



Summary Report

Ballarat 11 Waterways Flood Study

City of Ballarat

29 July 2025



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ACKNOWLEDGEMENT OF COUNTRY

The Board and employees of Water Technology acknowledge and respect the Aboriginal and Torres Strait Islander Peoples as the Traditional Custodians of Country throughout Australia. We specifically acknowledge the Traditional Custodians of the land on which our offices reside and where we undertake our work.

We respect the knowledge, skills and lived experiences of Aboriginal and Torres Strait Islander Peoples, who we continue to learn from and collaborate with. We also extend our respect to all First Nations Peoples, their cultures and to their Elders, past and present.



Artwork by Maurice Goolagong 2023. This piece was commissioned by Water Technology and visualises the important connections we have to water, and the cultural significance of journeys taken by traditional custodians of our land to meeting places, where communities connect with each other around waterways.

The symbolism in the artwork includes:

- Seven circles representing each of the States and Territories in Australia where we do our work
- Blue dots between each circle representing the waterways that connect us
- The animals that rely on healthy waterways for their home
- Black and white dots representing all the different communities that we visit in our work
- Hands that are for the people we help on our journey



EXECUTIVE SUMMARY

The City of Ballarat is proceeding with a proposed planning scheme amendment, which will see an update to the current Land Subject to Inundation Overlay (LSIO), Floodway Overlay (FO) and Special Building Overlay (SBO) layers within the City of Ballarat Planning Scheme.

During the “11 Waterways Flood Mapping Project” (2019) waterways were modelled and mapped with the outputs intended for use in a proposed planning scheme amendment. This modelling was undertaken across a range of catchment-based studies all using a “direct inflow” modelling methodology combining a RORB hydrologic model and a TUFLOW hydraulic model for each catchment. Since 2019, the municipality has seen significant growth, altering several of the modelled catchment flooding characteristics. New LiDAR data has also become available (captured in October 2019), an update to the previously referenced datasets from 2009-2012. These changes have resulted in the need to remodel all hydraulic models previously modelled by Water Technology.

Water Technology was engaged by the City of Ballarat to update sections of the hydrology (RORB) and hydraulic (TUFLOW) models of each catchment to include changes that would impact flood behaviour and extents. Most of the major topographical changes have been accounted for in the new LiDAR dataset, and any gaps where more recent works have been completed since 2019 were overlayed with digital elevation models (DEM), where available. Modelling of climate change scenarios has also been undertaken and modelling outputs from the climate change modelling is intended to be used in a proposed planning scheme amendment in line with current state planning policy under the Victorian Planning Provisions.

Given the large-scale extent of the study area and length of time needed to undertake hydrologic and hydraulic modelling, additions to the models were limited to development/works that had been finalised/scheduled to finish by late 2023.



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1 OVERVIEW

Water Technology was engaged by the City of Ballarat to review and update the existing hydrologic and hydraulic models developed between 2017 and 2019, covering 11 waterways within the City of Ballarat municipality. Each of the studies were originally undertaken separately and completed in succession with a relatively consistent methodology, with small variations based on the specific nature of each catchment. The updates completed as part of this study focussed on the aspects of each individual catchment and was not complete update of both hydrologic and hydraulic models to the extent of developing new models. Sections of the models were updated to reflect recent development/changes in catchment behaviour with the inclusion of LiDAR captured in 2019 and each hydraulic model was updated to the latest model software release. This allowed for faster model run times and finer output grid resolution.

An overview of the review and updates completed for the hydrologic and hydraulic model for each study included:

- Hydrologic Updates (RORB)
 - Each RORB model was reviewed to identify and update Fraction Impervious (FI) and/or reach types, specifically with areas that had undergone development since the previous modelling.
 - The revised RORB models were rerun and design flows at key locations were extracted using the same approach previous adopted in 2019.
- Hydraulic Updates (TUFLOW)
 - The base terrain in each model was updated to feature the 2019 LiDAR dataset.
 - Each model was updated to the latest TUFLOW model build (2023-03-AB) and run in Heavily Parallelised Compute (HPC) solver. Doing this ensured that each model is utilising the most recent modelling approaches in the TUFLOW software package. The HPC solver allowed for model simulations using GPU graphics cards, reduce the model run times and efficiency of the numerous models and events.

