# Design Modelling Report

## Horsham and Wartook Valley Flood Investigation

Wimmera CMA

07 September 2018

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## Project Details

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| **Client** | Wimmera CMA |
| **Client Project Manager** | Paul Fennell |
| **Water Technology Project Manager** | Ben Hughes |
| **Water Technology Project Director** | Ben Tate |
| **Authors** | Ben Hughes |
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PO Box 584
Stawell VIC 3380

| | |
|---|---|
| Telephone | 0438 510 240 |
| ACN | 093 377 283 |
| ABN | 60 093 377 283 |


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07 September 2018

Paul Fennell
Floodplain Management Team Leader
Wimmera CMA
24 Darlot Street
HORSHAM VIC 3400

Dear Paul

## Horsham and Wartook Valley Flood Investigation

Please see the attached Design Modelling and Mapping Report for the Horsham and Wartook Valley Flood Investigation.

If you have any queries, please don't hesitate to contact me.

Yours sincerely

**Ben Hughes**
Principal Engineer

ben.hughes@watertech.com.au

**WATER TECHNOLOGY PTY LTD**

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# 1 INTRODUCTION

Wimmera CMA has engaged Water Technology to undertake the Horsham and Wartook Valley Flood Investigation. The objective of the study was to update and extend the flood mapping across the study area, update the flood intelligence for emergency planning, and investigate flood mitigation measures along the Wimmera River at Horsham. Stormwater flooding in Horsham and Haven was also investigated.

A RORB hydrology model was developed for the Mackenzie River and minor tributaries that drain the study area and the flood frequency analysis completed in the Lower Wimmera Regional Flood Mapping Study was used for Wimmera River hydrology. Hydraulic models were constructed for both riverine and stormwater inundation. Riverine inundation was modelled using the Mike by DHI Flexible Mesh software, while the stormwater inundation was modelled using TUFLOW.

## 1.1 Reporting Stages

The project was delivered in stages, with milestone reports produced at each stage as follows:

- Data Collation and Review Report (Complete)
- Model Calibration Report (Complete)
- Design Modelling Report (Complete)
- Flood Mitigation Report
- Flood Intelligence Report
- Flood Warning and Assessment Report
- Planning Scheme Amendment Reporting
- Final Report

This report is the Design Modelling Report, discussing the hydrology and hydraulic model build, a brief summary of the model calibration (further detail can be found in the Model Calibration Report) build and hydrology and hydraulic design modelling. This report forms the basis for the Flood Mitigation Report, Flood Intelligence Report, Flood Warning and Assessment Report and Planning Scheme Amendment Report.

## 1.2 Study Area

The Wimmera River originates in the Pyrenees Ranges on the northern slopes of the Great Dividing Range and flows north west, intersecting Horsham. At this point the upstream catchment is over 4,000 $km^2$.

Approximately 25 km upstream of Horsham the Wimmera River splits to Yarriambiack Creek, a portion of which returns to the Wimmera River via Two Mile Creek further downstream. An overland flow path south of the Wimmera River also carries flood water breaking out from downstream of Drung to Riverside.

Several tributaries feed the Wimmera River between Horsham and Quantong with runoff from the northern Grampians Mountain Ranges. These include: Burnt Creek, Bungalally Creek, MacKenzie River, Norton Creek, Darragan Creek, and Sandy Creek.

The MacKenzie River, which is fed by the Wartook Reservoir, and intricately linked to Burnt Creek and Bungalally Creek. Burnt Creek receives an effluent distribution from the MacKenzie River. Further along Burnt Creek a similar distribution occurs to Bungalally Creek, which then flows back into the MacKenzie River.

The study area, including waterways to be mapped is shown in Figure 1-1.

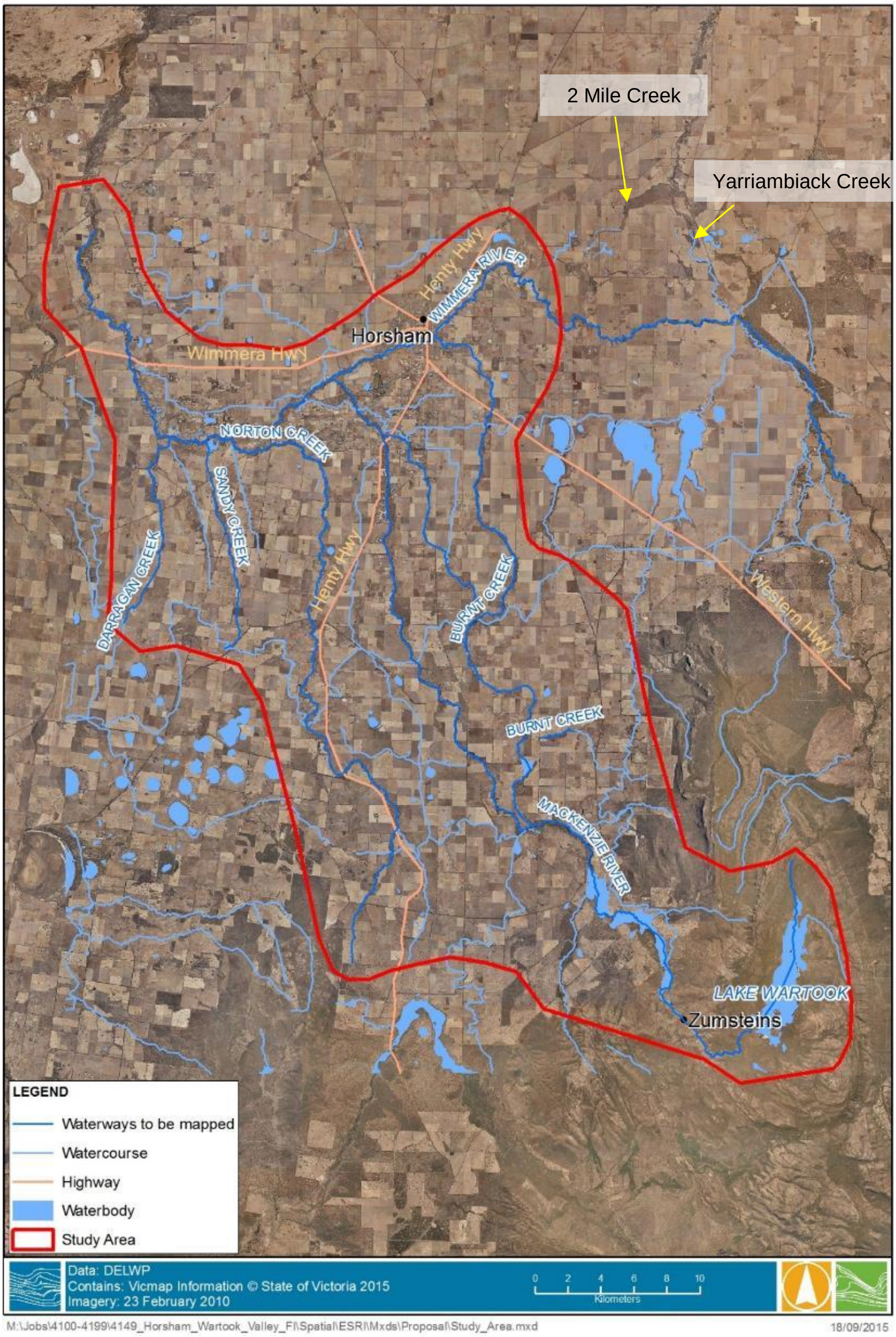


**FIGURE 1-1 STUDY AREA**

# 2 MODELLING METHODOLOGY

The study area is very large, requiring riverine flood modelling of the Wimmera and Mackenzie River floodplains, and numerous tributaries and anabranches. The study also requires flood mapping local storm events over Horsham itself.

An overview of the riverine and stormwater modelling methodologies is discussed below:

- Riverine Inundation
  - Flow in the Wimmera River was determined using the Horsham (Walmer) streamflow gauge, transposed to the Wimmera River model boundary. During calibration, the gauged flows were factored up and lagged in time iteratively until they reproduced the gauge record at Horsham (Walmer) gauge. The Wimmera River flow at the model boundary is separated into flow in the Wimmera River and on the floodplain south of the river. Modelling completed in the Warracknabeal and Brim Flood Investigation[1] was used to determine the flow split between the river and floodplain. Design flows used a flood frequency analysis of the Horsham (Walmer) gauge transposed to the model boundary.
  - Flow in the Mackenzie River downstream of Mackenzie Falls was determined by directly applying the Lake Wartook outflow. A flood frequency analysis was used for design flows.
  - Flow entering the study area from the Wimmera River tributaries, Burnt Creek, Bungalally Creek, Norton Creek, Darragan Creek and Sandy Creek was determined using a RORB runoff routing model for both historic and design flood events.
  - The gauged and modelled flows were input into a Mike Flexible Mesh (MIKEFM) model which modelled the flow behaviour of historic and design floods, producing flood level, depth, velocity and hazard outputs.
  - Model calibration was completed using the January 2011 and September 2016 events.
- Stormwater Inundation
  - Stormwater inundation in Horsham and Haven was modelled by directly applying historic and design rainfall to a TUFLOW hydraulic model topography. Rain accumulates within model cells and flows to the lowest adjacent cell, flow from multiple cells combine to form flow paths before pooling in low areas or flowing into a waterway. This type of modelling represents overland stormwater runoff during localised storm events.
  - Model calibration was completed using the January 2011 event.

A detailed description of each modelling methodology and how it was applied in the Horsham and Wartook Valley Flood Investigation is included in the following sections.

## 2.1 Riverine Inundation

### 2.1.1 Gauge flows

Modelling of the two major rivers within the study area used inflows extracted from gauge records at the Wimmera River at Horsham (Walmer) gauge and the Mackenzie River at Lake Wartook gauge. To apply flows from these gauges to the hydraulic model they were translocated, and in the case of the Wimmera River, were lagged, scaled and split between multiple model boundary locations. The streamflow gauge locations and their model input locations are show in Figure 2-1.

[1] Water Technology (2014), Warracknabeal and Brim Flood Investigation (Commissioned by Wimmera CMA)


**FIGURE 2-1 GAUGED MODEL INFLOWS**

Gauge flows for the Wimmera River at Horsham (Walmer) gauge were translocated to the hydraulic model boundary which required an increase in the peak flow and lagging the hydrograph backward in time. This was completed across several iterations in order to match the timing and attenuation between the model boundary and the Horsham gauge. At the model boundary the Wimmera River flow separates into flow along the main channel, and floodplain flow along an overland flow path through East Horsham. Modelling of the January 2011 event completed during the Warracknabeal and Brim Flood Investigation was used to determine this flow split, the September 2016 event did not engage this area of floodplain. The combined Wimmera River inflows and gauged flows for the January 2011 and September 2016 events are shown in Figure 2-2 and Figure 2-3 respectively.

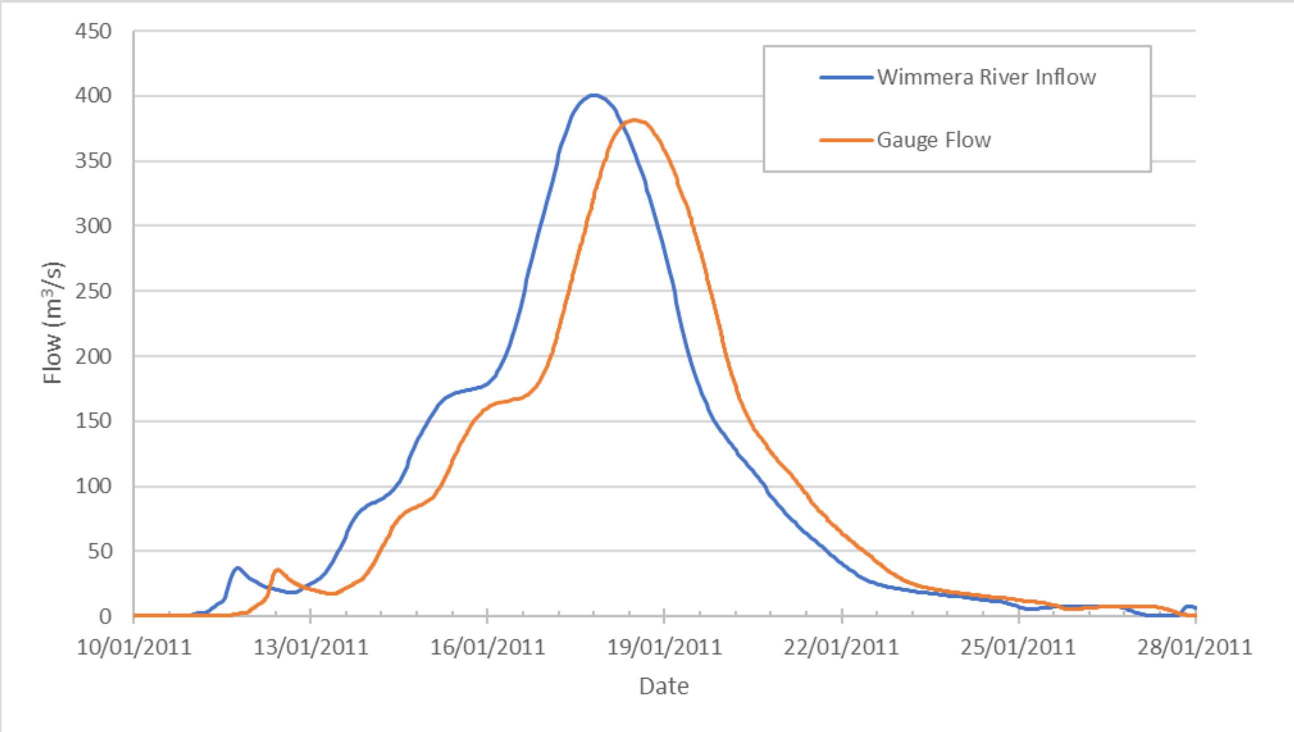


**FIGURE 2-2 JANUARY 2011 – WIMMERA RIVER MODEL INFLOWS AND WIMMERA RIVER AT HORSHAM (WALMER) GAUGE RECORD**

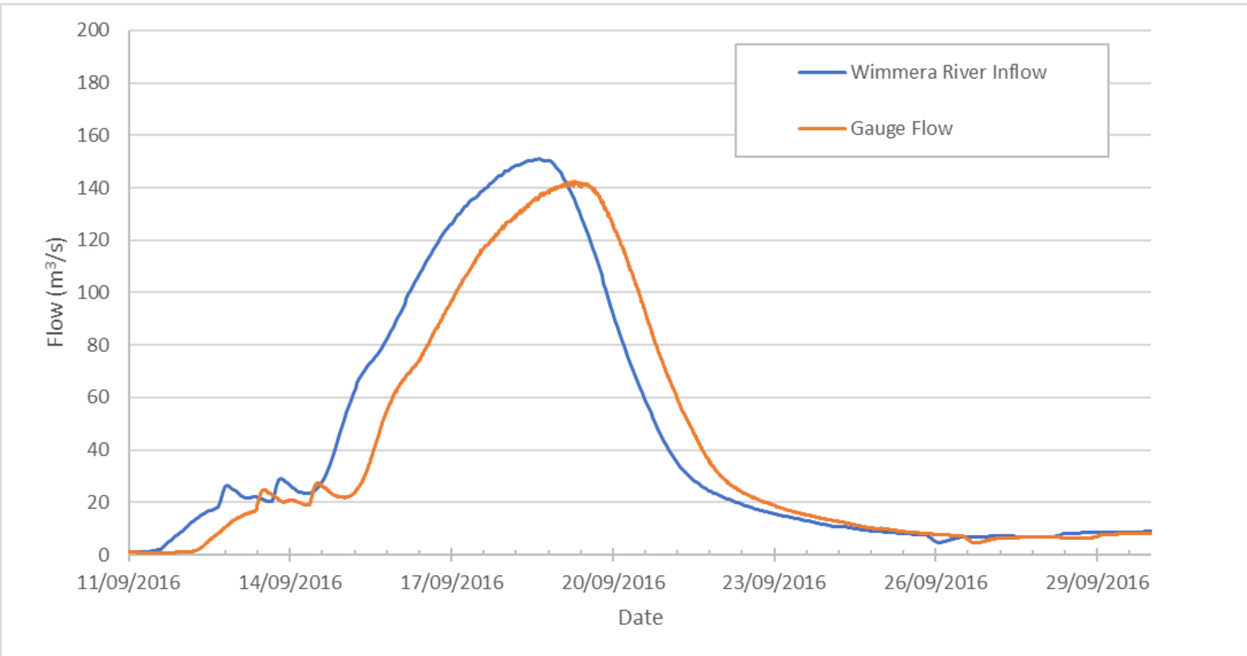


**FIGURE 2-3 SEPTEMBER 2016 – WIMMERA RIVER MODEL INFLOWS AND GAUGE RECORD AND WIMMERA RIVER AT HORSHAM (WALMER) GAUGE RECORD**

Gauge flows from the Mackenzie River at Wartook gauge were input directly into the model, translocated downstream of Mackenzie Falls. Given the steepness of this reach, the time lag is insignificant between the gauge location and the model boundary location, and did not warrant any adjustments to the inflow hydrograph.

The modelled January 2011 and September 2016 inflows are shown in Figure 2-4 and Figure 2-5 respectively.

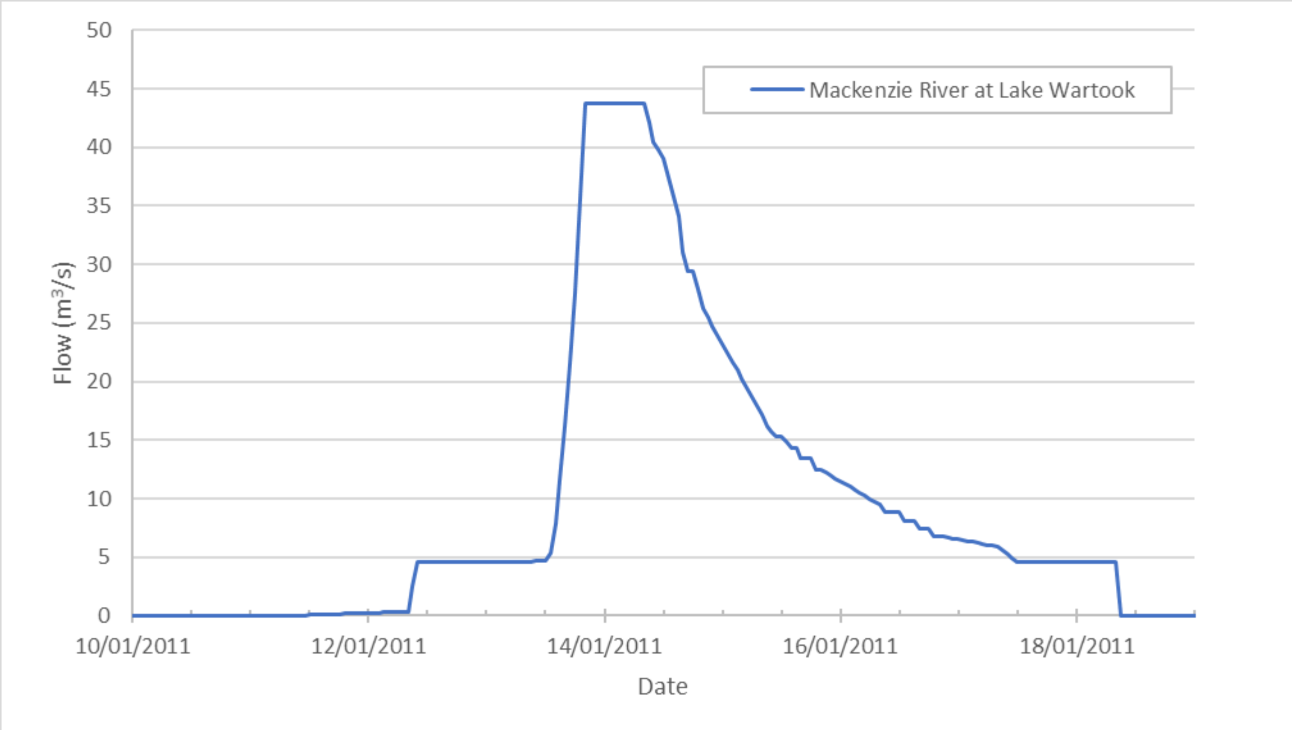


**FIGURE 2-4 JANUARY 2011 – MACKENZIE RIVER MODEL INFLOWS**

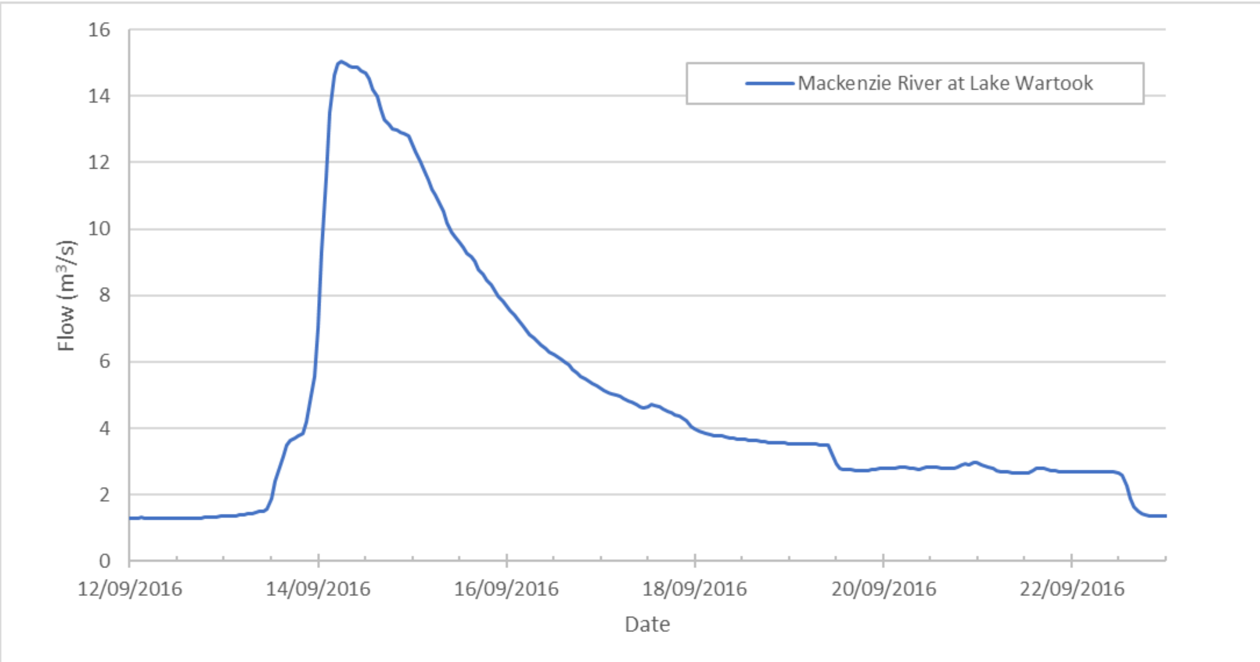


**FIGURE 2-5 SEPTEMBER 2016 – MACKENZIE RIVER MODEL INFLOWS**

### 2.1.2 RORB

A RORB model of the Wimmera River, Mackenzie River, Burnt Creek, Bungalally Creek, Darragan Creek, Norton Creek and Sandy Creek was constructed to develop inflows along each waterway. The RORB model was constructed using MiRORB (MapInfo RORB tools), RORB GUI and RORBWIN V6.15.

