WATER TECHNOLOGY
WATER, COASTAL & ENVIRONMENTAL CONSULTANTS

Yarrowee River and Gnarr Creek Hydrology and Hydraulics

Ballarat Flood Modelling Update

City of Ballarat

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EXECUTIVE SUMMARY

Water Technology was engaged by the City of Ballarat (CoB) to review and update the existing hydrologic and hydraulic models developed between 2017 and 2018 covering several waterways within the CoB municipality. The following report details the current hydrologic and hydraulic modelling for the Yarrowee River and Gnarr Creek. A summary of the changes made to the hydrologic and hydraulic models since the original study in 2018 are listed below.

- RORB
  - Created print node downstream of White Swan, Kirks and Gong Gong Reservoirs.
  - Created additional print nodes for subarea's 'O' and 'P'.
  - Resized subarea's 'U' and 'T' to better reflect the Warrenheip Creek catchment and the topographic features of the Western Freeway.
  - Change reach types of subareas 'FL', 'FN', 'FR', 'FS', 'FP', 'FT', 'T' and 'U' to Type 2 (excavated but unlined) from Type 3 (lined).
  - Reconfigured inflow on Havelock Street/Orkney Court
  - Subarea 'BE' reach was increased to a length of 1.8 km, up from 190 m, and its slope was reduced to 2.1% down from 8.9%.
- TUFLOW
  - The TUFLOW model was updated to the latest build (2023-03-AB) and run as HPC. This ensured that the updated model was utilising the most recent modelling approaches within the TUFLOW software package and the use of HPC reduced model run times.
  - Due to the presence of constructed channels that convey flows in the Yarrowee River and the Gnarr Creek through populated areas and the CBD, the hydraulic model adopted the use of Sub-Grid-Sampling (SGS) to model flows in the catchment. This was updated from 1D open channels in the previous modelling.
    - The SGS target distance of the hydraulic model was set to 1 metre, the same as the base LiDAR dataset.
  - Changed the layer used to represent bridge structures from Layered flow Constriction (2d_lfcsh) to Bridge (2d_bg) type.
    - The 2d_bg shape is similar to the 2d_lfcsh shape, but it is simplified and leaves less room for misrepresenting the bridge structure.
  - Added 2d_bg shape for the Oliver Street bridge in Ballarat East. This was previously not modelled as a 2d_lfcsh.
  - A new Office Works building at 118-122 Creswick Road was included in the model terrain using 2d_ztin and 2d_zsh shapes based on approved design plans.
  - Updated the culvert representation of MacArthur Street along the Gnarr Creek.
  - Moved the inflow region for subarea 'FT' into the Crompton Street basin. This was previous located in the Gnarr Creek channel, upstream of Brougham Street, and bypassed the detention basin in Crompton Street.
  - Updated the terrain of properties in Orkney Court as the 2019 LiDAR dataset captured the development partway through its completion.

- Inflows into the Yarrowee River, upstream of the Western Freeway, were split into four inflow regions. Two new inflows regions were place along the Gong Gong Creek and two were placed between White Swan Reservoir and Hillview Road.
- The inflow hydrograph for the Canadian Creek waterway previously used a RORB output. This was replaced with hydrographs generated from the 2023 Canadian Creek & Tributaries hydraulic model due to the significant variation in results.
- The inflow region for subarea 'BE' was split into 5 regions and spread along the extent of the Yarrowee River channel with its catchment. The hydrograph was reduced by a factor of 5 to accommodate for the 4 extra regions.
- Created a 0.5m DEM from feature survey and LiDAR to represent a short section of the Gnarr Creek channel that daylights between MacArthur Street and the Salvation Army Community House at 6 Crompton Street.
- Inflow regions for subareas 'FH' and 'FK' were changed to pit inflow regions.

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1 INTRODUCTION

1.1 Background

Water Technology was commissioned by the City of Ballarat to carry out the Yarrowee River and Gnarr Creek Flood Mapping Project in 2018. The original project was commissioned to improve the flood risk knowledge, address information gaps and provided valuable planning and flood intelligence within the Yarrowee River and Gnarr Creek catchments.

The Yarrowee River catchment rises to the north of the Ballarat CBD. Several of the townships water supply storages are located in the upper catchment including the Gong Gong, White Swan and Kirks Reservoir. The Yarrowee River flows south towards the Ballarat CBD, becoming channelised through much of the town (concrete lined). The channelised section of the Yarrowee River upstream of the CBD then flows into a sealed culvert section underneath the Bridge Street Mall, before reemerging downstream of Eastwood Street. The Gnarr Creek catchment rises to the northwest of the Ballarat CBD near the New Ballarat Cemetery and flows through densely populated residential areas via open concrete lined channels and submerged bluestone culverts. The Gnarr Creek flows into the Yarrowee River immediately upstream of the CBD where the waterway goes from an open channel to a sealed set of culverts. The catchment delineation of the Yarrowee River and Gnarr Creek is shown in Figure 1-1.

Water Technology has completed several studies across the City of Ballarat municipality including the Yarrowee River and Gnarr Creek Flood Mapping Update (2015) and the Ballarat Flood Risk and Opportunity Mapping (2017), mapping the City of Ballarat municipality using a rain-on-grid approach. Both of these projects were completed using Australian Rainfall and Runoff ARR (1987) parameters and recommendations. This project updates the previous flood modelling to be inline with ARR 2016 parameters and guidelines. The project is being completed as one of many across the municipality as the City of Ballarat being updated to improve flood intelligence and mapping for community awareness and planning.

1.2 Structure of the report

This report outlines the following components:

- Hydrologic modelling of the Gnarr Creek and Yarrowee River catchment including modelling methodology, inputs to the hydraulic model and results.
- Calibration of the Yarrowee River Hydrology model
- Hydraulic modelling of Gnarr Creek and Yarrowee River including modelling methodology, inputs to the hydraulic model and results.
- Flood mapping and discussion for the 1% AEP event, noting the remaining design events (20%, 10%, 5%, 2%, and the 0.5% AEP) flood events along with Climate Change are still to be modelled.

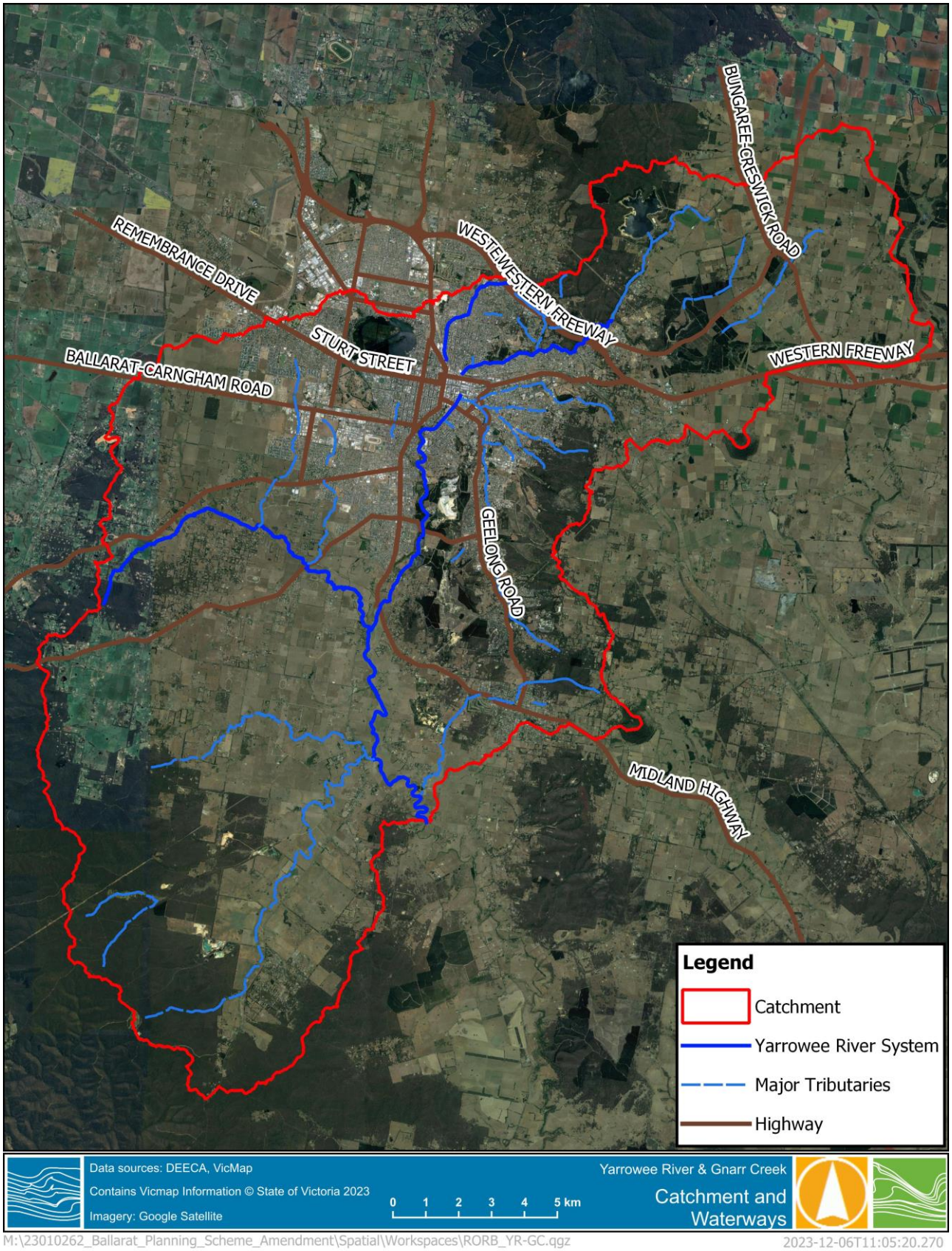


Figure 1-1 Yarrowee River and Gnarr Creek Catchment and Waterways

2 AVAILABLE INFORMTION

2.1 Overview

This section documents the data collated by Water Technology for the study. Data was sourced data from number of agencies and sources, including:

- City of Ballarat.
- Regional Roads Victoria (VicRoads).
- Department of Energy, Environment and Climate Action (formerly DELWP).
- Australian Bureau of Meteorology (BoM).

2.2 Rainfall

Historical rainfall is required to undertake the hydrological and hydraulic calibration of past flood events. There is an extensive daily rainfall gauge network across Victoria compared to sub-daily rainfall gauges which are more sporadic. Daily rainfall gauges can provide information on the spatial distribution and total rainfall depth for a given historic event, while sub-daily rainfall gauges can provide information on the temporal distribution of a given storm event.

2.2.1 Daily Rainfall

There are two active BoM daily rainfall gauges, White Swan Reservoir (89048) and Bungaree, Kirks Reservoir (87014) located within the catchments as shown in Figure 2-1. There a number of active daily rainfall gauges located outside of the study area catchments.

2.2.2 Sub-daily Rainfall

There are no sub-daily gauges available within the catchment. The closest sub-daily gauge is located at Ballarat Aerodrome (89002), about 7 km west from Ballarat CBD, just outside the Gnarr Creek catchment within the Burrumbeet Creek catchment. There are two other nearby sub-daily rainfall gauges, Mt Mercer (233215) and She Oaks (87168). Historical sub-daily information on the gauges was accessed from the BoM website. The Ballarat Aerodrome gauge (89002) records 6-minute rainfall increments and has been active since 2005 while the She Oaks (87168) has been operating since 2007 and the Mt Mercer gauge (233215) from 1997. The pluviograph rainfall data location is shown in Figure 2-1.

2.3 Streamflow

The Yarrowee River and Gnarr Creek do not have a streamflow gauge within Ballarat of the flood mapping area Tthere is a streamflow gauge located on the Leigh River (the Yarrowee River becomes the Leigh River downstream of Ballarat) at Mount Mercer approximately 50 km downstream of the Ballarat CBD. The streamflow gauge location is shown in Figure 2-1.

Details of the Leigh River at Mount Mercer streamflow gauge or summarised in Table 2-1 below.

Table 2-1 Available Streamflow Data for the Study Area

Streamflow Gauge No.	Location	Start Date	End Data	Data Type
233215	Leigh R @ Mt Mercer	Oct 1956	Nov 2023	Water Level/Discharge

2.4 Historia Flood Data

The Yarrowee River and Gnarr Creek catchment has been subject to a number of historic flood events including 1973, 1978, 1988, 2005, 2010, 2011 a lesser degree 2016. The largest flood of living memory was that of 1973.

There is currently no surveyed historic flood height data for the study area within the Victoria Flood Database (VFD), however a historic flood extent from the 1973 flood event is available. Historic flood levels were recorded by the City of Ballarat's surveyors along the Gnarr Creek 1988 and were provided for this assessment. Flood extent and level were also available from the Victoria Flood Database and was used in the previous Water Technology study in 2017. The VFD flood extent and 1988 flood height information locations are shown in Figure 2-1.

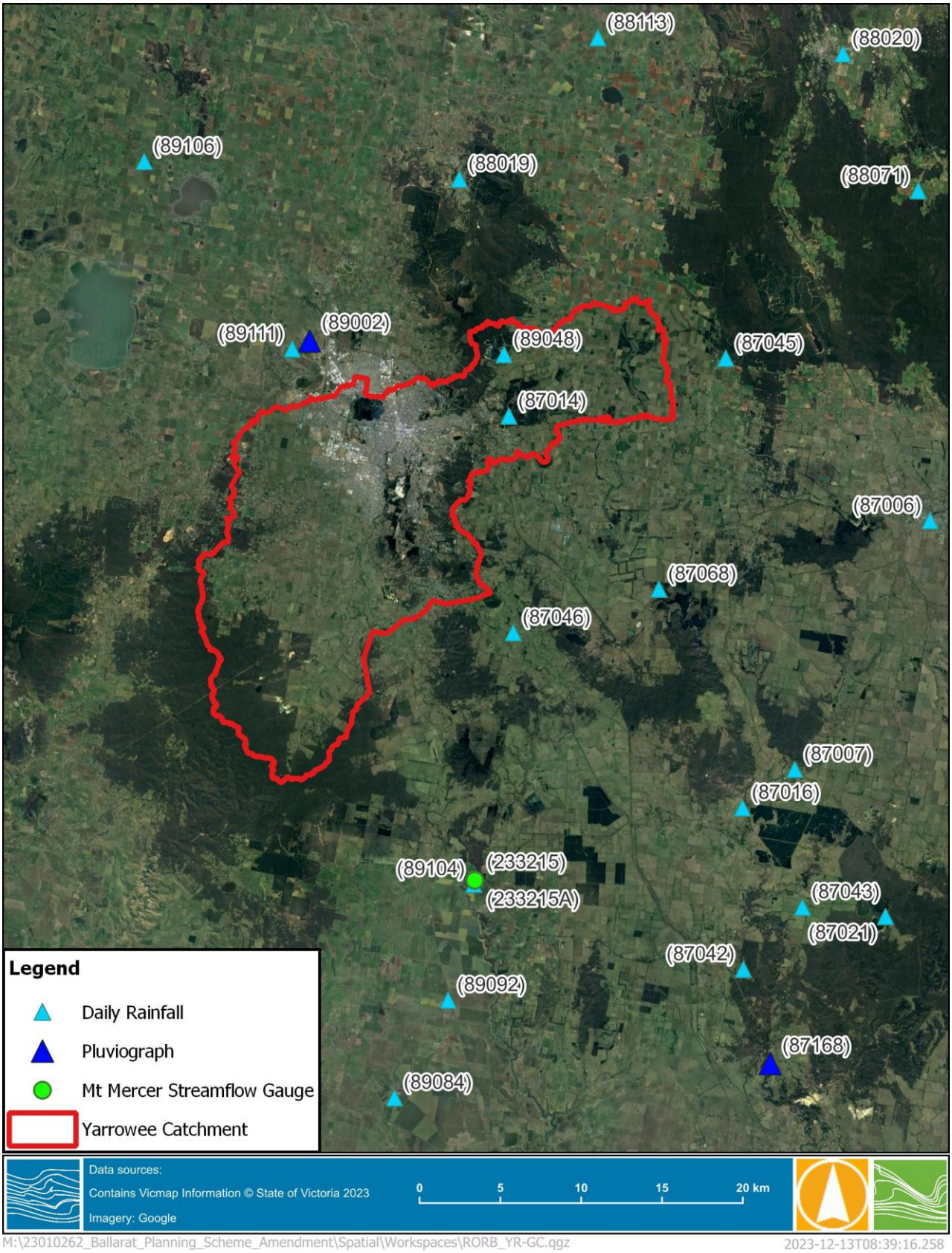


Figure 2-1 Rainfall Data Used in the Study

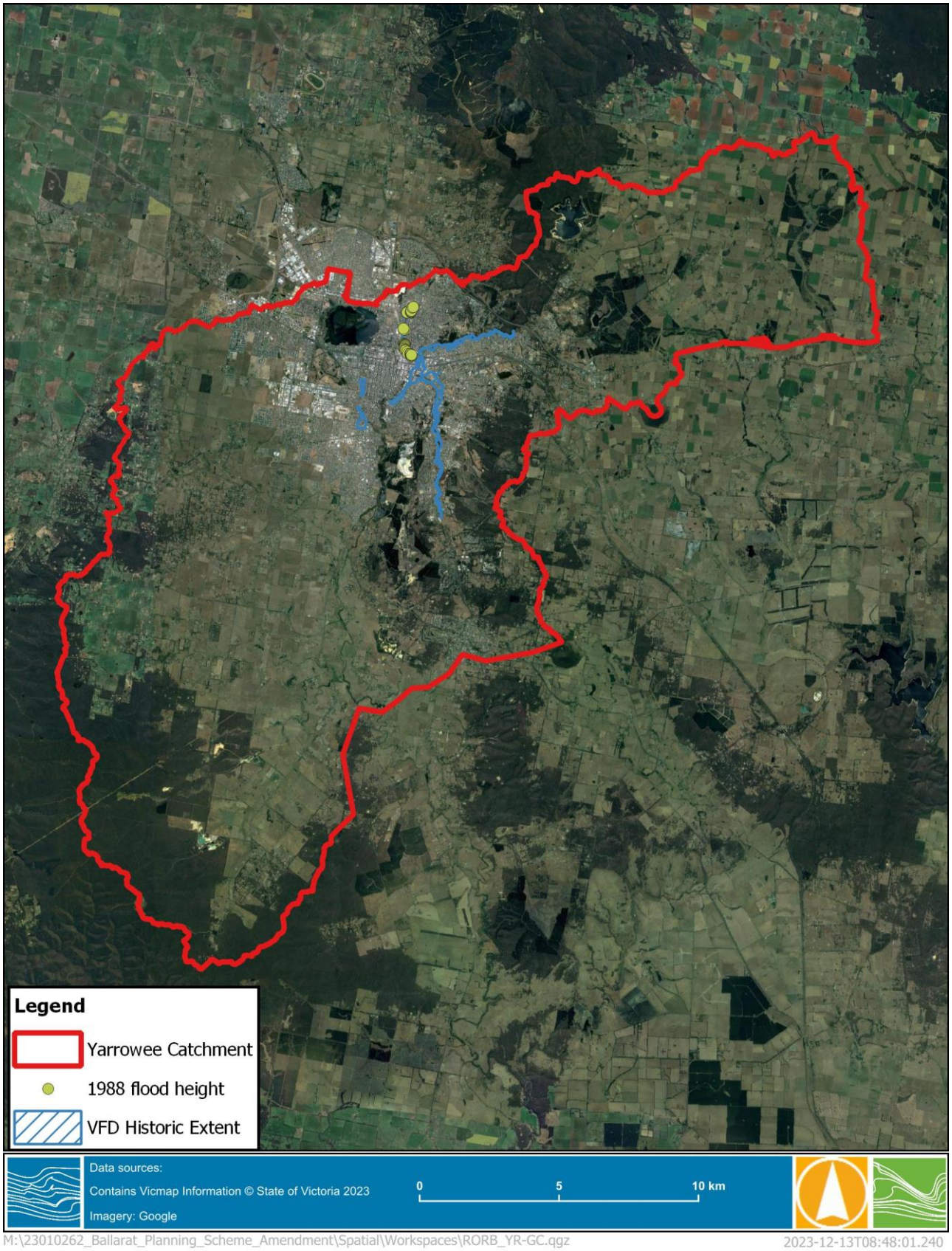


Figure 2-2 [Insert Figure Caption]

2.5 Topographic Data

The topography data largely comprised of Light Distance and Ranging (LiDAR) data, which was used to generate a Digital Elevation Model (DEM). The DEM enabled delineation of the catchment for the hydrological model, completed in 2018, utilising LiDAR data captured in 2011. The hydraulic model utilised LiDAR data captured in 2019.

2.6 Drainage Information

CoB provided the GIS layers of the drainage network, this included pit and pipe information. The provided layers were reasonably complete with pipe dimensions and pit depths. However, pit/pipe inverts were generally missing from the data sets. Where pit depths were available, inverts were assumed by subtracting these depths from the ground surface (based on LiDAR). Where the data was missing pit depths, invert levels were assumed by subtracting pipe diameter and standard pipe cover depth. The standard cover depth based on the pipe size outlined in Table 2-2.

Table 2-2 Standard Cover Levels for Stormwater Pipes

Pipe Size	Standard Cover Depth
≤ 900 mm	600 mm
> 900 mm	750 mm

3 HYDROLOGY

3.1 Overview

Hydrological analysis for Gnarr Creek and the Yarrowee River consisted of both calibration and design modelling using a Flood Frequency Analysis (FFA) and runoff routing modelling software (RORB). An overview of the process is shown below:

- Flood Frequency Analysis
  - A FFA was completed at the Leigh River at Mt Mercer gauge to determine peak design flow estimates for a range of design events.
- Hydrological Modelling
  - Calibration
    - A RORB model was constructed covering the catchment upstream of the Leigh River at Mt Mercer streamflow gauge.
    - The RORB model was calibrated using the August 2010, January 2012 and September 2016 events to determine calibration parameters including k_c value and rainfall losses.
  - Design Modelling
    - Verification of design peak flows in the RORB model against the FFA completed for the Leigh River at Mt Mercer streamflow gauge.
    - Following calibration to historic events and validation of the RORB model to the Leigh River at Mt Mercer streamflow gauge, the RORB model was trimmed to Yarrowee River Flood mapping extent.
    - The RORB model was run using the recommended ARR2016 rainfall depths, losses and methodology with some minor alterations to match the determined design peak flows at the Leigh River at Mt Mercer streamflow gauge.
    - Monte Carlo simulation
    - Selection of temporal patterns for design runs

3.2 Flood Frequency Analysis

3.2.1 Overview

A FFA was used to determine a range of peak design flow estimates for the Leigh River at Mount Mercer streamflow gauge. As discussed in Section 2.3, the gauge is located outside of the study area, however is located on the main waterway downstream of where the Yarrowee River becomes the Leigh River.

The FFA was undertaken using the annual maximum peak flow within each using the water year definition, 1 July to 30 June[1]. The extracted annual series was checked for missing data to ensure the peak flow within each year was captured. No changes to the gauge record were required.

Fitting of probability distribution to the annual maxima was undertaken using the Bayesian approach provided in the program TUFLOW FLIKE. This method is consistent with the approach recommended in ARR 2016.

[1] http://www.bom.gov.au/water/awid/product-water-status-water-market-reports.shtml

3.2.2 Mount Mercer at Leigh River (233215)

A continuous record of flow and water level on the Leigh River exists at Mount Mercer, data is available from 1956 to current day, 67 years of complete annual record. The FFA was undertaken during the 2018 flood study and accounted for 63 years of record from 1956-2018.

A series of annual maxima were extracted from the gauge record and are listed in Table 3-1.

