to 0.1 (normal) 0.15 (maximum) can be used. For other less densely vegetated areas of the river it is likely that a lower roughness may be suitable, this will be refined through calibration of the model in the next stage of works of this project.

The flexible mesh model was refined after the preliminary runs and was nearing completion and final calibration at the time of this report. A model run with the 33,000 ML/d (382 m^3/s) flow was completed and is discussed further below. The development of this Horsham to Lake Hindmarsh flexible mesh model will be fully detailed in the hydraulics report.

Figure 3-11 Typical Wimmera River conditions for assessing roughness

The preliminary flexible mesh model results using the current rating curve (version 17) with a peak flow of 381 m^3/s reproduced flood levels quite well along the Wimmera River. Of the 33 survey marks the model results were within 100 mm of the surveyed level at 21 points, another 8 were within

200 mm, and the remaining 4 were greater than 200 mm different to the survey. This was a very good result for the first calibration attempt.

The preliminary flexible mesh model results using the modelled rating curve assuming a roughness of 0.075, with a higher peak flow of 492 m^3/s resulted in water levels increasing between Horsham and Dimboola by around 300 mm, with the water level difference decreasing to about 100 mm between Dimboola and Lake Hindmarsh. Overall the current rating curve (version 17) produced much more accurate flood levels along the Wimmera River in comparison to the surveyed January 2011 flood levels. The two preliminary model extents for the January 2011 flood event are shown in Figure 3-13 below.

The flexible mesh model was refined to include more detail of the channel itself, moving from a reasonably uniform 15 x 15 m square elements with some triangle elements on bends, to a blend of long narrow quadrilateral elements along the waterway to better estimate channel capacity, transitioning out to triangular elements in the floodplain. This scheme allows a lot more detail in the river channel. This refined model was tested with a January 2011 flow of 33,000 ML/d (382 m^3/s).

For the refined flexible mesh model the model was within 100 mm of the observed survey level for 20 of the 33 survey marks. Another 8 points were within 200 mm, 3 more were just outside of 200 mm and two were over half a metre out. This was a very good result, with the extents matching quite well to observed aerial imagery along the river. This calibration will be detailed in the hydraulics report, and is discussed here as means of validating the January 2011 flow.

From the above analysis it was concluded that the current rating curve (version 17), with a peak January 2011 flow of 33,000 ML/d (382 m^3/s), accurately represents the January 2011 historic hydrograph and reproduces the observed flood levels and flood behaviour of the January 2011 event. This analysis does not infer anything regarding the accuracy of the rating curve at lower flows.

As a means of sanity checking this analysis on the rating curve a Manning's Equation flow calculation was performed on the cross-section at the streamflow gauge location. The cross-section is presented below in Figure 3-12 with the peak water level from January 2011 plotted on the cross-section.

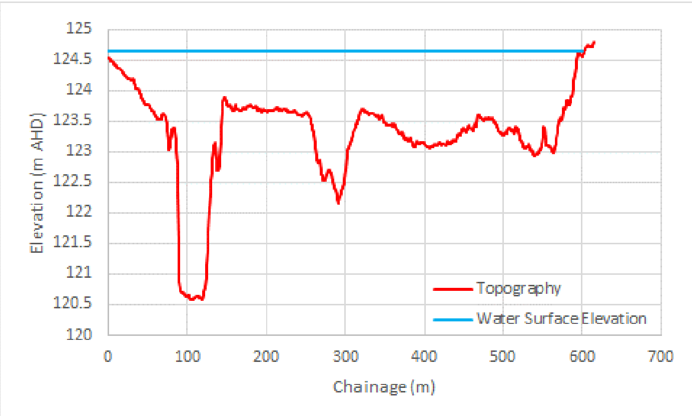

Figure 3-12 Wimmera River floodplain cross-section for Manning's flow calculation

The difficulty in using a simple Manning's Equation approach is that it assumes a uniform slope and velocity across the floodplain. A water surface elevation slope was calculated from the hydraulic model as roughly 1 in 2700, and a range of roughness values were used (from 0.05 to 0.1). The Manning's Equation flow calculations for the January 2011 peak water level ranged from 17,200 to 34,600 ML/d with roughness values from 0.1 to 0.05 respectively.