#### 2.1.2.1 Sub-areas and Reaches

Sub-area boundaries and reaches were delineated using ArcHydro and revised as necessary to allow flows to be extracted at the points of interest. The sub areas and reaches were delineated from the 2004-2005 Wimmera CMA LiDAR, covering their entire management area. Nodes were placed at areas of interest, the centroid of each sub-area and the junction of any two reaches. Nodes were then connected by RORB reaches, each representing the length, slope and reach type.

Reach types in the model were set to be consistent with the land use across the catchment. All reaches were set to natural reach types in RORB, representative of the open grassed areas and natural waterways in the catchment.

The RORB subarea and reach delineation is shown in Figure 2-6.

#### 2.1.2.2 Fraction Impervious

Fraction Impervious (FI) values were calculated using MiRORB. Default sub-area FI values were calculated based on the current Planning Scheme Zones, the fraction impervious values used for each zoning is shown in Table 2-1, with the zones mapped in Figure 2-7.

The area weighted average FI of the catchment was calculated to be 0.03, reflecting the predominantly rural nature of the catchment. The spatial distribution of the weighted average FI for each sub-area is shown in Figure 2-8.

TABLE 2-1 RORB MODEL FRACTION IMPERVIOUS VALUES AND ZONES[2]

| Zone | Description | Typical Fraction Impervious |
|---|---|---|
| FZ | Farming Zone | 0 |
| PCRZ | Protection of natural environment or resources. | 0 |
| PPRZ | Main zone for public open space, incl. golf courses. | 0.1 |
| PUZ1 | Power lines, Pipe tracks and retarding basins | 0.05 |
| PUZ2 | Schools and Universities | 0.7 |
| PUZ3 | Hospitals | 0.7 |
| PUZ7 | Museums | 0.6 |
| RDZ1 | Major roads and freeways. | 0.7 |
| RLZ | Predominantly residential use in rural environment. | 0.2 |
| TZ | Small township with little zoning structure | 0.55 |

[2] Melbourne Water, 2010 – Music Guidelines, Recommended input parameters and modelling approaches for MUSIC users

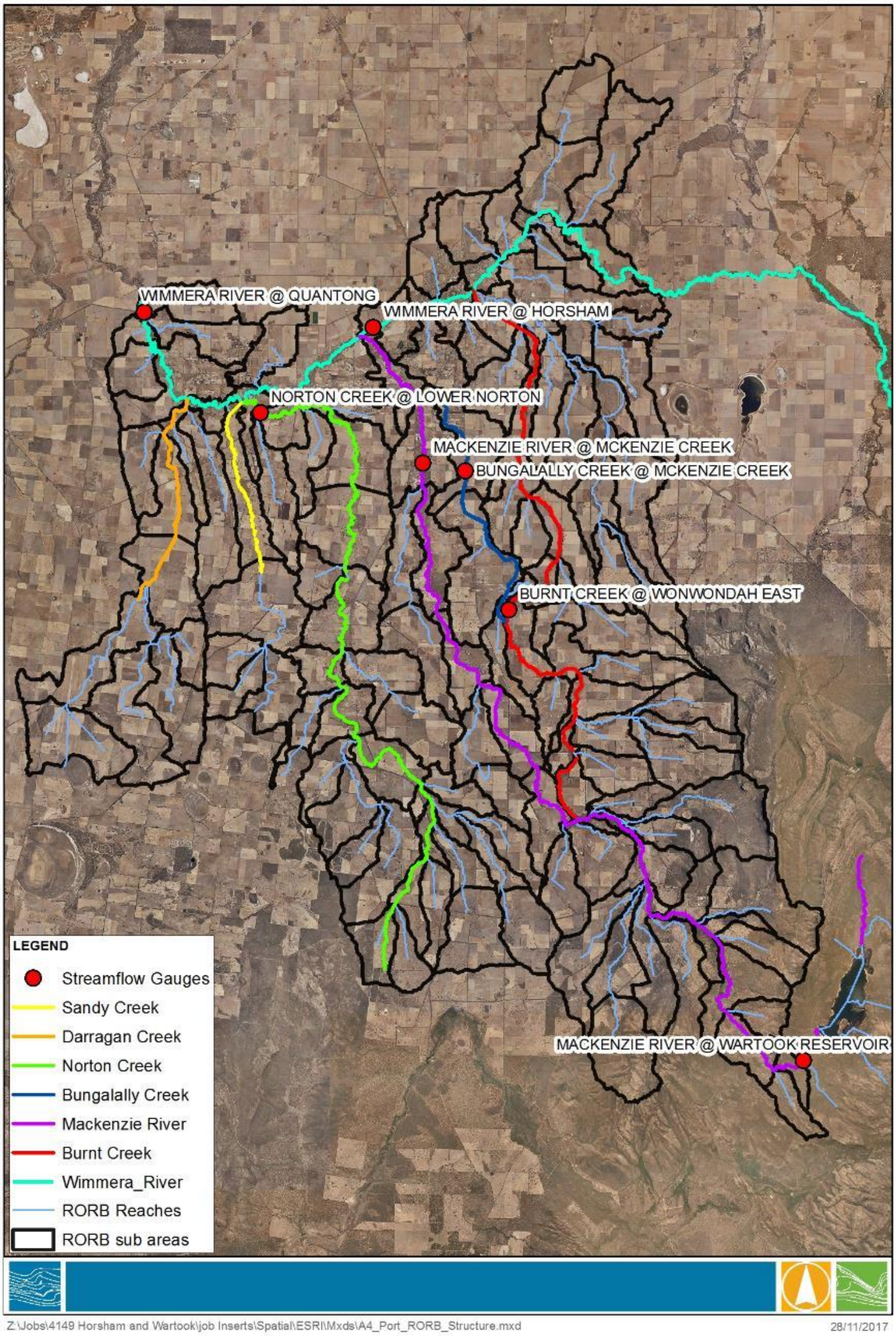


**FIGURE 2-6 RORB SUBAREA AND REACH DELINEATION**

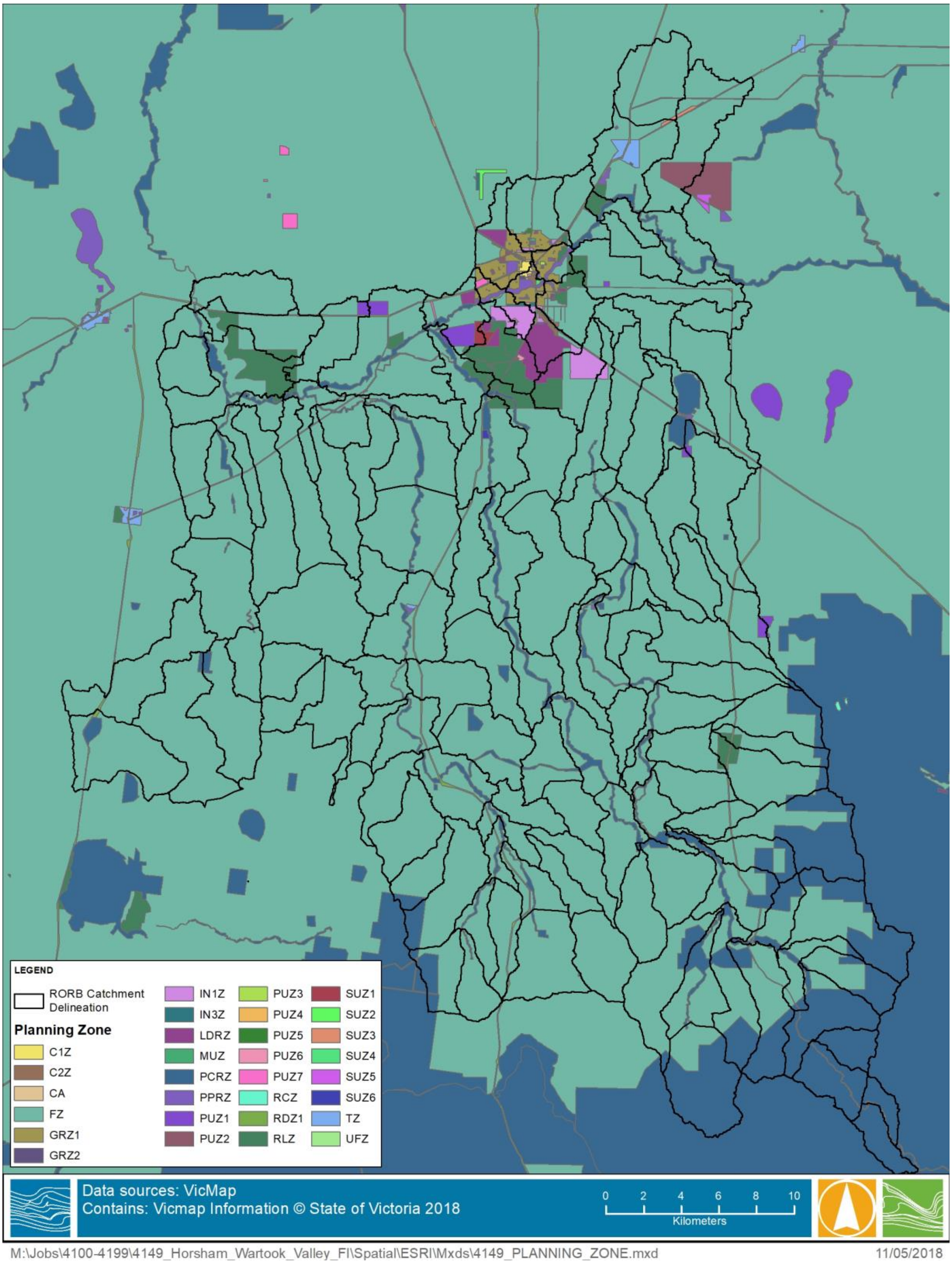


**FIGURE 2-7 RORB MODEL PLANNING ZONES**

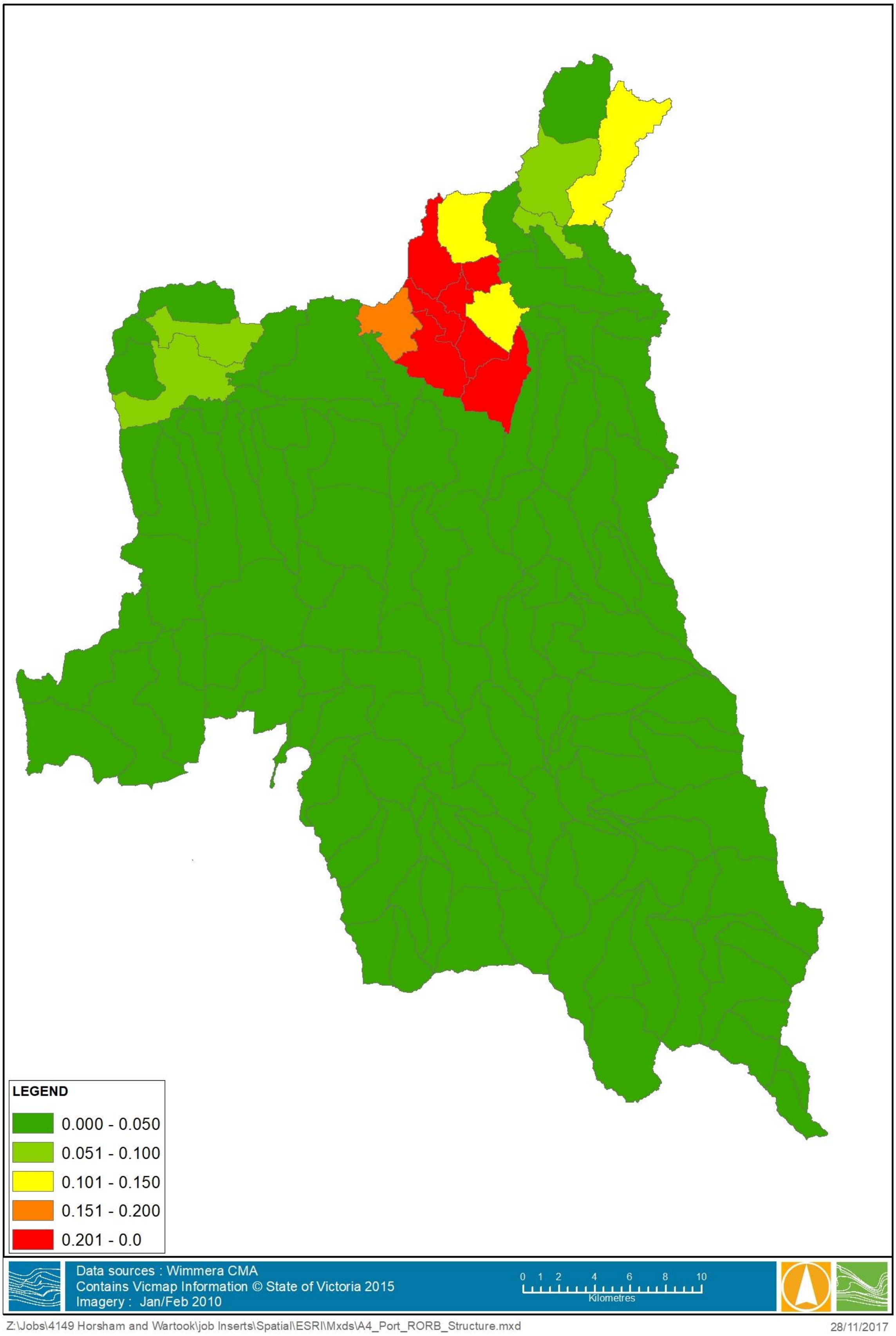


**FIGURE 2-8 RORB MODEL FRACTION IMPERVIOUS CALCULATED DISTRIBUTION**

#### 2.1.2.3 Model Parameters

The RORB model was broken up into a series of interstation areas; these areas had a kc, m, initial loss and continuing loss applied to them. Several model iterations were run, determining inflows to the hydraulic model, which was then compared to observed flood heights.

The kc for each interstation area was determined using the Victorian data estimate available in RORB (Pearse et al, 2002[3]) - $kc=1.25*D_{av.}$

We have found this to be the best match for rural Victorian catchments.

Losses were initially determined using the ARR data hub, these were then modified to get the best match between the hydrology and hydraulics for each calibration event.

The RORB m value was left at 0.8, as per the RORB Manual recommendations.

### 2.1.3 Mike Flexible Mesh Hydraulic Model

The Mike Flexible Mesh (MIKEFM) model is comprised of several key components:

- Topography – represented as a mesh
- Boundaries – model inflows and outflows
- Roughness – a representation of resistance to flow due to vegetation/permeable structures etc.

Each of these components are discussed in the following sections.

#### 2.1.3.1 Model Mesh

The MIKEFM model was comprised of triangular and quadrilateral elements. Generally, the waterways were modelled using quadrilateral elements with the surrounding floodplains modelled using triangular elements. The mesh was developed ensuring structures and each waterway channel was represented in enough detail to allow a good representation of the flow capacity, but not in too much detail to make the model simulation times impractical.

The MIKEFM model extent is shown below in Figure 2-9 with an example of the model mesh shown in Figure 2-10.



[3] Pearse et al, 2002 – A Simple Method for Estimating RORB Model Parameters for Ungauged Rural Catchments, Water Challenge: Balancing the Risks: Hydrology and Water Resources Symposium, 2002