Modelling of the 20%, 10%, 5%, 2%, 1% and 0.5% AEP events, as well as climate change scenarios for the year 2100 (based on Representative Concentration Pathways (RCP)4.5, 6 and 8.5) have been completed for the 1% AEP event. The catchments covered by this study include:

- Yarrowee River and Gnarr Creek
- Canadian Creek and Tributaries
- Bonshaw Creek
- Kensington Creek
- Redan Creek
- The Chase
- Warrenheip Creek and Ryan's Drain
- Little Bendigo Creek and Hit or Miss Gully

The location of these waterway's, in relation to the Yarrowee River catchment (the Study Area), is highlighted in Figure 1-1.

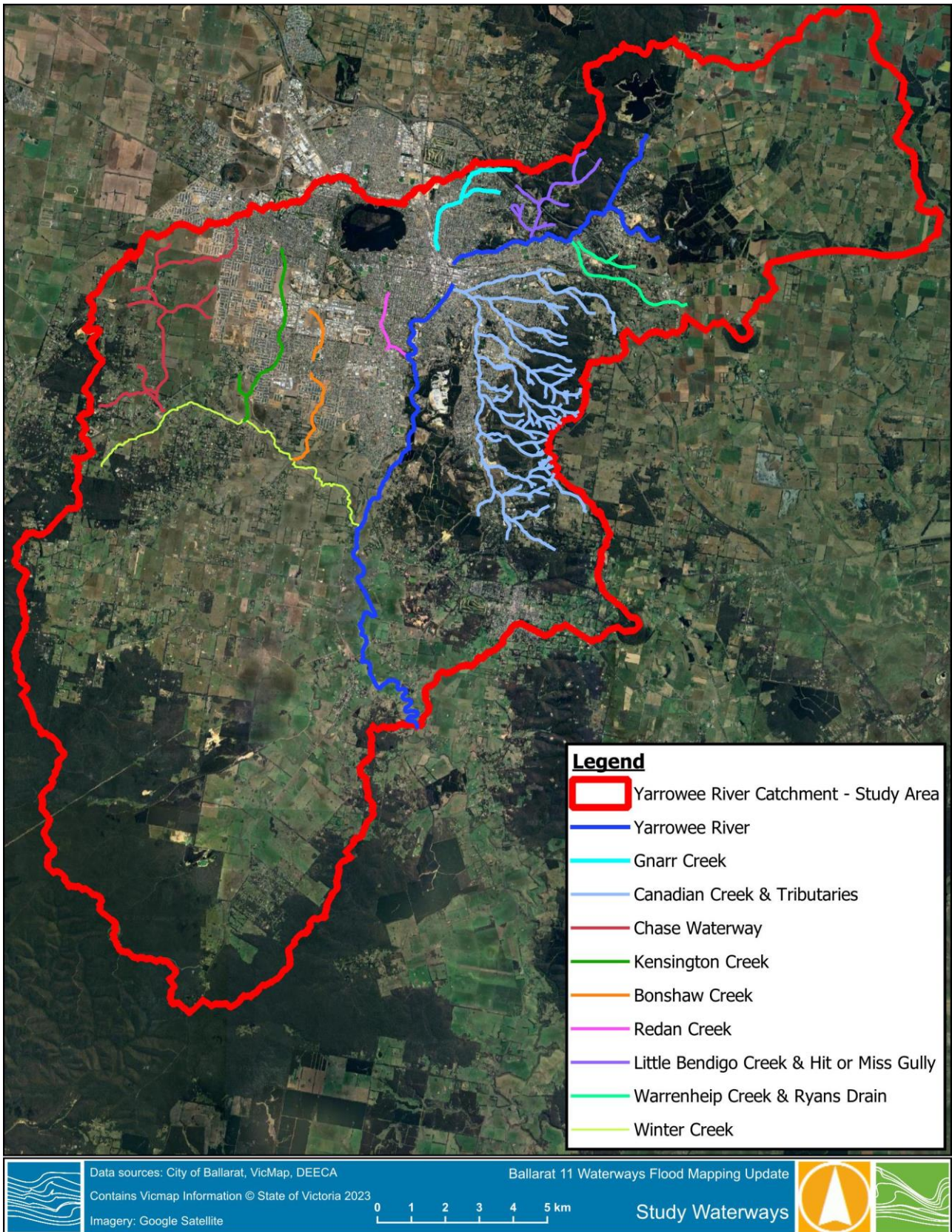


Figure 1-1 Study Waterways



2 PREVIOUS REPORTING

There have been numerous flood mapping projects previously completed across Ballarat. The modelling and mapping completed along the modelled waterways during this project, supersedes the previous studies. Many of the previous studies were undertaken using recommendations set out in Australian Rainfall and Runoff 1987¹ (ARR87) release, except for the 2019 Ballarat 11 Waterways² flood study which used Australian Rainfall and Runoff 2016 (ARR2016) recommendations. This update has adopted the same hydrological methodologies as the 2019 flood study including some of the minor changes included in the Australian Rainfall and Runoff 2019 (ARR2019) update. There are some areas where the previous mapping will still be appropriate for use, predominantly modelling completed during the Ballarat Flood Risk and Opportunity Mapping Project³ which used a direct rainfall on grid modelling approach to identify the potential for overland stormwater flooding across much of the City of Ballarat municipality.

Relevant flooding and drainage projects previously completed within the study area include:

- Canadian Creek Flood Study (Willing & Partners Pty Ltd, 1985).
- Yarrowee River Flood Study (Willing & Partners Pty Ltd, 1987).
- Yarrowee River Flood Mitigation Study. Report (Willing & Partners Pty Ltd, 1988).
- Yarrowee River and Tributaries (GHD, 1994).
- Urban Stormwater Research Project – Second Progress Report (Perera B.J.C, Maheepala U.K. & Cheung P.M., 1999).
- RORB Modelling (Tony Jones - Corangamite Catchment Management Authority, 1999).
- Stormwater management plan (The Water Group, 2002).
- Design flood estimation for Ballarat Urban Waterways (Ecological Engineering, 2004).
- Ballarat Urban Waterways Floodplain Mapping Report (Water Technology, 2007).
- Ballarat Flood Risk and Opportunity Mapping Project (Water Technology, 2014).
- Ballarat Flood Mapping Update (Water Technology, 2014).
- Bonshaw Creek Flood Investigation (Engeny, 2014).
- Canadian Creek Tributaries Flood Mapping Project (Water Technology, 2014).
- Ballarat 11 Waterways Flood Mapping Project (Water Technology, 2019)

¹ Institution of Engineers, Australian (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

² Water Technology (2019), Ballarat 11 Waterways Flood Mapping

³ Water Technology (2014), Ballarat Flood Risk and Opportunity Mapping Project