Table 3-1 Summary of annual peak flows for mt mercer (233215)

Year	Max Flow (m^3/s)	Year	Max Flow (m^3/s)	Year	Max Flow (m^3/s)	Year	Max Flow (m^3/s)	Year	Max Flow (m^3/s)
1956	161	1970	80	1984	99	1998	15	2012	72
1957	25	1971	139	1985	38	1999	26	2013	8
1958	130	1972	18	1986	76	2000	125	2014	12
1959	57	1973	526	1987	98	2001	16	2015	7
1960	155	1974	156	1988	90	2002	18	2016	136
1961	44	1975	82	1989	66	2003	34	2017	36
1962	169	1976	81	1990	128	2004	40	2018	15
1963	152	1977	134	1991	45	2005	121	2019*	64
1964	109	1978	352	1992	102	2006	7	2020*	89
1965	192	1979	72	1993	95	2007	20	2021*	30
1966	73	1980	27	1994	13	2008	16	2022*	314
1967	4	1981	115	1995	133	2009	26	2023*	28
1968	87	1982	5	1996	123	2010	127		
1969	22	1983	112	1997	13	2011	313		

* This data was captured following the FFA undertaken during the 2018 flood study and has only been included for reporting purposes

Review of the data indicated the November 1978 recorded event has an unusually flat top that may indicate an equipment malfunction. This was also reported in Leigh River Flood Study[2]. The recorded data shows a peak flow of 212 m^3/s, where the CMA study estimated the peak to be 352 m^3/s. The amended peak flow for the November 1978 event was included in the current analysis.

An annual series FFA was completed at Mt Mercer gauge to determine design flow estimates for comparison. The full extended available period of record at this gauge used for this assessment and includes 63 years of available record.

This period of gauge record was used to complete an annual series FFA in FLIKE. The analysis was completed on a raw annual peak flow series and a modified annual series with low flow censoring to remove years of low flow using the Multiple Grubbs Beck test. This determined a low flow threshold of 57.16 m^3/s, removing 26 years from the 63-year record during the censored assessments.

[2] Corangamite CMA, 2017, Leigh River Flood Study

The Log Normal (LN), Log Pearson Type 3 (LP3), Generalised Extreme Value (GEV), Generalised Pareto GP) and Gumbel distributions were tested. Of these distributions, the LP3 matched well for both the raw and censored annual series, while a number of the alternative distributions appeared to over or underestimate the flows best on the best fit. Further to this the confidence limits of many of the distributions were large with many flows sitting outside these limits. Although LP3 and GP is producing similar flows, LP3 is chosen over GP as this is commonly used methods for Victorian flood analysis.

A comparison of the FFA results for all distributions for the raw and censored annual series are shown in Table 3-2. The FFA plots for the LP3 raw, LP3 censored, fit and are shown in Figure 3-1 and Figure 3-2. The resulting 1% AEP flows and confidence limits of the various distributions is shown in Figure 3-3.

An LP3 probability distribution of the Censored data annual series resulted in a 1% AEP peak flow estimate of 477 m^3/s at Mount Mercer and is considered to be the most suitable distribution method. The FFA estimated flood quantiles at Mt Mercer are presented in Table 3-3.

Table 3-2 Flood frequency comparison – Mt Mercer

Design Event (AEP)	Log Normal (m^3/s)		LP3 (m^3/s)		Gumble (m^3/s)		GEV (m^3/s)		GP (m^3/s)	
	Raw	Censored	Raw	Censored	Raw	Censored	Raw	Censored	Raw	Censored
10%	235	194	214	200	177	195	212	199	216	213
5%	359	260	290	270	217	242	312	263	287	284
2%	579	361	395	379	268	303	499	362	386	388
1%	796	449	477	474	306	349	699	449	465	476

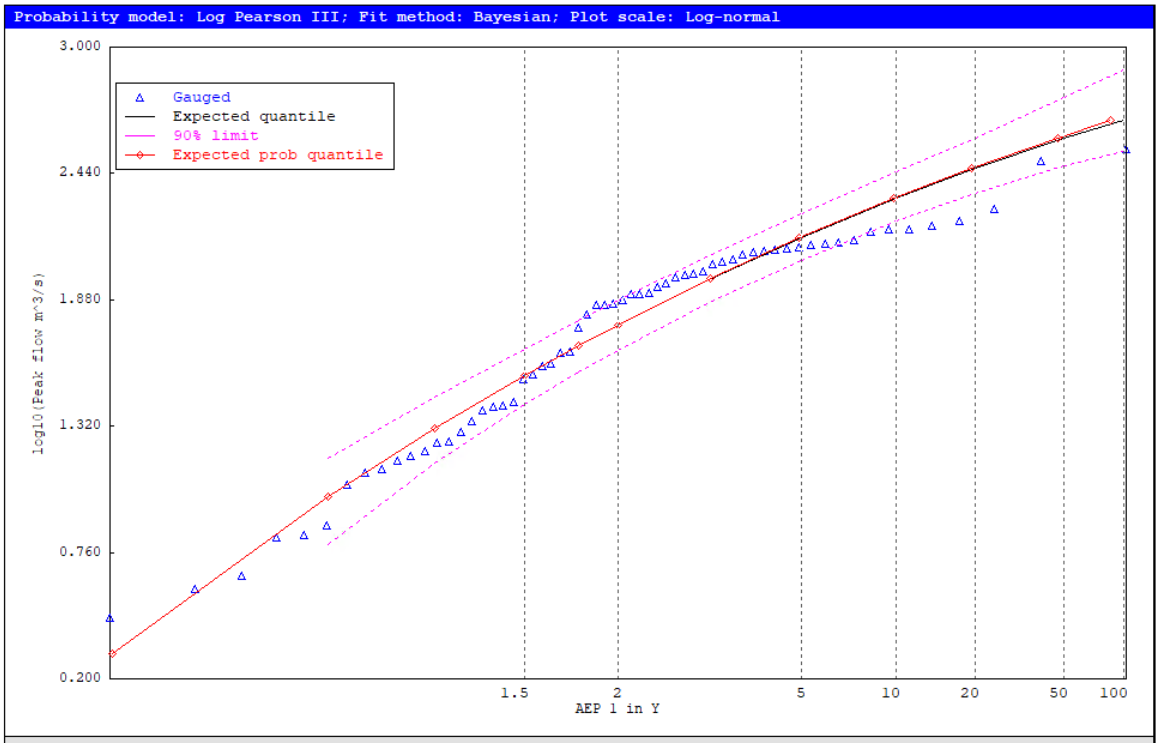


Figure 3-1 Leigh River at Mt Mercer Raw Data - Annual Series FFA of, Log Pearson III distribution

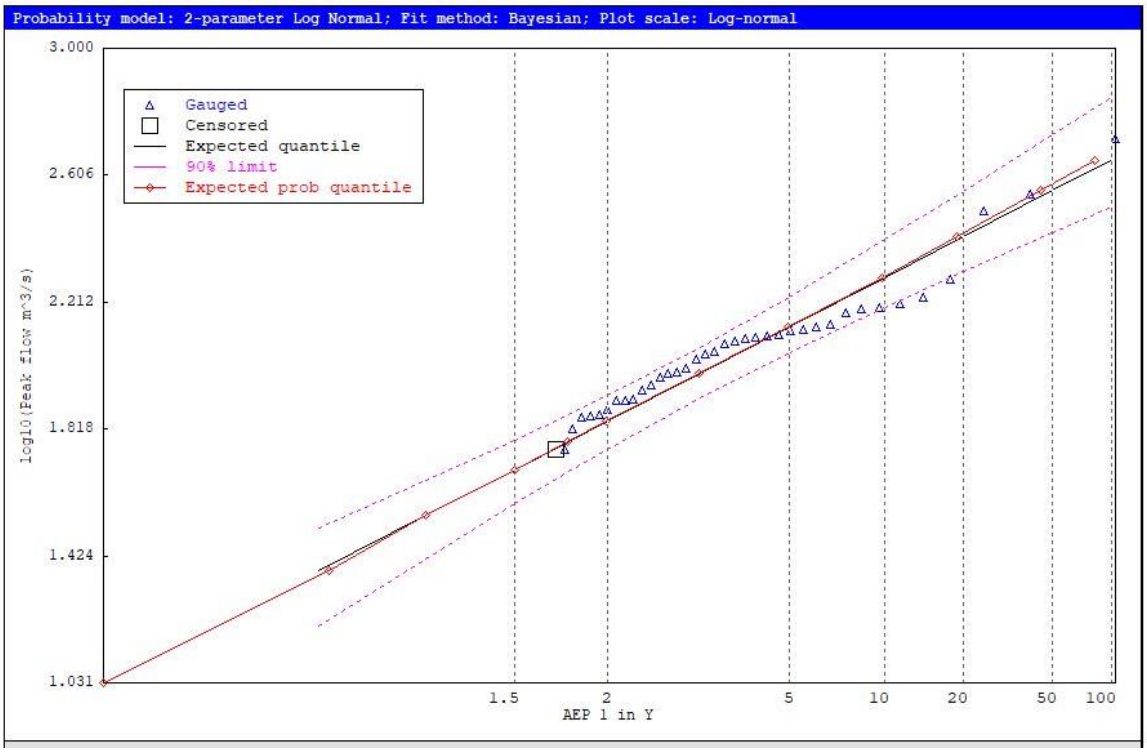


Figure 3-2 Leigh River at Mt Mercer Censored Data - Annual Series FFA of, Log Pearson III distribution

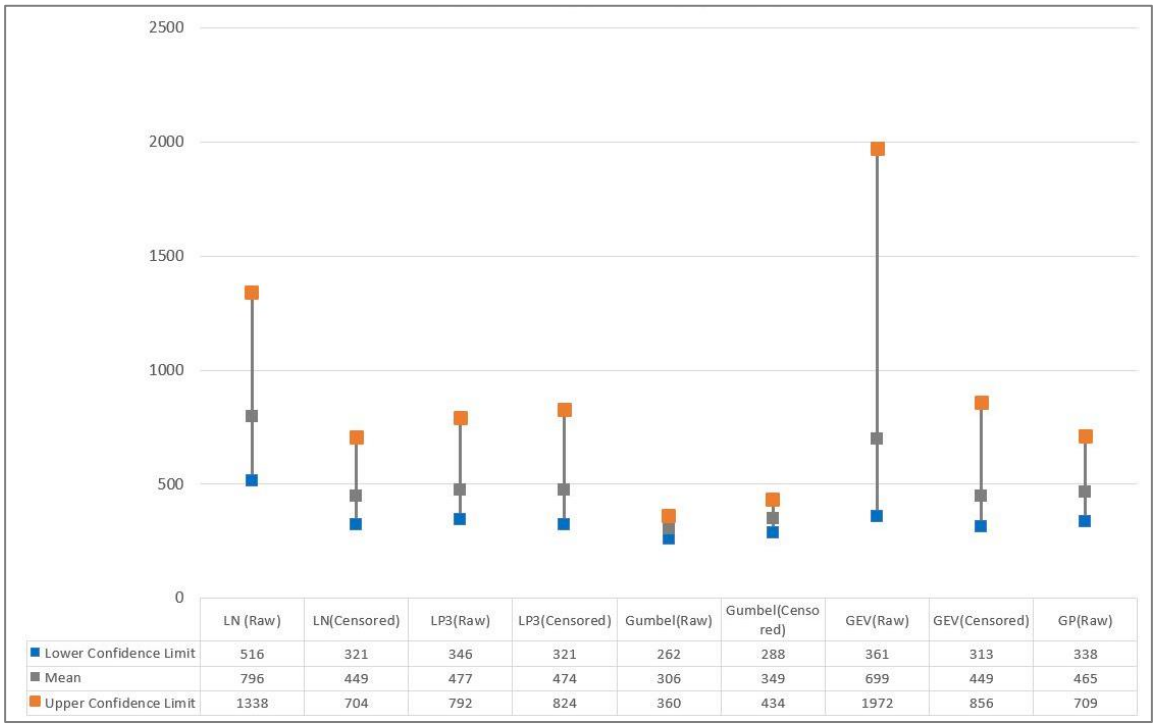


Figure 3-3 Leigh River at Mt Mercer 1% AEP FFA distribution

Table 3-3 Summary of FFA estimated flood quantiles at Mount Mercer

AEP	Flood quantiles estimates (m^3/s)	Monte Carlo 90% quantiles probability limits
10%	214	170 - 279
5%	290	225 – 396
2%	395	297 – 601
1%	477	346 – 792

The 1% AEP and other design quantiles were compared with the peak flow estimates undertaken by the Corangamite CMA for this gauge based on a reduced record and shortened series (1957-2017) as part of the Leigh River Flood Study[2]. A comparison of these results with the current adopted design flows along with the design flow estimate from the Regional Flood Mapping – Barwon River, Thompson Creek and Woady Yaloak[3] based on period of record (1956-2013) is shown in Table 3-4. The Corangamite CMA also completed a partial series analysis for flows > 5000 ML/day (57.9 m^3/s). the FFA completed showed similar results, with the partial series showing lower results.

Table 3-4 Comparison of FFA estimated flow with previous studies

AEP	FFA (current study)		FFA (Corangamite CMA, 2017)		GHD (2016)
	Raw Series	Censored Series	Annual Series	Partial Series	
10%	214	200	211	187	191
5%	290	270	286	242	259

[3] GHD (2016), Regional Flood Mapping – Barwon River, Thompson Creek and Woady Yaloak – Hydrology and Hydraulic Modelling Report

AEP	FFA (current study)		FFA (Corangamite CMA, 2017)		GHD (2016)
	Raw Series	Censored Series	Annual Series	Partial Series	
2%	395	379	392	336	369
1%	477	474	476	427	473

3.3 RORB Model Development

RORB was adopted as the hydrology modelling package. RORB was used to calculate inflow hydrographs from the available rainfall and catchment data. RORB is a non-linear rainfall runoff and streamflow routing model for calculation of flow hydrographs in drainage and stream networks. The model requires catchments to be divided into subareas, connected by a series of conceptual reaches and storage areas. Observed or design storm rainfall is input to the centroid of each subarea. Specific initial and continuing losses are then deducted, and the excess runoff is routed through the reach and storage network.

The adopted methodology was based on current guidelines described in the 2019 revision of Australian Rainfall and Runoff (ARR2019). The 20%, 10%, 5%, 2%, 1% and the 0.5% AEP flood events were modelled using Monte-Carlo and Ensemble approaches as recommended in ARR2019.

A RORB model was built to model catchment contributions (inflow hydrographs for the hydraulic model) and stream routing within the tributaries of the Yarrowee River and Gnarr Creek. A RORB model is comprised of several key data inputs to produce accurate results, these include:

- Catchment delineation.
- Fraction impervious.
- Routing parameter (kc)
- Design inputs
  - Rainfall depth
  - Temporal patterns
  - Spatial pattern
  - Losses

Each of these inputs are discussed in the following sections.

3.3.1 Catchment Delineation

The Yarrowee River and Gnarr Creek catchment was delineated based on LiDAR (Light Detection and Ranging) data captured in 2011. The LiDAR data was processed in ESRI's terrain modelling software ArcHydro, delineating the catchment into 227 sub catchments and associated drainage reaches.

The calibration and validation of the RORB model was undertaken based on a full catchment model upstream of the Leigh River at Mt Mercer. Following calibration and validation of the whole catchment model, the RORB model was trimmed to the Yarrowee River flood mapping extent at a model interstation. The trimmed model area consisted of 171 sub-areas.

Trimming of the RORB model to the flood mapping extent does not alter design flow rates or hydrographs due the model parameters being set upstream of the Yarrowee River interstation area. The trimmed model layout is shown below and has been used within the design modelling.

The sub-catchment and reach delineation of the trimmed model is shown in Figure 3-4.

The objective of the delineation was to ensure an even distribution of similar sized catchments. Generally, three sub catchments are used prior to each inflow point into the mainstream. However, in some areas a single sub catchment inflow was used, particularly along the main waterway. The model reaches were defined as 'natural', 'lined channel' or 'pipe' based on the typical flow regime along each section of the catchment. These definitions were derived from expected characteristics based on the aerial photography and the site visit.

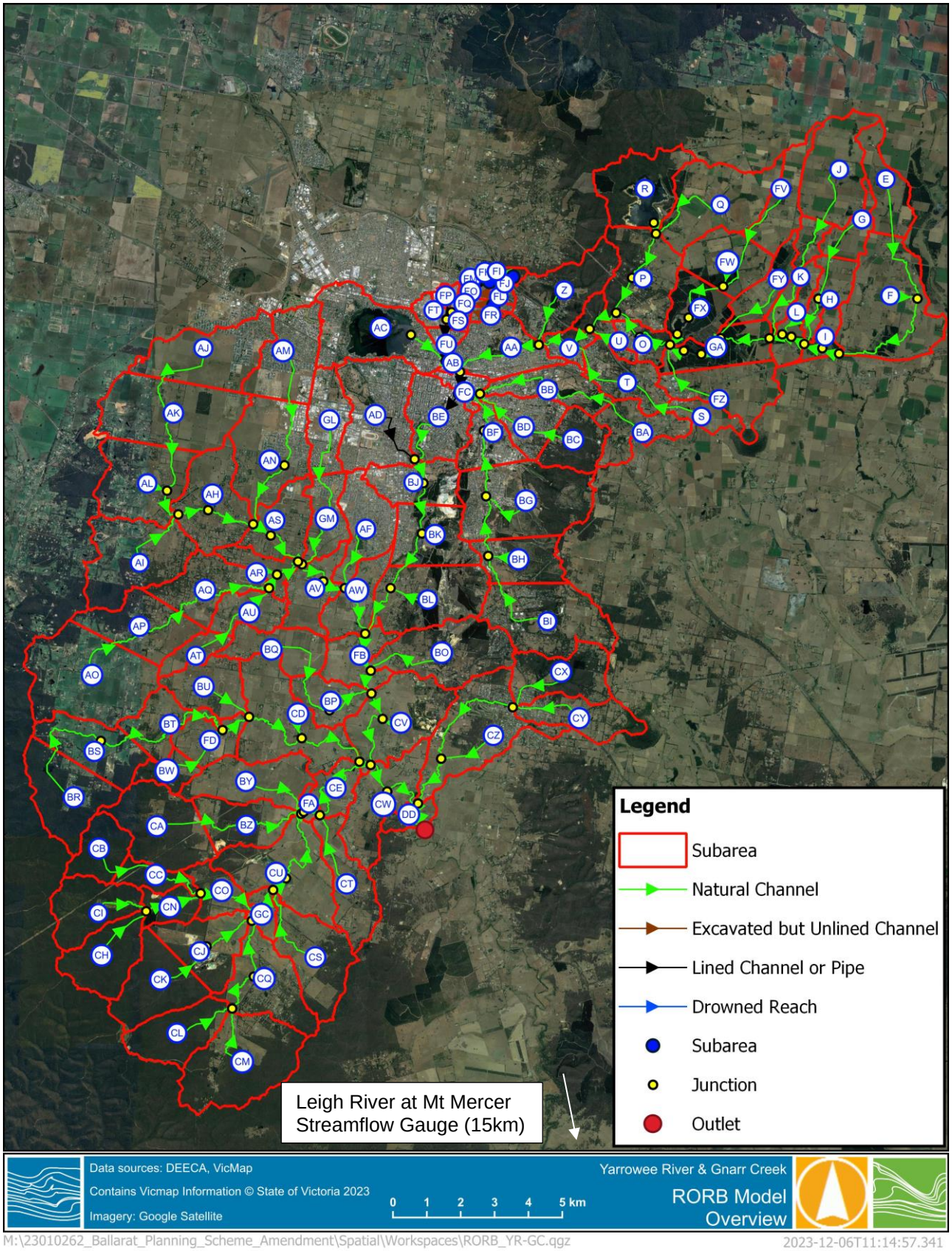


Figure 3-4 RORB Model Structure

3.3.2 Fraction Impervious

Impervious fractions values were determined for the different land use types across the catchment within each sub catchment, represented by a Fraction Impervious (FI). FI values were determined according to City of Ballarat planning zones as per Melbourne Water's Guidelines[4] and verified against aerial imagery. The catchment was largely separated into three main land uses; open space (including farming), residential and industrial. The adopted values for each are provided in Table 3-5, a map of the designated land uses is shown in Figure 3-5, with the adopted sub catchment FI values shown in Figure 3-6. A fraction impervious greater than zero was adopted for areas of open space due to the presence of constructed drains in both the parks and agricultural areas.

Table 3-5 Adopted FI Values used in RORB Model

Land Use	Adopted FI
Business Zone	0.9
Farming Zone	0.1
Industrial Zone	0.9
Residential Zone	0.6
Road Zone	0.7
Rural Living Zone	0.2
Urban Growth Zone	0.6