These Manning's Equation flow estimates cover a large range, with the upper flow bound in the vicinity of the gauged flow. This Manning's Equation estimate can't be used with any confidence given the complexity of the floodplain at the gauging location.

Water Technology has far more confidence in the flow measurements that were carried out at the Western Highway during January 2011 by the contracted hydrographers than the flow estimates made by the Manning's Equation described above.

Figure 3-13 Wimmera River Horsham to Lake Hindmarsh preliminary and refined flexible mesh January 2011 modelled flood extents

3.5.6 Impact of Mackenzie River

The Mackenzie River flows into the Wimmera River approximately 1 km downstream of the Horsham (Walmer) gauge. There has long been speculation as to the impact of Mackenzie River on the Horsham gauge. A series of hydraulic model scenarios were run to test the potential impact of Mackenzie River on Wimmera River flow gauging.

The results showed that with a low Wimmera River flow of 10 m^3/s (864 ML/d) the Mackenzie River can have a significant impact on the Wimmera River gauge with water levels increasing at the gauge by 0.37 m with the Mackenzie flow increasing from 25 to 50 m^3/s (2,160 to 4,320 ML/d). This demonstrates that at low Wimmera River flows Mackenzie River can have a significant impact on the water level in the Wimmera River at the Horsham gauge. At these low Wimmera River flows, an increase in water level at the gauge of this magnitude translates to an increase in flow of approximately 400-500 ML/d.

At higher flows, with the Wimmera River at 200 m^3/s (17,280 ML/d), an increase in Mackenzie River flows from 10 to 100 m^3/s (864 to 8,640 ML/d) results in a water level increase at the Horsham gauge of 0.19 m. This is a significant increase with respect to the sensitivity of the rating curve on estimated flow. At high Wimmera River flows an increase in water level of this magnitude translates to an increase in flow of approximately 4,000-5,000 ML/d.

As discussed previously in this report the Mackenzie River generally peaks 2.5 to 3.5 days prior to the peak of the Wimmera River. At the time of the Wimmera River peak flow at Horsham the Mackenzie River at McKenzie Creek gauge has measured between 200-630 ML/d of flow over a number of historic flood events where concurrent gauging was available. These low Mackenzie River flows that generally occur at the same time as the Wimmera River peak flows are unlikely to have any real impact on the water level at the Horsham (Walmer) gauge and no impact on flood levels back in Horsham.

If after considering this analysis Wimmera CMA still has concerns regarding the impact of Mackenzie River on flow gauging on the Wimmera River at Horsham (Walmer) gauge, Water Technology can develop a set of alternative rating curves assuming different Mackenzie River flow rates. An example of what these curves may look like is included below. Note that these curves are not based on modelled data, just a sketch illustrating the concept of developing different rating curves for different Mackenzie River flow rates.