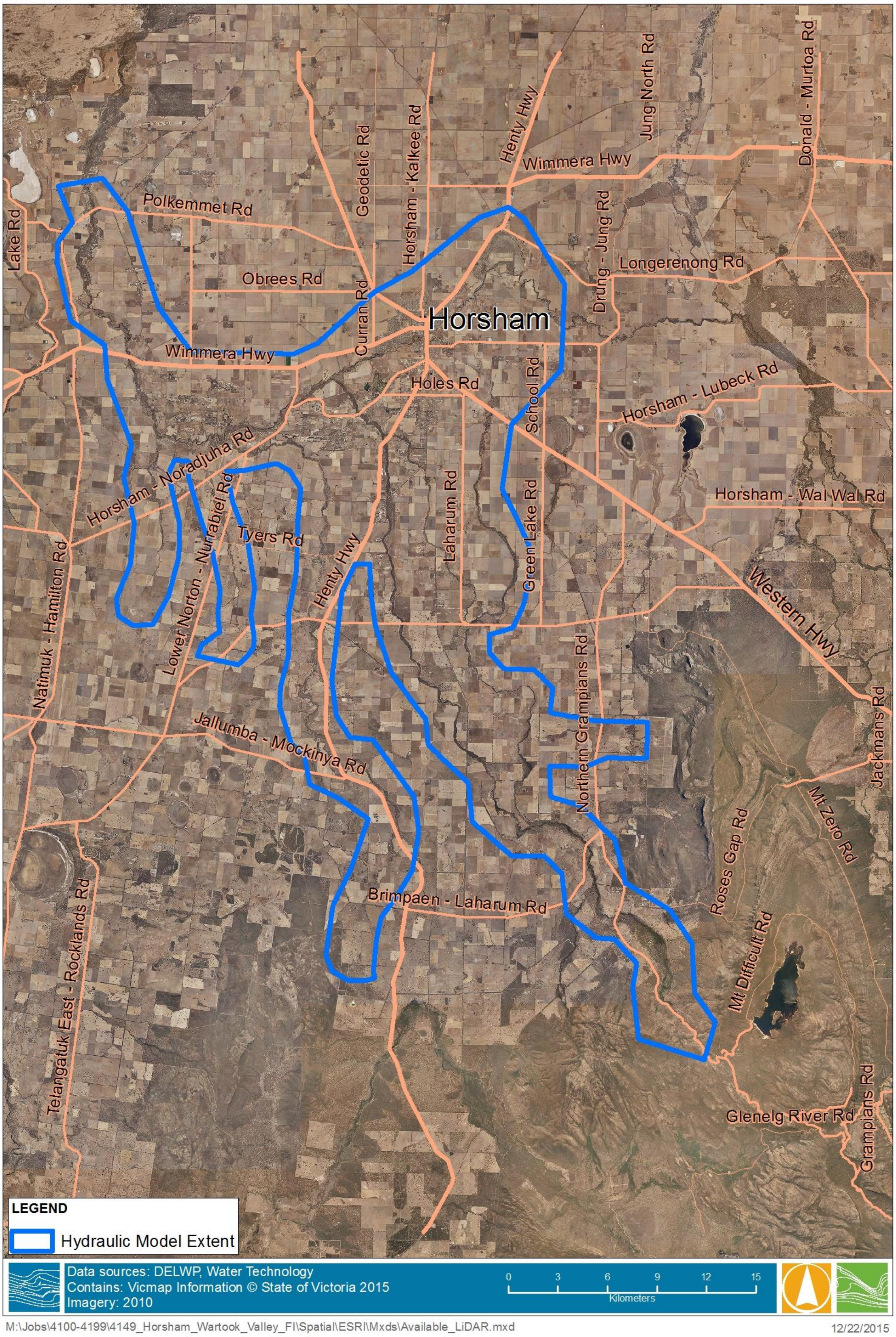


**FIGURE 2-9 MIKEFM MODEL EXTENT**

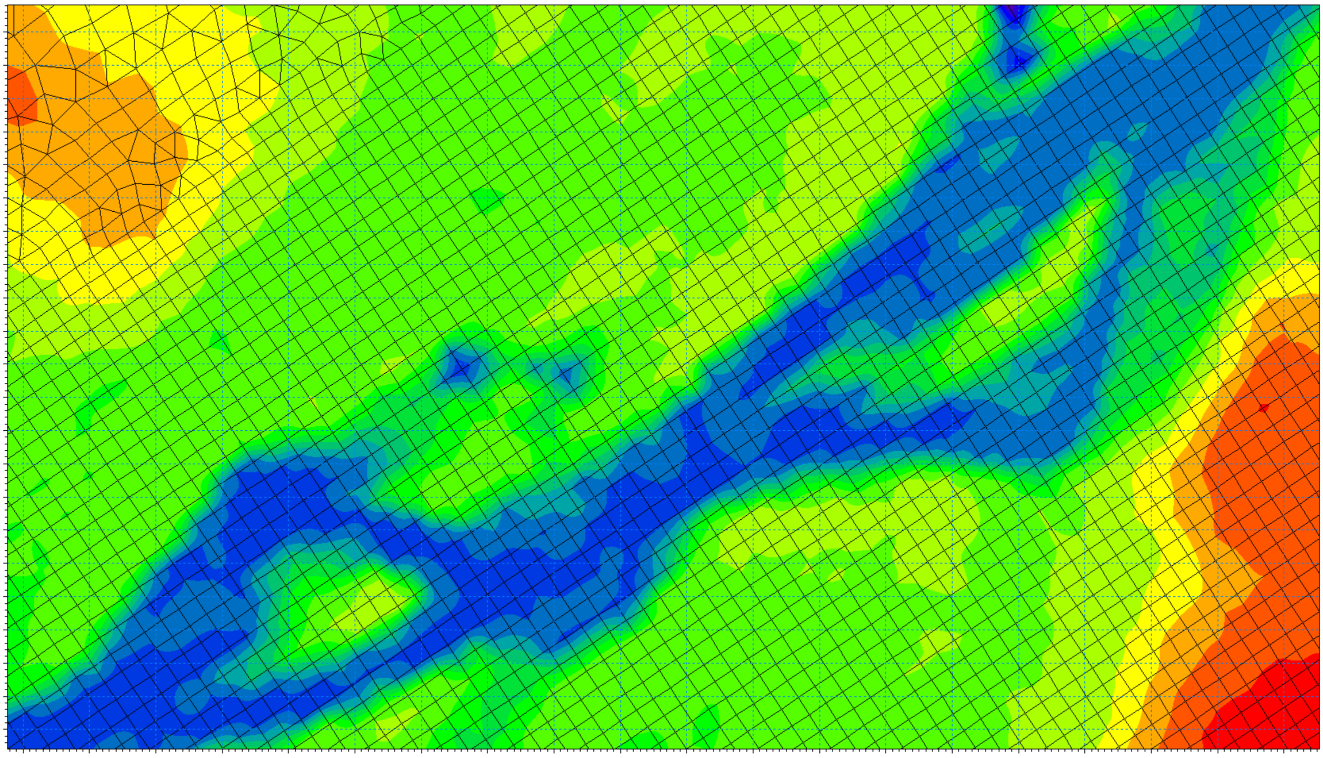

FIGURE 2-10 MIKEFM EXAMPLE PORTION OF MESH

As discussed in the Data Verification component of this project[4], there are three LiDAR datasets available to be used as the basis of the model topography:

- 2016 Horsham LiDAR
- 2004 WCMA LiDAR
- 2010 ISC LiDAR

The 2004 Wimmera CMA LiDAR has been verified across numerous projects including:

- East Horsham Channel Decommissioning Modelling (Water Technology, 2013) (Commissioned by HRCC)
- Warracknabeal and Brim Flood Investigation (Water Technology, 2016) (Commissioned by Wimmera CMA)[5]
- Dunmunkle Creek Flood Investigation (Water Technology, 2016) (Commissioned by Wimmera CMA)[6]
- Natimuk Flood Investigation (Water Technology, 2012) (Commissioned by Wimmera CMA)[7]

The 2010 ISC LiDAR data was not used as the base topography in the above projects due to inconsistencies in the data, these have included datum shifts and water in the channel in several waterways. This is explained in detail in the Warracknabeal and Brim Flood Investigation[5] and Dunmunkle Creek Flood Investigation[2] data verification reports, while the 2016 Horsham LiDAR was verified as part of this project.

[4] Water Technology (2016), Horsham and Wartook Valley Flood Investigation, Data Verification Memo
[5] Water Technology (2016), Warracknabeal and Brim Flood Investigation, Wimmera CMA
[6] Water Technology (2016). Dunmunkle Creek Flood Investigation, Wimmera CMA
[7] Water Technology (2012), Natimuk Flood Investigation, Wimmera CMA

During the January 2011 calibration the 2004 LiDAR was used as the basis for the model topography while the September 2016 calibration was complete with the inclusion of the 2016 data taking precedence over that captured in 2004. Design modelling will be completed with the same topography as the September 2016 model calibration.

#### 2.1.3.2 Model Boundaries

The hydraulic model boundaries used both streamflow gauge records and hydrographs from a RORB model. The boundary locations are highlighted in Figure 2-11, outlining the two gauge boundaries, with the remainder based on RORB model inflows.

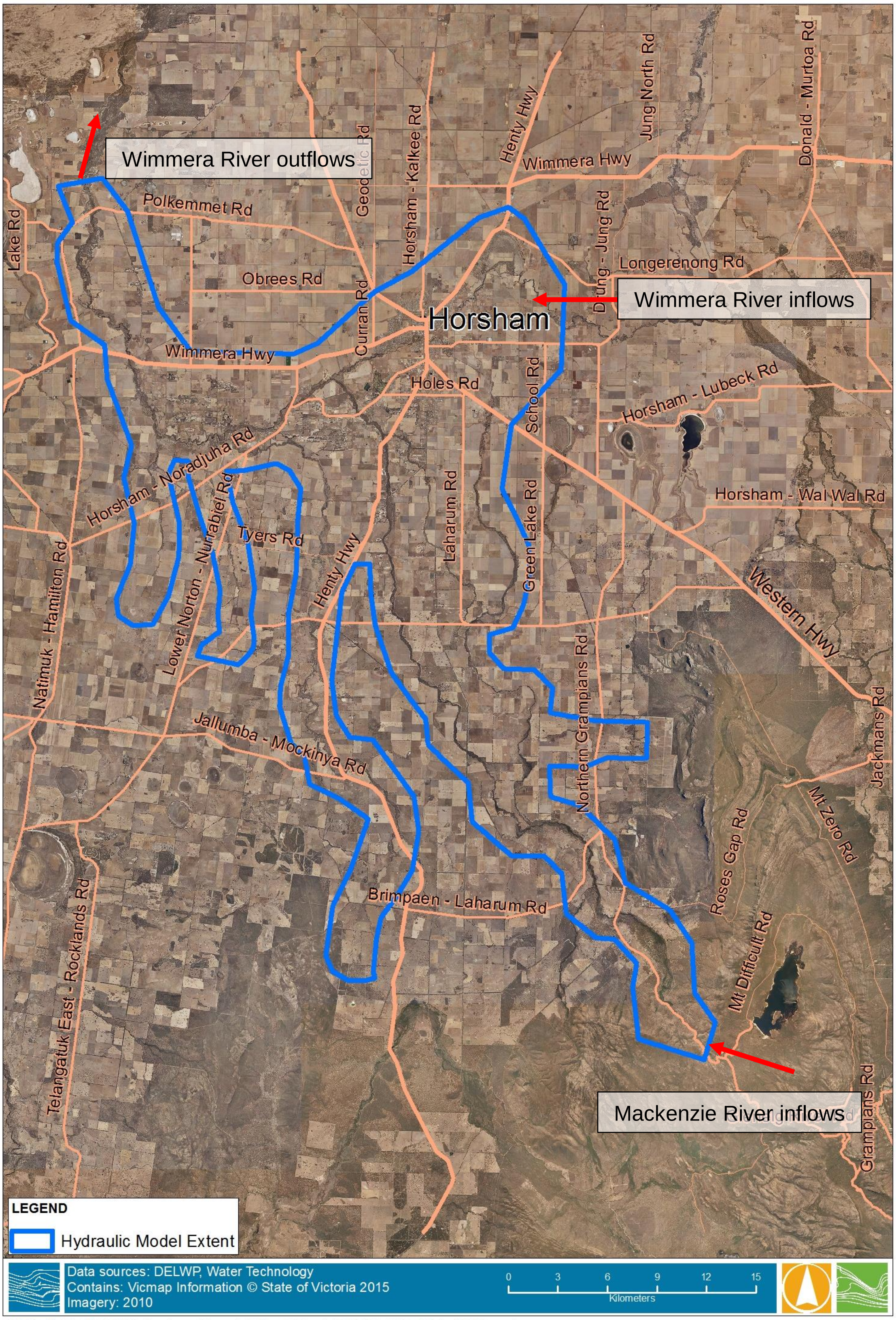


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**FIGURE 2-11 HYDRAULIC MODEL BOUNDARIES**

#### 2.1.3.3 Hydraulic Roughness

The hydraulic model roughness was represented by Manning's 'n' based on land use and aerial photography. A 2D grid of the estimated hydraulic roughness was developed based on those recommended in Open Channel Hydraulics[8]. The adopted roughness values for each land use are outlined in Table 2-2 and shown graphically in Figure 2-12.

TABLE 2-2 ADOPTED MANNING'S 'N' VALUES FOR RIVERINE FLOOD MODEL

| Description | Manning's 'm' | Manning's 'n' (1/m) |
|---|---|---|
| Residential areas | 12.5 | 0.08 |
| Floodplain areas | 25 | 0.04 |
| Treed or forested areas | 20 | 0.05 |
| Thick riverine vegetation | 20 | 0.05 |
| Sparse riverine vegetation | 33 | 0.03 |
| Open Water | 50 | 0.02 |



[8] Chow (1959), Open Channel Hydraulics

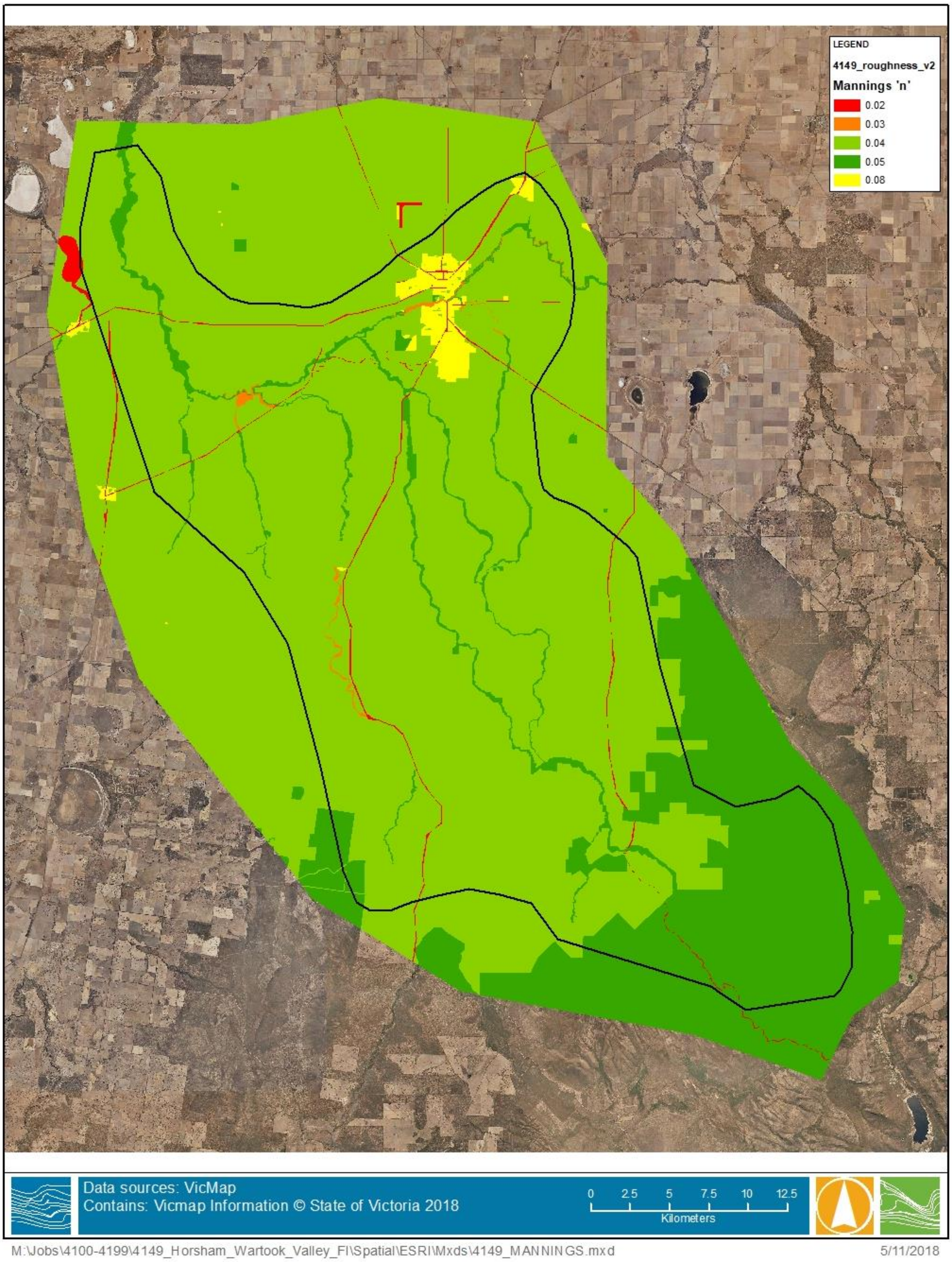



**FIGURE 2-12 ADOPTED MANNING'S 'N' VALUES FOR RIVERINE FLOOD MODELLING**

## 2.2 Stormwater Inundation – TUFLOW

A direct rainfall on grid hydraulic model of Horsham and Haven was developed across two TUFLOW models, north and south of the Wimmera River. Each model had rainfall directly applied to the topography, allowing water to flow overland, pool in low areas and flow to the Wimmera River via the Horsham stormwater drainage system. The model extent for each of the northern and southern models along with the drainage system included in the model is shown Figure 2-13. The drainage system details were reasonable, but some assumptions had to be made in order to connect pipes where no invert data was known.

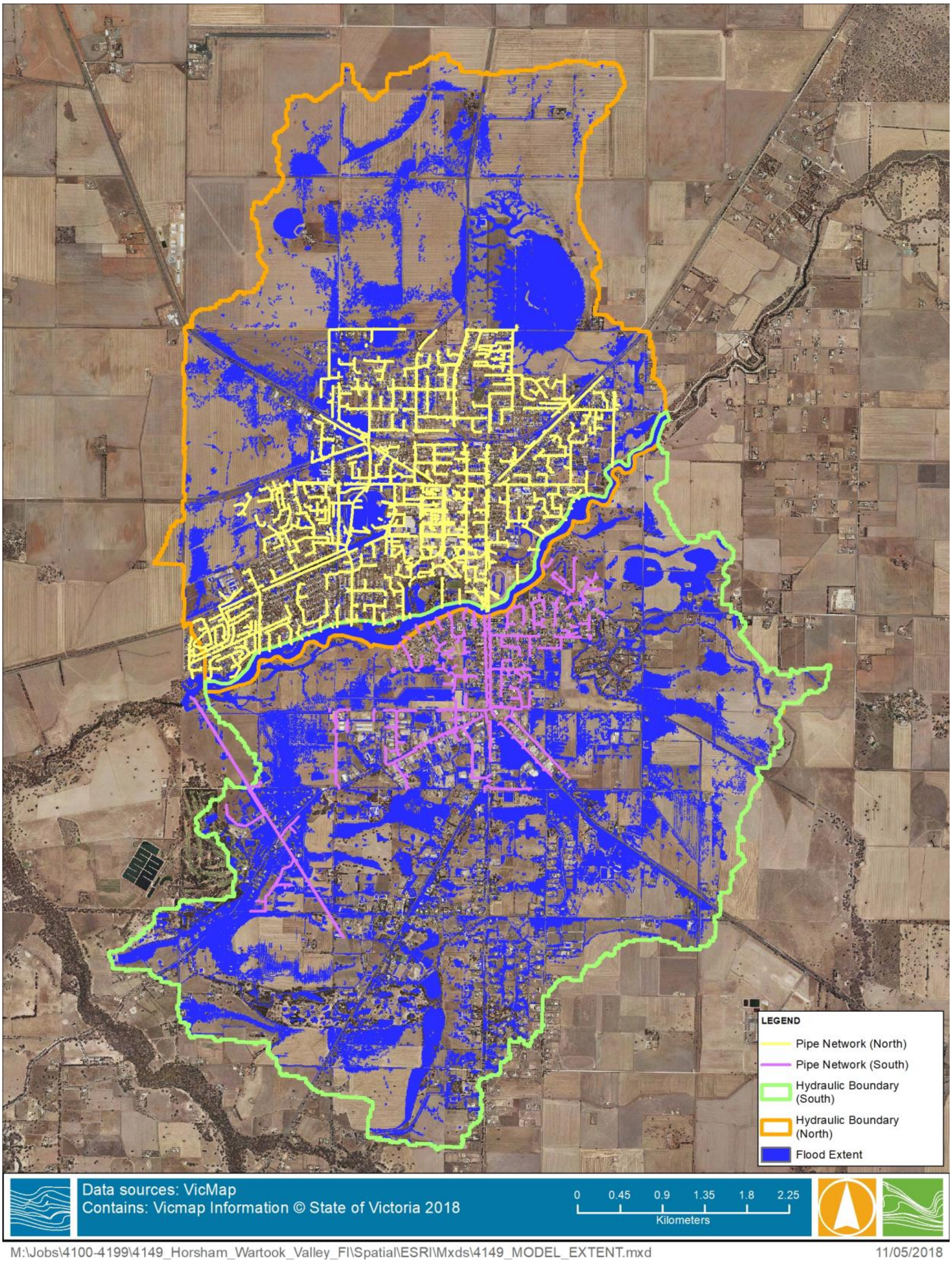



**FIGURE 2-13 RAIN ON GRID – MODEL EXTENTS**

### 2.2.1 Model Topography

The model topography was based on a combination of the 2004 and 2016 LiDAR datasets with the 2016 data taking precedence in areas of overlap. The 1x1 m resolution LiDAR was resampled at a 3x3 m grid resolution. This resolution was chosen as it gives an accurate representation of council roads and drainage paths and reasonable model run times given both model areas are reasonably large.

### 2.2.2 Rainfall

Rainfall was directly applied to the model topography for each storm scenario with a uniform spatial pattern, and a temporal pattern based on historic record or a chosen design temporal pattern. The chosen temporal pattern for each event is outlined below in Section 4.3.2 when presenting results for each storm scenario.

### 2.2.3 Hydraulic Roughness

The rain on grid hydraulic roughness was delineated based on land use and aerial photography. The estimated hydraulic roughness values were developed based on those recommended in Open Channel Hydraulics8. The adopted roughness values for each land use are outlined in Table 2-3 and shown graphically in Figure 2-14. The adopted roughness values were different to that used in the Flexible Mesh model due to their very different model type and extent.