[4] Melbourne Water (2010), Melbourne Water's MUSIC Guidelines

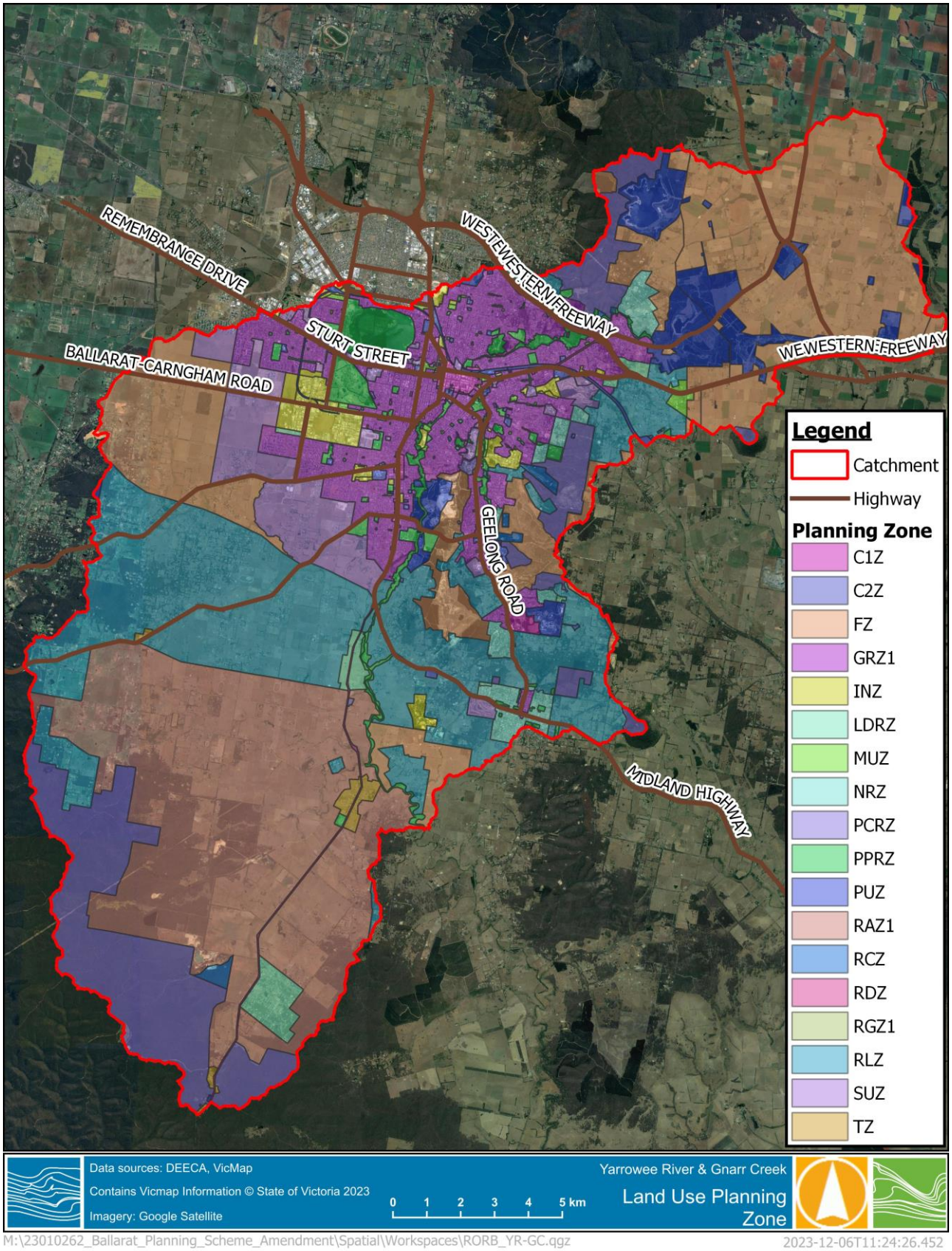


Figure 3-5 Land Use areas based on Planning Zones

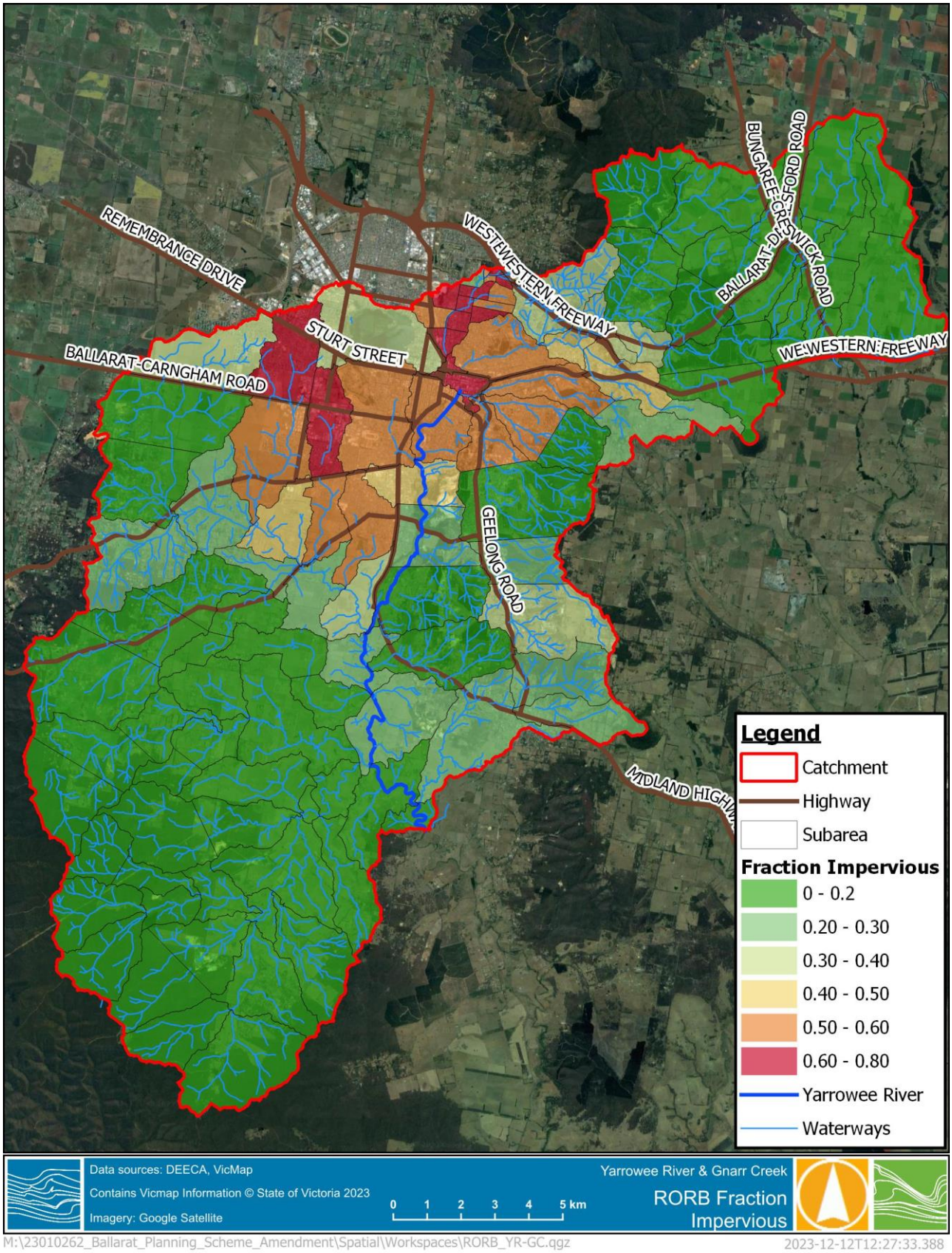


Figure 3-6 Fraction Impervious values used in the RORB model

3.3.3 Routing Parameter (kc)

As mentioned in Section 3.2.2, the Mount Mercer streamflow gauge is located at the outlet of the catchment wide RORB model and was used to calibrate the RORB model by adjusting the k_c parameter with the m parameter remaining the recommended value of 0.8.

Given the significant variation in catchment characteristics along Gnarr Creek and the Yarrowee River the catchment was separated into five separate interstation areas. This allows separate k_c parameters to be utilised to represent the differing catchment conditions. The areas were as follows:

- Yarrowee River at Little Bendigo
- Ballarat CBD
- Gnarr Creek
- US Mt Mercer (trimmed model outlet)
- Mt Mercer gauge (model outlet) – this was excluded in the trimmed RORB model

McMahon and Muller (1983) showed that k_c is directly proportional to the average flow distance (d_{av}). The relationship is expressed as

$$k_c = C_{0.8}\, d_{av}$$

- *Equation 3-1*

where $C_{0.8}$ is a characteristic of the catchment that is independent of catchment size, and c is the weighted average flow distance from the RORB model nodes to the catchment outlet.

Pearse et al (2002) analysed three large databases of kc parameters collated by different sources and reported the average and range of $C_{0.8}$ values for each dataset:

- CRC for Catchment Hydrology – 72 catchments from all states of Australia and the ACT, as described in Dyer et al (1994)
- Yu (1989) – 119 catchments located in New South Wales, Queensland, Victoria and Western Australia
- Pearse et al. (2002) – 39 Victorian catchments from the Hansen et al (1986) study and other models calibrated by SMEC Victoria

Table 3-6 shows the range of $C_{0.8}$ and predicted k_c values from the three datasets.

Table 3-6 Expected Value and Range of $C_{0.8}$

Source	$C_{0.8}$	k_c
CRC for Catchment Hydrology	1.25 (range: 0.75 – 2.07)	3.39 (range: 2.03 – 5.61)
Yu (1989)	0.96 (range: 0.47 – 1.94)	2.60 (range: 1.27 – 5.26)
Pearse et al. (2002)	1.14 (range: 0.61 – 2.13)	3.09 (range: 1.65 – 5.77)

For the Yarrowee River and Gnarr Creek catchment, the Pearse et. al. (2002) estimation method of k_c was chosen a starting point for the model calibration. The data the equation is based on is most relevant data (Victorian based). $C_{0.8}$ was taken to have a value of 1.14, consistent with the expected value from Pearse et. Al. (2002).

Given that d_{av} varies across the interstation areas, k_c was calculated for each area, as shown in Table 3-7.

Post calibration, k_c values values for 'Yarrowee at Little Bendigo' and 'US Mt Mercer' were found to be higher than the expected design values. The k_c values used in the calibration events gave the best fit to the observed hygrograph at Mt Mercer and were therefore adopted. The calibration process has bee described in Section 3.4 above.

Table 3-7 Expected Rainge of k_c Values for each Interstation Area (Pearse et. al., 2002)

Interstation	d_{av} (km)	k_c (expected)	k_c (lower)	k_c (upper)	k_c (adopted)
Yarrowee at Little Bendigo	10.43	11.9	6.4	22.2	30.00
Ballarat CBD	5.61	6.4	3.4	11.9	6.74
Gnarr Creek	2.34	2.7	1.4	5.0	2.96
US Mt Mercer	14.76	16.8	9.0	31.4	30.00

3.3.4 Storage Characteristics

3.3.4.1 Overview

There are several water storages and retarding basins across the study area, as highlighted in Section 1. Reservoirs within the upper catchment of the Yarrowee River and outside the hydraulic model extent were modelled in RORB, these included; Pincotts Reservoir, Kirks Reservoir, Gong Gong Reservoir and White Swan Reservoir. The location of these reservoirs is presented in Figure 1-1, all are used for water supply purposes. Retarding basins within the hydraulic model extent were represented in the model topography. Details of the major water storages are presented in the following sections.

Pincotts Reservoir (constructed 1867)

Water flows from an aqueduct into Pincotts Reservoir. The reservoir has a capacity of 218 ML at a full supply level of 552.66 m AHD. The reservoir is located on Leigh Creek, running from the northern slopes of Mt. Warrenheip.

Water can be diverted from Pincotts Reservoir into the Ballarat Main, a stone lined natural watercourse into Kirks Reservoir, to Gong Gong Reservoir by a diversion weir and open channel or piped into White Swan Reservoir.

Kirks Reservoir (constructed 1862)

Kirks Reservoir is a small terminal storage constructed on Giles Creek. Its capacity is 400 ML at a full supply level of 510.20 m AHD. Apart from natural catchment, Kirk Reservoir receives water from Pincotts Reservoir.

Gong Gong Reservoir (constructed 1877)

Gong Gong Reservior has a capacity of 1902 ML at full supply level of 514.32 m AHD. It receives water from its own catchment and from the overflow from Pincotts diverted upstream of Kirks. The combined Kirks, Pincotts and Gong Gong Reservoir catchment is 2553 Ha.

White Swan Reservoir (constructed 1952)

White Swan is the largest of the terminal reservoirs in the Ballarat system. It has a capacity of 14,107 ML at a full supply level of 536.57 m AHD. The direct catchment to White Swan reservoir is 1117 Ha.

3.3.4.2 Storage-Elevation-discharge relationship

No stage-storage information was available for Gong Gong Reservoir, Kirk Reservoir or Pincott Reservoir. The storage-elevation relationship was determined by GIS analysis of the LiDAR data. In instances where the 2m resolution LiDAR was not available, the 5 m resolution LiDAR data was used. At the time the LiDAR was collected, it is understood that water level was below spillway crest level; however, the underlying bathymetry of the reservoir was occluded by the water surface. This is not significant in terms of hydrological modelling, as it was assumed that the dam water level would be at spillway crest level prior to start of flood event.

To determine the required information to estimate the relationship between the depth and volume of the lake several assumptions were made. Several cross sections of the lake were extracted from the LiDAR to determine the general shape of the reservoir bed, these included:

- Immediately downstream of the embankment, to be used as proxy for the likely shape and depth of the foundations; and,
- The embankment crest and spillway.

The extracted cross sections immediately downstream of the embankment and along the embankment crest for Gong Gong Reservoir, Kirk Reservoir and Pincott Reservoir are presented in Figure 3-7, Figure 3-8 and Figure 3-9 respectively.

The elevation-discharge relationship through spillway for Gong Gong, Kirk and Pincott reservoirs was estimated assuming flow over broad crested weir equation, as highlighted in Equation 2-1, with a C value of 1.7. The value of L (Length) was determined from the LiDAR.

$$Q = CLH^{\frac{3}{2}} \qquad \textit{Equation 2-1}$$

The resulting storage-elevation relationship for Gong Gong Reservoir, Kirk Reservoir and Pincott Reservoir, are shown in Figure 3-10 to Figure 3-12.

The storage characteristics at White Swan Reservoir and Lake Wendouree was represented by a storage formula in the hydrological model with a 20m spillway at 536.7m AHD as shown in Figure 3-13.

Lake Wendouree was represented in the hydrological model with the storage formula described in Equation 2-2 and shown in Figure 3-14 below. the storage formula in the hydrological model had a spillway at 400.2 m AHD with a 1m width. This is representative of the riser pipe.

$$S = Storage\ Volume\ (m^3)$$
$$H = Elevation\ (m\ AHD)$$
$$a = 3.33 \times 10^6 \qquad S = a(H - H_O)^b \qquad \textit{Equation 2-2}$$
$$b = 1.0$$
$$H_O = 400.0$$