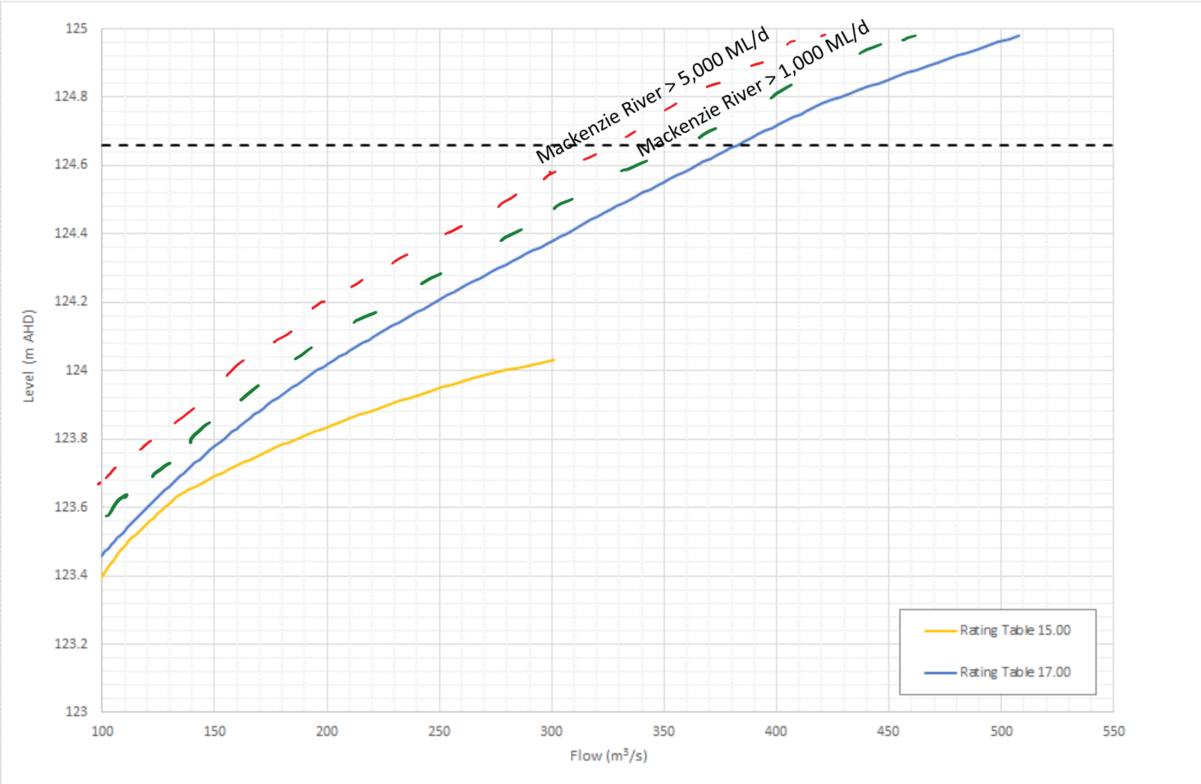

Figure 3-14 Wimmera River at Horsham (Walmer) rating curve with example of revised rating curves showing impact of Mackenzie River flows

3.6 Flood Frequency Analysis

3.6.1 Peak Flow

A Flood Frequency Analysis (FFA) was used to determine peak design flows for the range of modelled design events. An annual series was constructed from the available instantaneous flow record, and historic information sourced by Abdul Aziz. The larger historic peak flows used to construct the annual series were displayed earlier in Table 3-3, this was supplemented with smaller flows from other years. A complete annual series was constructed from 1889 to 2015. The low flows were filtered using the Grubbs Beck test, censoring 58 of the 127 years of annual series. It should be noted that the annual series used the Wimmera River at Horsham (Walmer) flow data without any adjustment due to the impact of Mackenzie River backwater. For Wimmera River flood flows it has been demonstrated that the impact of Mackenzie River on peak water levels at the gauge is generally quite low. The Mackenzie River tends to peak 2.5 to 3.5 days earlier than the Wimmera River and at the time of the Wimmera River peak the Mackenzie River flow tends to be relatively low, justifying the adoption of the Wimmera River flows unadjusted.

A range of statistical distributions were trialled in Flike including LP3, log-normal, Gumbel, GEV, and Generalised Pareto. The LP3 distribution plotted the best against the historic series.

Table 3-5 Wimmera River at Horsham FFA results (LP3 with low flow censoring)

AEP (%)	Peak Flow (ML/d)	Peak Flow (m^3/s)
20	13,100	152
10	19,200	222
5	25,000	289
2	31,900	369
1	36,500	423
0.5	40,700	471
0.2	45,400	525