#### TABLE 2-3 RAIN ON GRID - ADOPTED MANNING'S 'N' VALUES

| Description | Manning's 'n' |
|---|---|
| Residential - Urban (higher density) # | 0.35 |
| Residential - Rural (lower density) # | 0.15 |
| Residential Footprint - Urban (higher density) * | 0.4 |
| Residential - Urban (higher density) * | 0.1 |
| Residential Footprint - Rural (lower density) * | 0.4 |
| Residential - Rural (lower density) * | 0.05 |
| Industrial/Commercial or large buildings on site | 0.3 |
| Significant Drainage Easement (regardless of zone type) | 0.05 |
| Open Space or Waterway - minimal vegetation | 0.04 |
| Open Space or Waterway - moderate vegetation | 0.06 |
| Open Space or Waterway - heavy vegetation | 0.09 |
| Open water (with reedy vegetation) | 0.065 |
| Open water (with submerged vegetation) | 0.02 |
| Car park/pavement/wide driveways/roads | 0.02 |
| Railway line | 0.125 |
| Concrete lined channels | 0.016 |

*# when building footprints and remainder of parcel are modelled together (with one roughness value)*

** when building footprints are modelled separately to remainder of parcel*

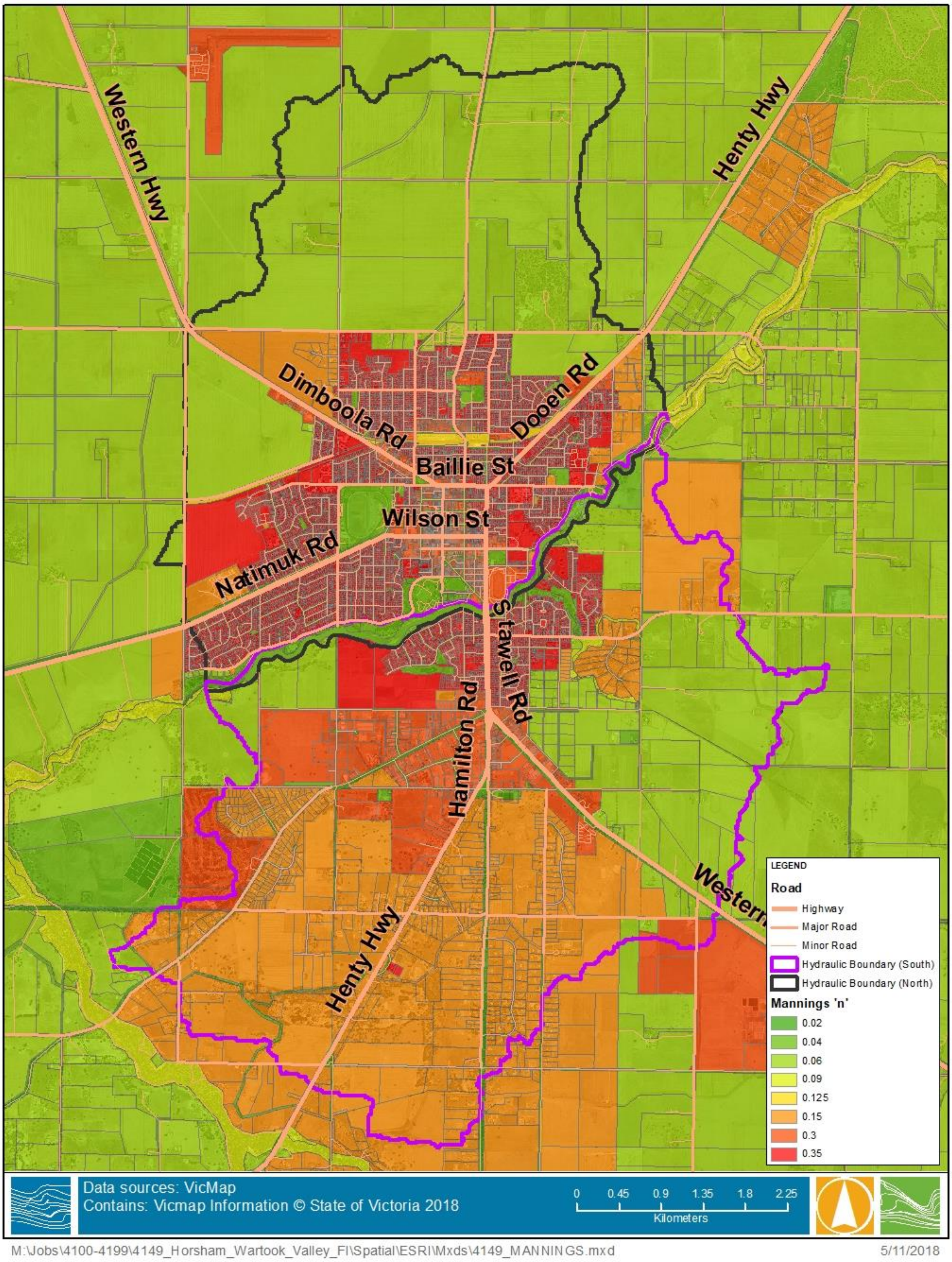



**FIGURE 2-14 RAIN ON GRID - ADOPTED MANNING'S 'N' VALUES**

### 2.2.4 Rainfall Losses

Rainfall losses were adopted in the rain on grid model representing the rainfall which does not become runoff. A continuing loss model was adopted, the adopted values are discussed within the calibration and design modelling sections, Section 3 and 4 respectively.

# 3 CALIBRATION SUMMARY

## 3.1 Riverine Inundation

### 3.1.1 January 2011

As discussed in the Model Calibration Report[9], there were numerous calibration data sources available from the January 2011 event. These included:

- Water level and flow information at the following streamflow gauges:
  - Wimmera River at Horsham (Walmer).
  - Wimmera River at Quantong.
  - Burnt Creek at Wonwondah East.
  - Mackenzie River at McKenzie Creek.
- Peak flood height survey captured after the event by Wimmera CMA.
- Aerial flood photography.
- Streamflow information recorded by hydrographers at the Western Highway bridge over the Wimmera River.

The January 2011 event was modelled numerous times using the MIKEFM model, changing the model topography, inserting roads and levees, and adjusting the roughness values to achieve a suitable model calibration. Some iteration of the RORB hydrology and the lagging and scaling of the Wimmera River inflow boundary was also completed to achieve a suitable calibration.

The following sections compare the model results to observed data, assessing the model calibration. The final area of inundation for January 2011 is shown in Figure 3-1.



[9] Water Technology (2018), Horsham and Wartook Valley Flood Investigation, Model Calibration Report

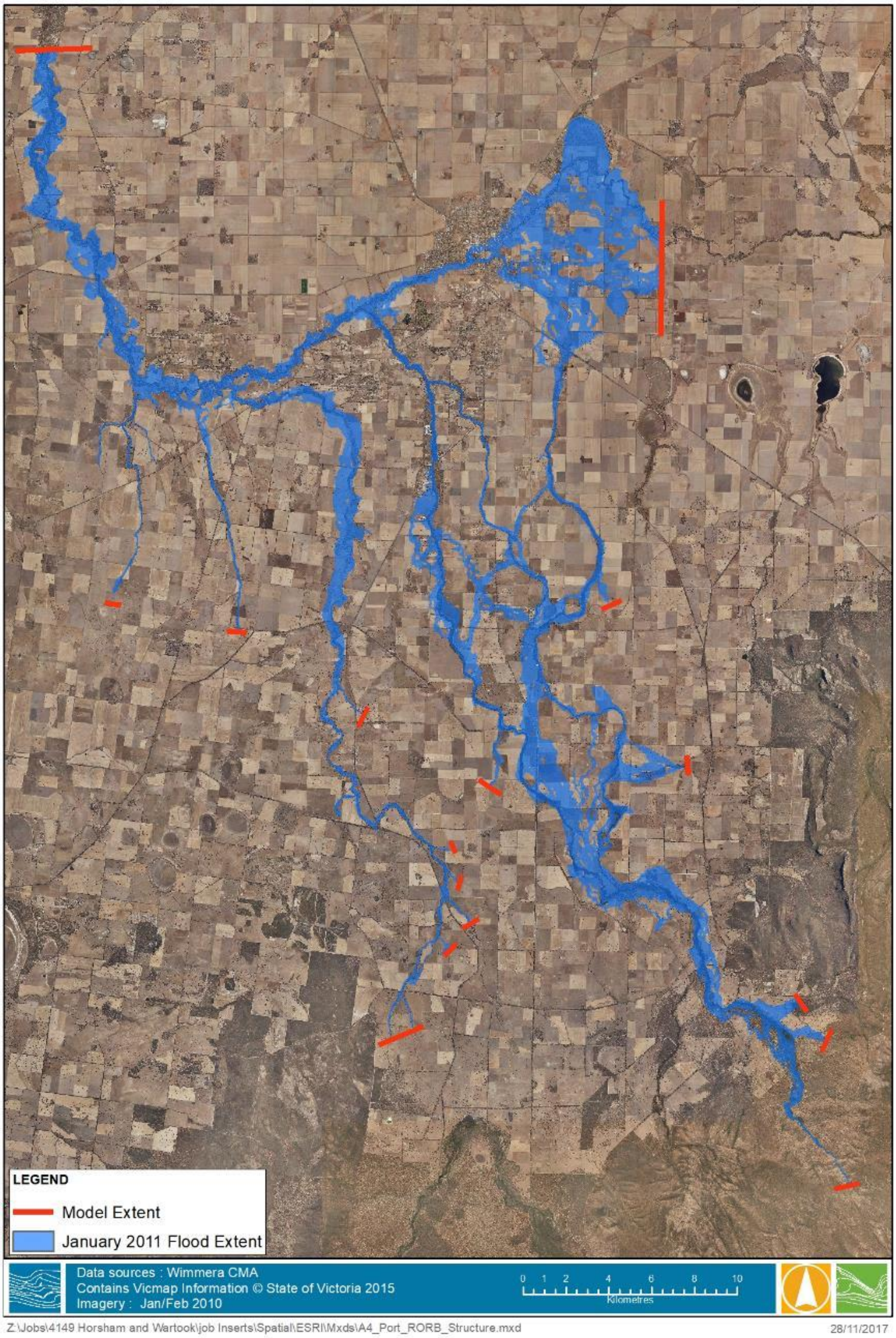



**FIGURE 3-1 JANUARY 2011 – MODELLED INUNDATION EXTENT**

Of the available calibration datasets surveyed flood heights gave the best overall description of hydraulic model calibration and they are used as an example of the model calibration in this report. A comparison of the model results and other observed datasets is shown in the Horsham and Wartook Valley Model Calibration Report [9]. There were 95 peak flood heights surveyed during and after the January 2011 event, marking the estimated peak flood level at each specific location. These peak flood heights were compared to the peak modelled water level to give an indication of how well the model was performing. Of the surveyed heights, 47 matched the model results within 100 mm of that surveyed, 81 points within 200 mm of that surveyed, leaving 14 points with a difference of greater than 200 mm. This is an excellent calibration result.

The difference between the surveyed and modelled peak flood heights was thematically mapped to give a spatial understanding of the model results. The mapping was completed using the differences between surveyed and modelled levels. The difference between surveyed and modelled levels was calculated as follows:

*Difference = Modelled peak level – surveyed peak level*

This gives a positive value where the model results are higher than that observed and a negative value when the model results are lower than that observed. The mapping categories are outlined in Figure 3-2, and mapped for the entire model area in Figure 3-3. The same difference classification has been used for all calibration events.

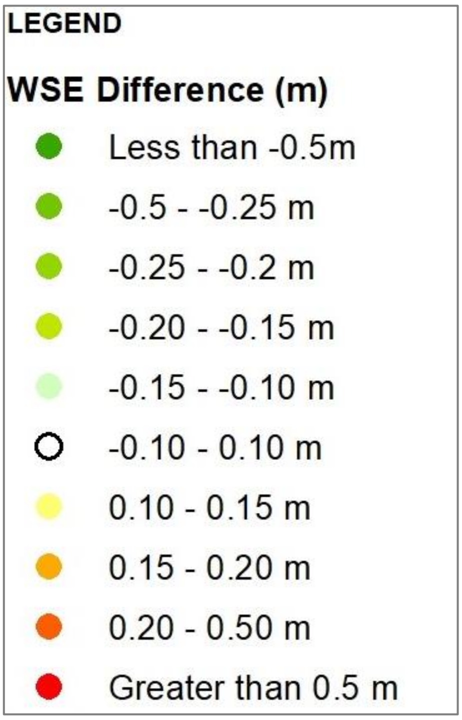



**FIGURE 3-2 THEMATIC MAPPING CATEGORIES**

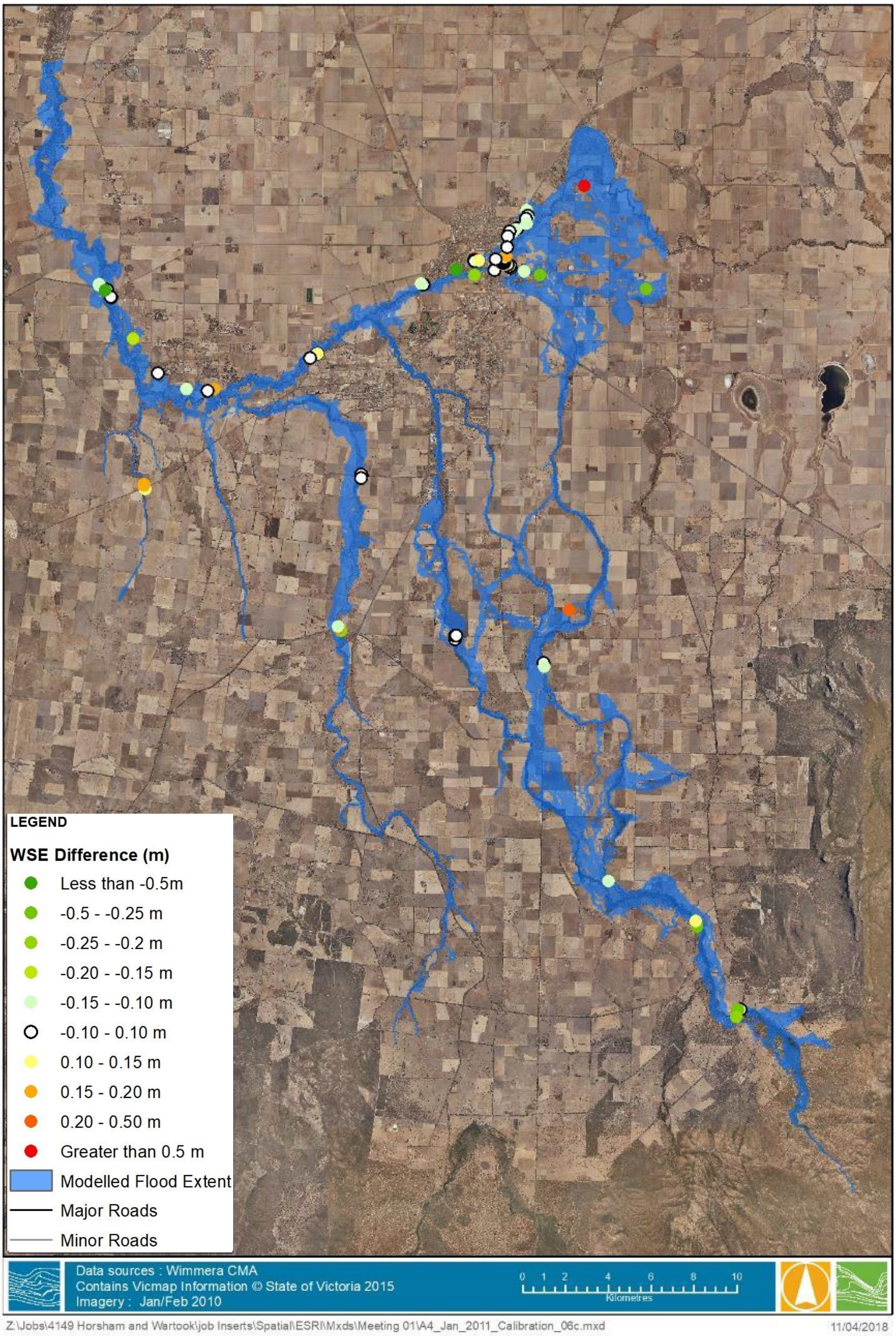



FIGURE 3-3 JANUARY 2011 MODELLED AND SURVEYED PEAK FLOOD HEIGHT COMPARISON

The 14 points with a difference between surveyed and modelled levels greater than 200 mm were interrogated more rigorously. There are nine points showing the model results are too low, and six too high.

The nine points that are showing the model results too low are discussed further below:

- Mackenzie River (2 points)
  - Mt Victory Road – the modelled level was 0.26 m below that surveyed and downstream of another point where the modelled level is 0.2 m lower than observed. Immediately upstream of the point the modelled and surveyed levels match within 0.1 m. The points are all on the edge of the flood extent.
  - Brimpaen Laharum Road – the modelled level was 0.34 m below that surveyed and immediately upstream of a point with a modelled level 0.16 m lower than that observed. Downstream of the point two surveyed heights are showing the modelled levels to be 0.38 m and 0.14 m above that surveyed.
- Norton Creek (1 point) – the modelled level was 0.23 m below that surveyed and is immediately upstream of a point with a modelled level 0.2 m below that surveyed. However, downstream of the point there are two surveyed points where the modelled level was 0.36 m higher than that observed and within 0.1 m of that observed.
- East Horsham (3 points)
  - School Road – the modelled level was 0.28 m lower than that surveyed. No other points were in the vicinity.
  - East of Riverside East Road – the modelled level was 0.43 m below that surveyed. There is a point 25 m north of the point 0.59 m above that observed.
  - Horsham Lubeck Road – the modelled level is 0.26 m below that surveyed, there is a point immediately west with a modelled level 0.16 m below that observed. Downstream of the point there are numerous points matching within 0.1 m.
- Horsham (2 points)
  - Major Mitchell Drive – the modelled level was 0.22 m lower than that surveyed, there is a point immediately east with a modelled level 0.2 m below that surveyed.
  - Bennett Road – the point is north of the Wimmera River, the model results do not show water reaching this point.

Quantong (1 point) – the modelled level was 2.1 m below that surveyed. There are points immediately upstream and downstream with modelled levels within 0.1 m of that surveyed, the surveyed point is clearly in error.

### 3.1.2 September 2016

The September 2016 event occurred at the beginning of this project, it was a smaller event and therefore the same quantity of data wasn't collected as January 2011. The data available for the model calibration included:

- Water level and flow information at the following streamflow gauges:
  - Wimmera River at Horsham (Walmer)
  - Wimmera River at Quantong
  - Burnt Creek at Wonwondah East
  - Mackenzie River at McKenzie Creek
- Peak flood height information captured after the event by Wimmera CMA.

Out of the available calibration datasets surveyed flood heights gave the best overall description of hydraulic model calibration and they are used as an example of the model calibration in this report. A comparison of the model results and other observed datasets is shown in the Horsham and Wartook Valley Model Calibration Report. There were 41 surveyed peak flood heights captured by Wimmera CMA during and after the September 2016 event. Like January 2011, the surveyed flood heights were compared to the modelled levels and mapped thematically (see Figure 3-2).

A comparison of modelled and surveyed levels across the entire model area is shown in Figure 3-4.

The 41 points are distributed across the study area floodplain as follows:

- Mackenzie River – 7 points
- Bungalally Creek – 4 points
- Wimmera River – 11 points
- Burnt Creek – 19 points

Of the 41 points there are 19 modelled levels within 200 mm of that surveyed, and 10 within 100 mm of that surveyed.

Along the Mackenzie River the upstream most point matches within 0.1 m at Brimpaen Laharum Road, the remaining points are at the lower end of the Mackenzie River and are all showing the modelled levels higher than that surveyed.

At Old Hamilton Road (the Mackenzie River at Mackenzie Creek gauge) the modelled level is 0.89 m above that observed. While at the Henty Highway there are three points at the bridge structure and at Three Bridges Road there are two.

At the Mackenzie River at Mackenzie Creek gauge the surveyed level was 135.69 m AHD, this compared to a modelled height of 136.58 m AHD. The gauge recorded a height of 136.19 m AHD. Comparing to the surveyed heights the model produced a water level 0.89 m higher than the surveyed point, however comparing to the gauge record the modelled water levels were only 0.39 m higher. Given the surveyed flood height is 0.5 m lower than the recorded stream flow gauge at this location, the accuracy of the survey is considered questionable.

There were two surveyed heights upstream of the Henty Highway, both levels were showing the modelled heights to be higher than that surveyed, one by 0.79 m the other 0.3 m. These levels are directly beside one another. The point on the downstream side of the Henty Highway is showing a modelled level 0.12 m above that surveyed.

At three Bridges Road there are levels upstream and downstream of the bridge structure, upstream of the bridge the modelled level is 0.24 m above that surveyed, while the downstream level is within 0.1 m.

Along Bungalally Creek there are six surveyed levels, four in the lower reach, two at Henty Highway and two at Old Hamilton Road, and two in the upper reach, immediately after the distribution from Burnt Creek. At the Henty Highway, the upstream point has a modelled water level 0.16 m lower than observed, while the downstream modelled water level is within 0.1 m of that observed. At Old Hamilton Road the two points show the modelled water level 0.2 and 0.18 m lower than that observed. In the upper Bungalally Creek the two points are 0.27 m too low, and within 0.1 m.

In East Horsham there are seven points scattered across the floodplain. Four of these points are located outside the modelled flood extent, however, there is some thought the levels may have been generated by direct rainfall accumulation. Three of the points are clustered at the end of Riverside East Road, the modelled levels at these points are within 25 m of each other and the modelled levels match that observed by 0.0 m, 0.12 m and 1.16 m. There is clearly an issue with one of the surveyed marks.

On the Wimmera River directly upstream of Horsham there are five surveyed flood heights, of these points two match within 0.1 m, one 0.12 m and the other 0.25 m.

Along the lower end of Burnt Creek there are 14 survey points, five of these points are located along Horsham Lubeck Road, while the remaining nine are in a cluster south of Horsham Lubeck Road. Of the points on Horsham Lubeck Road one point shows a modelled level within 0.1 m of that surveyed, two are approximately 0.15 m lower than that surveyed and the remaining two are greater than 0.4 m above that surveyed. In the cluster of nine surveyed points the modelled levels are generally 0.3 m lower than that surveyed.