3 METHODOLOGY

3.1 Overview

This section details the methodology used to determine design flows and water levels within each catchment. The modelling and reporting were separated into two major technical components; hydrology (determining flows) and hydraulics (determining water levels, depths and extents). The hydrology was completed in the rainfall-runoff routing program RORB, while the hydraulic modelling was completed in TUFLOW.

3.2 Modelling Focus, Exclusions and Assumptions

The modelling completed during this project focused on both inundation along the main waterway and inundation of urban areas along main flow paths within each catchment. Inundation was mapped where the main waterway or pipe capacity was exceeded. Mapping excluded the following types of inundation:

Several waterways in the City of Ballarat municipality were not covered by this project. These include but are not limited to:

- Winter Creek.
- Ross Creek.
- Dog Trap Creek.
- Union Jack Creek.
- Lake Wendouree (outflow from the lake included in the Gnarr Creek & CBD study area).

Each waterway was initially modelled and mapped separately over the period 2017 - 2019. Urban development and drainage infrastructure may have been constructed since the modelling was completed; however, City of Ballarat and Water Technology have attempted to model the infrastructure in place at mid-2023 as best possible.

3.3 Third Party Review

As well as Water Technology's own internal review process, a third-party review was undertaken on three separate occasions over the course of the Ballarat 11 Waterways Flood Study Project. A further peer review has been undertaken as part of this work. These reviews are summarised as follows:

- Technical Review by DEECA (formerly DELWP) Panel (2017)
 - The hydrologic and hydraulic modelling report completed during the Kensington Creek project (the first of the waterway projects completed) was submitted for a technical review of the adopted methodology to a panel managed by the Department of Environment, Land, Water and Planning (DELWP). The purpose of the review panel is typically to review studies being completed by DELWP; however, given several studies were adopting a similar approach using the new ARR2016 guidelines, it was considered prudent to confirm the applied methodology. The reviewer found the approach to be technically sound.
- Review of Report Outputs by Neil M. Craigie Pty Ltd (2018)
 - Individual reporting outputs were submitted to Neil M. Craigie Pty Ltd for review. Recommendations were made around the consistency and clarity of reporting, as well as the inclusion or exclusion of recently built or stormwater infrastructure. In general, the reporting was determined to be of sound technical content. Changes were made to clarify the reporting for community consumption and the decision to include or exclude newly or partially constructed stormwater infrastructure was postponed until after community consultation and potential changes to model results.