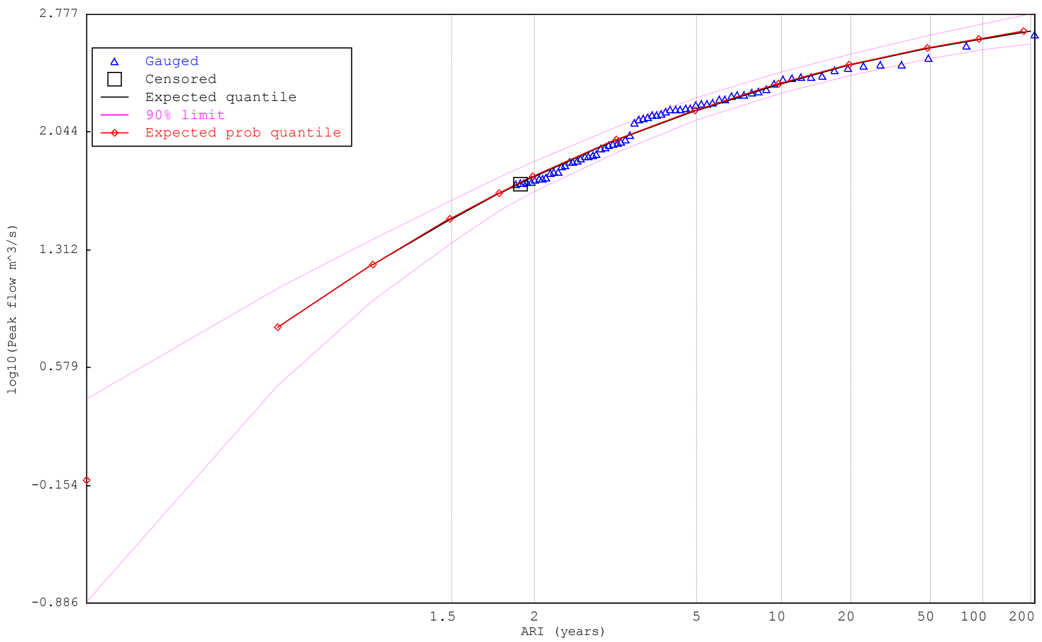

Figure 3-15 Wimmera River at Horsham FFA (LP3 with low flow censoring)

3.6.2 Event Volume

A flood frequency analysis was completed following a similar procedure as described above for peak flow. A number of historic events were analysed and it was found that large flood events on the Wimmera River at Horsham can last between 6 to 8 days, with flows above 5,000 ML/d. A 7 day volume flood frequency analysis was carried out, using an annual series from 1910 to current and censoring 54 years with low 7 day event volumes.

Table 3-6 Wimmera River at Horsham FFA results of seven day volume

AEP (%)	Seven day event volume (ML)
20	53,800
10	85,800
5	110,600
2	132,400
1	142,600
0.5	149,100
0.2	154,200

3.7 Calibration Events

For hydraulic model calibration the streamflow hydrograph for the Wimmera River at Horsham gauge was used directly as the inflow boundary to the hydraulic model.

As documented earlier in the report this hydrograph was tested in a preliminary version of the Horsham to Lake Hindmarsh flexible mesh model. Sensitivity of the model to the design flow hydrograph was also carried out by running a hydrograph with a peak flow approximately 30% higher. This higher flow resulted in flood levels approximately 300 mm higher upstream of Dimboola and only 100 mm higher downstream of Dimboola.

The next stage of the project (hydraulic model calibration and design modelling) adopted the gauged January 2011 flood hydrograph but undertook sensitivity testing of the January 2011 event with and without tributary inflows downstream of Horsham. This is documented in the Hydraulics Report (R03).

3.8 Design Flow Hydrographs

It was recommended that the January 2011 event be adopted for the Wimmera River design hydrograph shape. The design hydrographs were adjusted to match the peak design flow estimates and event volume from flood frequency analysis.

3.9 PMF Estimation

The Probable Maximum Flood (PMF) is the flow generated from the theoretical maximum precipitation for a given duration under current climate conditions. A PMF estimate for the Wimmera River at Horsham gauge was prepared using the Quick Method of Nathan et al. (1994). This method applies a set of empirical equations to compute a triangular PMF hydrograph. The equations are set out below.

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

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), 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 following values have been determined based on the Walmer gauge.