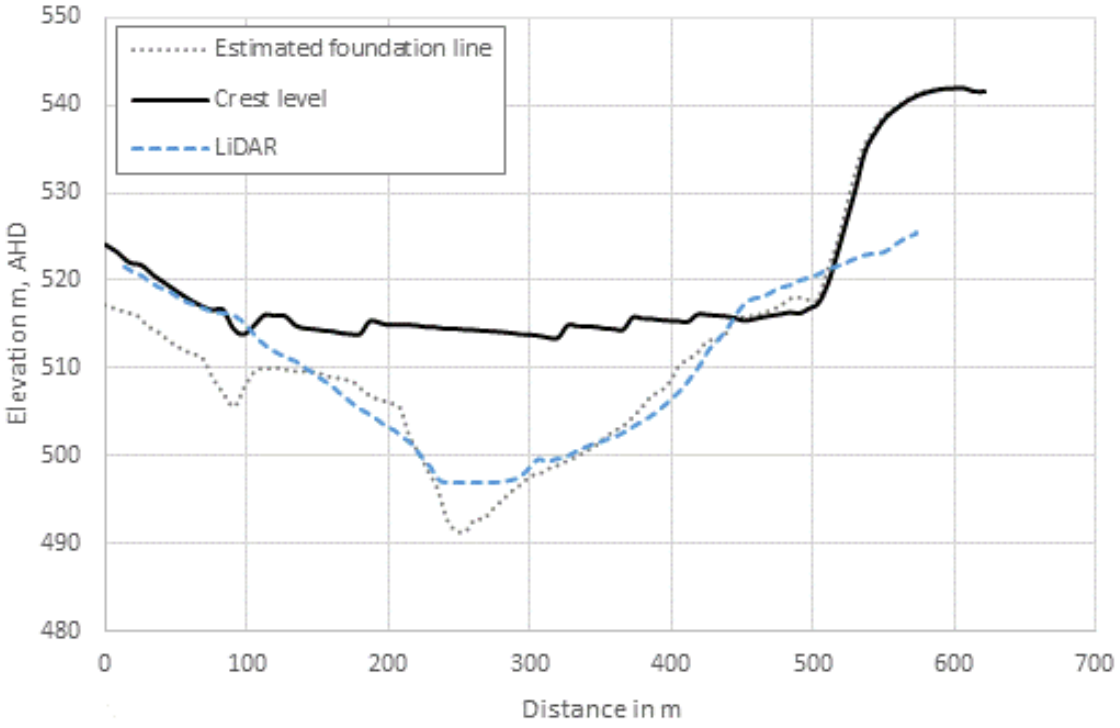


Figure 3-7 Long section of Gong Gong Reservoir

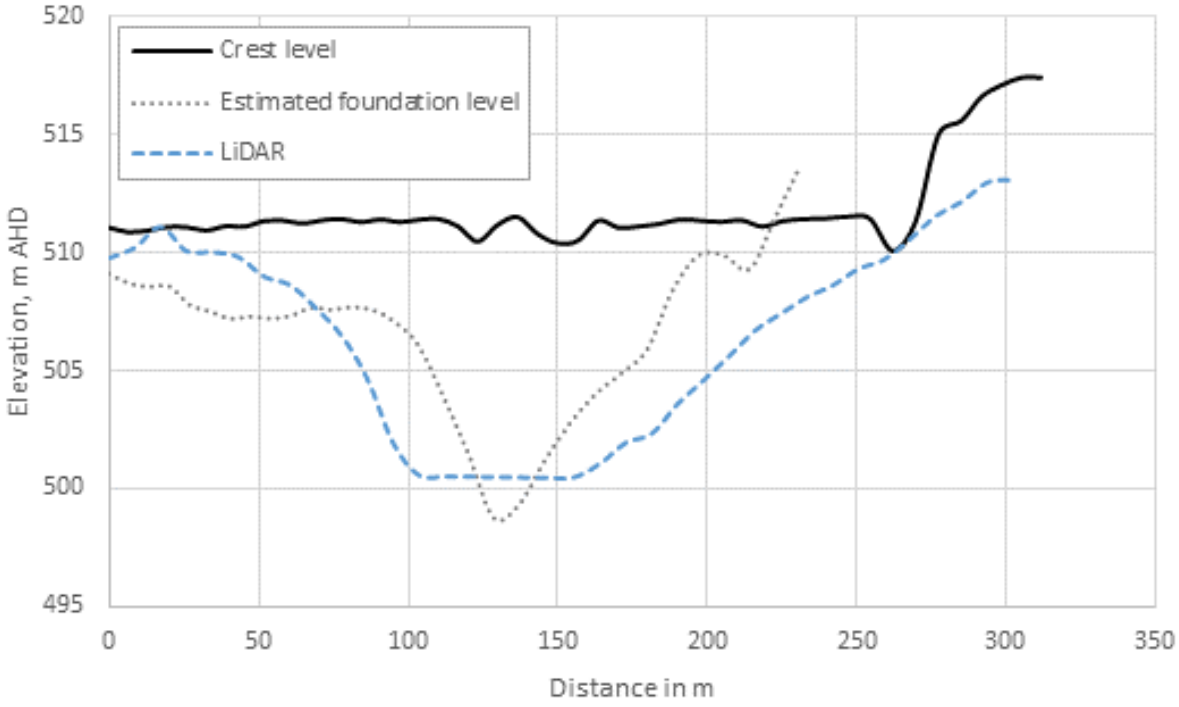


Figure 3-8 Long section of Kirks Reservoir

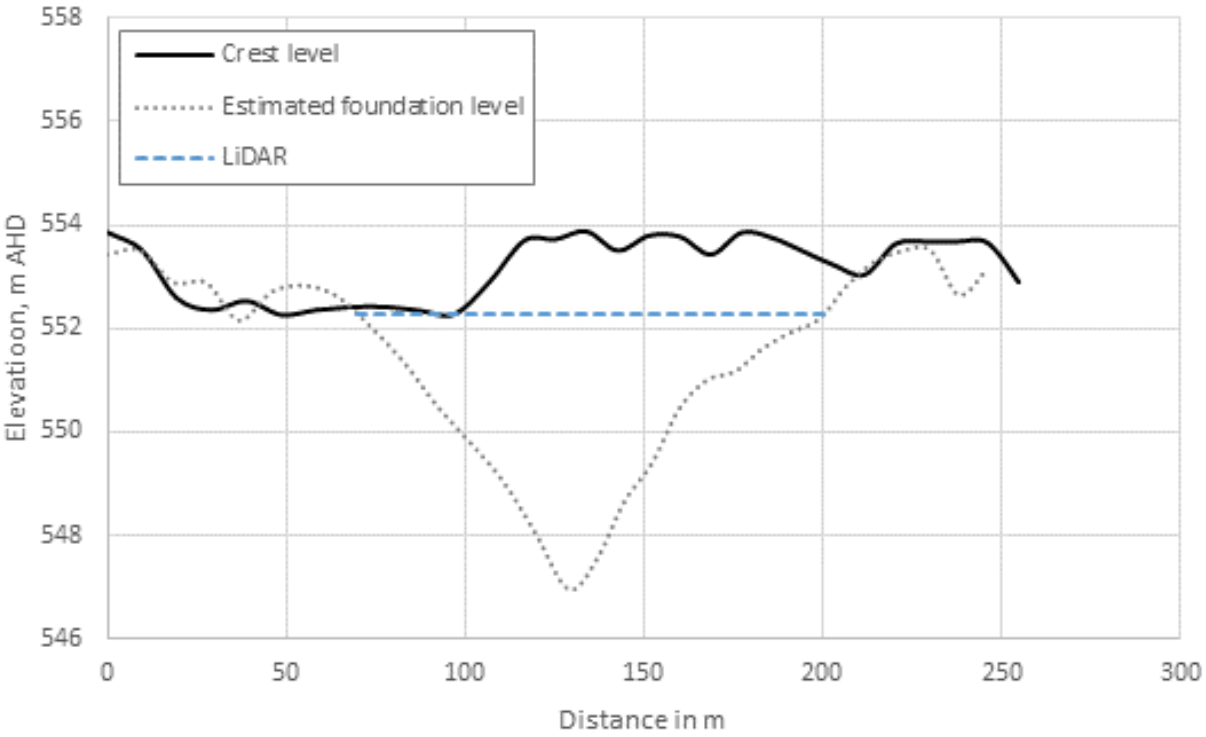


Figure 3-9 Long section of Pincott Reservoir

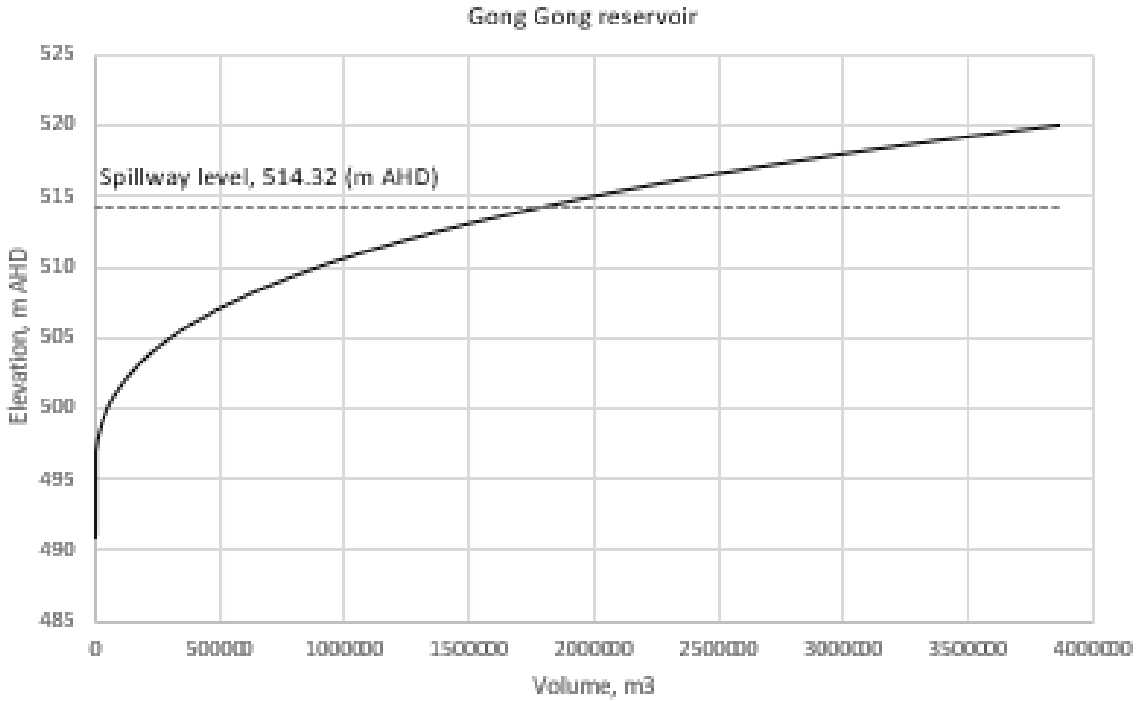


Figure 3-10 Gong Gong Reservoir Storage-Elevation relationship

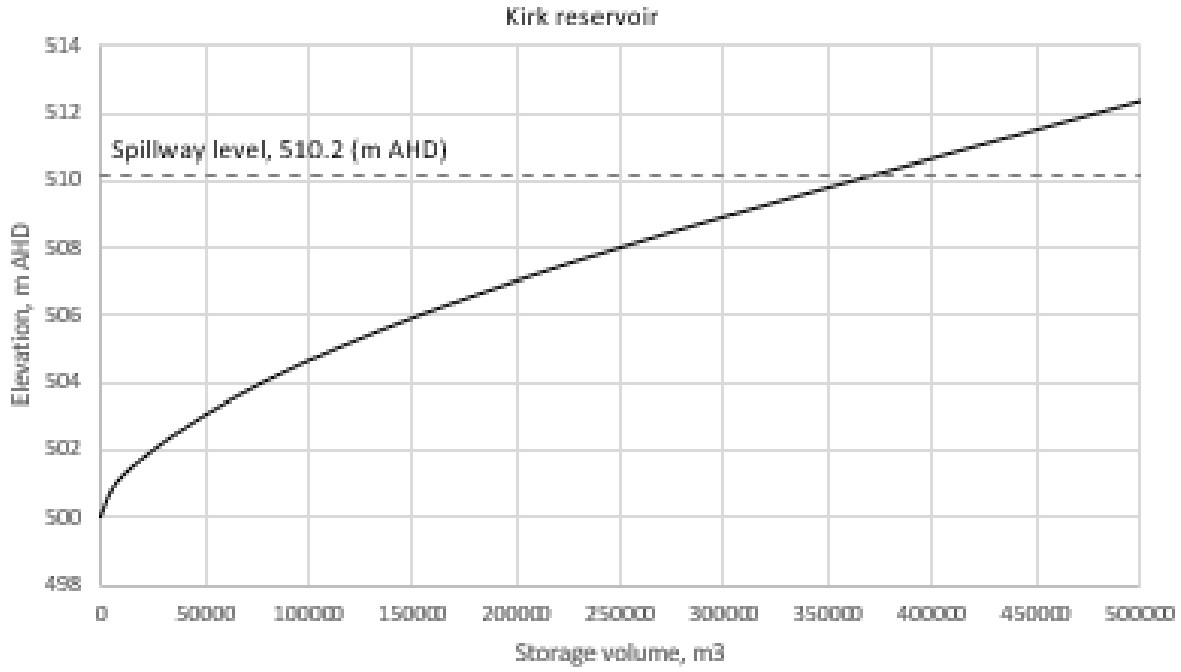


Figure 3-11 Kirk Reservoir Storage-Elevation relationship

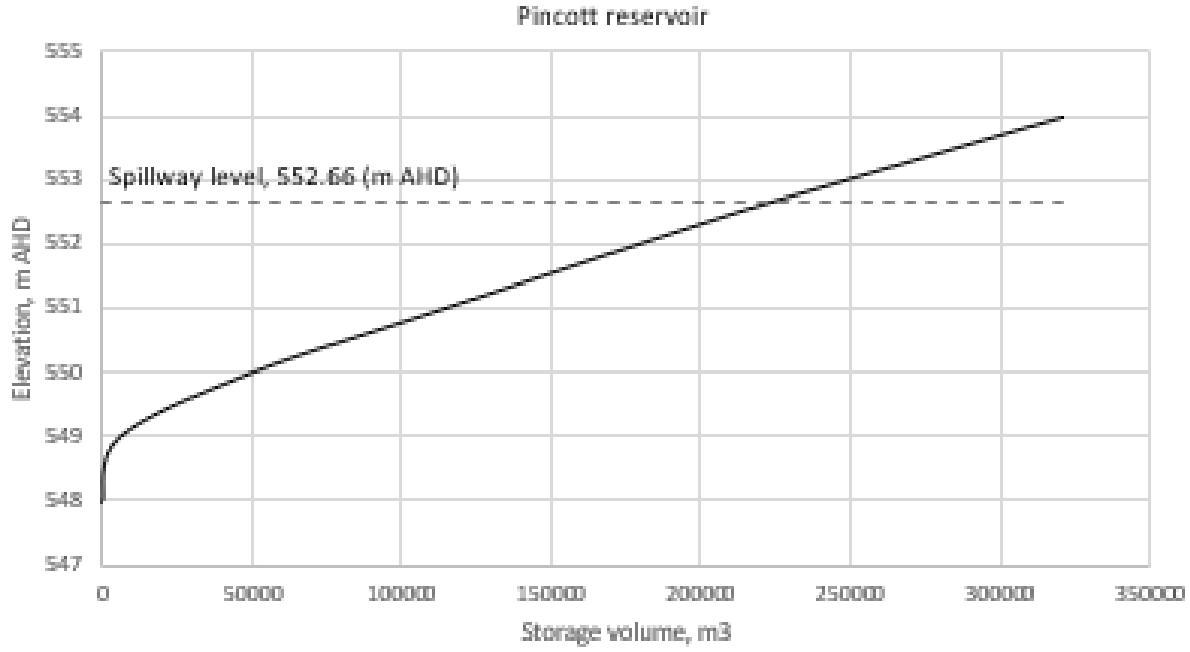


Figure 3-12 Pincott Reservoir Storage-Elevation relationship

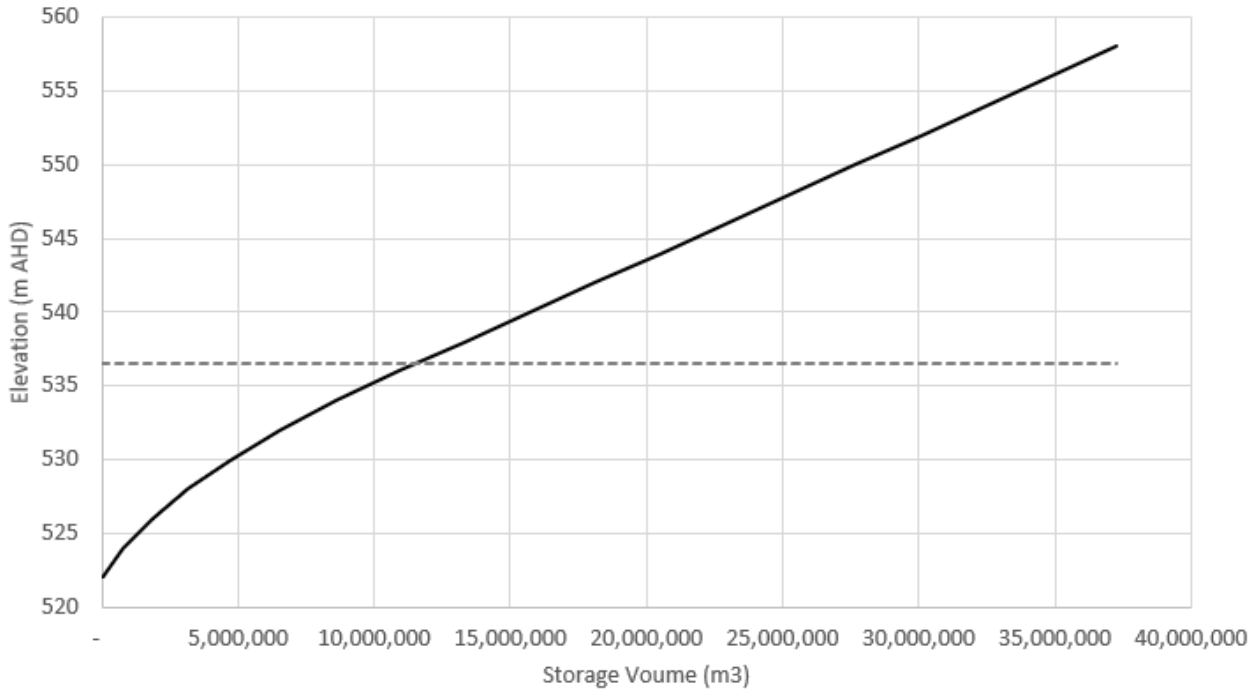


Figure 3-13 White Swan Reservoir Storage-Elevation relationship

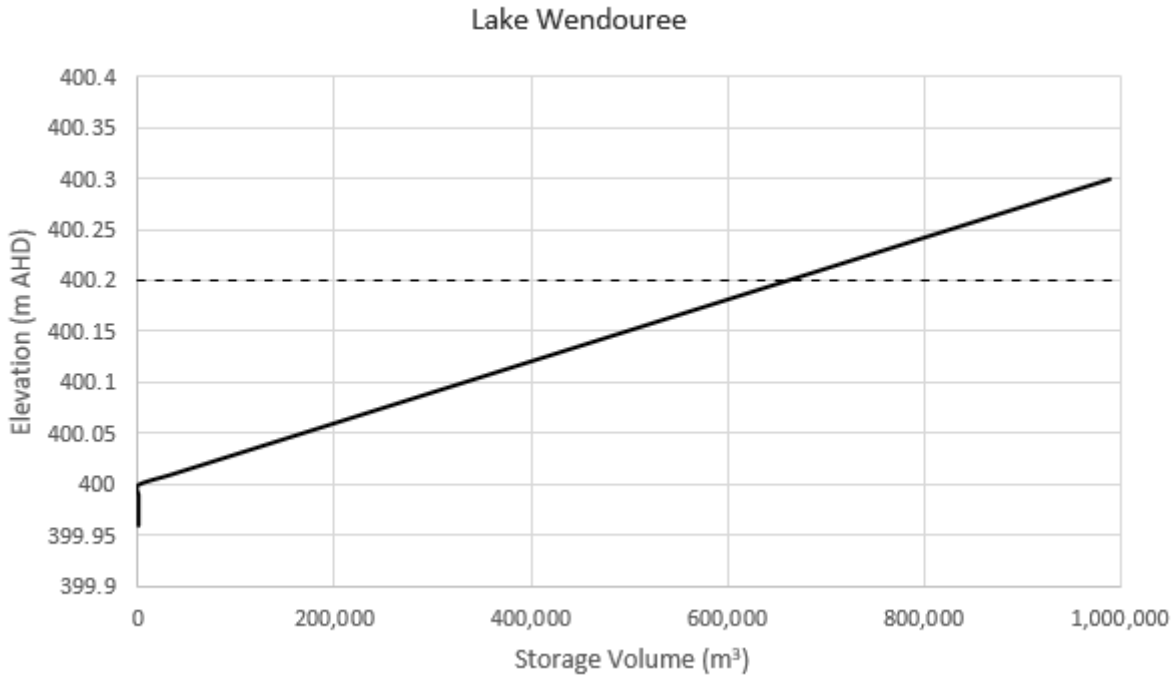


Figure 3-14 Lake Wendouree Stage-Storage relationship

3.4 Model Calibration

3.4.1 Modelling Approach

Calibration of the catchment wide RORB model was completed using the Mount Mercer streamflow gauge, the only available flow record within the catchment. As the Mount Mercer streamflow gauge is outside the Yarrowee River flood mapping extent, the RORB model developed for the design modelling cut to an interstation location on the edge of the flood mapping extent. Figure 3-15 shows the Mount Mercer RORB model catchment extent.

The available flow record for the Mount Mercer gauge extends from 1957 to current day. A statistical analysis of the peak flow gauge data established the design discharge at this site as presented in Section 3.2. A statistical analysis approach with a flow record of 60 years is considered a more reliable method to estimate design discharges than relying on using recommended design parameters in a runoff model.

The parameters derived from the calibration and losses derived from the verification to the design discharges at Mt Mercer was used in design flow estimates for the 2D modelling using methods recommended by ARR 2016.

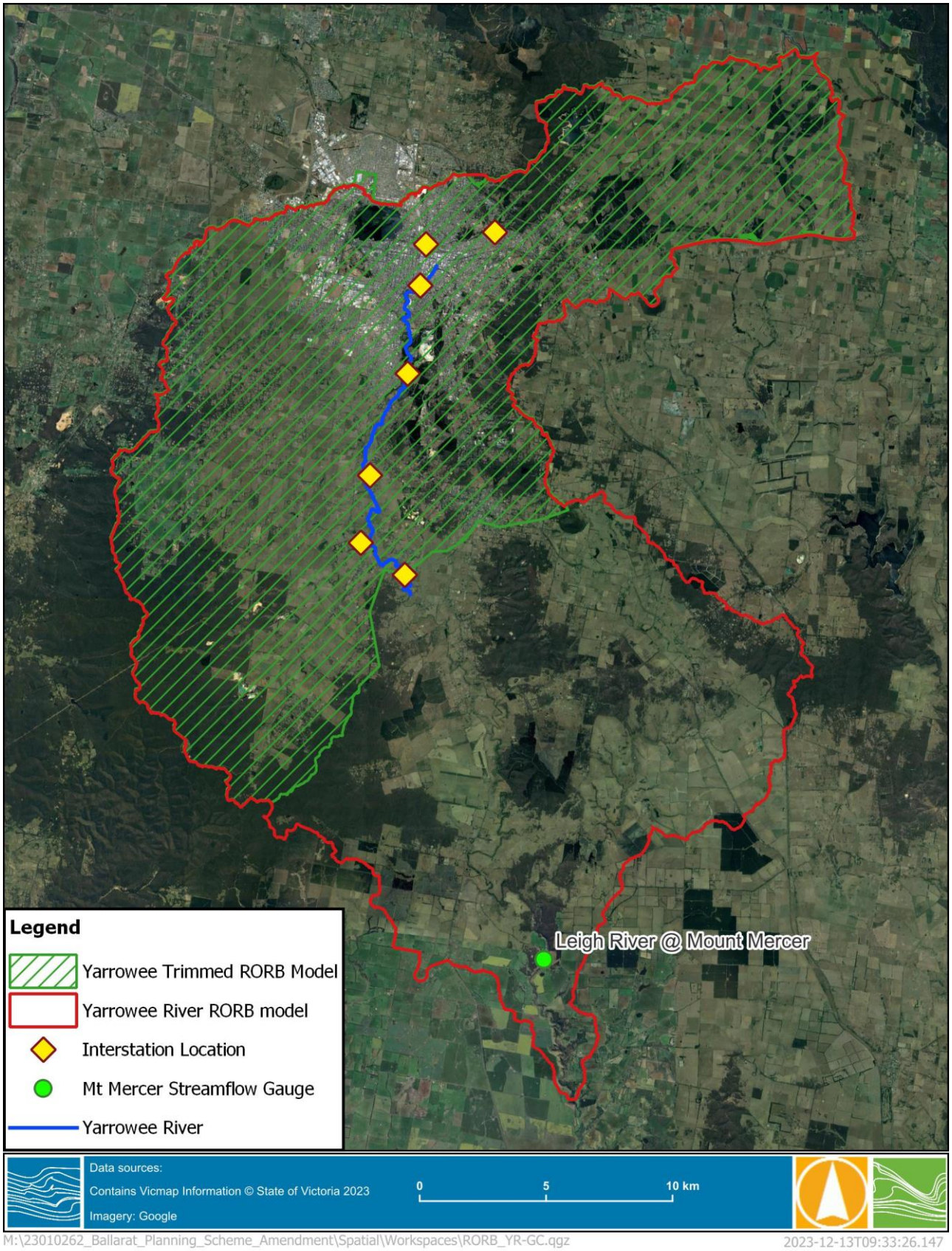


Figure 3-15 Mt Mercer RORB catchment for calibration

3.4.1.1 Calibration Events

Three historic events were used for calibration of the RORB model; August 2010, January 2011 and September 2016. These events were chosen because of their flow magnitude and relatively recent occurrence, limiting catchment changes and increasing community and agency recollection of the events. Unique temporal and spatial rainfall patterns were generated from local rainfall gauge records for each event and the outflow hydrographs from the RORB were then compared to recorded stream gauge records at Mt Mercer.

Figure 3-16, Figure 3-17 and Figure 3-18 show the rainfall distribution (spatial pattern) across the catchment for the three calibration events, with Figure 3-19 showing the temporal patterns for the pluviograph at the Ballarat Aerodrome AWS.

3.4.1.2 Calibration of RORB parameters

The RORB model was simulated using an initial loss/continuing loss model. RORB parameters were fitted for each calibration event to give the best fit to the observed hydrograph at the Leigh River at Mt Mercer streamflow gauge. The routing parameter k_c was varied within the range as calculated from Pearse et. al. (2002) as presented in Table 3-7. The exponent *m* was set to 0.8 as per RORB recommended value.

The final calibration model parameters for each of event are summarised in Table 3-8. The fit of the RORB modelled hydrographs to the gauged hydrographs at Mount Mercer for August 2010, January 2011 and September 2016 are shown in Figure 3-20, Figure 3-21 and Figure 3-22 respectively. The shape, peak and timing of the fitted hydrographs generally agrees well with gauged data for all events.

The initial losses tend to be higher than expected design values, however the continuing losses tend to reasonable. This is especially true of the January 2011 event with an initial loss of 150 mm for the US Mt Mercer interstation.

Table 3-8 RORB calibration parameters

	kc	m	IL(mm)	CL (mm/h)
September 2016				
Yarrowee at Little Bendigo Creek	30	0.8	5	2
Gnarr Creek	2.9		9.9	1.65
Ballarat CBD	6.7		12.4	1.65
US Mt Mercer	30		40	2
January 2011				
Yarrowee at Little Bendigo Creek	30	0.8	5	1
Gnarr Creek	2.96		9.9	1.65
Ballarat CBD	6.7		9.9	1.65
US Mt Mercer	30		150	1
August 2010				
Yarrowee at Little Bendigo Creek	30	0.8	1	0
Ballarat CBD	2.96		1	1.65
Gnarr Creek	6.7		1	1.65
US Mt Mercer	30		30	1

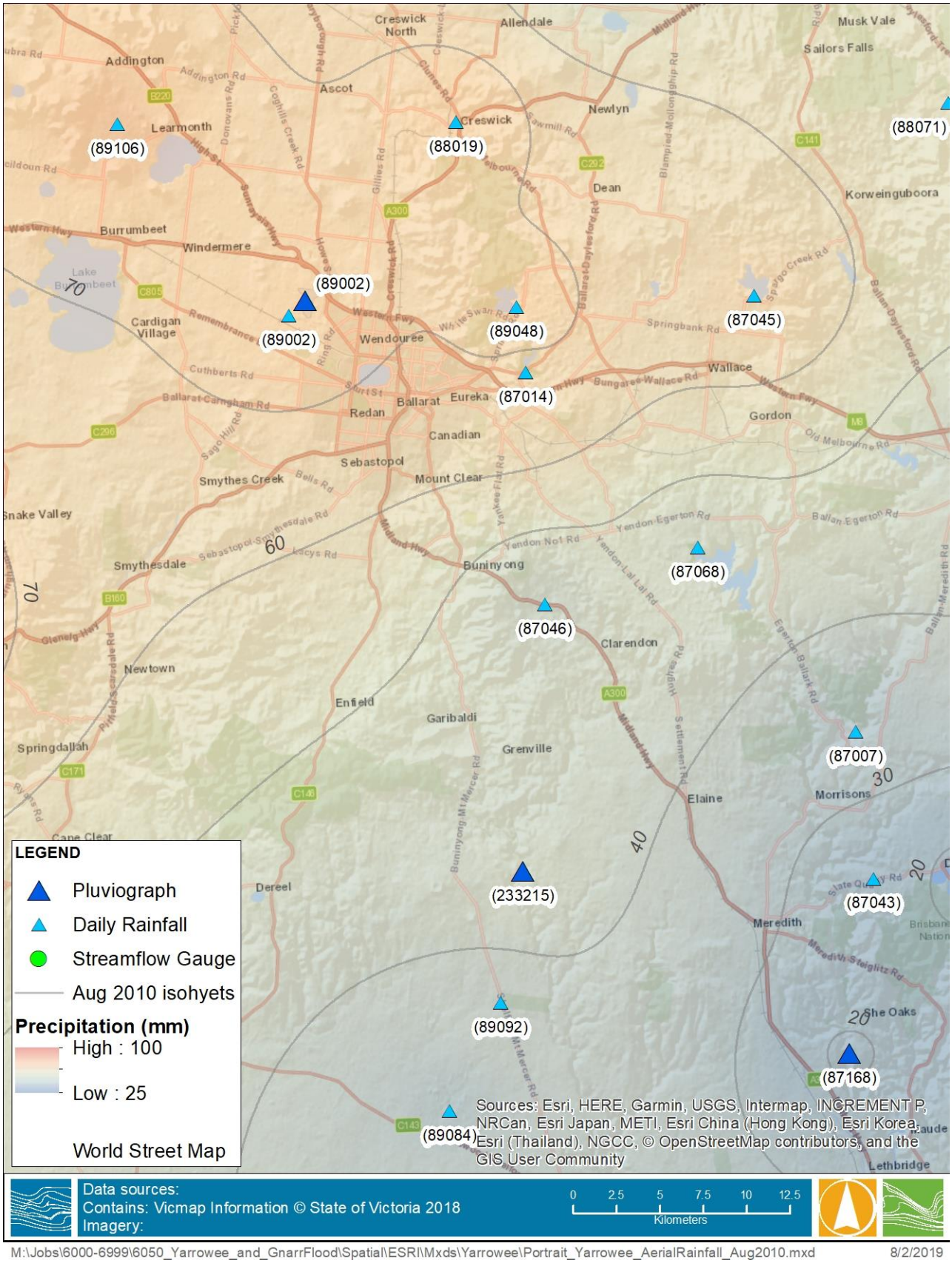
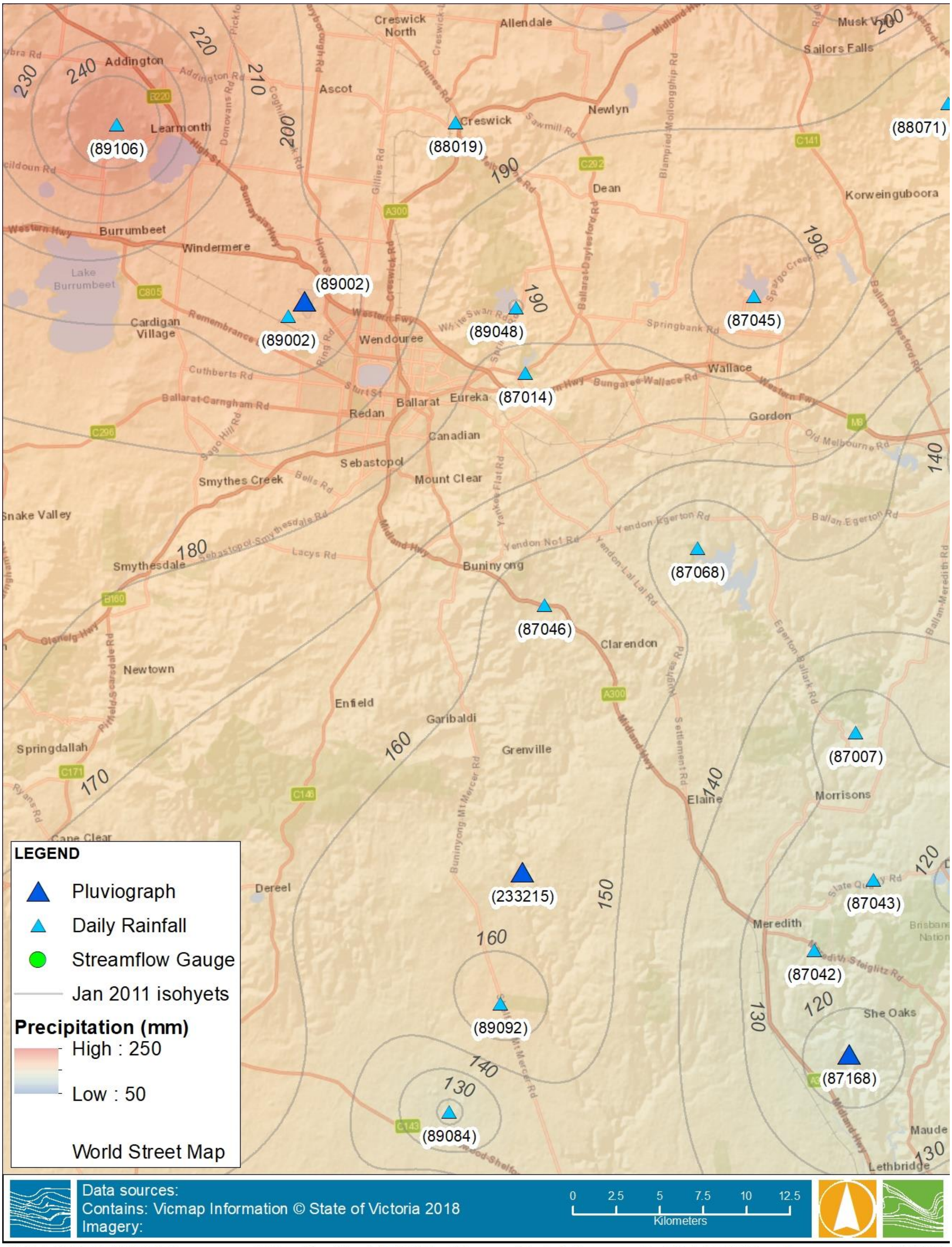