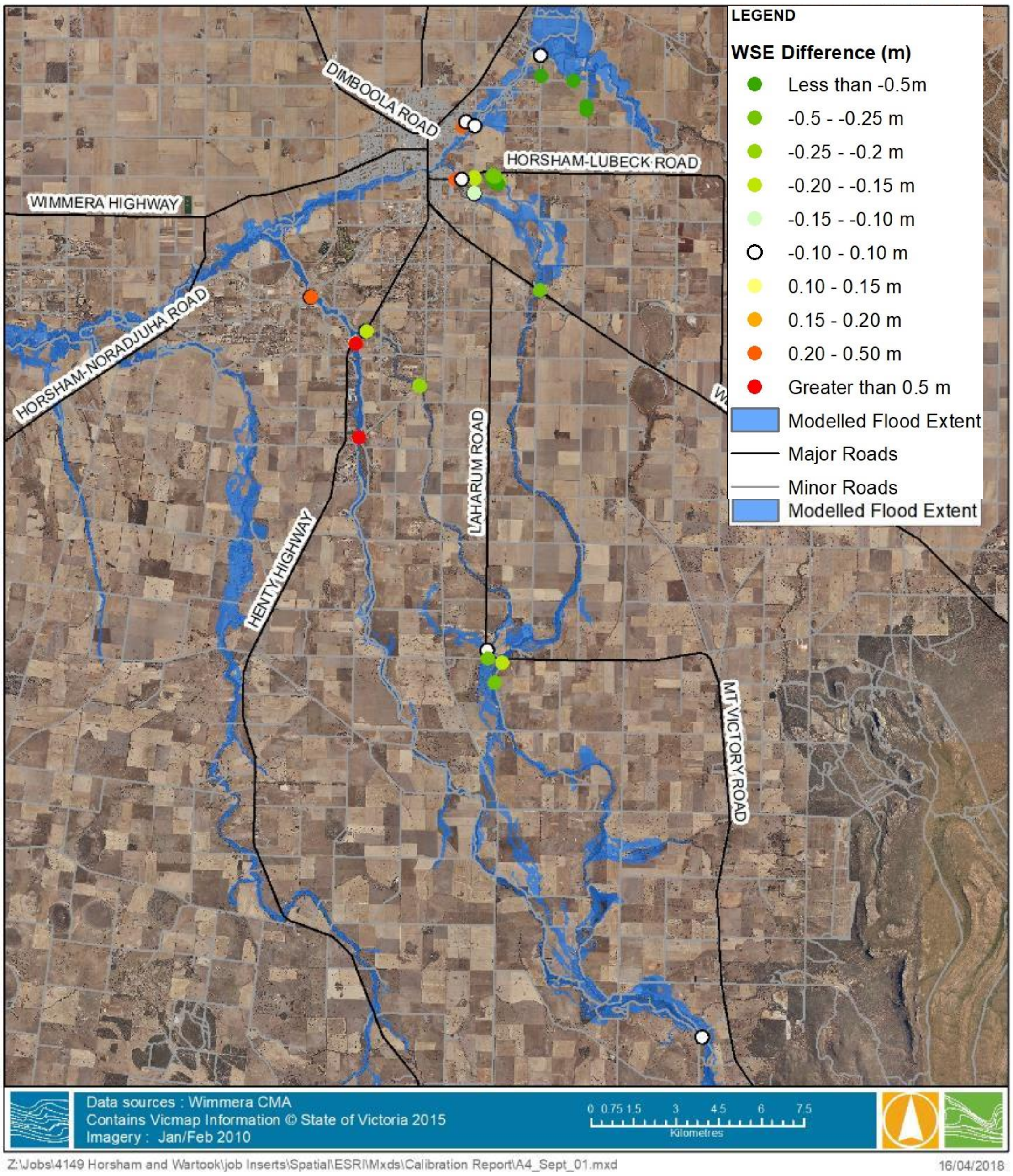



**FIGURE 3-4 SEPTEMBER 2016 MODELLED AND SURVEYED LEVEL COMPARISON**

## 3.2 Stormwater Inundation

The stormwater inundation model verification was undertaken using the January 2011 event only. There was no surveyed calibration information available, however a reasonable amount of anecdotal information was available through several community meetings. These meetings were both open to the public and with targeted community members who had been actively involved in responding to inundation or had specifically contacted Wimmera CMA.

January 2011 modelling was completed using the Horsham AWS temporal pattern and rainfall depths, applied with a uniform spatial pattern.

The model was run with standard loss values of 4 mm initial and 1.5 mm/hr continuing losses, the Manning's 'n' values are detailed in Section 2.1.3.3.

Horsham was modelled in two separate models, north and south of the Wimmera River. Anecdotally, the model results matched observations from Council employees and a selected group of the community who were involved in the stormwater response.

### 3.2.1 January 2011

The January 2011 modelled inundation depths for the north and south modelled areas are provided in Figure 3-5 and Figure 3-6 respectively.

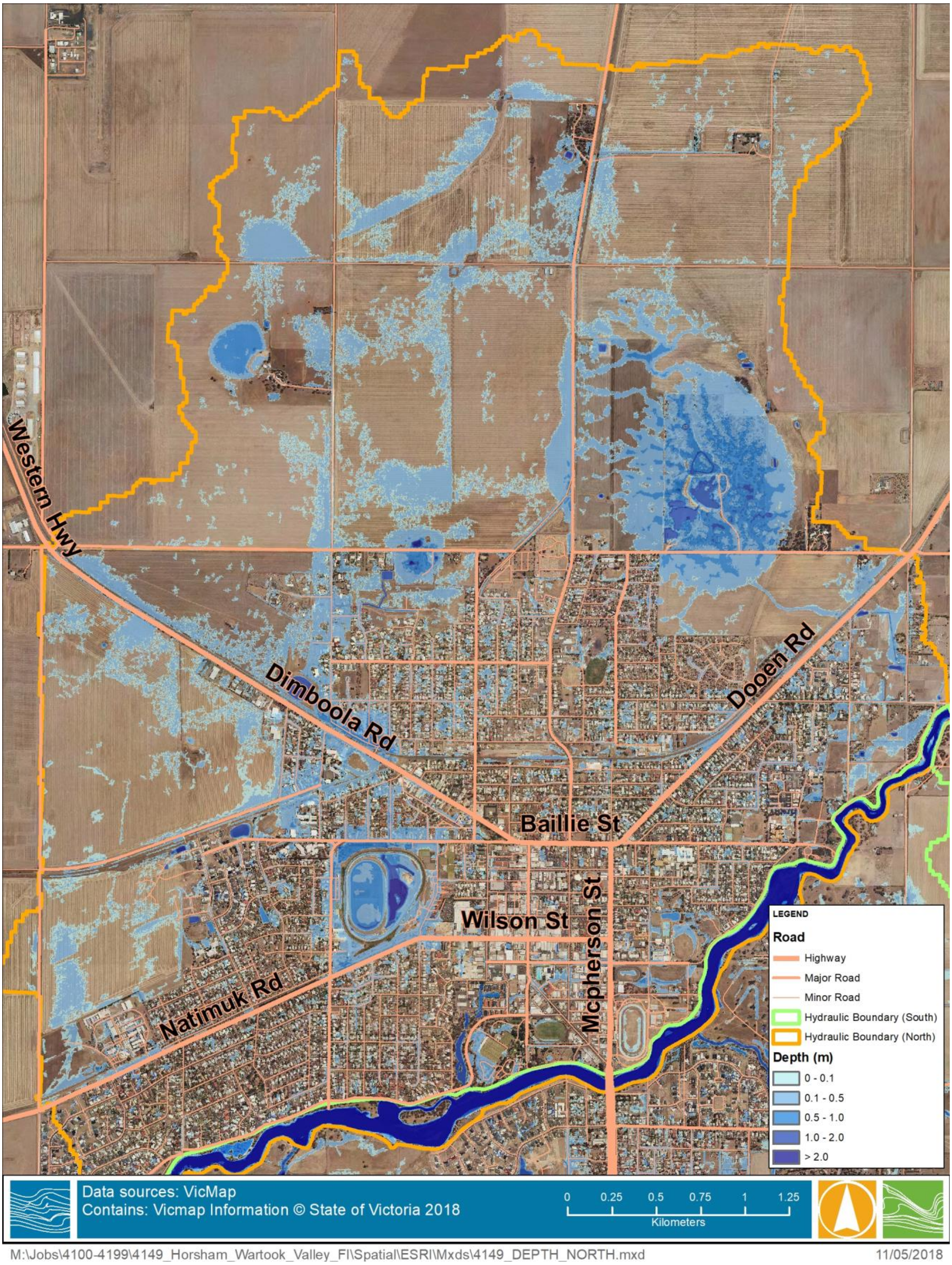



**FIGURE 3-5 NORTH HORSHAM STORMWATER MODELLING – JANUARY 2011**

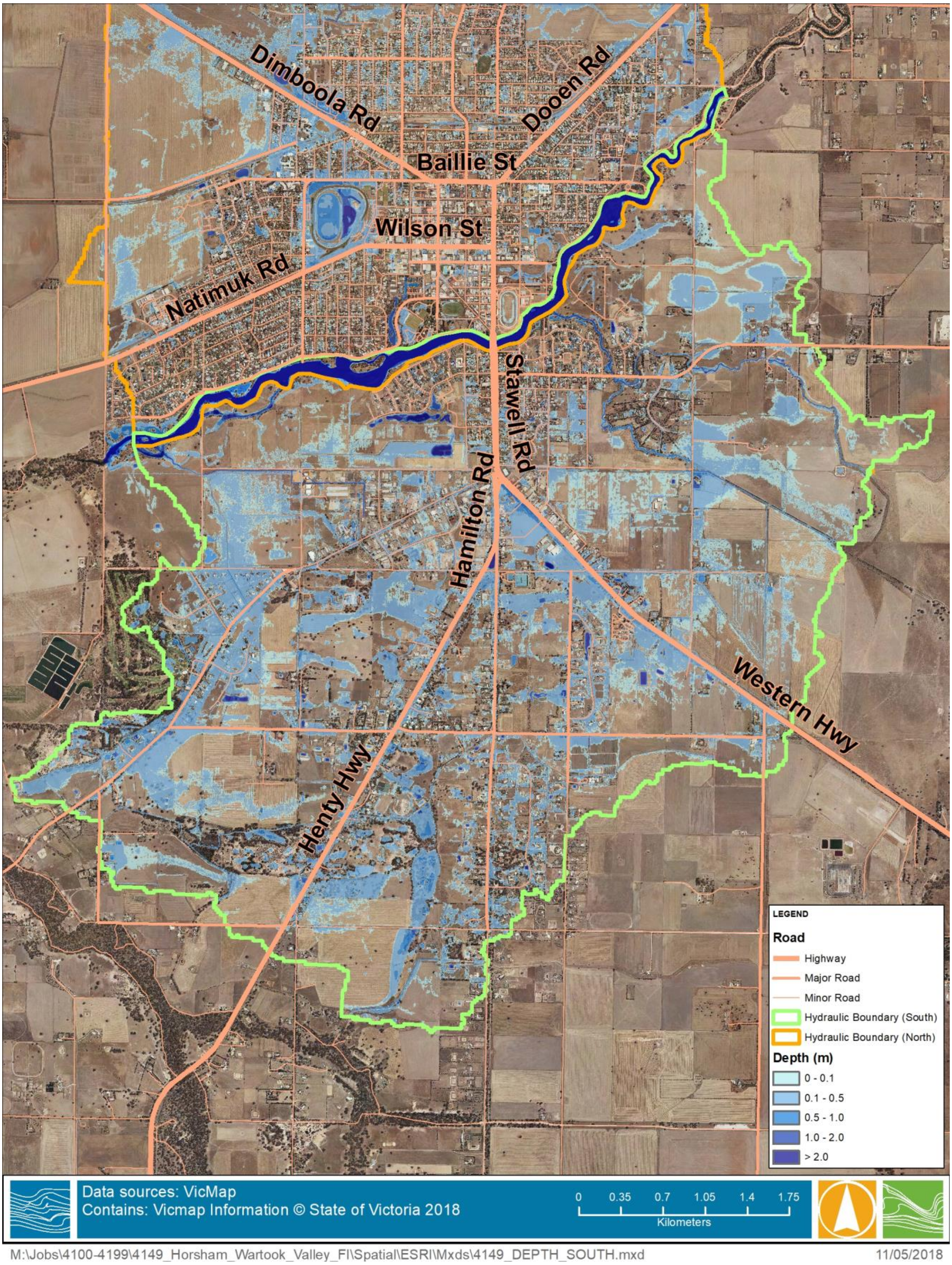


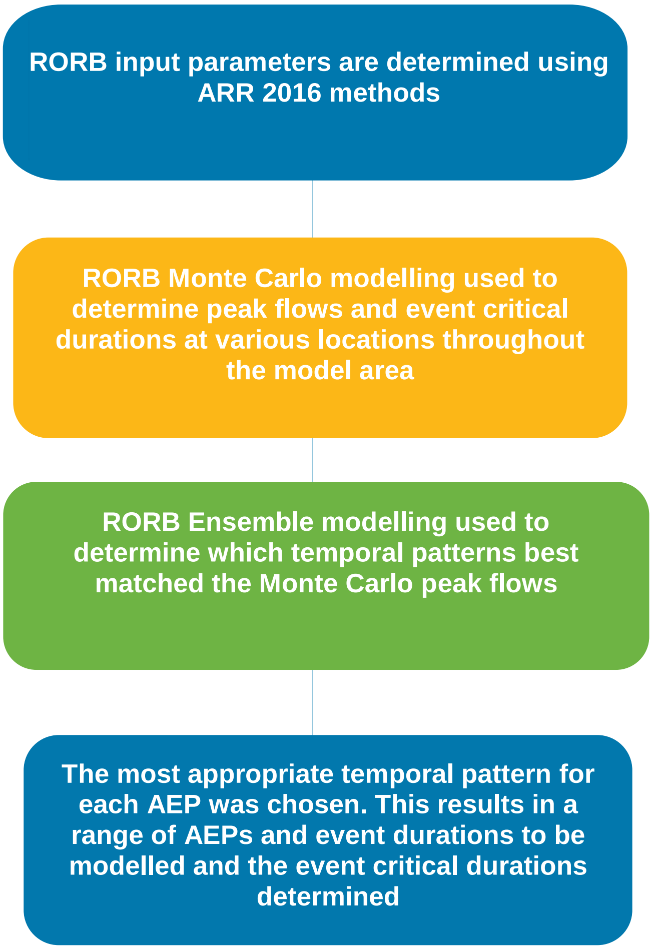

**FIGURE 3-6 SOUTH HORSHAM STORMWATER MODELLING – JANUARY 2011**

# 4 DESIGN MODELLING

## 4.1 Summary

Wimmera River and upper Mackenzie River inflows were based around Flood Frequency Analysis undertaken at Wimmera River at Horsham and Mackenzie River at Wartook gauges, while tributary flows and catchment contributions within the study model area were determined by the RORB model detailed in Section 2.1.2.

RORB modelling was undertaken using Monte Carlo and Ensemble approaches recommended in Australian Rainfall and Runoff 2016 (ARR2016)[10]. The methodology for developing inflows to the hydraulic model was as follows.




The determined design flows were modelled in the calibrated hydraulic model (as outlined in Section 3) to produce design depth, flood levels, velocities and extents.

[10] Australian Rainfall and Runoff (2016) - Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors), 2016, Australian Rainfall and Runoff: A Guide to Flood Estimation, Commonwealth of Australia

## 4.2 Hydrology

### 4.2.1 Wimmera River

#### 4.2.1.1 Walmer Gauge Review

Design flows on the Wimmera River were produced using a Flood Frequency Analysis (FFA) at the Wimmera River at Horsham (Walmer) gauge. The FFA was undertaken during the Lower Wimmera River Regional Flood Mapping Project[11], and adopted for this study. The analysis undertaken was reviewed by the Technical Review Panel facilitated by the Department of Environment, Land, Water and Planning (DELWP), with positive feedback on the approach adopted. This report describes the FFA input data, methodology and results.

The Horsham streamflow gauge (Walmer) has a daily flow record spaning 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 are available. Together, these periods of gauging provide 124 years of complete record to develop an annual series for FFA.

Figure 4-1 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 4-1 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 record, 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 4-3, along with the recorded Quality Codes.

The Wimmera CMA[12] sourced several highly valuable documents from the Horsham Historical Society and the State archives. These combined with the gauge record allowed a detailed historical record of Wimmera River streamflow at Horsham to be developed.

[11] Water Technology (2016), Lower Wimmera River Regional Flood Mapping Project
[12] Abdul Aziz – Floodplain Officer

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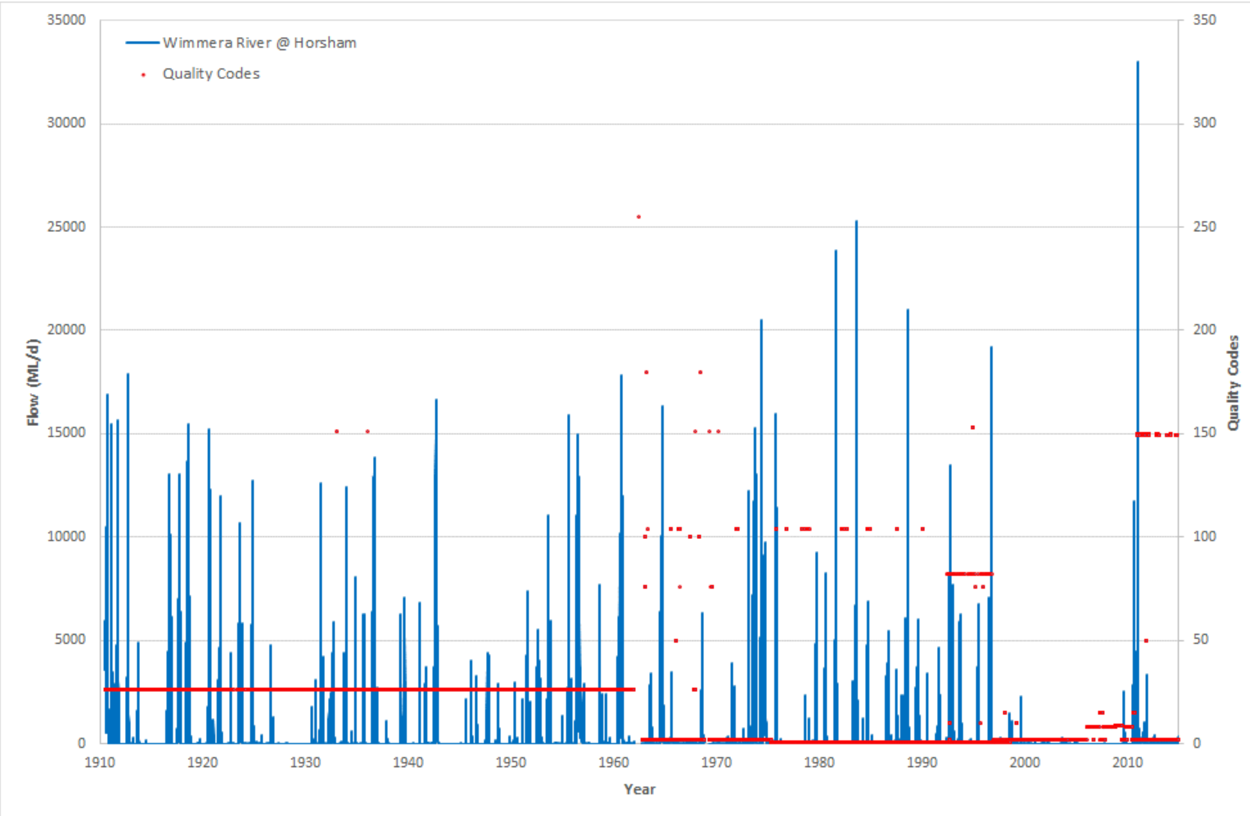


**FIGURE 4-1 GAUGE RECORD AT WIMMERA RIVER AT HORSHAM (WALMER) SHOWING FLOW AND THE QUALITY CODES**[13]

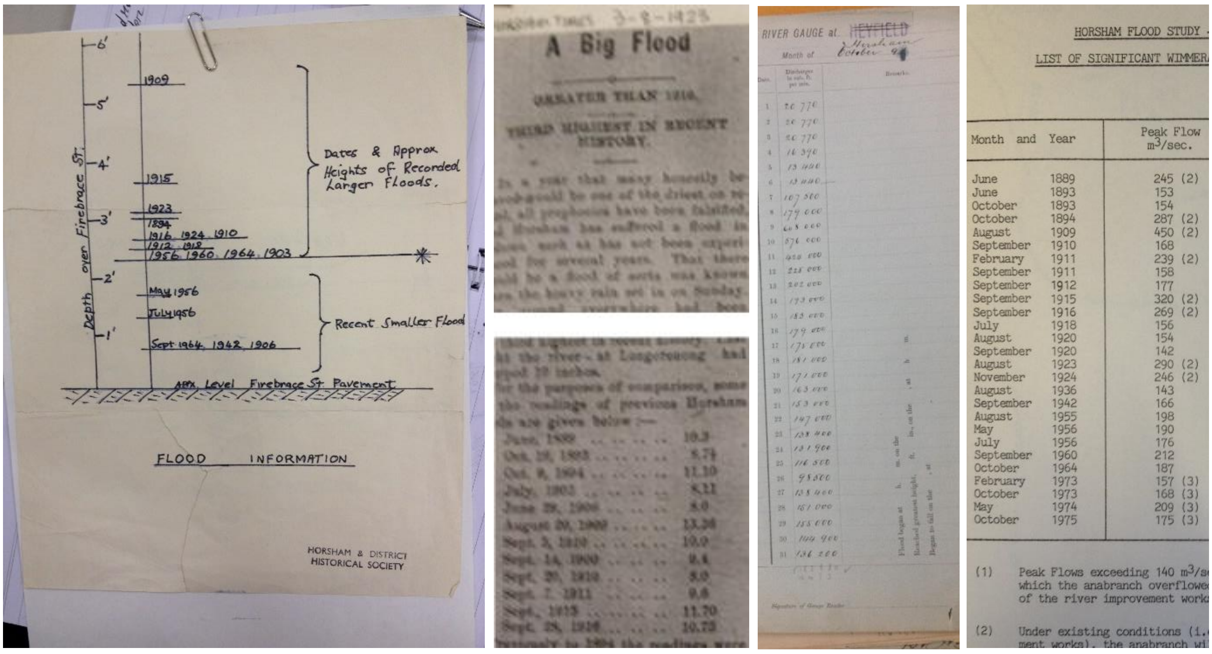


**FIGURE 4-2 EXAMPLE OF HISTORICAL INFORMATION SOURCED FOR WIMMERA RIVER AT HORSHAM**

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

**TABLE 4-1 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 |
| 2016 | DELWP gauge | 12,319 | 143 |

The above historic peak flows along with other smaller flow years were included in the FFA.