A = 4,066 km^2, Q_p = 21,586 m^3/s (1,865,035 ML/d), V = 1,771,692 ML, T_p = 17.6 hours, T_r = 45.6 hours

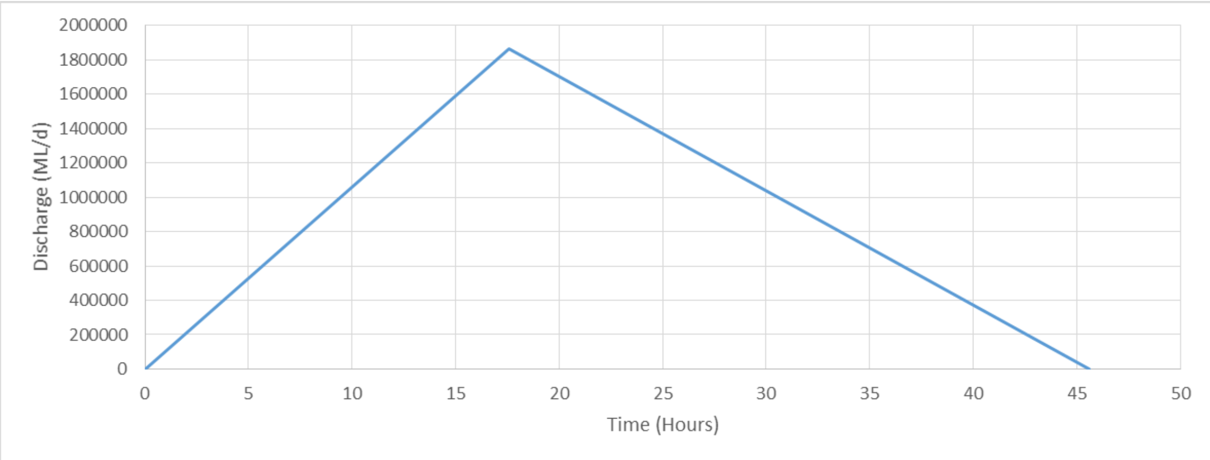

Figure 3-16 PMF Hydrograph from Nathan et. al. Quick Method – not adopted

It is suggested that this PMF may be an overestimate, due to the storages in the catchment and the flat lowland nature of the floodplain upstream of Horsham most likely having a different 1% AEP to PMF ratio than the upland catchments this method was mainly based on. Water Technology investigated an alternative means of developing a PMF flow based on 1% AEP to PMF ratios from other studies within the Wimmera River catchment. We used the Upper Wimmera Flood Investigation (BMT WBM, 2014) and the Mount William Creek Flood Investigation (BMT WBM, 2014), both of which used a Generalised Southeast Australia Method (GSAM) PMP estimate in RORB to estimate a PMF at locations within the catchment. The PMF to 1% AEP flow ratio for Mount William Creek at Lake Lonsdale was 11.4, with Wimmera River at Glynwylln having a ratio of 10.9. An average of the two ratios was taken and 11.2 was adopted. This ratio was applied to the 1% AEP design hydrograph at Horsham giving a PMF peak flow of 409,000 ML/d.

The PMF flow for the Wimmera River at Horsham was adopted as 409,000 ML/d. Water Technology believes that this is a far more reasonable estimate as compared to 1,865,000 ML/d from the Nathan et. al. quick method.

4. CONCLUSIONS

An earlier version of this report was reviewed independently by a DELWP review panel. A review by Wimmera CMA was also completed. This final version of the hydrology report addressed all feedback, and added additional information regarding historic events, clearing up uncertainty in the gauged January 2011 peak flow and the re-rating of the Horsham gauge.

The design hydrology provides a more comprehensive analysis of Wimmera River flows at Horsham than earlier studies. Significant effort was directed toward testing and validating the Wimmera River at Horsham (Walmer) streamflow gauge rating curve and constructing the best possible annual peak flow series for flood frequency analysis. It is suggested that this analysis provides the best available estimate of design flood flows for the Wimmera River at Horsham.

The hydraulic model calibration and design modelling documented in the Hydraulics Report (R03), has adopted the hydrology discussed in this report and presents the results of that modelling. It is the hydraulic model results that truly validate the hydrology approach and it is suggested that the reader views all Lower Wimmera Flood Investigation reports to obtain a full appreciation of the study findings.