Figure 3-16 Rainfall distribution across the catchment for the August 2010 calibration event



M:\Jobs\6000-6999\6050_Yarrowee_and_GnarrFlood\Spatial\ESRI\Mxds\Yarrowee\Portrait_Yarrowee_AerialRainfall_2011.mxd 8/2/2019

Figure 3-17 Rainfall distribution across the catchment for the January 2011 calibration event

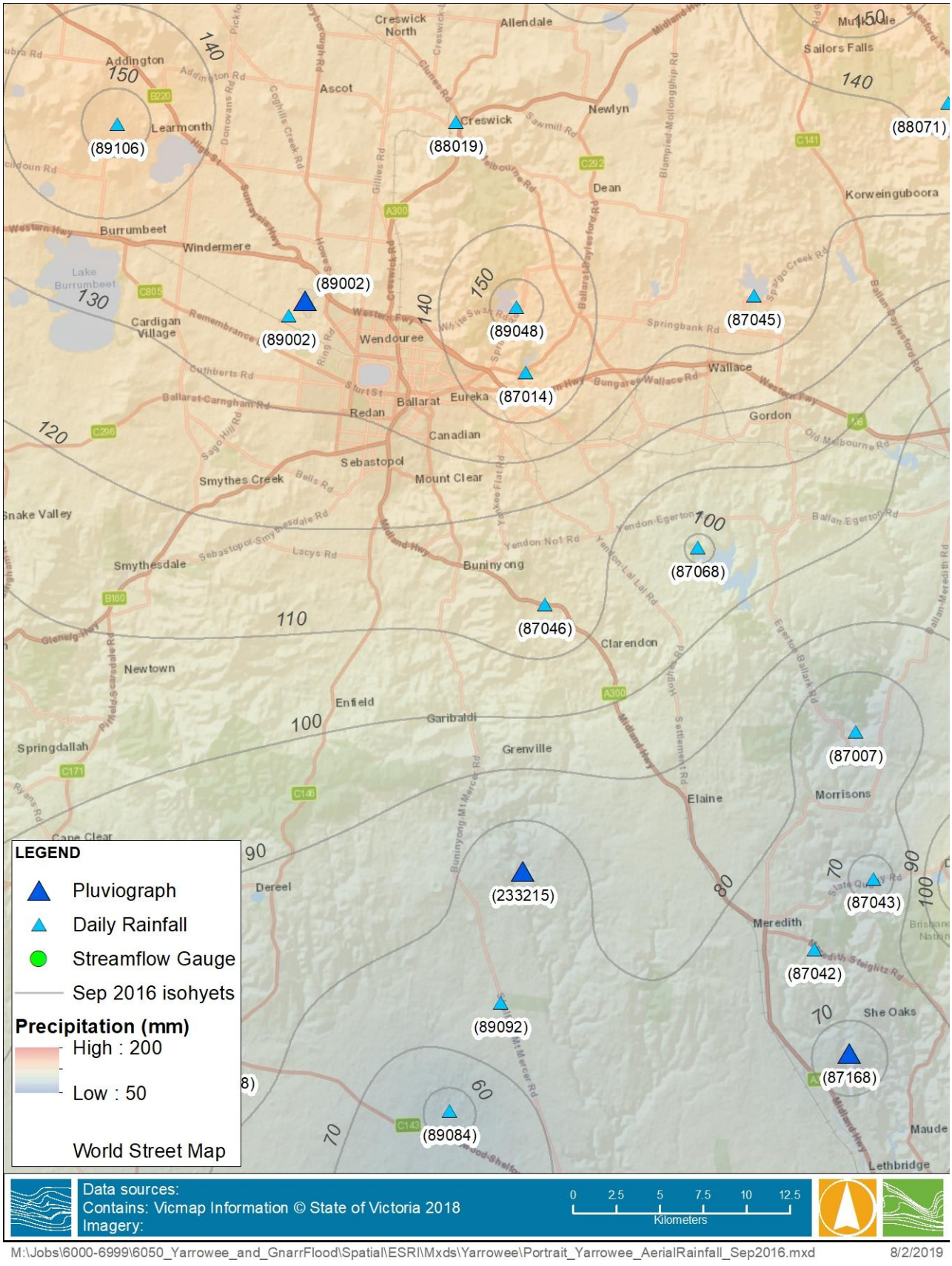


Figure 3-18 Rainfall distribution across the catchment for the September 2016 calibration event

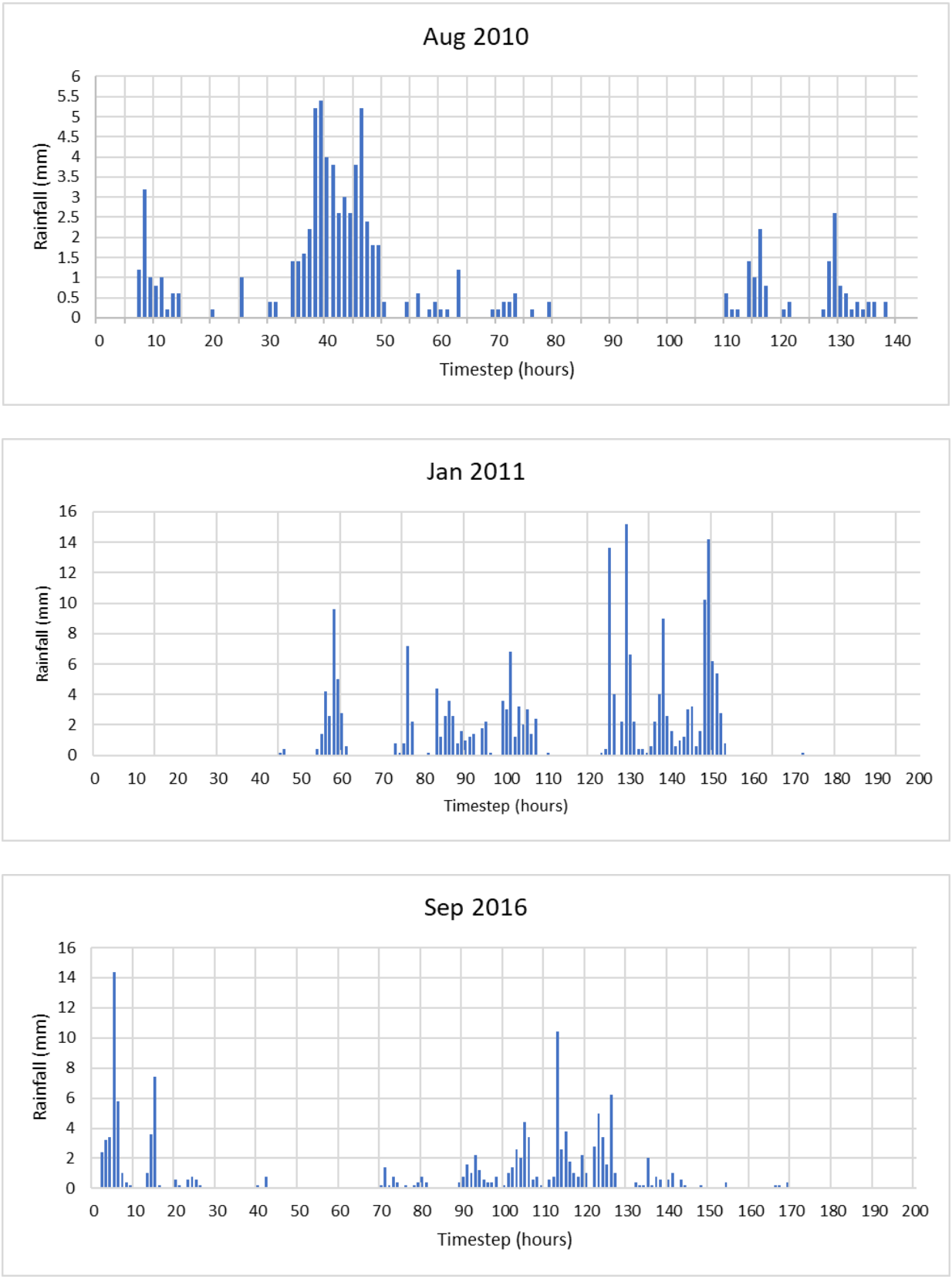


Figure 3-19 Calibration events – Rainfall temporal patterns at Ballarat AWS (mm/hr)

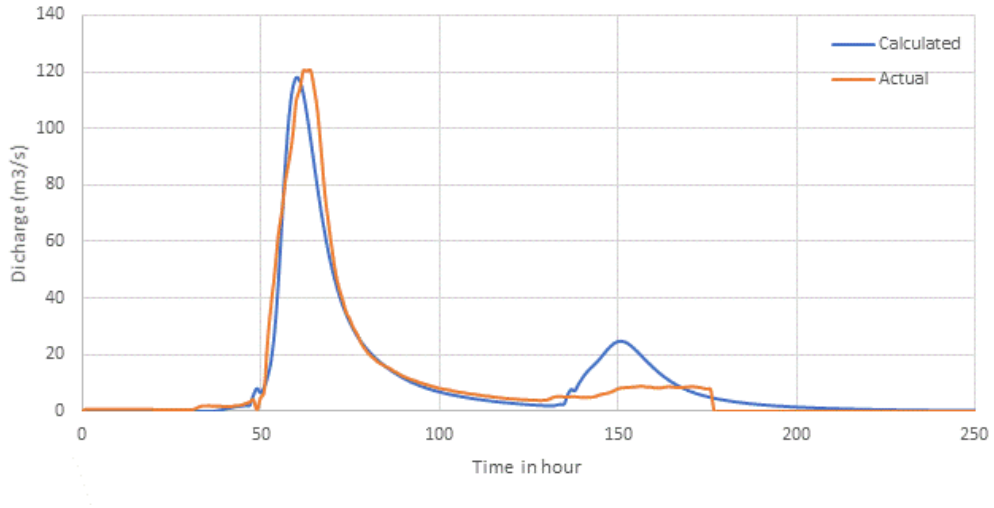


Figure 3-20 August 2010 - Modelled and gauged Hydrographs

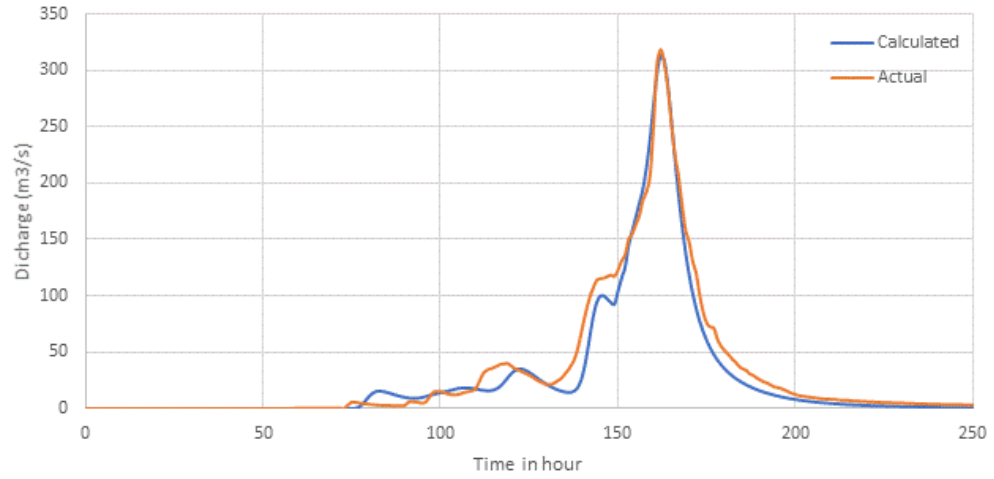


Figure 3-21 January 2011 - Modelled and gauged Hydrographs

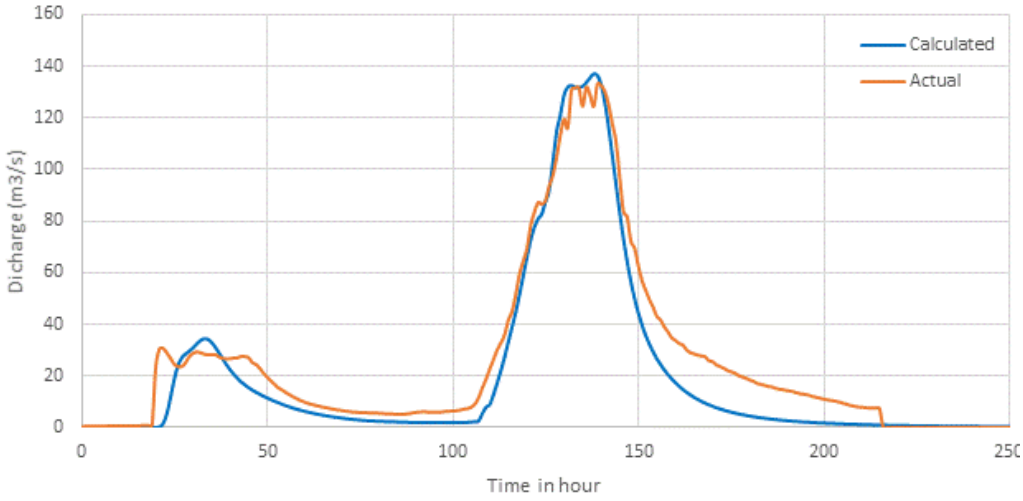


Figure 3-22 September 2016 - Modelled and gauged Hydrographs

3.5 Design Modelling

3.5.1 Overview

Design modelling was carried out in Monte Carlo framework. The Monte Carlo analysis in RORB was used to determine the design peak flows at several key locations within project catchment.

The RORB Monte Carlo analysis was undertaken adopting the determined losses and k_c value discussed in Section 3.3.3. During a Monte Carlo analysis, the RORB model runs many times, this entails 10,000 model simulations, sampling for an extensive range of temporal patterns and rainfall initial loss. This is completed in combination with the other set model parameters of spatial pattern, continuing loss, aerial reduction factors, k_c and m. The model then takes the hydrographs from all model runs and produces a statistical design peak flow at each RORB output location. A schematic diagram of Monte Carlo approach is presented in Figure 3-23.

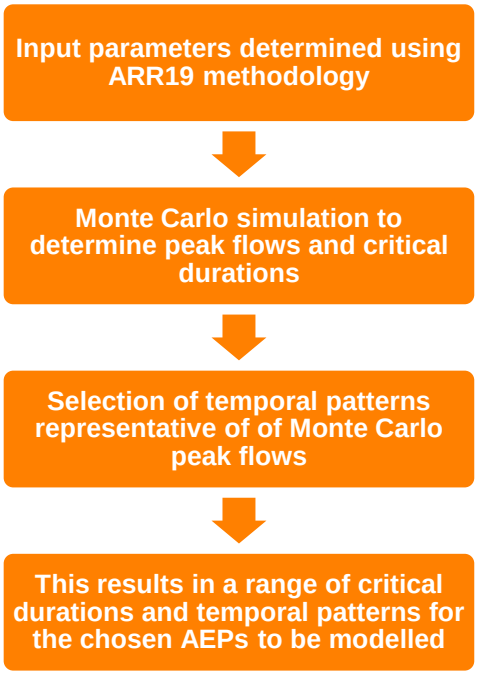


Figure 3-23 Design Modelling Flow Chart

3.5.2 Monte Carlo Analysis

The RORB Monte Carlo analysis was undertaken adopting the determined losses and k_c value discussed in Section 3.3.3. During a Monte Carlo analysis, the RORB model runs many times, sampling for an extensive range of temporal patterns and rainfall initial loss. This is completed in combination with the other set model parameters of spatial pattern, continuing loss, aerial reduction factors, k_c and m. The model then takes the hydrographs from all model runs and produces a statistical design peak flow at each RORB output location. A schematic diagram of Monte Carlo approach is presented in Figure 3-24.

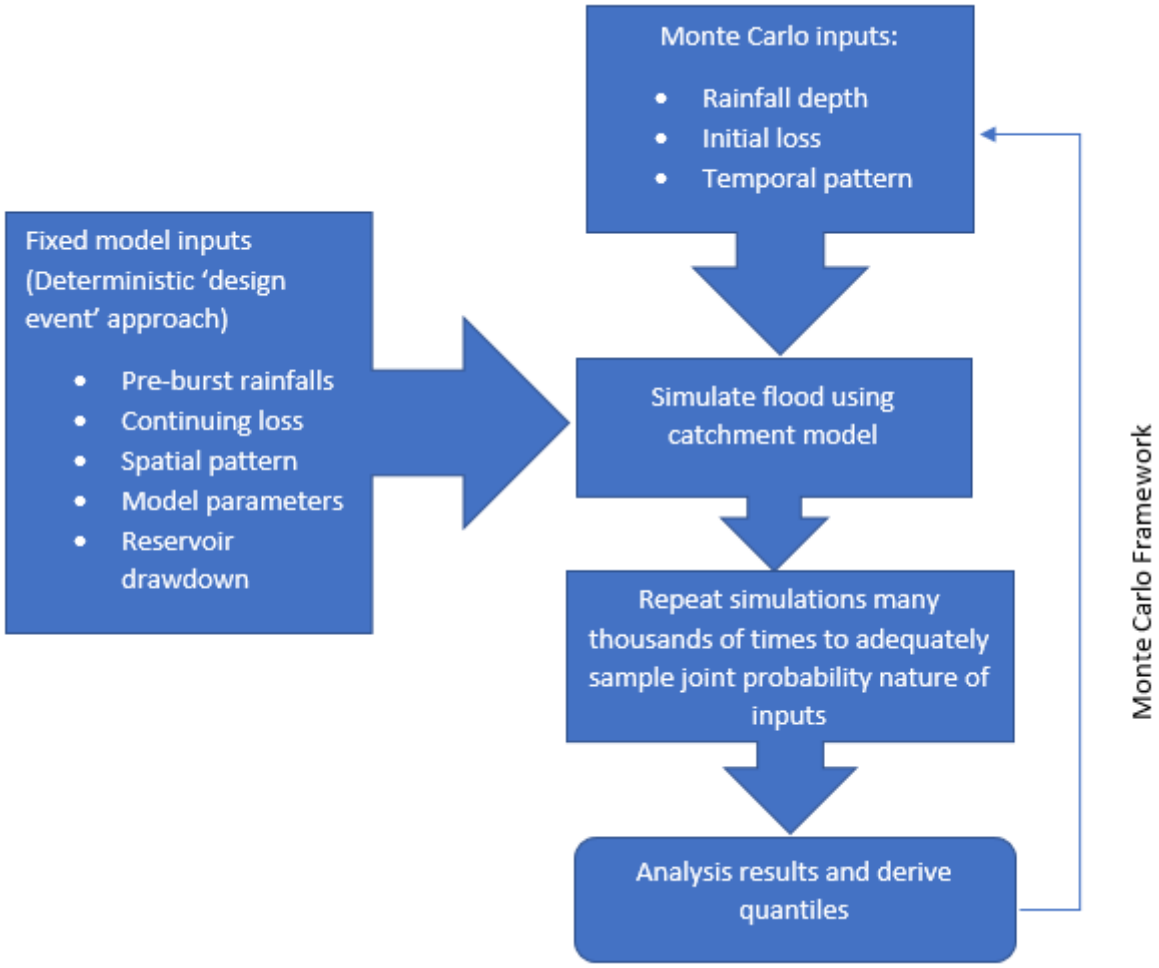


Figure 3-24 Overview of Monte Carlo Analysis

Table 3-9 RORB Critical Durations along Yarrowee River & Gnarr Creek

Location	10% AEP	5% AEP	2% AEP	1% AEP
Gnarr Creek	30m			
Little Bendigo Creek	12hr			
Peel St at Eastern Oval	1hr	2hr		1hr
DS Western Freeway at Humffray St	48hr			
Canadian Creek	12hr			
Wallaby Park	6hr		3hr	
Yuille Park	1hr			
Whitehorse Road Reserve	2hr	1hr	2hr	
Winter Creek	48hr	24hr		
Colac-Ballarat RD at Cambrian Hill	6hr			
Rose Creek	48hr	24hr	48hr	24hr
Union Jack Creek	48hr	24hr	12hr	

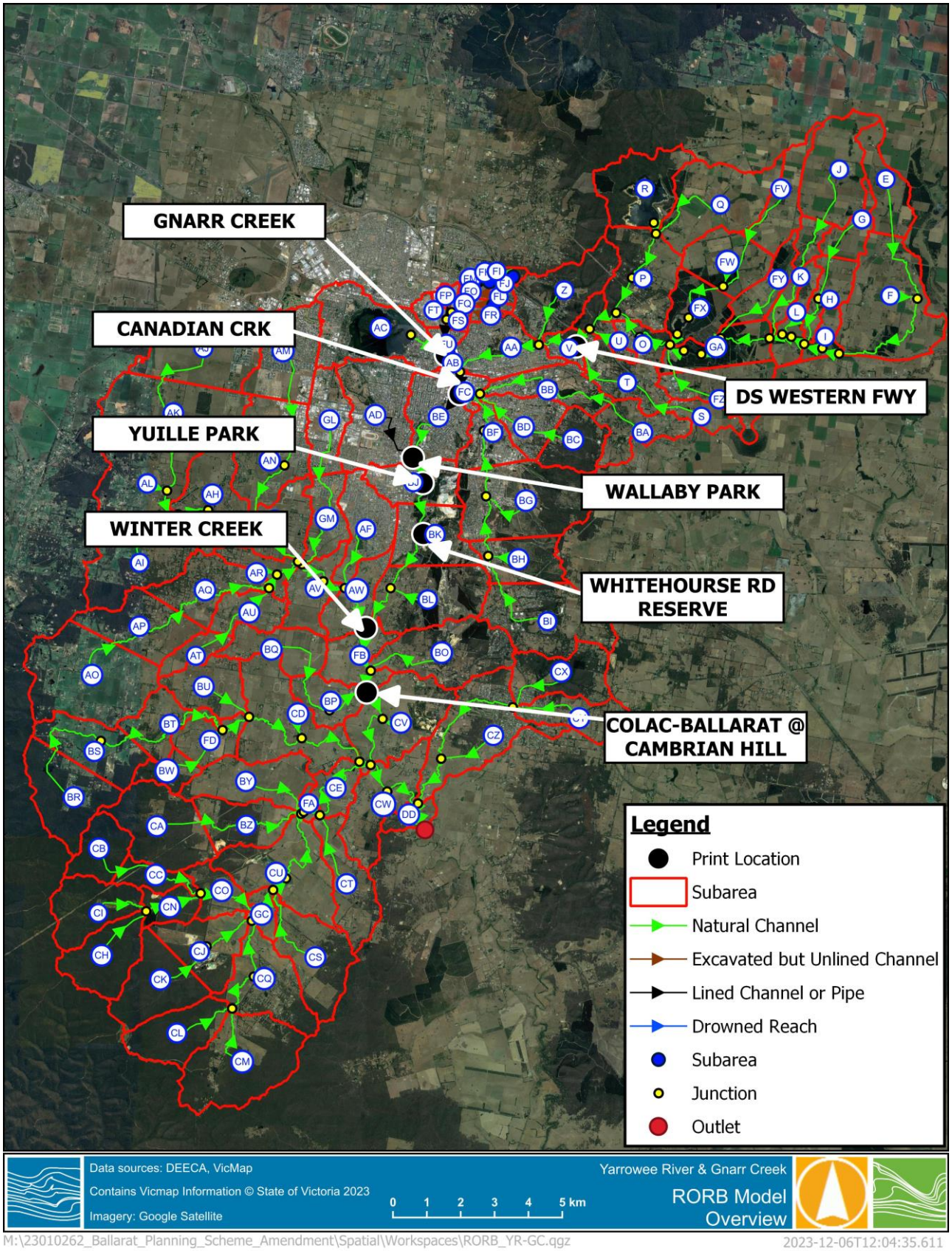


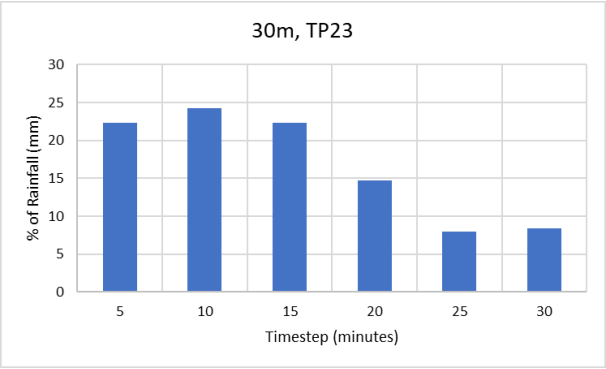
Figure 3-25 Yarrowee River Hydrograph Print Locations

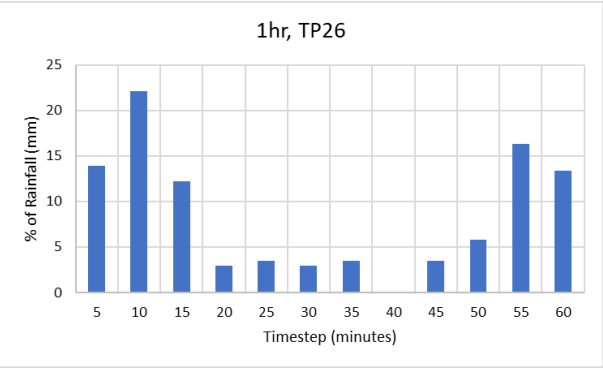
3.5.3 Ensemble Analysis

The RORB model was also run using the Ensemble Analysis, using the determined k_c value and losses. The RORB Ensemble Analysis was run for all ARR19 recommended temporal patterns for each event duration. 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 various output locations. The temporal pattern resulting in an Ensemble Analysis peak flow closest to the Monte Carlo analysis peak flow was selected for each output location. To reduce the potential number of hydraulic model runs, temporal patterns that yielded peak flows similar to those produced in the Monte Carlo analysis at each of the key locations were simplified to produce a set of selected temporal patterns for each design event. These are summarised in Table 3-10 with the distribution of rainfall for the adopted temporal patterns in the 1% AEP event displayed in Figure 3-26.