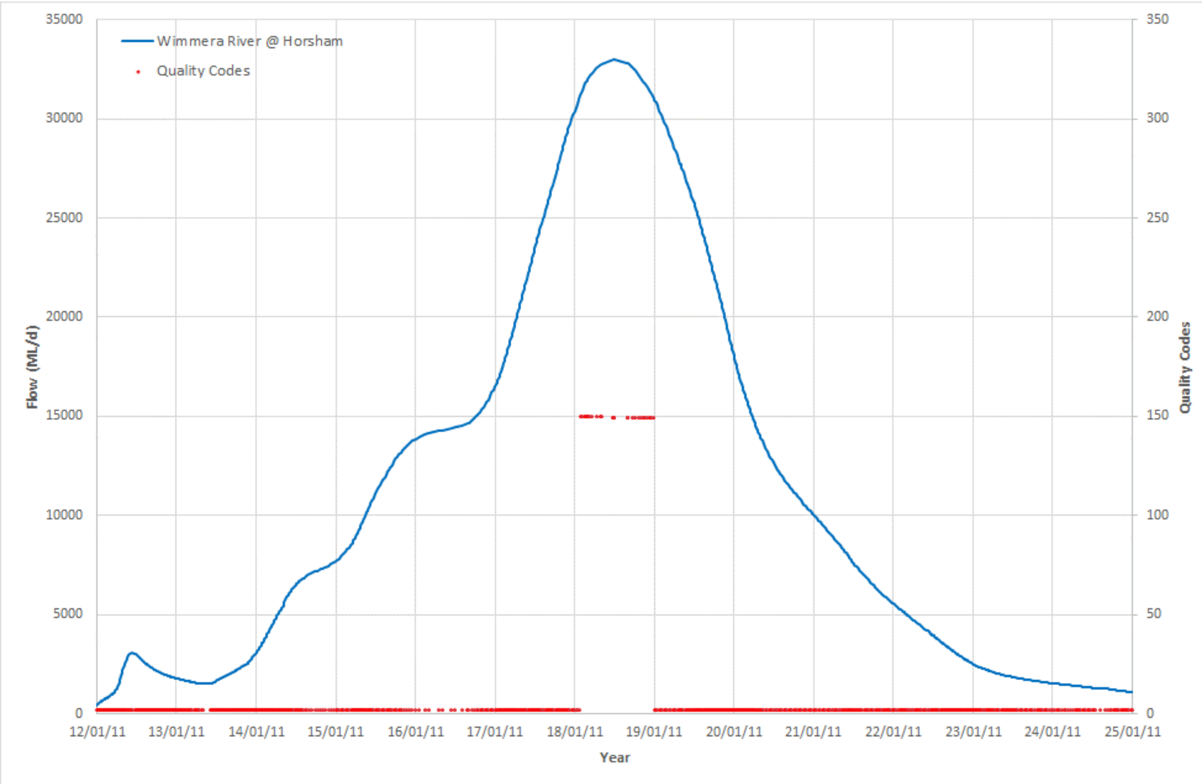


**FIGURE 4-3 JANUARY 2011 HYDROGRAPH RECORDED AT THE WIMMERA RIVER AT HORSHAM (WALMER) STREAMFLOW GAUGE**

During January 2011, the Wimmera River flowrate was measured at the Western Highway Bridge (6 km upstream of the Horsham streamflow gauge) by contract hydrographers[14], the gauging was completed at this location due to the Horsham gauge being too dangerous for hydrographers to access. The location of the Horsham gauge (Walmer) and the Western Highway Bridge are shown in Figure 4-4. The Horsham gauge (Walmer) is located near the Horsham Rifle Range, immediately upstream of the Mackenzie River confluence. The gauge is 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 4.2.1.1.3. The gauge is in a poor location for measuring high Wimmera River flows and 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 gauge rating and historic gauging measurements are shown in Figure 4-5, with the previous (v15) and current (v17) rating curves shown in Figure 4-6.

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.

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 following section.

[14] Pers. Comm. – Ventia (Rebekah Webb) (Formerly Thiess Environmental)


**FIGURE 4-4 WIMMERA RIVER AT HORSHAM (WALMER) GAUGE AND WESTERN HIGHWAY JANUARY 2011 MEASUREMENT LOCATIONS**

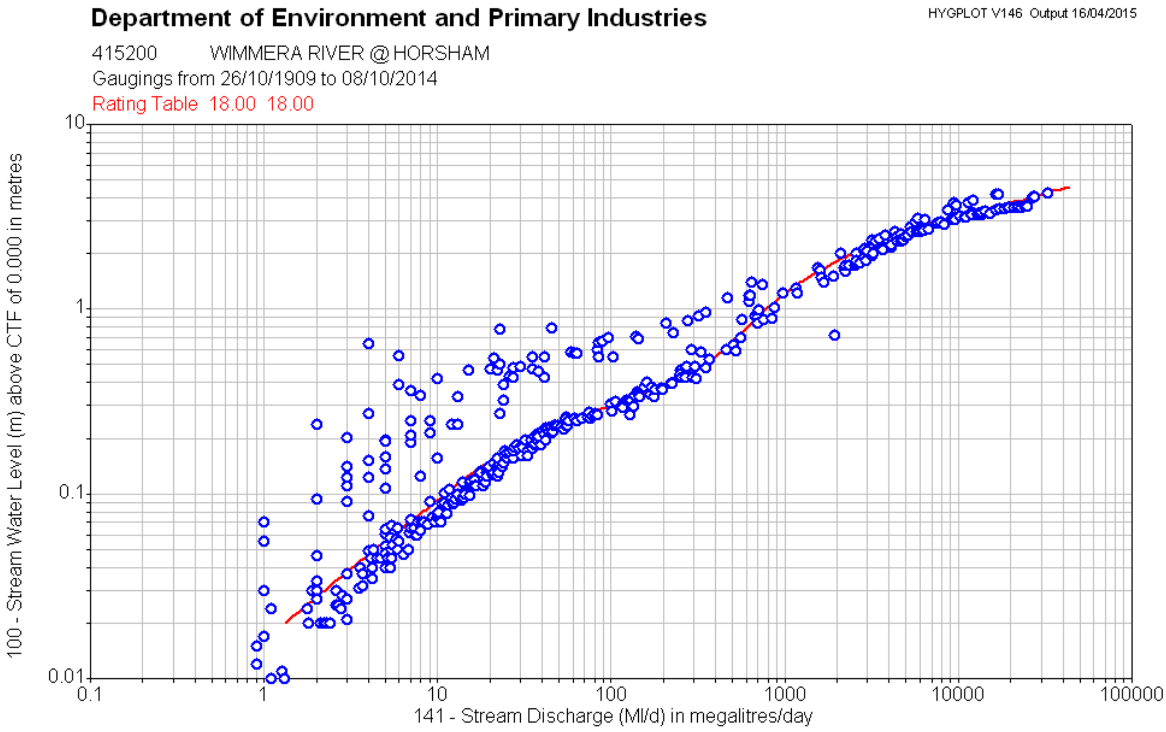


**FIGURE 4-5 WIMMERA RIVER AT HORSHAM STREAMFLOW GAUGE RATING CURVE AND MEASUREMENTS[15]**

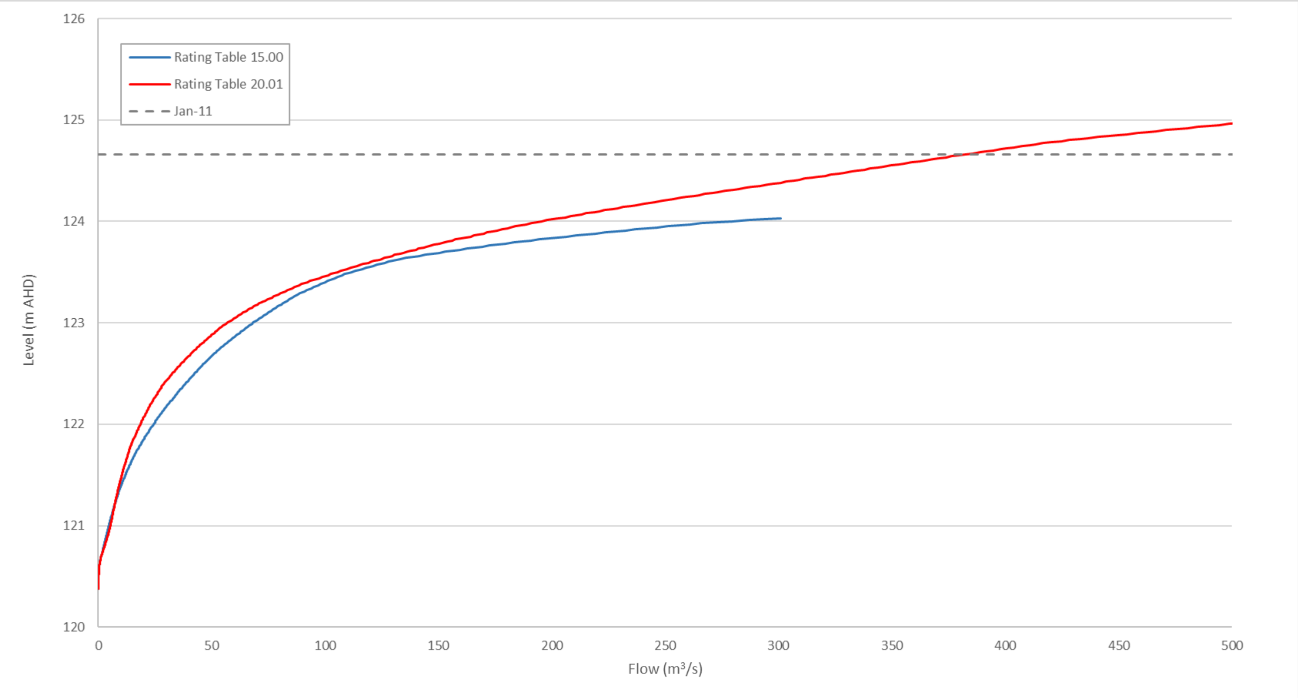


**FIGURE 4-6 WIMMERA RIVER AT HORSHAM CURRENT AND PREVIOUS RATING CURVES**

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

#### 4.2.1.1.1 MEETING WITH HYDROGRAPHERS

As part of a review of the January 2011 flood event, Water Technology was supplied with an email from Wimmera CMA shortly after the event quoting a preliminary peak flowrate undertaken at the Western Highway. The peak 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 Lower Wimmera River Regional Flood Mapping study team (Water Technology and 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 12 noon 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 4-2.

TABLE 4-2 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[16]. 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 were of sufficient accuracy for use in the Lower Wimmera Regional Flood Mapping Project and are fit for adoption in this study.

#### 4.2.1.1.2 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 for the flood peak, this would

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

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 Western 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 1,000 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).

##### 4.2.1.1.3 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.

During the Lower Wimmera River Regional Flood Mapping Study, modelling 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 the flow estimate of approximately 400-500 ML/d from the existing rating curve.

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 the estimated flow of approximately 4,000-5,000 ML/d from the existing rating curve.

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 several 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.

#### 4.2.1.2 Flood Frequency Analysis

##### 4.2.1.2.1 PEAK FLOW

This study has adopted the Wimmera River design flows developed during the Lower Wimmera River Regional Flood Mapping Study. During this project 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 Wimmera CMA. The larger historic peak flows used to construct the annual series were displayed earlier in Table 4-1, 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.

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 4-3 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 |

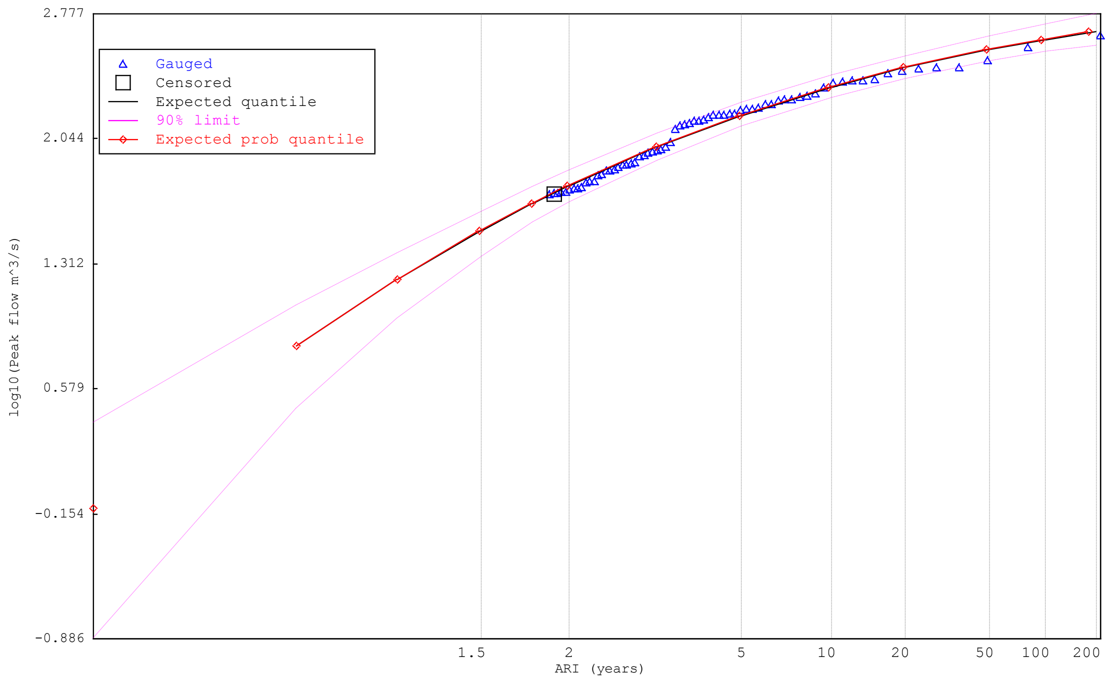


FIGURE 4-7 WIMMERA RIVER AT HORSHAM FFA (LP3 WITH LOW FLOW CENSORING)

#### 4.2.1.2.2 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 4-4 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 |

#### 4.2.1.3 Design Flow Hydrographs

The January 2011 event was adopted for the design hydrograph shape. The design hydrographs were adjusted to match the peak design flow estimates and event volume from the FFA.

#### 4.2.1.4 Application of Model Inflows and Gauge Flows

As discussed in Section 2.1.3.2, Wimmera River inflows were applied to the hydraulic model at the eastern extent of the model, east of School Road. The design hydrology was determined for the Wimmera River at the Wimmera River at Horsham (Walmer) gauge, which is to the west of Horsham, a considerable distance from the hydraulic model upstream boundary. The design flow hydrographs were factored up for each AEP so that when they were run through the hydraulic model they reproduced the design flows determined for the Wimmera River at Horsham (Walmer) streamflow gauge.

The model results show the Wimmera River inflows match the FFA determined peak flow within 1-2% for each AEP event.

TABLE 4-5 PEAK FLOWS DETERMINED BY FFA, MODEL RESILTS AND MODEL INFLOWS

| AEP (%) | Peak flow ($m^3/s$) | | | |
|---|---|---|---|---|
| | Horsham (Walmer) Gauge FFA | Hydraulic Model at the Gauge | % difference | Hydraulic Model Inflow |
| 20 | 152 | 151 | -1% | 162 |
| 10 | 222 | 222 | 0% | 235 |
| 5 | 289 | 285 | -1% | 333 |
| 2 | 369 | 361 | -2% | 392 |
| 1 | 423 | 417 | -1% | 449 |
| 0.5 | 471 | 460 | -2% | 498 |

## 4.2.2 Tributaries

### 4.2.2.1 Overview

As discussed in Section 2.1.2 the Wimmera River tributaries between upstream of Horsham to Quantong were modelled in RORB to determine both calibration and design flow estimates.

The design flow methodology adopted during the study was in line with ARR2016 recommendations[10]. The following sections outline how each of the key RORB design inputs were determined.

### 4.2.2.2 Rainfall Depths

The Intensity Frequency Duration (IFD) rainfall depths were sourced from the Bureau of Meteorology (BoM) online IFD tool[17]. Areal reduction factors and temporal patterns were sourced from the ARR Data Hub[18]. Both data sets were based on the coordinates of the catchment centroid (-36.88527778, 142.2022222).

Rainfall depths for rare events (less than 0.5% AEP) are only supplied for storm durations greater than 24 hours. Therefore, the required points were extrapolated for shorter durations using the growth factors from the 24 hour duration.

Rainfall was spatially distributed across the RORB subareas for each AEP based on the same ARR (1987)[19] IFD distribution. This was completed using the 12 hour, 2% AEP depth grid available from the BoM. There were no ARR2016 rainfall grids available at the time the hydrology was being completed, but point comparisons were made across the catchment. There was a reasonable change in rainfall depths across the RORB model area with a maximum difference of 25%, north to south. Most of the spatial variation was close to the Grampians National Park. It was concluded that the spatial pattern of the design rainfall from ARR1987 was appropriate to use, with the actual rainfall depths adopted from the ARR2016 IFD.

### 4.2.2.3 Losses

Losses for the RORB model were initially determined using the ARR online datahub, suggesting the use of 34mm initial loss and 3mm/hr continuing loss.

The hydraulic model calibration process determined an initial loss of 35mm and a continuing loss of 4mm/hr for January 2011 and an initial loss of 35mm and a continuing loss of 2.5mm/hr for September 2016.

Given the similarities between the calibration and ARR Data Hub losses it was determined the Datahub recommended losses would be adopted as shown in Table 4-6 for design purposes. The initial loss was adopted as the initial loss applied in all the RORB Ensemble runs, and was the median initial loss for the Monte Carlo runs.

**TABLE 4-6 ADOPTED LOSSES**

| Loss Type | Loss |
|---|---|
| Initial Loss | 34 mm |
| Continuing Loss | 3 mm/hr |

[17] http://www.bom.gov.au/water/designRainfalls/revised-ifd/?year=2016
[18] http://data.arr-software.org/
[19] Institution of Engineers, Australia (1987) Australian Rainfall and Runoff: A Guide to Flood Estimation, Vol. 1, Editor-in-chief D.H. Pilgrim, Revised Edition 1987 (Reprinted edition 1998), Barton, ACT

#### 4.2.2.4 KC

As outlined in Section 2.1.2.3 the initial kc value for each interstation area was determined using the Victorian data estimate available in RORB (Pearse et al, 2002[20]) where kc=1.25*$D_{av}$. This resulted in the kc values outlined in Table 4-7.

**TABLE 4-7 CALIBRATION AND DESIGN KC VALUES**

| Catchments | Kc |
|---|---|
| Norton Creek, Sandy Creek, Darragan Creek | 64.9 |
| Burnt Creek and Mackenzie River | 43.2 |

#### 4.2.2.5 M

As modelled in both the January 2011 and September 2010 calibration events the RORB model 'm' value was maintained at 0.8. This is generally accepted as an industry standard value unless observed information indicates it should be changed to achieve a better calibration.