Table 3-10 Chosen Representative Temporal Patterns and Durations for each AEP

	20%	10%	5%	2%	1%	0.5%
Critical Duration & Temporal Pattern	30m, TP10	1hr, TP20	30m, TP11	30m, TP28	30m, TP23	30m, TP30
	1hr, TP09	2hr, TP20	1h, TP20	1hr, TP28	1hr, TP26	1hr, TP28
	1hr, TP10	6hr, TP19	6hr, TP19	2hr, TP30	2hr, TP29	2hr, TP25
		12hr, TP10	12hr, TP04	3hr, TP21	3hr, TP24	3hr, TP28
		48hr, TP04	24hr, TP02	6hr, TP30	6hr, TP28	6hr, TP23
		48hr, TP05	48hr, TP10	12hr, TP10	12hr, TP06	12hr, TP10
				24hr, TP08	24hr, TP08	24hr, TP08
				48hr, TP10	48hr, TP07	48hr, TP05





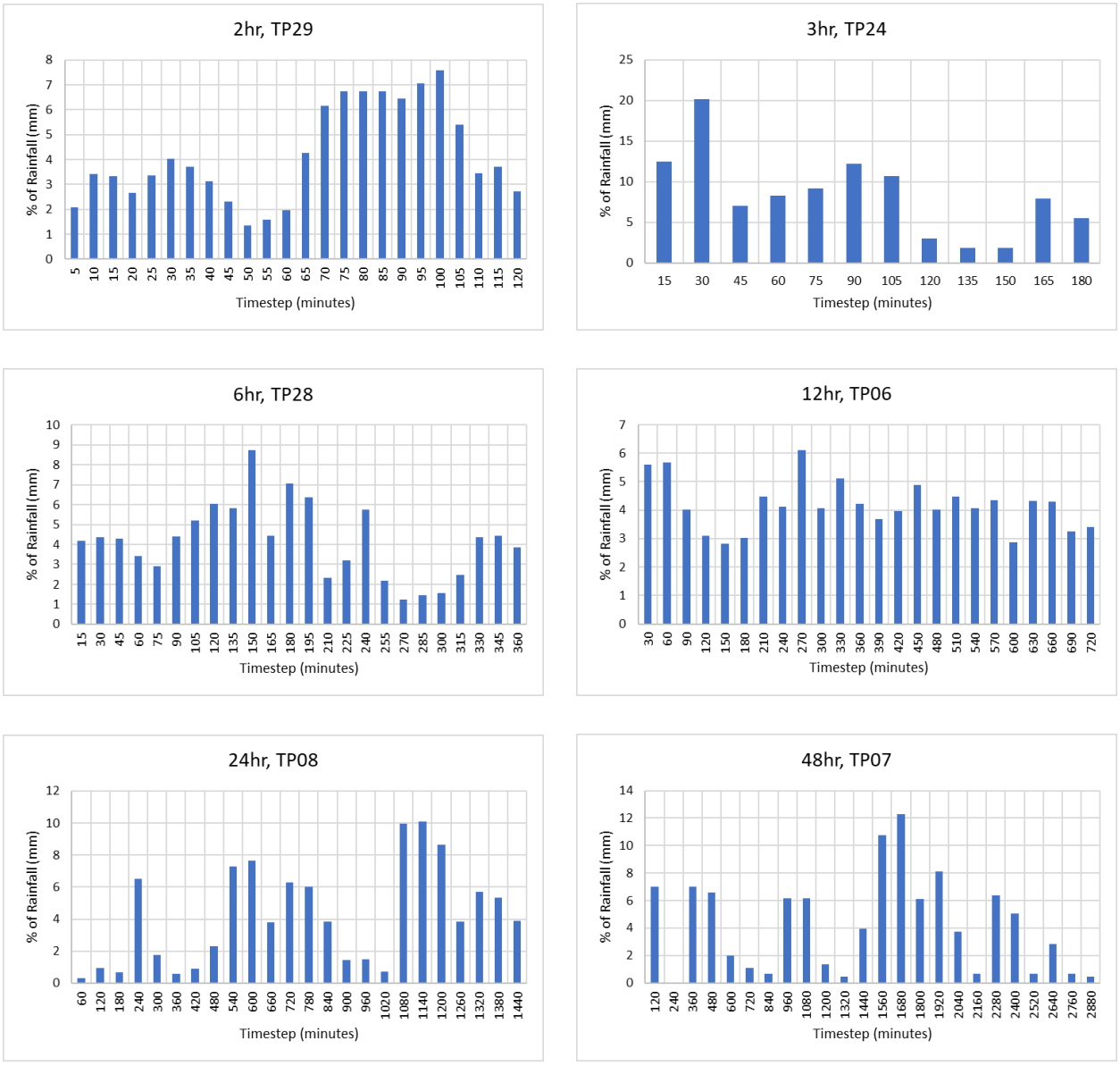


Figure 3-26 Adopted Temporal Patterns for 1% AEP Design Modelling

3.5.4 Design Simulations

Hydraulic model inflow hydrographs were produced for the 20%, 10%, 5%, 2%, 1% and 0.5% AEP events. The resultant flows in the Yarrowee River at its confluence with the Union Jack Creek are plotted in Figure 3-27 below.

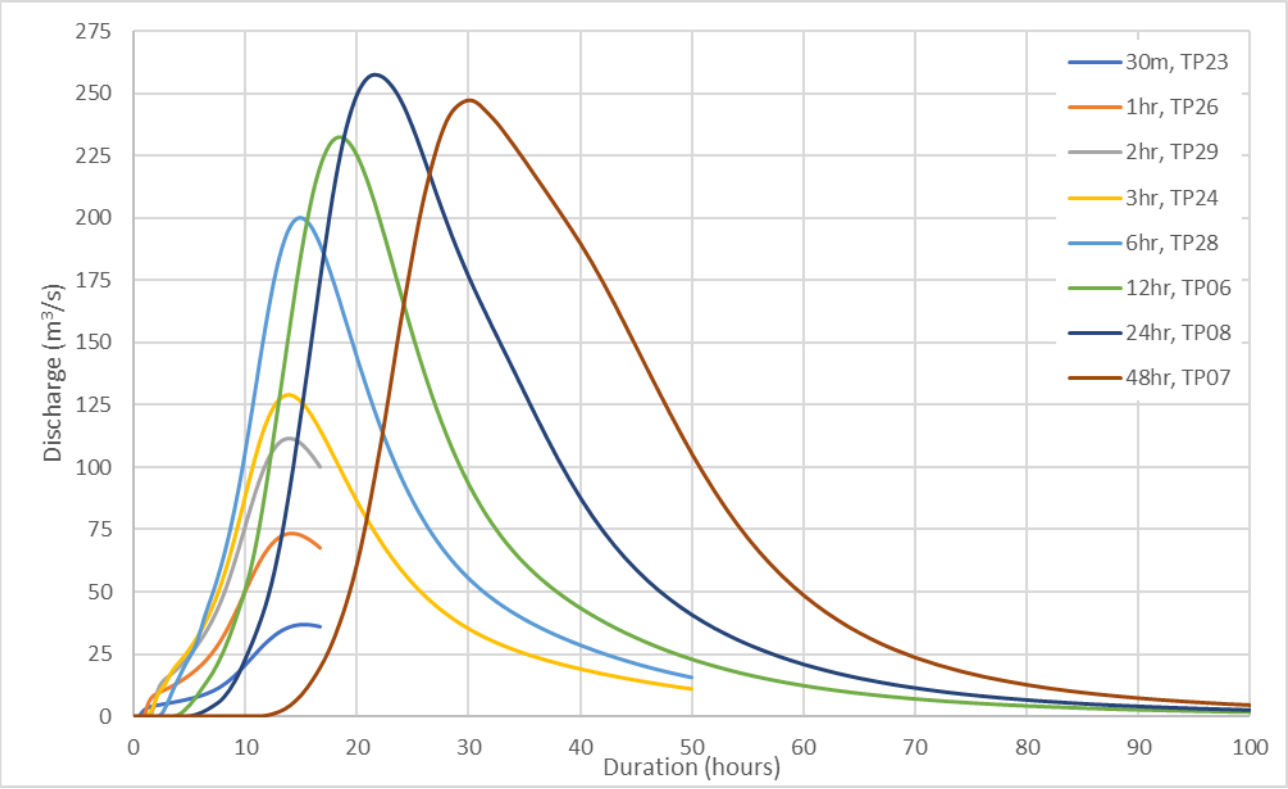


Figure 3-27 1% AEP Flows at the Confluence of the Union Jack Creek

4 HYDRAULIC MODELLING

4.1 Overview

This section provides the description of the TUFLOW hydraulic model setup. Model simulations were performed with a Highly Parallelised Computing (HPC) solution scheme using the 2023-03-AB build of TUFLOW. HPC technology enables 2D modelling software to utilise the parallel processing ability of graphics cards, with many thousand processors operating in unison, significantly speeding up simulation run times.

Design flood modelling included the 20%, 10%, 5%, 2%, 1% and 0.5% AEP events along with the 1% AEP with the inclusion of climate change under 2100 RCP 4.5, RCP 6 and RCP 8.5. Currently only the 1% AEP events have been modelled.

4.2 2D Domain

4.2.1 Topography

Hydraulic modelling covered the Yarrowee River and Gnarr Creek from the water storages (i.e., White Swan Reservoir) down to the confluence of the Union Jack Creek in Buninyong. This extent also included the Gnarr Creek which extends from the Ballarat CBD to upstream of the Western Freeway near the Ballarat Cemetery. The 2D model extent is shown in Figure 4-1 below.

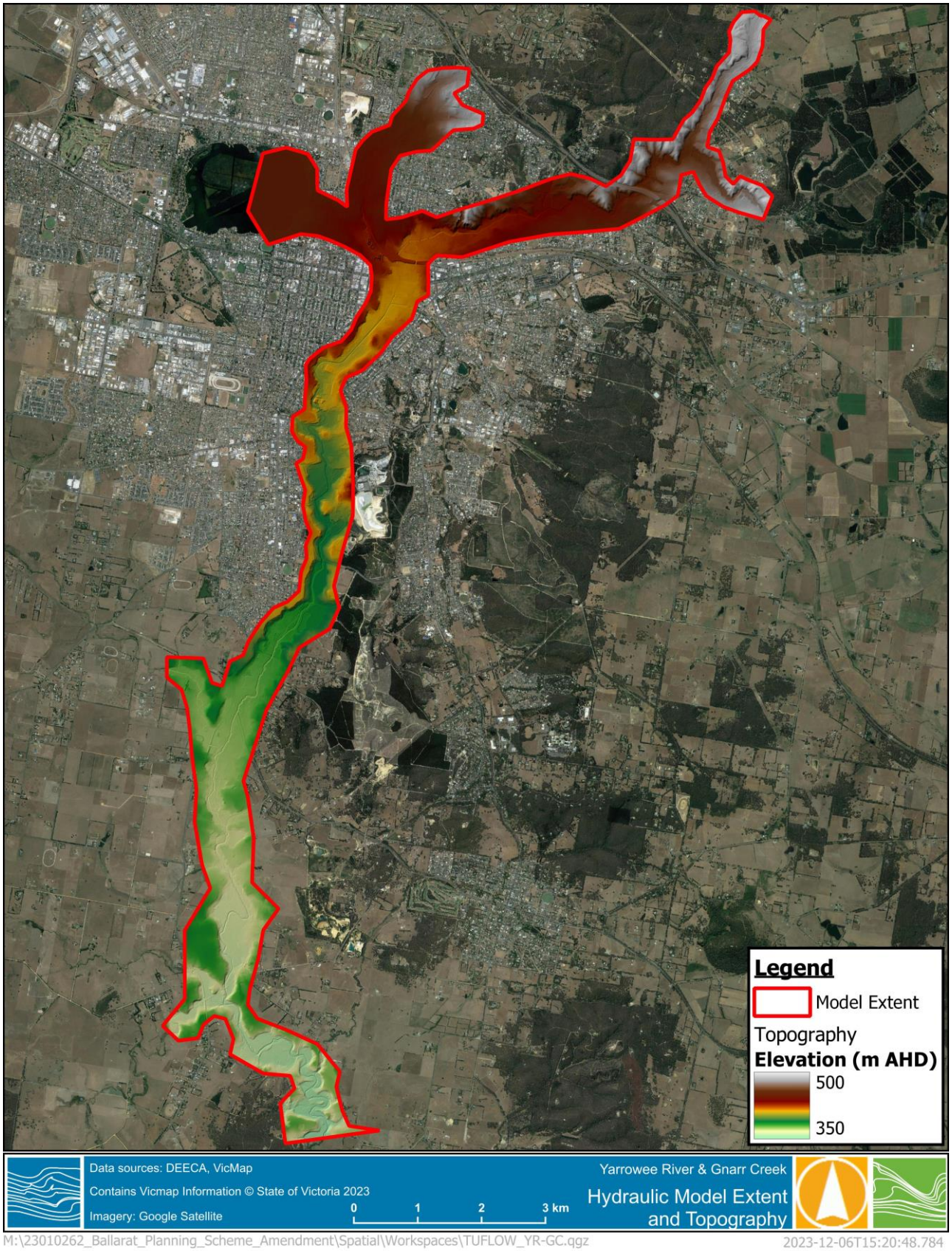


Figure 4-1 Hydraulic Model Area and Topography

4.2.2 Surface Roughness

Hydraulic roughness was determined using planning layers and verified using aerial imagery. The Manning's 'n' roughness values adopted for each land use are presented in Table 4-1. The adopted roughness's were based on standard industry accepted values (VicRoads Road Design Guidelines).

Table 4-1 Manning's Roughness used in the Model

Land Type	Manning's Value (*n*)
Residential – Urban (higher density) - when building footprints and remainder of parcel are modelled together (with one roughness value)	0.350
Residential – Rural (lower density) - when building footprints and remainder of parcel are modelled together (with one roughness value)	0.150
Industrial/Commercial or large buildings	0.300
Open Space or Waterway – minimal vegetation	0.040
Open Space or Waterway – moderate vegetation	0.060
Open Space or Waterway – heavy vegetation	0.090
Open water (with submerged vegetation)	0.020
Car park/pavement/wide driveways/roads	0.020
Buildings	0.400
Constructed Channels	0.04

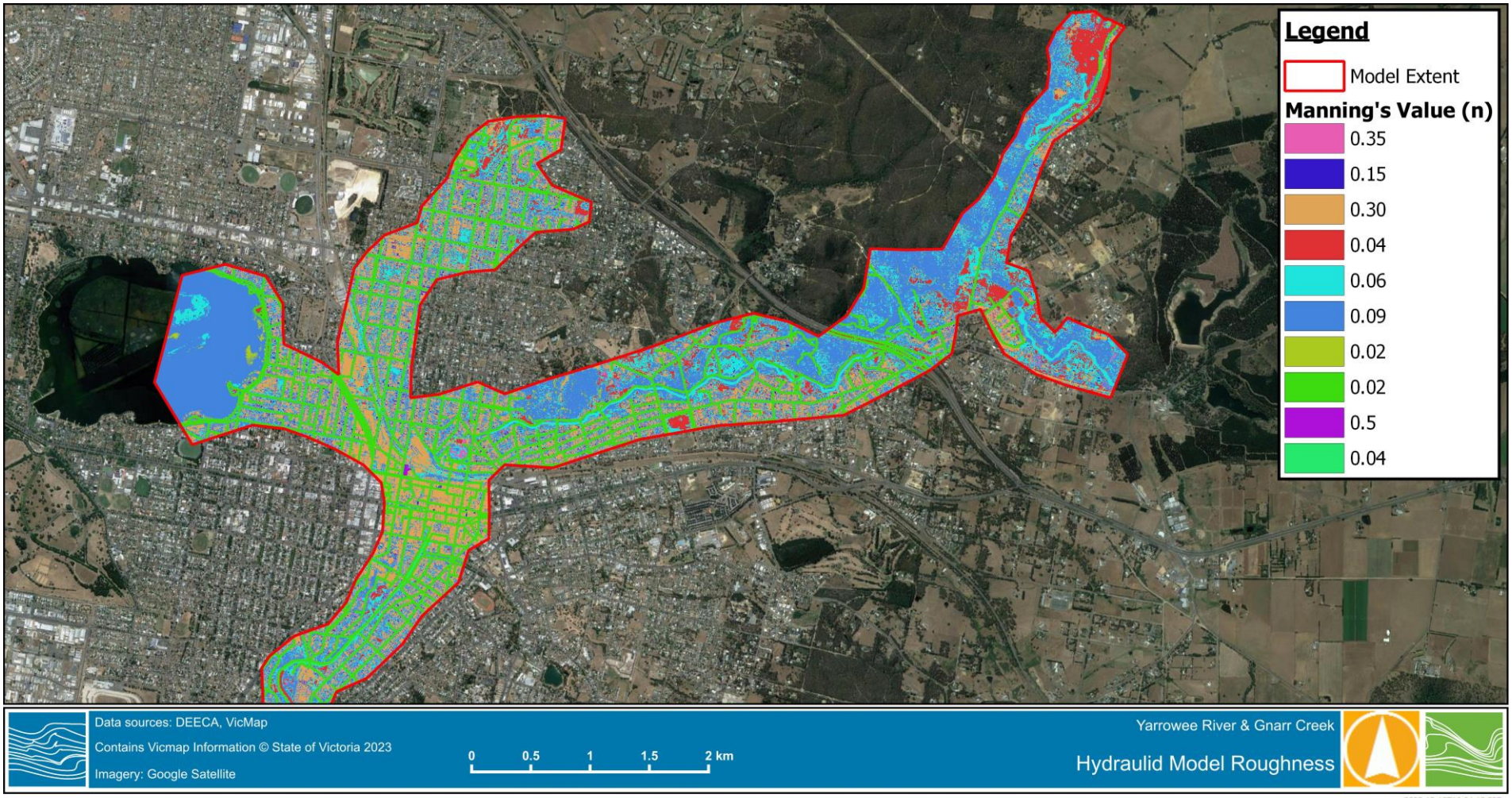


Figure 4-2 Detailed Hydraulic Roughness Map – North

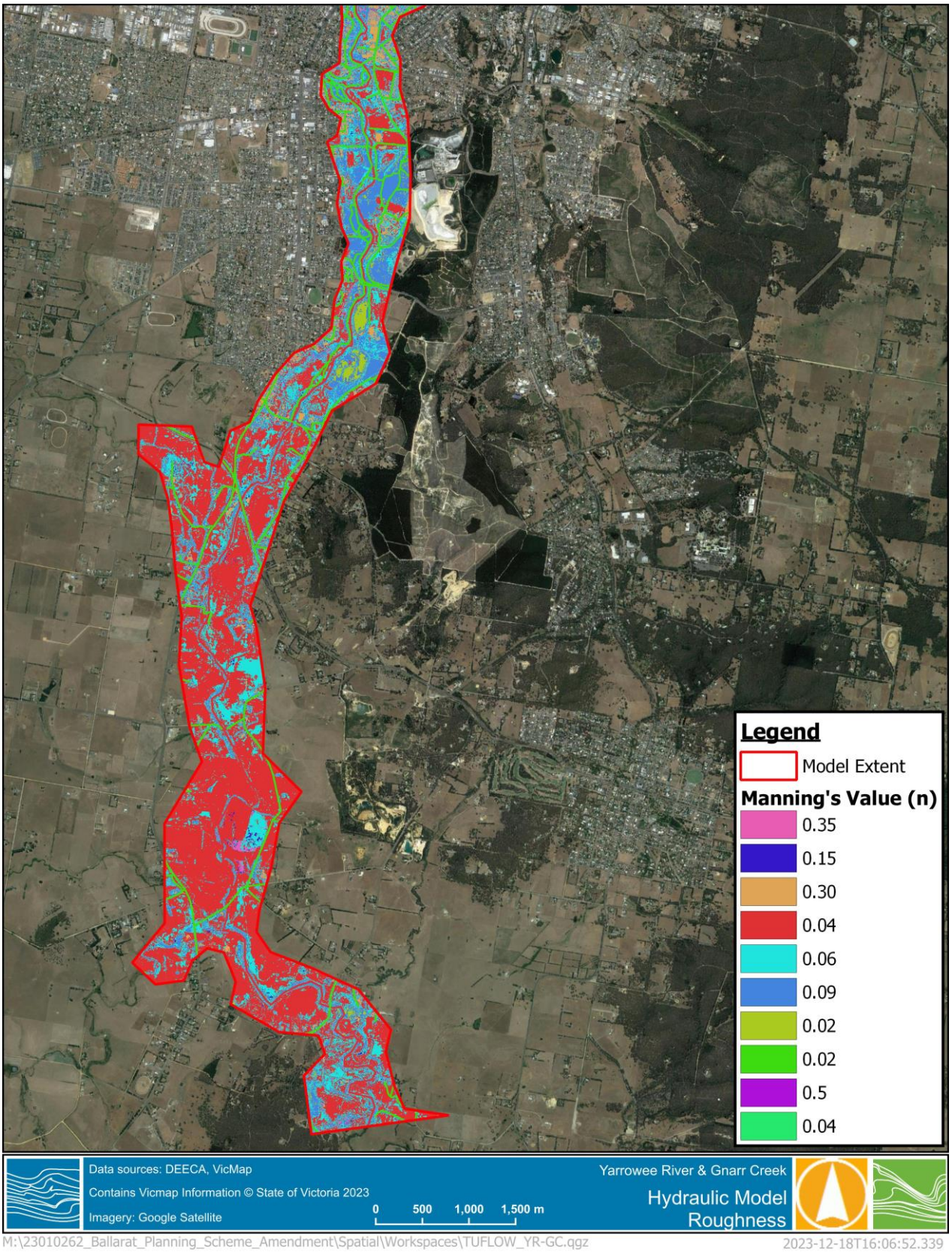


Figure 4-3 Detailed Hydraulic Roughness Map

4.3 1D Network

The drainage infrastructure (culverts, pipes and pits) was modelled as a 1D (one-dimensional) network in the model.

Council provided a GIS database containing their drainage assets across the municipality. All the relevant drainage network GIS databases were reviewed and separated into two components: pipes and pits. Pipes in the area of inundation and with a diameter greater than 300 mm were included in the model.

During the review process, gaps in the provided drainage network data sets were found. In some instances it was possible to infer the missing information based on site visit, engineering judgement, topographical information and cross-checks with *Google Street View*.

Pits were incorporated in the 1D (one-dimensional) network as 'weir pits'. Pits were connected to the surface with an SXL connection (an external connection that lowers the surrounding cells) which lowered them by 100 mm to encourage flow to enter the pits.

A Manning's 'n' roughness value of 0.013 was adopted for the pipes. The culvert, pipes and pits modelled are shown in Figure 4-4 and Figure 4-5.

4.4 Boundary Conditions

The hydraulic model requires inflow and outlet boundaries to allow water into and out of the model. External inflow boundaries accounted for flow generated from outside of the model extent, whereas internal boundaries accounted for inflow locations within the model extent. The downstream boundaries which allow water out of the hydraulic model used a stage-storage discharge relationships.

The model included one external inflow boundary which represented flows into the model from the Canadian Creek & Tributaries catchment. These flows were developed from the Canadian Creek & Tributaries hydraulic model after the development of the original flood studies. This approach was adopted due to the significant difference in flows between the RORB model and TUFLOW model. The RORB model overestimated the flow getting to the Yarrowee River due to the exclusion of the key hydraulic controls within the Canadian Creeks catchment which were represented in the TUFLOW model. All other inflows were included as internal boundaries represented as either direct inflow or pit inflow.

A total 36 internal inflow boundaries were applied. 34 of the inflow boundaries were applied as source area (SA) where inflow hydrographs were applied to a region in the 2D domain, while two of the inflow boundaries located in the Orkney Court and on the corner of Doveton Street North and Market Street were applied to the stormwater network via pits in the 1D domain. This was considered a suitable approach as much of the study area features open channels, but parts of the upper Gnarr Creek are heavily developed. The location of these boundaries is shown in Figure 4-4 and Figure 4-5.

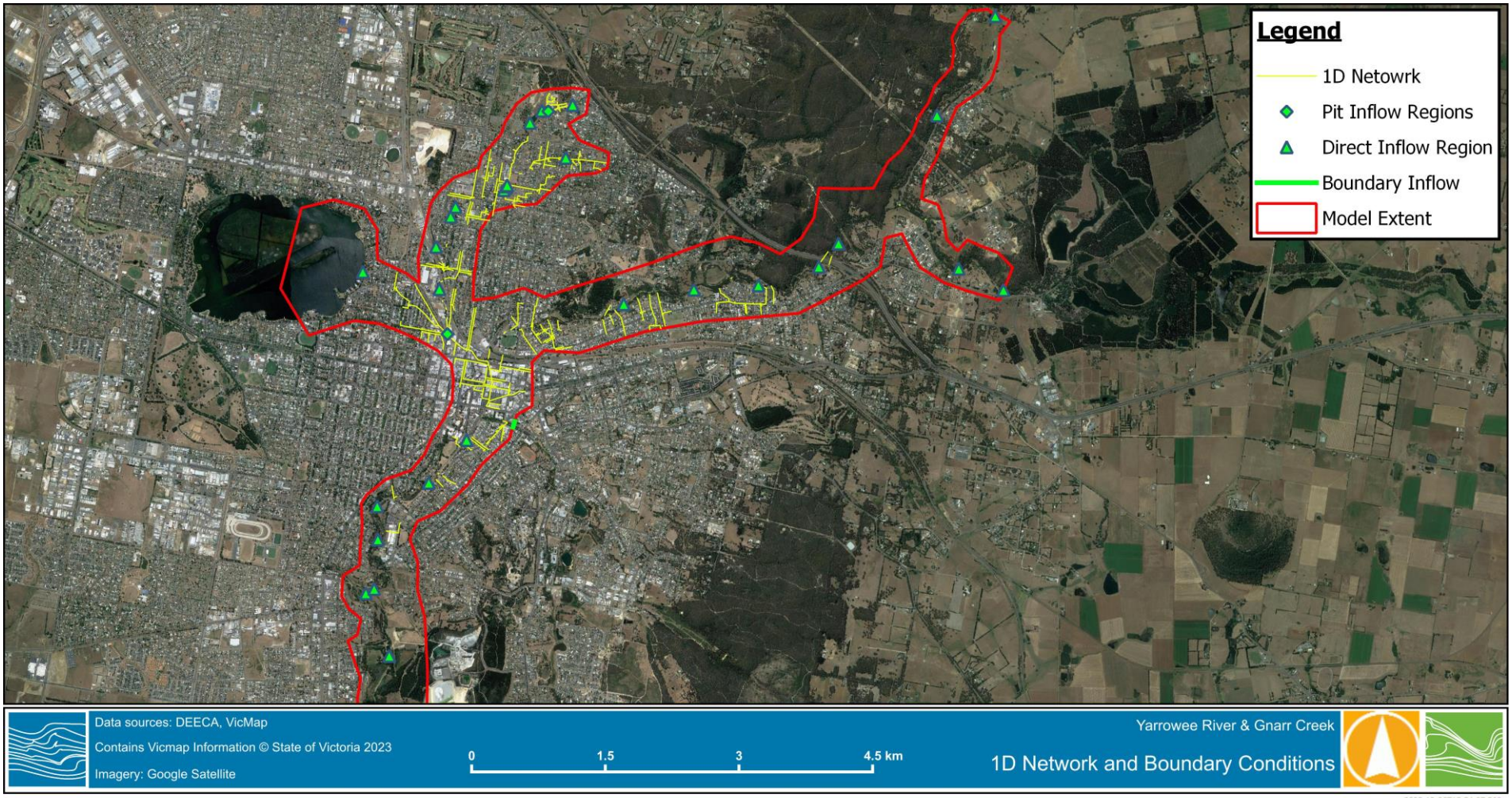


Figure 4-4 Drainage Infrastructure and Model Boundaries - North

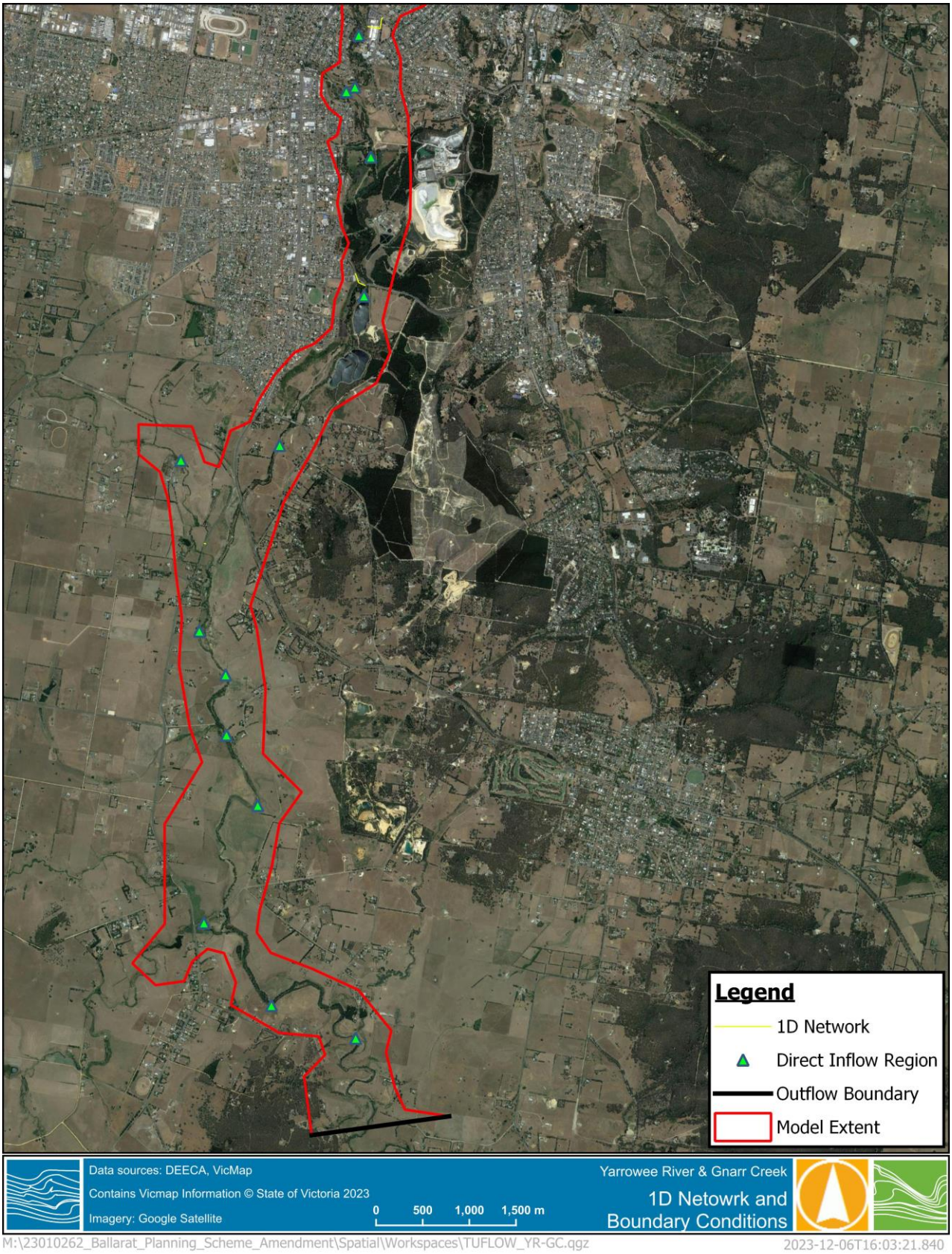


Figure 4-5 Drainage Infrastructure and Model Boundaries - South

4.5 Design Event Modelling

Hydraulic modelling will be undertaken for the 0.5%, 1%, 2%, 5%, 10% and 20% Average Exceedance Probability (AEP) design storm events as well as the 2100 RCP 4.5, 6 and 8.5 scenarios. Results from the design events will be used to undertake existing conditions flood mapping to produce updated overlays and emergency management information. Currently, only 1% AEP mapping has been undertaken.

5 HYDROLOGIC/HYDRAULIC MODEL COMPARISON

There are no streamflow gauges within the hydraulic model extent. To verify flows within the hydraulic model, a comparison to the RORB model flows was made to confirm that routing across both model types was similar.

A comparison of flow hydrographs on the Yarrowee River downstream of the Ballarat CBD where the Yarrowee River daylights and where it merges with the Union Jack Creek (the model outlet) is presented in Figure 5-1 and Figure 5-2 below.

The hydraulic model shows a peak flow much lower than the hydrology model (approximately 80 m^3/s less) due to the hydraulic model including hydraulic controls upstream of the CBD and the influence of the Canadian Creeks inflow driving much of the RORB peak flow at this location as discussed in Section 4.4. Additionally, the hydrology model routes runoff all the way to the model outlet unless a storage has been applied. The hydraulic model features two major controls which have not been included in the hydrology model, these are the Western Freeway embankment and the railway embankment.

The below comparison is for the 1% AEP 2-hour TP29 event.

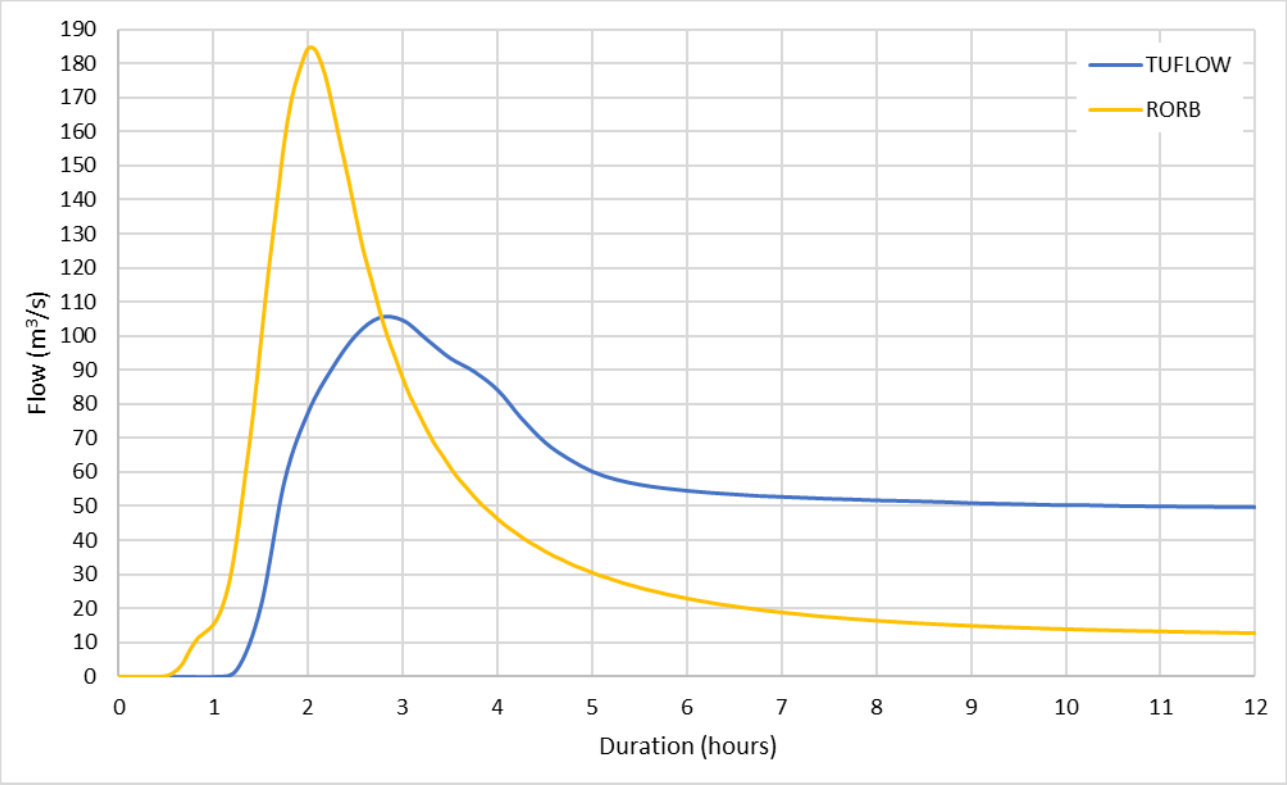


Figure 5-1 Hydrologic and Hydraulic Model Flow Hydrograph Comparison at Downstream of the Ballarat CBD

Peak flows in the TUFLOW and RORB models are a closer match at the end of the modelled catchment (the confluence of the Yarrowee River with the Union Jack Creek) when compared to the downstream of the CBD flows comparison at the critical duration for this location (24-hour storm event). A difference of approximately 3 m^3/s is observed between the two models, with the TUFLOW model being slightly higher than the RORB model. Timings of the peaks do differ with the TUFLOW peak occurring slightly earlier than the RORB peak.

This can be attributed to lower manning's n values in the main flows paths and the consideration of flow path slope in the TUFLOW model. The RORB model adopted natural reach types for most of the lower catchment make up which does not consider reach slope.

The below comparison is for the 1% AEP 24-hour TP08 event. In this event, the overestimation of the Canadian Creeks inflow has less of an influence on the RORB peak flow compared to the 2-hour duration event shown in Figure 5-1.

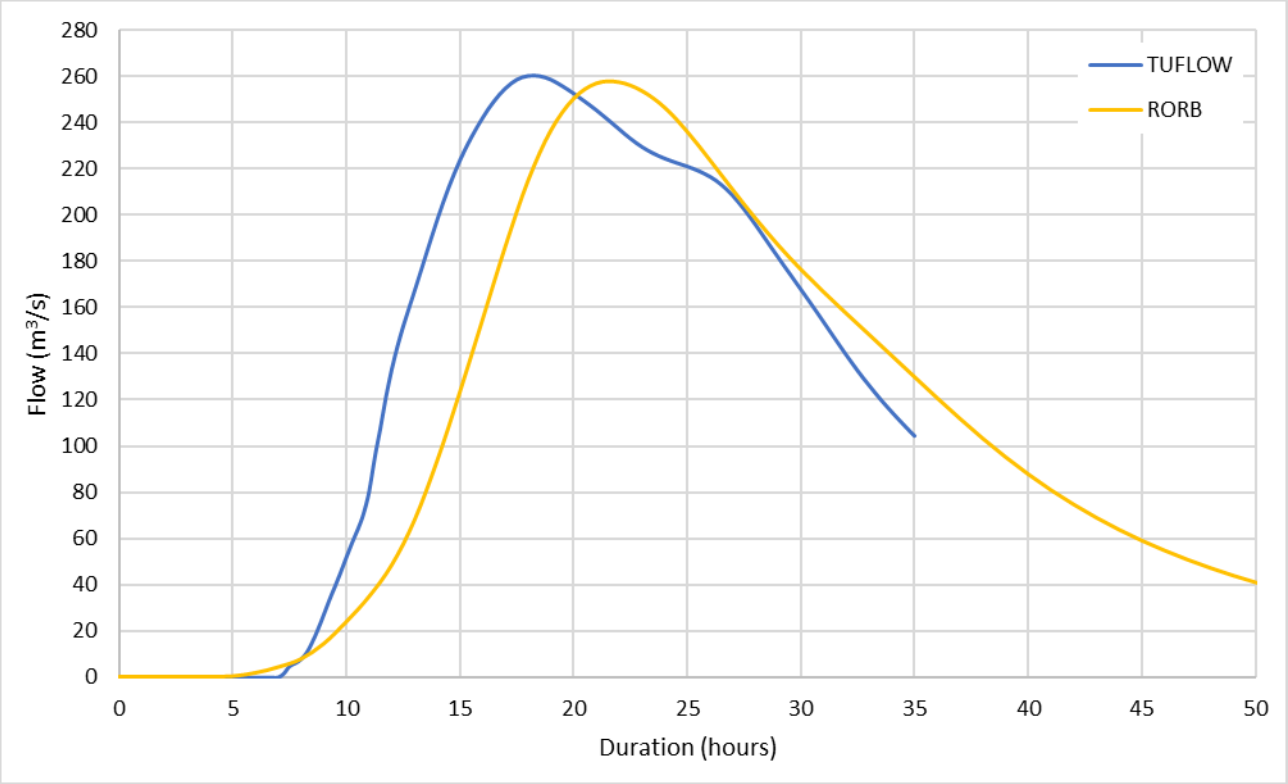


Figure 5-2 Hydrologic and Hydraulic Model Hydrograph Comparison at Confluence with Union Jack Creek (model outlet)

6 FLOOD MAPPING AND RESULTS

This section provides an overview of the floodplain mapping process used in the study and presents a selection of the existing conditions mapping outputs. The model produced a series of geo-referenced datasets defining peak water levels, depth, velocities and hazard throughout the model domain.

1% AEP event flood depths are presented in Figure 6-1 to Figure 6-8 below.

Results show that the Western Freeway embankment in the upper catchment of the Yarrowee River has a significant impact on inundation and flows into the Ballarat CBD. Additionally, the rail embankment upstream of the CBD is a significant hydraulic control that directly impacts inundation in the CBD. Flows within the Yarrowee River are contained within the capped section of the river that flows under the CBD, between Mair Street and Eastwood Street (approximately 500 metres). Inundation through the CBD is driven by floodwaters rising north of the rail embankment and engaging the pedestrian tunnel and Peel Street South road reserve as overland flow paths. Flood waters then proceed south, through the CBD inundating the Bridge Mall before flowing further south to Eastwood Street. Few pits in the CBD show signs of surcharge during the 1% AEP event but impact a localised area only.

The constructed open channel sections of the Gnarr Creek show inundation to the immediately adjacent properties during the 1% AEP storm event. Areas such as Howitt Street, Gregory Street, Howard Street, and Brougham Street see waters in the Gnarr Creek escape the channel and begin to flow overland through properties and down road reserves.