#### 4.2.2.6 Model results

##### 4.2.2.6.1 MONTE CARLO

As discussed in Section 4.1, RORB modelling was completed running the Monte Carlo methodology initially to determine statistical peak flows. This was then followed by the Ensemble methodology. 1,000 Monte Carlo runs were completed sampling randomly from the potential temporal patterns and initial loss distribution. The Monte Carlo peak flows were determined for 10 locations within the RORB model. The determined peak flows for each AEP are shown in Table 4-8, Table 4-9 shows the critical duration highlighted for each location and event. The 12 hour event is clearly the most prevalent critical duration, particularly in the more common events, while at rarer AEPs the 24hr and 48hr events are most the most common critical duration. In locations where the 72hr event was critical it was only marginally higher than the next highest duration peak flow, typically the 12 hour event for the upper reaches of the tributaries. For example, at the Mid Mackenzie River print point in a 5% AEP event the critical duration was 72hrs with a peak flow of 21.5 $m^3/s$, only marginally higher than the 12hr event at 21.1 $m^3/s$.

[20] Pearse et al, 2002 – A Simple Method for Estimating RORB Model Parameters for Ungauged Rural Catchments, Water Challenge: Balancing the Risks: Hydrology and Water Resources Symposium, 2002

TABLE 4-8 MONTE CARLO DETERMINED PEAK FLOWS

| Location | Peak flow ($m^3/s$) | | | | | |
|---|---|---|---|---|---|---|
| | 20% AEP | 10% AEP | 5% AEP | 2% AEP | 1% AEP | 0.5% AEP |
| Mackenzie Upper | 10.1 | 37.9 | 74.0 | 124.8 | 168.6 | 220.6 |
| Mackenzie Mid | 2.0 | 10.4 | 21.5 | 38.5 | 54.3 | 72.2 |
| Mackenzie Lower | 2.8 | 15.7 | 34.4 | 64.2 | 94.6 | 127.3 |
| Burnt Mid | 8.4 | 38.1 | 74.5 | 139.6 | 199.1 | 269.7 |
| Norton Mid | 1.7 | 8.4 | 18.1 | 33.0 | 47.5 | 64.3 |
| Norton Lower | 2.2 | 9.2 | 20.1 | 38.1 | 61.6 | 87.9 |
| Sandy Mid | 2.1 | 4.4 | 7.7 | 12.9 | 18.9 | 24.7 |
| Sandy Lower | 0.7 | 1.9 | 3.7 | 7.1 | 10.4 | 14.5 |
| Darragan Mid | 0.4 | 2.6 | 6.0 | 11.4 | 17.8 | 25.6 |
| Darragan Lower | 0.7 | 3.1 | 7.1 | 13.9 | 19.1 | 28.1 |

TABLE 4-9 MONTE CARLO DETERMINED PEAK FLOW CRITICAL DURATIONS

<table>
<tr><th rowspan="2">Location</th><th colspan="6">Peak flow (m³/s)</th></tr>
<tr><th>20% AEP</th><th>10% AEP</th><th>5% AEP</th><th>2% AEP</th><th>1% AEP</th><th>0.5% AEP</th></tr>
<tr><td>Mackenzie Upper</td><td colspan="6">12hr</td></tr>
<tr><td>Mackenzie Mid</td><td colspan="2">12hr</td><td>72hr</td><td colspan="3">12hr</td></tr>
<tr><td>Mackenzie Lower</td><td colspan="2">12hr</td><td>72hr</td><td>12hr</td><td colspan="2">72hr</td></tr>
<tr><td>Burnt Mid</td><td colspan="4">12hr</td><td colspan="2">24hr</td></tr>
<tr><td>Norton Mid</td><td colspan="2">12hr</td><td>72hr</td><td colspan="2">12hr</td><td>48hr</td></tr>
<tr><td>Norton Lower</td><td colspan="4">12hr</td><td colspan="2">24hr</td></tr>
<tr><td>Sandy Mid</td><td colspan="3">12hr</td><td colspan="3">24hr</td></tr>
<tr><td>Sandy Lower</td><td>24hr</td><td>12hr</td><td>72hr</td><td>48hr</td><td>24hr</td><td>48hr</td></tr>
<tr><td>Darragan Mid</td><td colspan="2">12hr</td><td colspan="2">72hr</td><td>24hr</td><td>48hr</td></tr>
<tr><td>Darragan Lower</td><td colspan="2">12hr</td><td colspan="2">72hr</td><td>24hr</td><td>48hr</td></tr>
</table>

#### 4.2.2.6.2 ENSEMBLE

The RORB model was run using an Ensemble Analysis, using the determined kc values and recommended ARR2016 losses. The RORB Ensemble Analysis was run for all ten ARR2016 recommended temporal patterns for each event duration. For this case, six design events were modelled, resulting in 60 design event simulations for each of the four durations (12hr, 24hr, 48hr and 72hr), totalling 240 model simulations. The peak flows determined in the Monte Carlo analysis were used to find a temporal pattern from the Ensemble Analysis producing a hydrograph with a similar peak flow. This comparison of peak flows between the Monte Carlo and Ensemble Analysis was completed at each of the ten output locations along the Wimmera River tributaries, this is summarised in Table 4-10 shows which temporal pattern generated the closest match, opting for the temporal pattern which produced a peak slightly higher than the Monte Carlo analysis determined.

TABLE 4-10 TEMPORAL PATTERN NUMBER WHICH IS CLOSEST TO THE MONTE CARLO ANALYSIS PEAK FLOW

<table>
<tr><th colspan="11">Temporal Pattern</th></tr>
<tr><th>AEP (%)</th><th>Mackenzie Upper</th><th>Mackenzie Mid</th><th>Mackenzie out</th><th>Burnt Mid</th><th>Norton Mid</th><th>Norton Lower</th><th>Sandy Mid</th><th>Sandy Lower</th><th>Darragan Mid</th><th>Darragan Lower</th></tr>
<tr><td>20</td><td>10</td><td colspan="3">2</td><td>10</td><td colspan="2">2</td><td>7</td><td colspan="2">10</td></tr>
<tr><td>10</td><td>2</td><td colspan="2">10</td><td colspan="2">2</td><td>10</td><td colspan="2">8</td><td colspan="2">10</td></tr>
<tr><td>5</td><td>2</td><td colspan="2">3</td><td>8</td><td>3</td><td>2</td><td>8</td><td>10</td><td colspan="2">3</td></tr>
<tr><td>2</td><td>2</td><td colspan="6">8</td><td colspan="2">3</td><td>10</td></tr>
<tr><td>1</td><td>3</td><td>8</td><td colspan="2">3</td><td>8</td><td colspan="5">3</td></tr>
<tr><td>0.5</td><td colspan="2">1</td><td colspan="8">3</td></tr>
<tr><th colspan="11">Ensemble Peak Flow Matching the Monte Carlo Peak Flow Closest</th></tr>
<tr><th>AEP (%)</th><th>Mackenzie Upper</th><th>Mackenzie Mid</th><th>Mackenzie out</th><th>Burnt Mid</th><th>Norton Mid</th><th>Norton Lower</th><th>Sandy Mid</th><th>Sandy Lower</th><th>Darragan Mid</th><th>Darragan Lower</th></tr>
<tr><td>20</td><td>10.2</td><td>2.1</td><td>2.4</td><td>8.7</td><td>1.6</td><td>1.9</td><td>2.1</td><td>0.7</td><td>0.4</td><td>0.7</td></tr>
<tr><td>10</td><td>39.7</td><td>9.6</td><td>14.7</td><td>34.1</td><td>7.6</td><td>8.8</td><td>4.5</td><td>1.7</td><td>2.5</td><td>2.8</td></tr>
<tr><td>5</td><td>75.1</td><td>38.2</td><td>64.4</td><td>67.0</td><td>33.3</td><td>16.2</td><td>7.9</td><td>7.8</td><td>14.4</td><td>18.3</td></tr>
<tr><td>2</td><td>130.3</td><td>40.4</td><td>63.5</td><td>143.1</td><td>33.6</td><td>35.8</td><td>14.2</td><td>7.3</td><td>23.4</td><td>26.1</td></tr>
<tr><td>1</td><td>173.5</td><td>63.5</td><td>151.7</td><td>218.1</td><td>52.5</td><td>63.4</td><td>20.0</td><td>10.7</td><td>18.2</td><td>20.1</td></tr>
<tr><td>0.5</td><td>225.9</td><td>72.8</td><td>183.3</td><td>302.3</td><td>77.9</td><td>93.7</td><td>26.8</td><td>14.8</td><td>27.0</td><td>29.8</td></tr>
</table>

During review of the most common temporal patterns it became apparent there were large discrepancies between the Monte Carlo and Ensemble determined peak flows for events with a critical duration of 72 hours. For example, at the Lower Mackenzie River location the RORB 1% AEP Monte Carlo peak flow was 94.6 $m^3/s$, with the 1% AEP, 72hr duration, with the ensemble of temporal patterns resulted in peak flows ranging from 5 to 191 $m^3/s$ as shown in Table 4-11.

**TABLE 4-11 1% AEP, 72 HOUR DURATION – PEAK FLOWS IN THE LOWER MACKENZIE**

| Temporal Pattern | Peak Flow ($m^3/s$) |
|---|---|
| 1 | 25.1 |
| 2 | 4.7 |
| 3 | 151.7 |
| 4 | 74.4 |
| 5 | 25.2 |
| 6 | 6.2 |
| 7 | 57.4 |
| 8 | 39.3 |
| 9 | 25.0 |
| 10 | 191.0 |

The scenarios producing flows on either side of the Monte Carlo peak flow were significantly different and too far apart for adoption without adjustment. The peak flows clearly show temporal pattern 3 and 10 are significantly higher than the remaining patterns. These temporal patterns for the 1% AEP, 72hr event are plotted in Figure 4-8. In both instances between 35 to 40% of the total rainfall depth fell in a single 3 hour time increment. These patterns are clearly very different to the rest of the temporal patterns for the 72 hour, 1% AEP ensemble. Further analysis showed that these temporal patterns were sampled from gauges high on the Great Dividing Range (High Camp, north of Kilmore, and Jerangle, north of Cooma). Given the inability of the temporal pattern ensembles for the 72 hour duration to be able to reproduce a peak flow close to that of the Monte Carlo analysis, and the fact that the 72 hour peak flow was very similar to other durations anyway, the 72 hour duration was removed from the analysis.

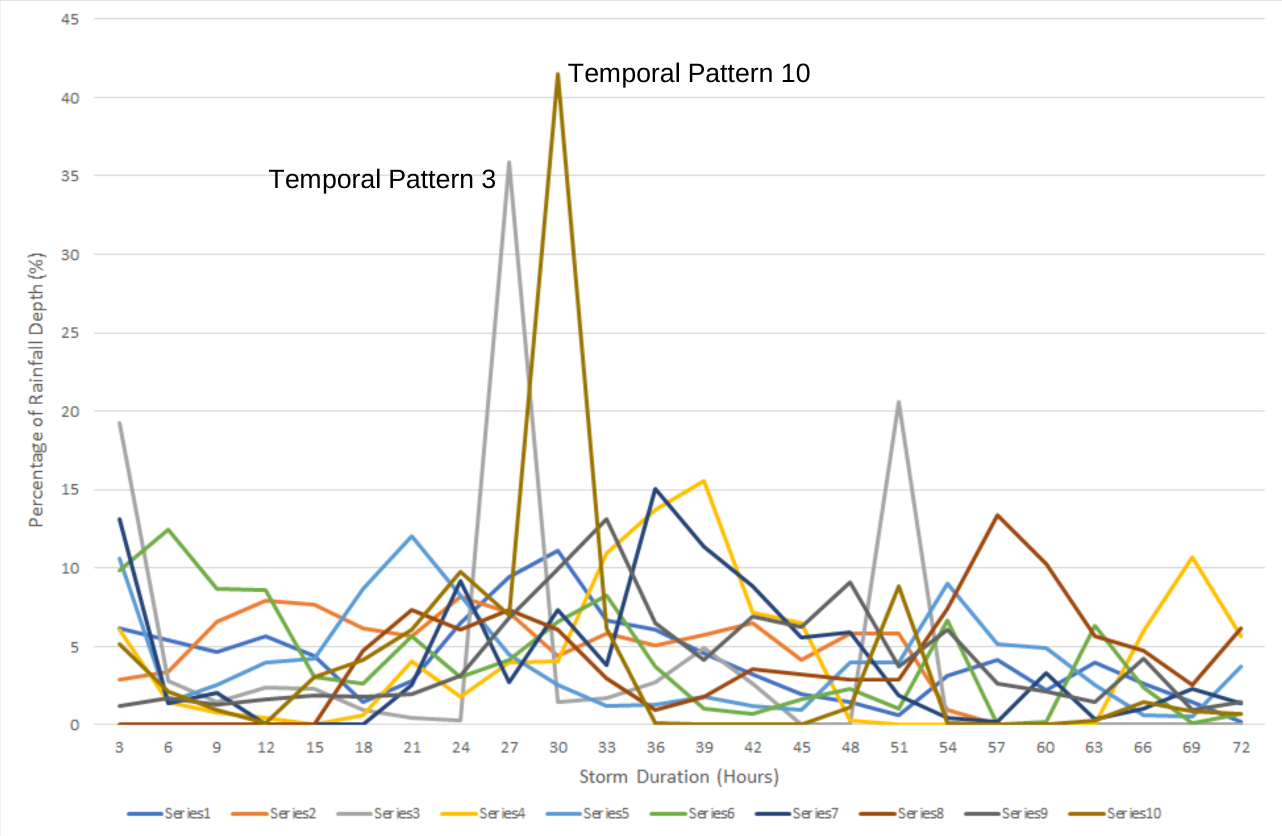


FIGURE 4-8 72 HOUR, 1% AEP TEMPORAL PATTERNS

To reduce the potential number of hydraulic model runs a single temporal pattern for each AEP was chosen. For instance, temporal pattern 3 was shown to produce peak flows most similar to those produced in the Monte Carlo analysis at eight of the ten locations within the tributary catchments for the 1% AEP event, and it was therefore chosen as the temporal pattern to be used to produce inflows to the hydraulic model across the six event durations for the 1% AEP. The chosen temporal patterns for each of the AEP events are shown in Table 4-12.

TABLE 4-12 CHOSEN REPRESENTITIVE TEMPORAL PATTERNS FOR EACH AEP

| AEP (%) | Chosen Temporal Pattern |
|---|---|
| 20 | 2 |
| 10 | 10 |
| 5 | 3 |
| 2 | 8 |
| 1 | 3 |
| 0.5 | 3 |

## 4.3 Hydraulics

### 4.3.1 Riverine Inundation

Design hydraulic modelling was completed by introducing the tributary design flow hydrographs into the hydraulic model, followed by the Wimmera River design flow hydrographs. A timing difference between the tributaries and the Wimmera River was based around historic observations at the Burnt Creek streamflow gauge at Wonwondah and the Wimmera River streamflow gauge at Horsham (Walmer). Historically, the timing difference at this gauge has been slightly more than 4 days. This also lines up with URBS runoff routing modelling completed during the Horsham Bypass Hydrology and Hydraulics Assessment[21]. This is demonstrated in Table 4-13.

TABLE 4-13 TIMING DEFERENCE BETWEEN THE HORSHAM AND WONWONDAH STREAMFLOW GAUGES

| Event | Burnt Creek @ Wonwondah | Wimmera River @ Walmer | Time between peaks |
|---|---|---|---|
| October 1996 | 01/10/1996 0:38 | 05/10/1996 4:00 | 4 days, 3 hours |
| September 2010 | 05/09/2010 4:30 | 09/09/2010 12:00 | 4 days, 7 hours, |
| January 2011 | 14/01/2011 5:45 | 18/01/2011 11:30 | 4 days, 6 hours |
| December 2016 | 14/09/2016 14:45 | 19/09/2016 5:45 | 4 days, 15 hours |
| Previous Model predictions | - | - | 4 days, 6 hours |

Model inflows were placed directly into the hydraulic model at the specified model boundaries as shown in Section 2.1.3.2.

The hydraulic model setup, roughness and other modelling parameters for design modelling was the same as that of the calibrated model.

The draft 1% AEP depths are shown in Figure 4-9.

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[21] Water Technology (2013) – Horsham Bypass Hydrology and Hydraulics Assessment

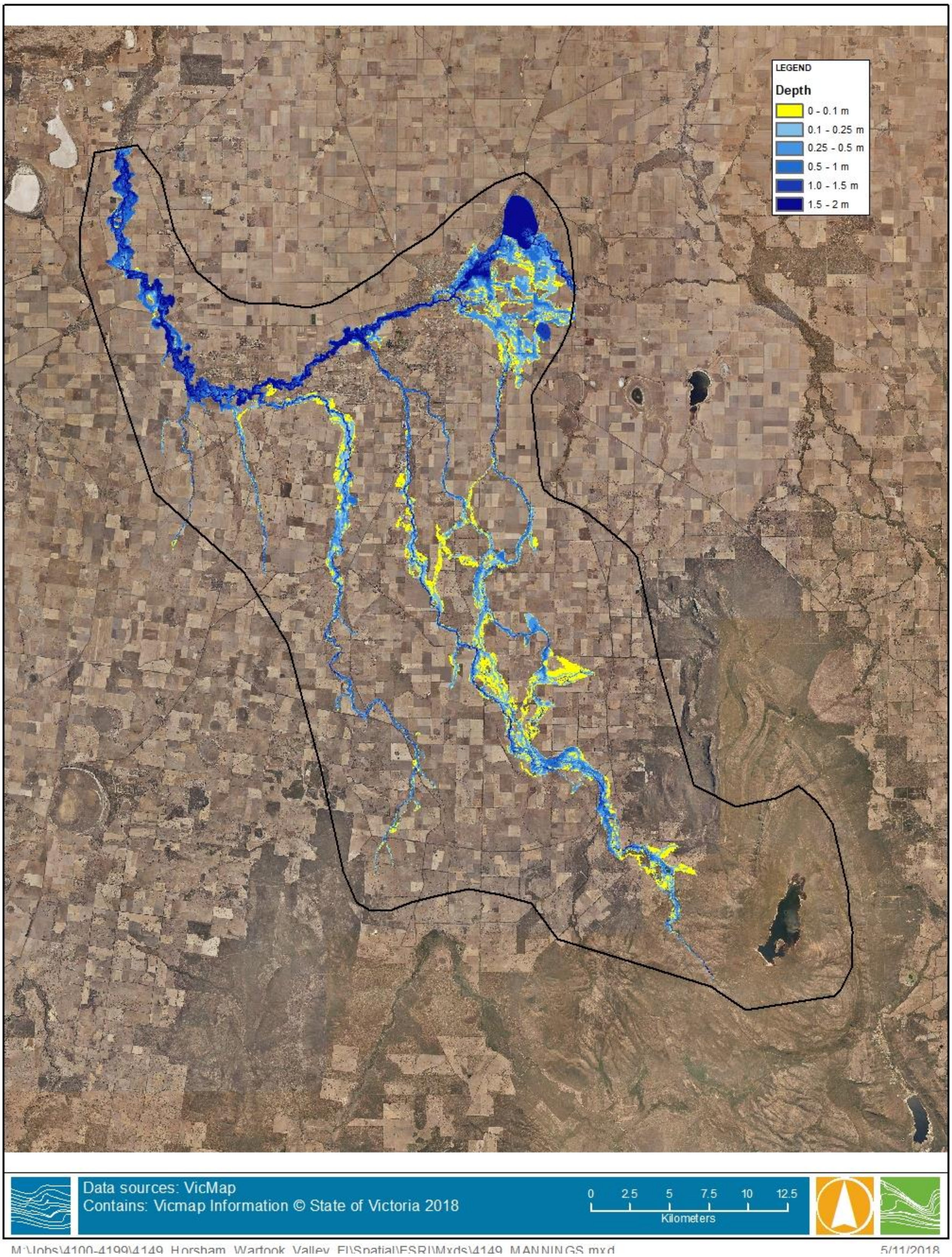


**FIGURE 4-9 1% AEP DESIGN MODEL EXTENT**

### 4.3.2 Stormwater Inundation

Similar to the design RORB modelling, the rain on grid stormwater model was run using the ARR2016 recommended temporal patterns. The rainfall losses determined during model verification were adopted, as outlined in Section 3.2.1.

Modelling of the 1% AEP event was completed for all ten of the recommended temporal patterns, the water levels produced were compared to determine which temporal pattern produced the most 'average' set of results. This was done by creating an average water level grid, then mapping the temporal patterns which most closely matched the average value. This is shown in Figure 4-10 for the northern model extent and Figure 4-11 for the southern model extent.

Temporal Pattern 2 produced the most average water surface elevation and this temporal pattern was adopted for the remaining design model runs.