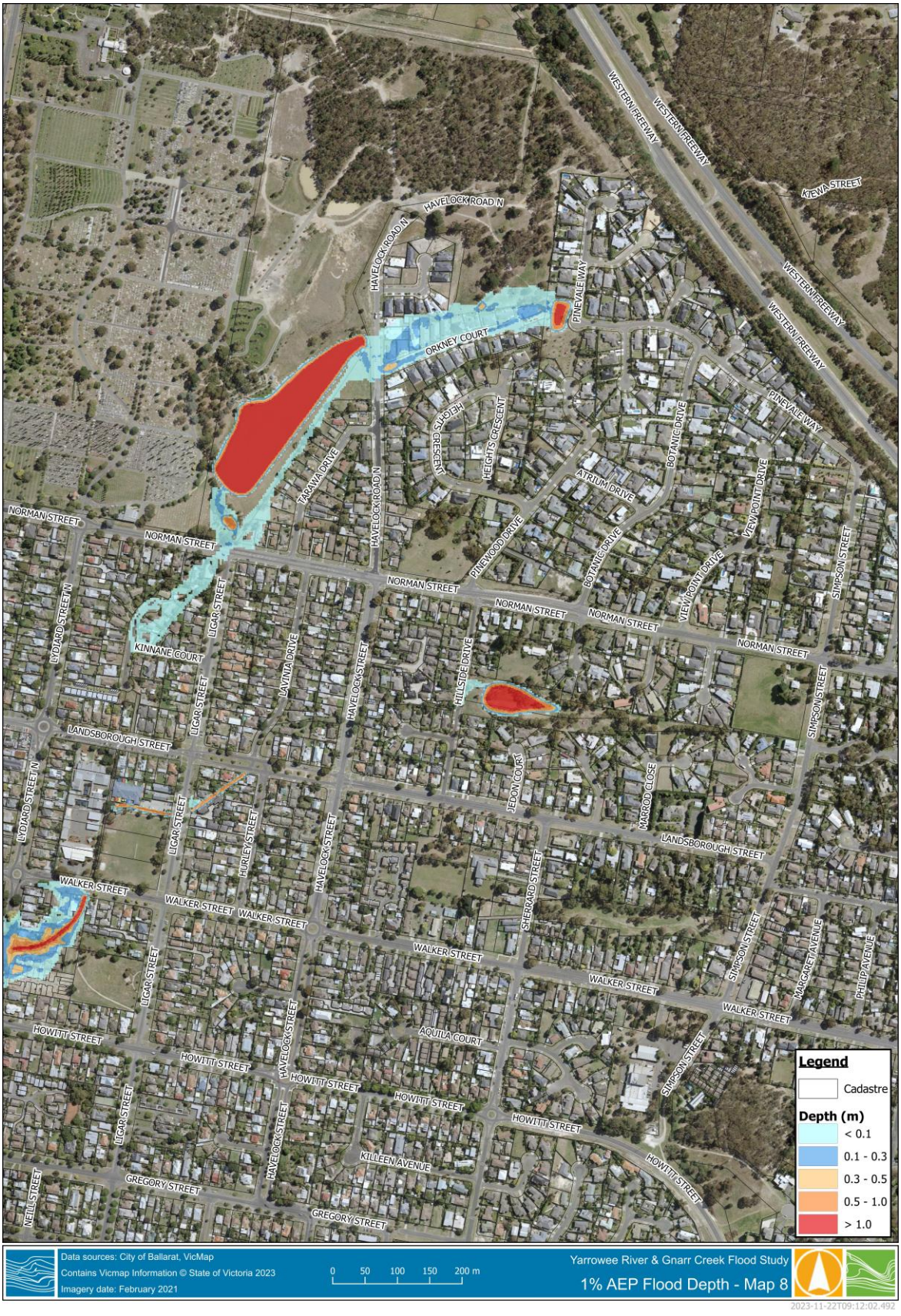


Figure 6-1 1% AEP Flood Depth – Devils Gully



Figure 6-2 1% AEP Flood Depth – Gnarr Creek

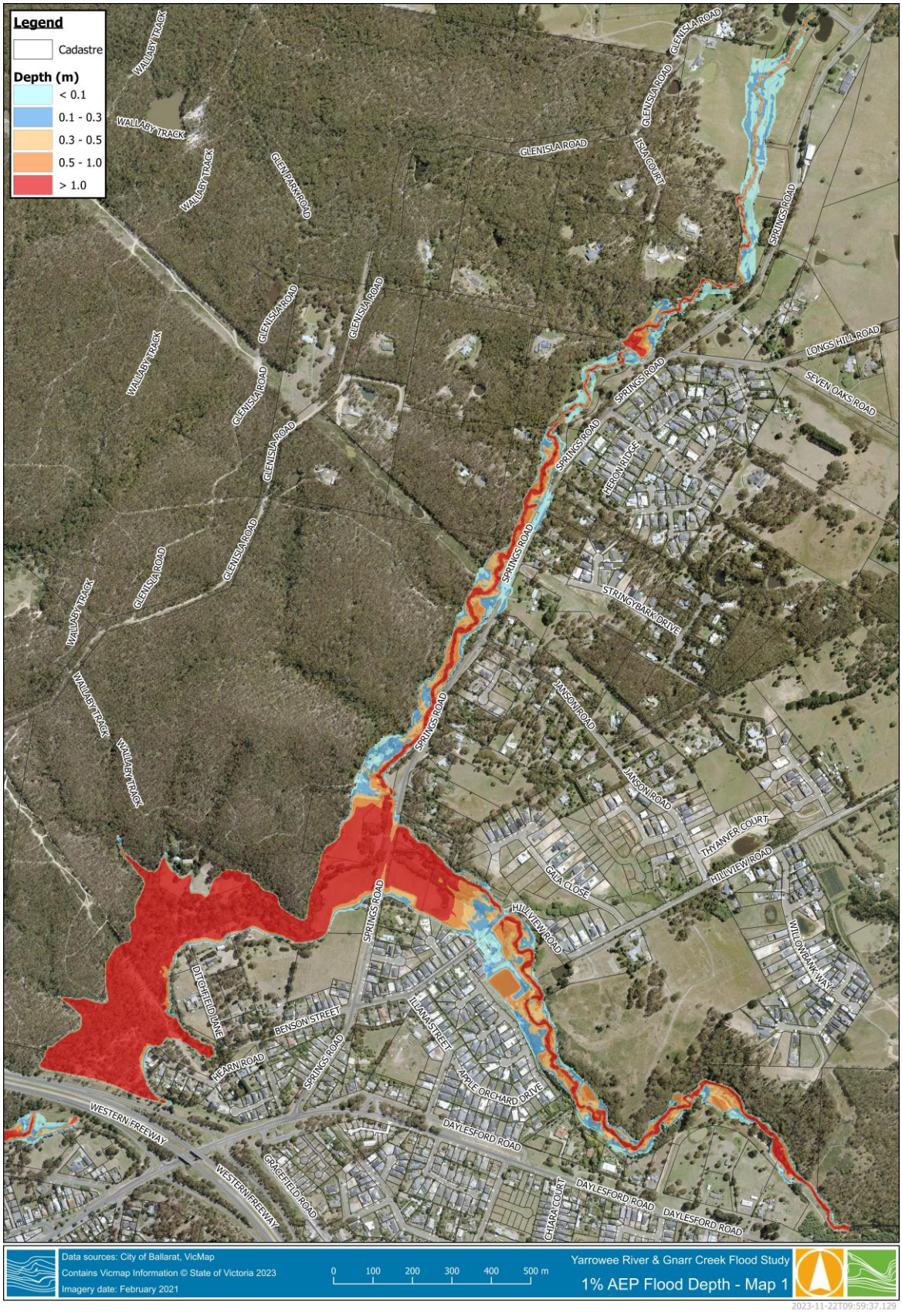


Figure 6-3 1% AEP Flood Depth – US Western Freeway

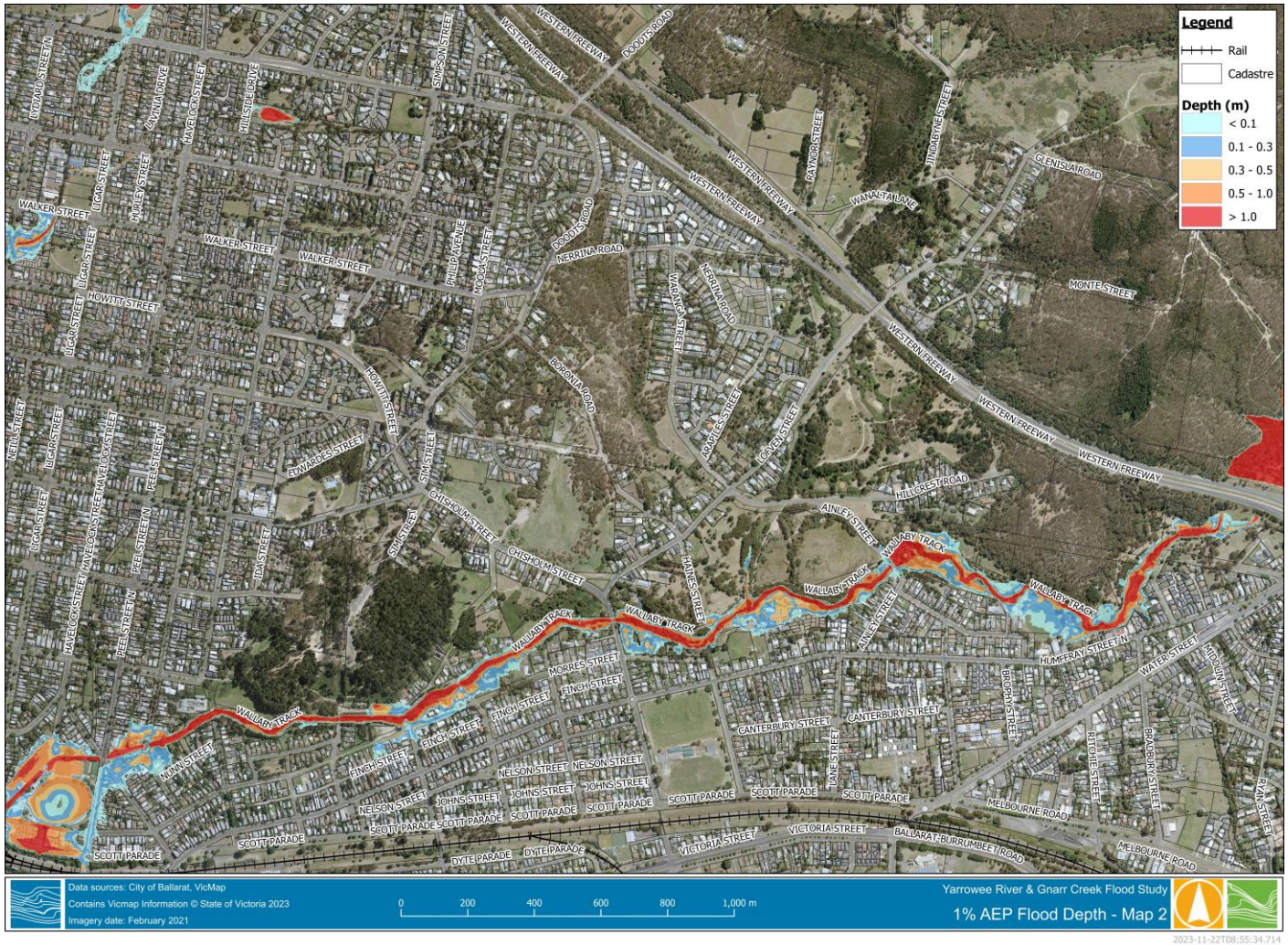


Figure 6-4 1% AEP Flood Depth – DS Western Freeway

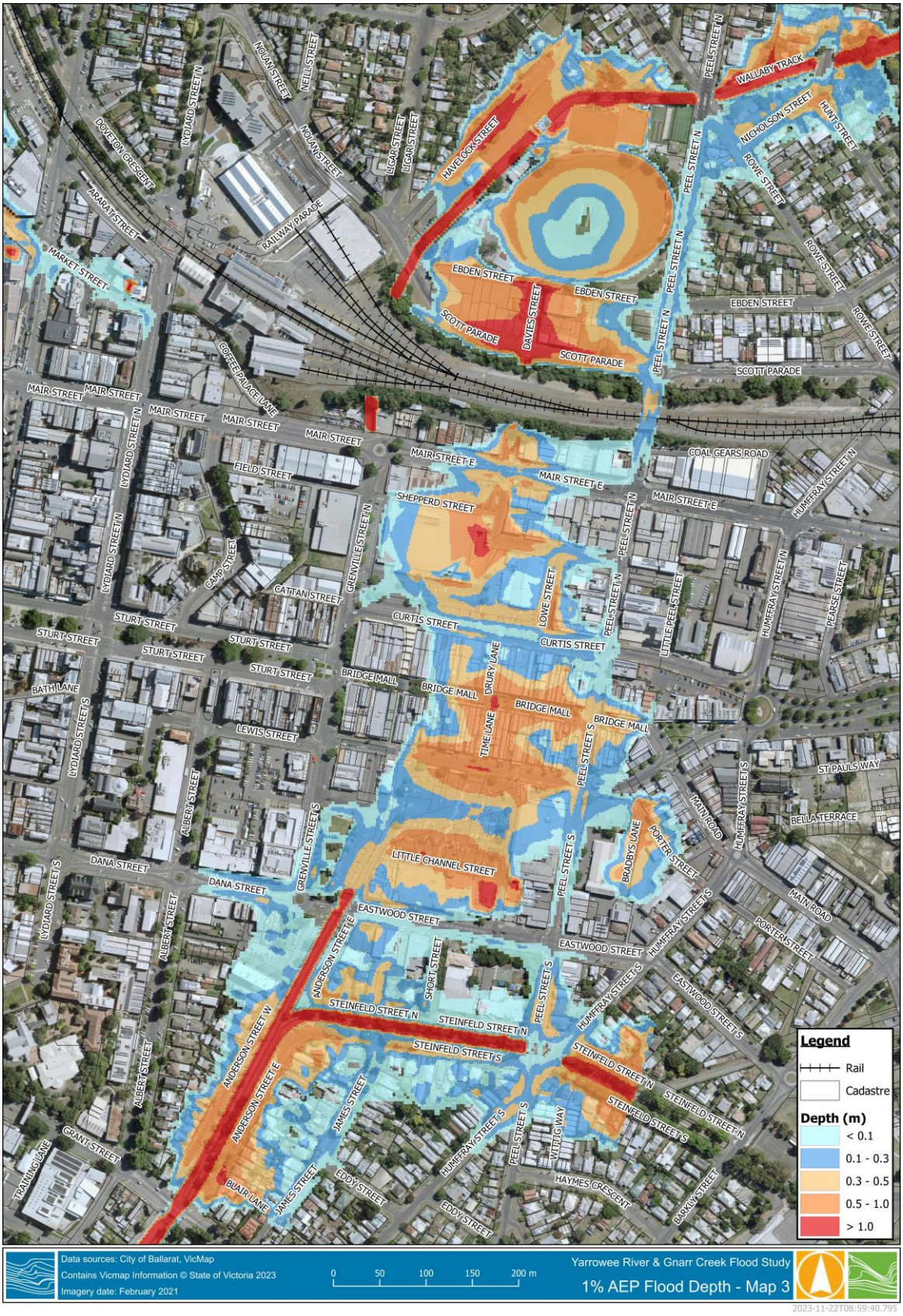


Figure 6-5 1% AEP Flood Depth – Ballarat CBD

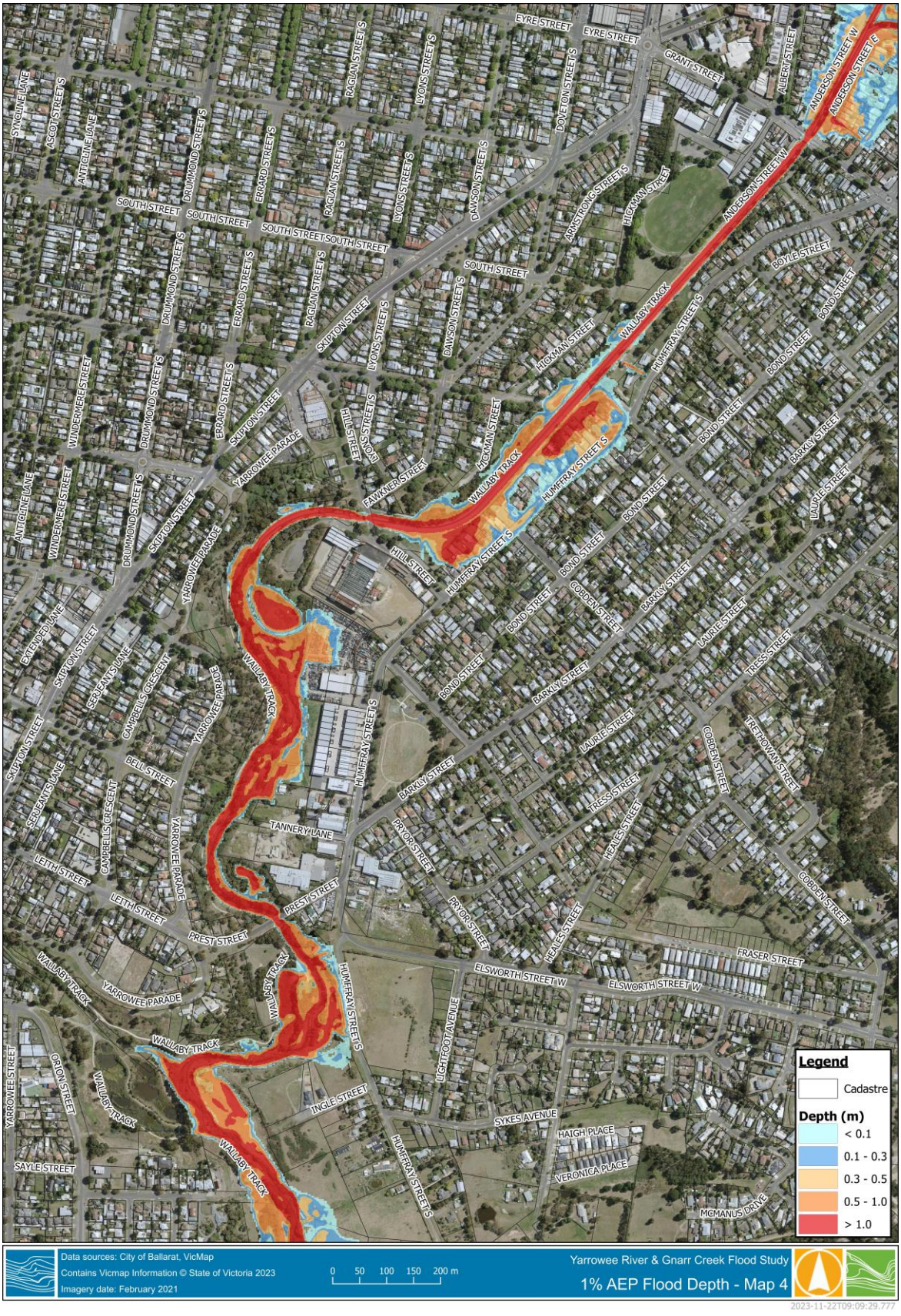


Figure 6-6 1% AEP Flood Depth – DS of Ballarat CBD

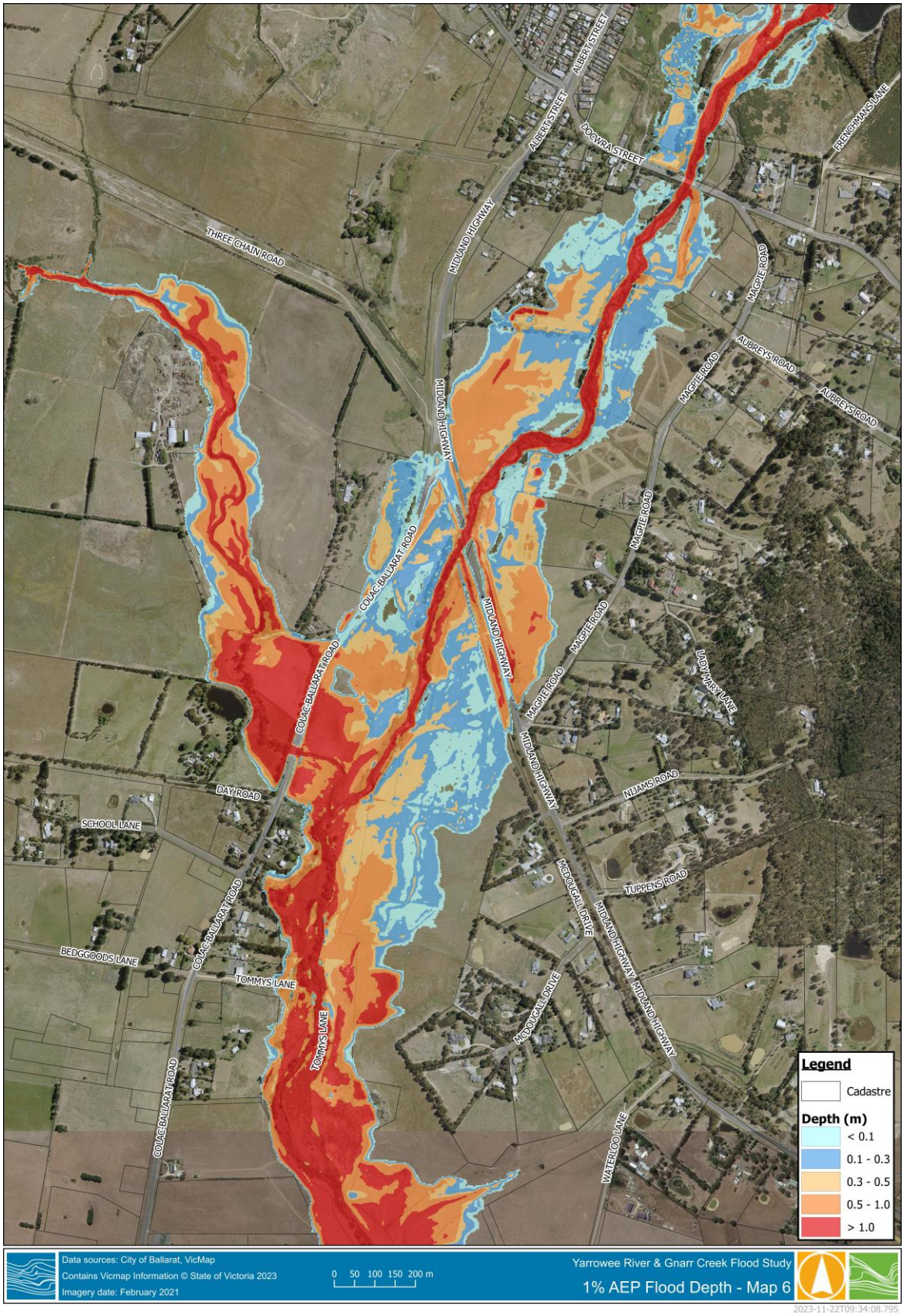


Figure 6-7 1% AEP Flood Depth – Winter Creek Confluence

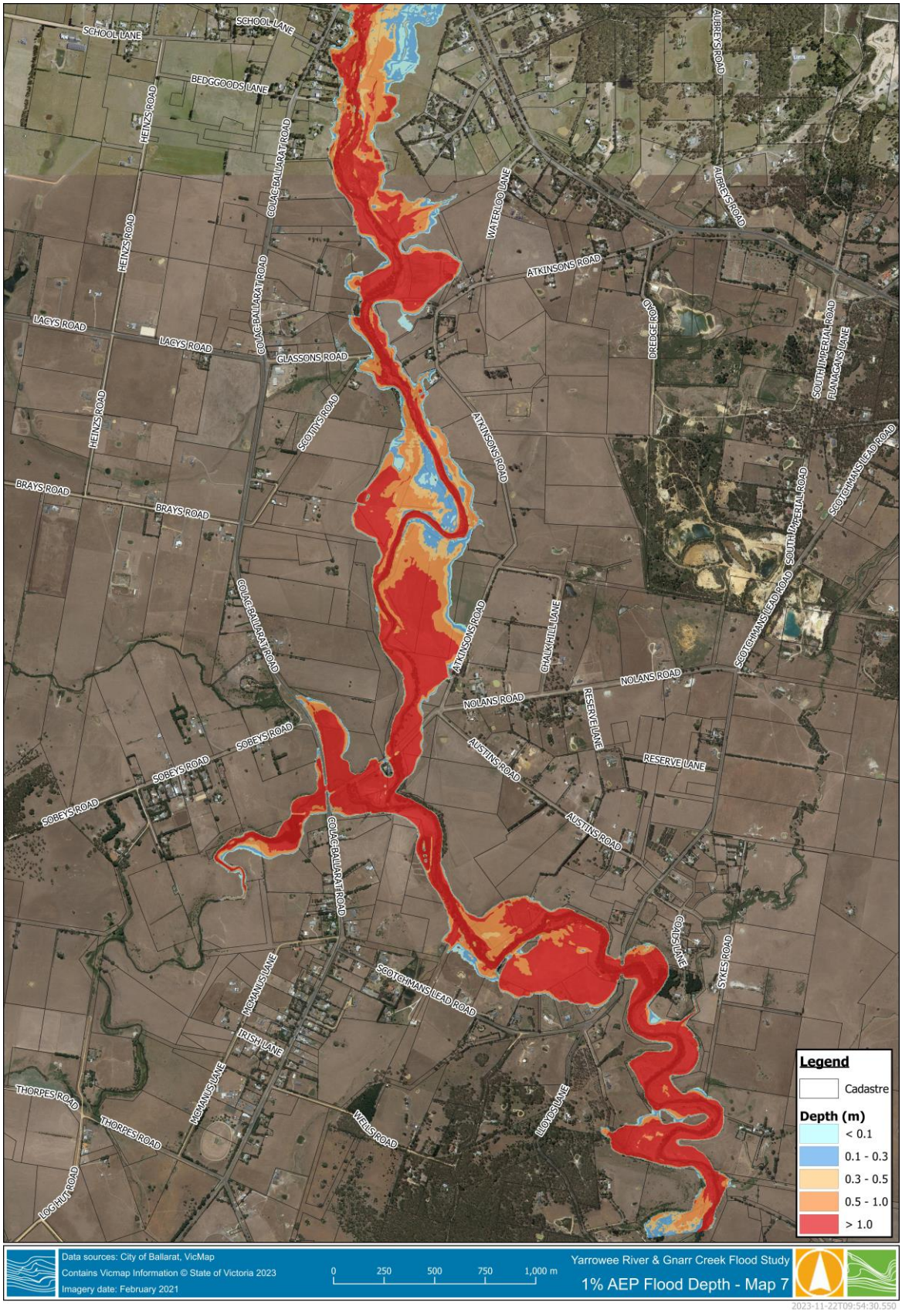


Figure 6-8 1% AEP Flood Depth – DS of Winter Creek Confluence

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