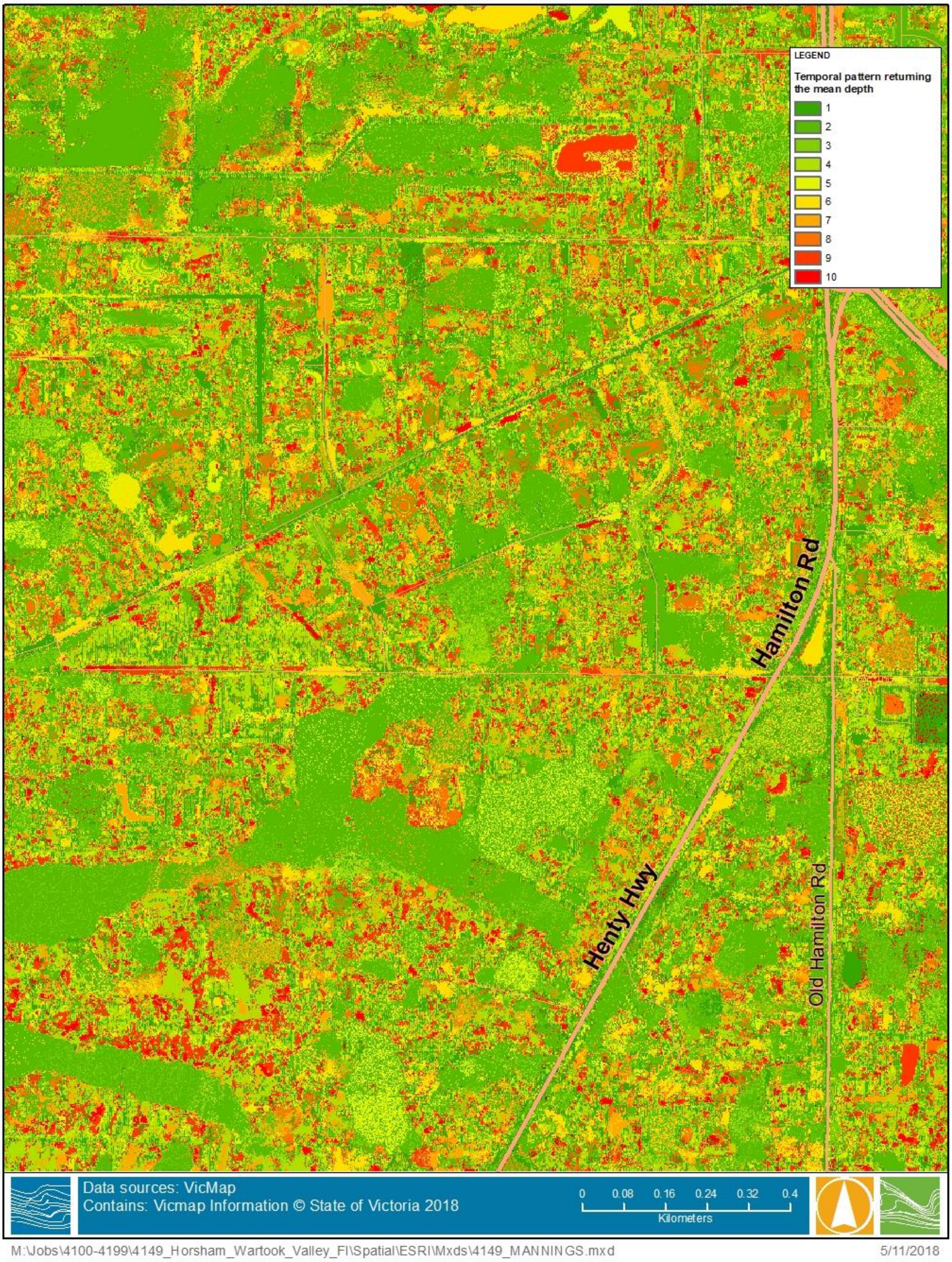


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**FIGURE 4-10 TEMPORAL PATTERNS MOST CLOSELY MATCHING THE AVERAGE WATER LEVELS – NORTHERN MODEL**

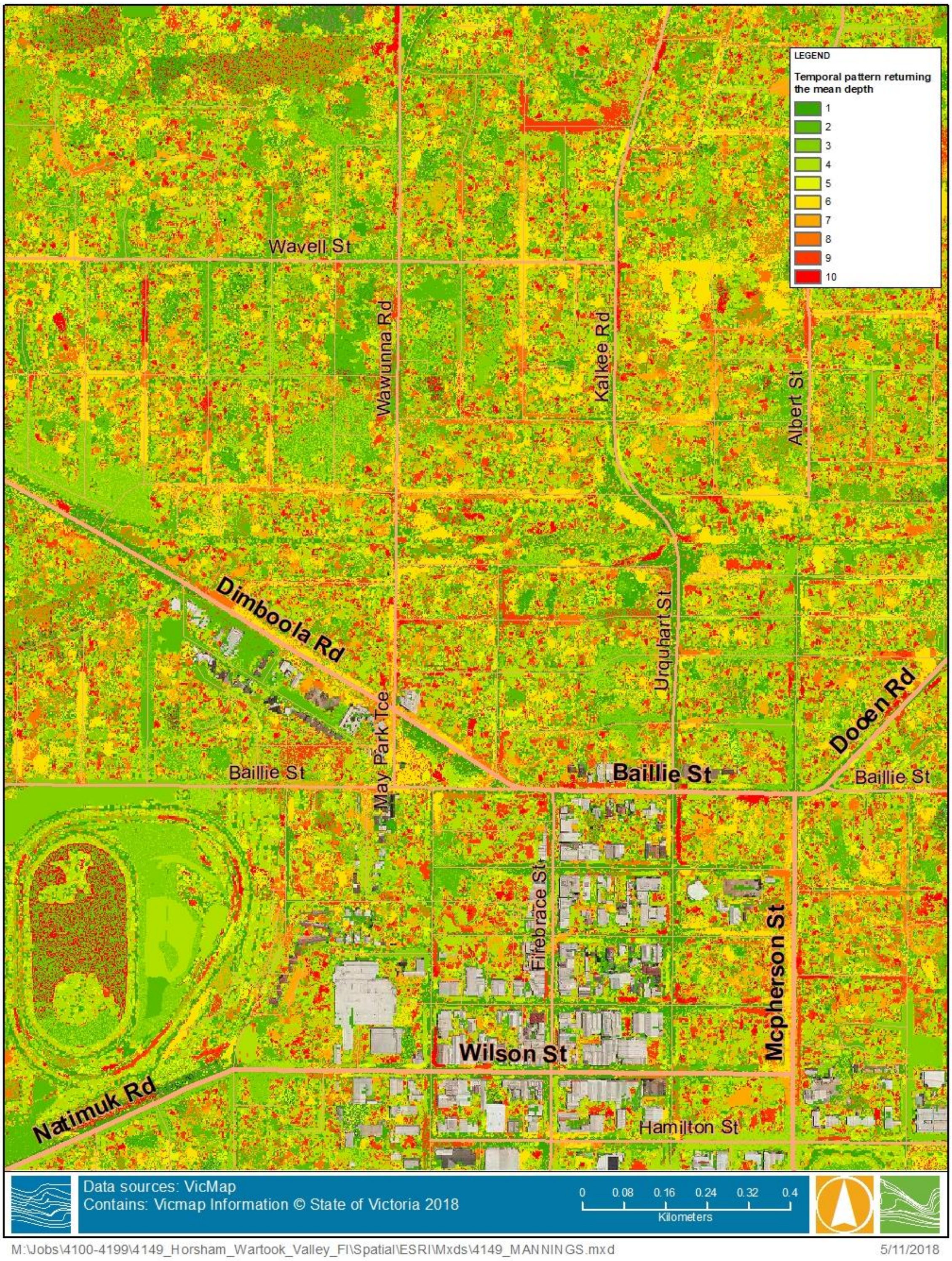


**FIGURE 4-11 TEMPORAL PATTERNS MOST CLOSELY MATCHING THE AVERAGE WATER LEVELS – SOUTHERN MODEL**

The 1% AEP inundation depths are shown in Figure 4-12.

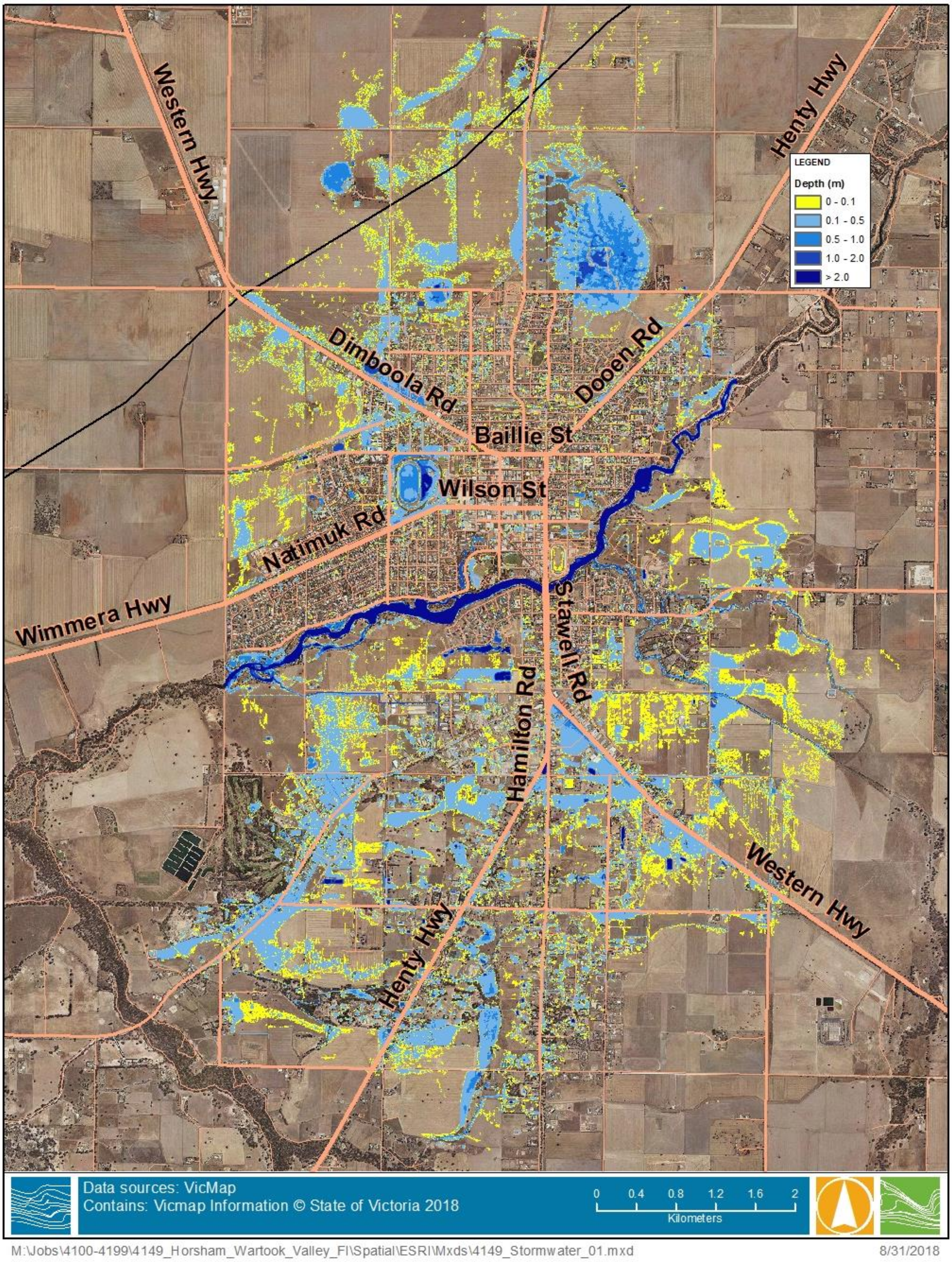


**FIGURE 4-12 1% AEP STORMWATER INUNDATION IN HORSHAM**

### 4.3.3 Riverine Model Comparison

A brief comparison between the 1% AEP water levels produced as part of this project (Wimmera River flows only) and the Horsham Bypass Hydrology and Hydraulics Investigation (2013) was completed as an initial guide for the expected changes to planning scheme and to ensure changes were consistent and expected, this is shown in Figure 4-14.

The comparison shows increases in both extent and water levels along the Wimmera River and within the Horsham Township. Increases in water level reach up to 200mm but are in generally 50-150 mm. The increases are largely focused on the area upstream of the Western Highway bridge.

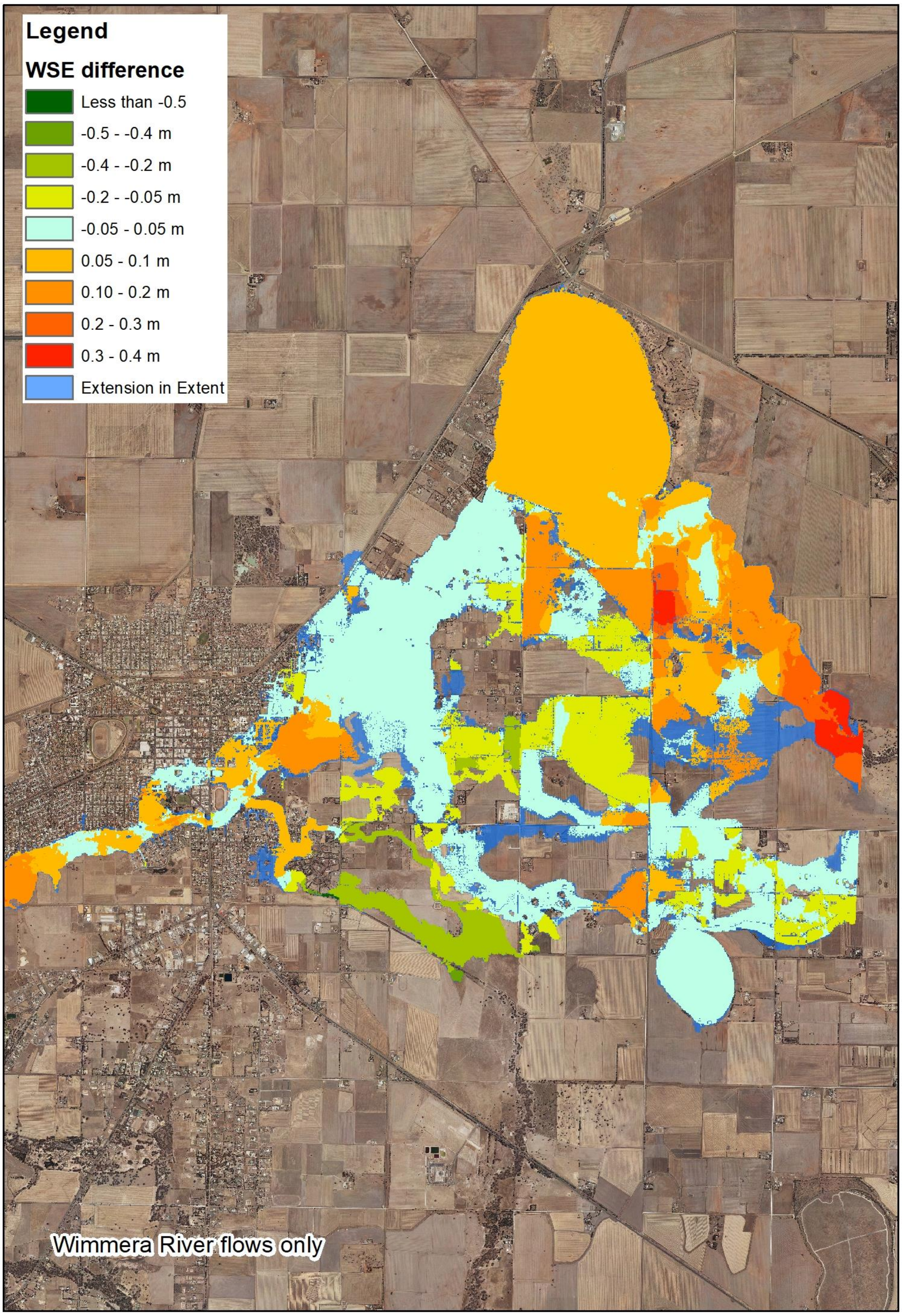


**FIGURE 4-13 1% AEP FLOOD LEVELS PRODUCED AS PART OF THIS STUDY AND THOSE PRODUCED DURING THE HORSHAM BYPASS HYDROLOGY AND HYDRAULICS INVESTIGATION (2013)**

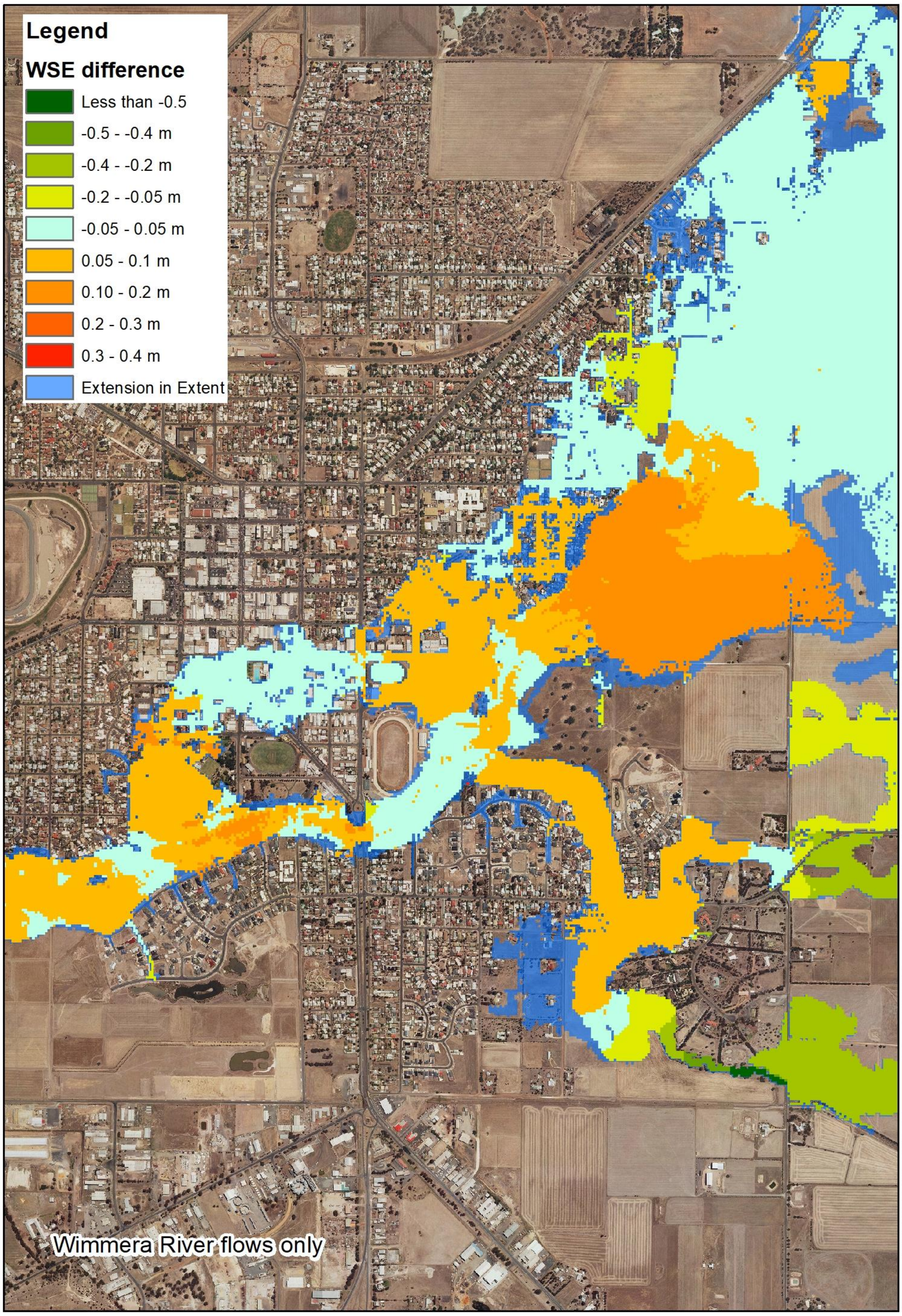


**FIGURE 4-14 1% AEP FLOOD LEVELS PRODUCED AS PART OF THIS STUDY AND THOSE PRODUCED DURING THE HORSHAM BYPASS HYDROLOGY AND HYDRAULICS INVESTIGATION (2013) – HORSHAM TOWNSHIP**

# 5 NEXT STEPS

The study team are currently considering getting some additional survey of the Wimmera River channel to confirm potential changes to bathymetry since the high flow events of 2011 and 2016. This process will occur concurrently with the DELWP review process.

Once the review and survey requirements are determined the modelling will be used as a basis for the mitigation and flood intelligence outputs.

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## Melbourne

15 Business Park Drive
Notting Hill VIC 3168
Telephone (03) 8526 0800
Fax (03) 9558 9365

## Brisbane

Level 3, 43 Peel Street
South Brisbane QLD 4101
Telephone (07) 3105 1460
Fax (07) 3846 5144

## Adelaide

1/198 Greenhill Road
Eastwood SA 5063
Telephone (08) 8378 8000
Fax (08) 8357 8988

## Perth

Ground Floor
430 Roberts Road
Subiaco WA 6008
Telephone 0438 347 968

## Geelong

PO Box 436
Geelong VIC 3220
Telephone 0458 015 664

## Gippsland

154 Macleod Street
Bairnsdale VIC 3875
Telephone (03) 5152 5833

## Wangaratta

First Floor, 40 Rowan Street
Wangaratta VIC 3677
Telephone (03) 5721 2650

## Wimmera

PO Box 584
Stawell VIC 3380
Telephone 0438 510 240

www.watertech.com.au

info@watertech.com.au