- Yarrowee River Hydrological Calibration and Losses Review by Tony Ladson (2019)
 - Calibration of the Yarrowee River and Gnarr Creek hydrological model determined losses much lower than recommended by the Australian Rainfall and Runoff Datahub (2019) loss values. The hydrological model was calibrated to the Leigh River at Mount Mercer (233215) streamflow gauge. The purpose of the review was to:
 - Assess the validity of using the stream gauge, Leigh River @ Mount Mercer, to calibrate the model.
 - The appropriateness of using this gauge as guide to flood behaviour in the other catchments included in this study; and
 - The appropriateness of the determined losses used to estimate runoff and subsequent design flow hydrographs.
 - The review found that the losses recommend in the ARR Datahub are not reliable and are likely biased high for this study area and the calibration makes use of what local data is available, therefore representing a more appropriate approach until better information becomes available.
 - Since the completion of Losses review by Tony Ladson in 2019, Melbourne Water and DEECA (formerly DELWP) commissioned a study to benchmark the performance of ARR2019 in the state of Victoria. The outcome of the assessment revealed that the use of the standard ARR2019 design inputs for Victoria would likely result in an underestimation of design flood peak flows. This indicates that if regional design information is relied upon without undertaking any local calibration, then the results of design flood estimates are likely to be lower than actual.
- Peer Review of Modelling Approaches by Stantec (2024)
 - The hydrological and hydraulic models of each study were submitted to Stantec for peer review to give opinion and relevant recommendations on the completed studies. The peer review found that the approach adopted for measuring runoff in the hydrological model varied to what would typically be found in models post 2019. The recommendation by Stantec was to undertake a sensitivity analysis on the Bonshaw Creek comparing how the two methodologies influence flood levels and extents for the 1% AEP event.
 - Further sensitivity analysis undertaken showed that the number of inundated properties was marginally affected. As a result, the previously adopted approach was maintained.
 - The review also found several recommendations to enhance the integrity of the hydraulic models. These recommendations were adopted and incorporated into the final models.



3.4 Hydrology

3.4.1 Overview

The studies completed can be separated into calibrated and uncalibrated RORB models. The only project with sufficient streamflow data to inform a model calibration was the Gnarr Creek and the Yarrowee River catchment.

Section 3.4.2 details general RORB model construction methodology and parameter choices for design modelling, while Section 3.4.2.4 specifically discusses calibration of the Gnarr Creek and Yarrowee River RORB model. The calibrated RORB model was used to select design loss parameters adopted for the remaining ungauged catchments.

3.4.2 RORB Model Construction and Parameters

RORB uses several key data inputs to produce results, these include:

- Sub catchment and reach delineation
- Fraction Impervious (FI).
- Rainfall depth information.
- Rainfall losses.
- Rainfall temporal pattern.
- Rainfall spatial pattern.
- k_c – RORB model routing parameter.
- m – RORB model parameter describing the degree of catchment non-linearity.

Each of these inputs are discussed in the following sections.

3.4.2.1 Catchment and Reach Delineation

Each catchment was delineated based on the available Light Detection and Ranging (LiDAR) topographic data captured in 2019, the exact date of the data capture is dependent on the catchment modelled. The LiDAR data was processed in the ESRI terrain modelling software ArcHydro, delineating the broader project area catchment into various sub-catchments and associated drainage reaches. An example of this is sub-catchment and reach delineation for Bonshaw Creek, as shown in Figure 3-1.

The objective of the delineation was to ensure a relatively even distribution of similar sized sub-catchments and a detailed representation of major flow paths along each waterway. Generally, three sub-catchments are used prior to each inflow point into the hydraulic model. However, in some areas a single sub-catchment inflow was used, this was usually to represent direct catchment inflows along the main waterway. In these specific cases, the single sub-catchment flow was assessed with the main waterway flow to ensure there was not a significant spike in flow rates.

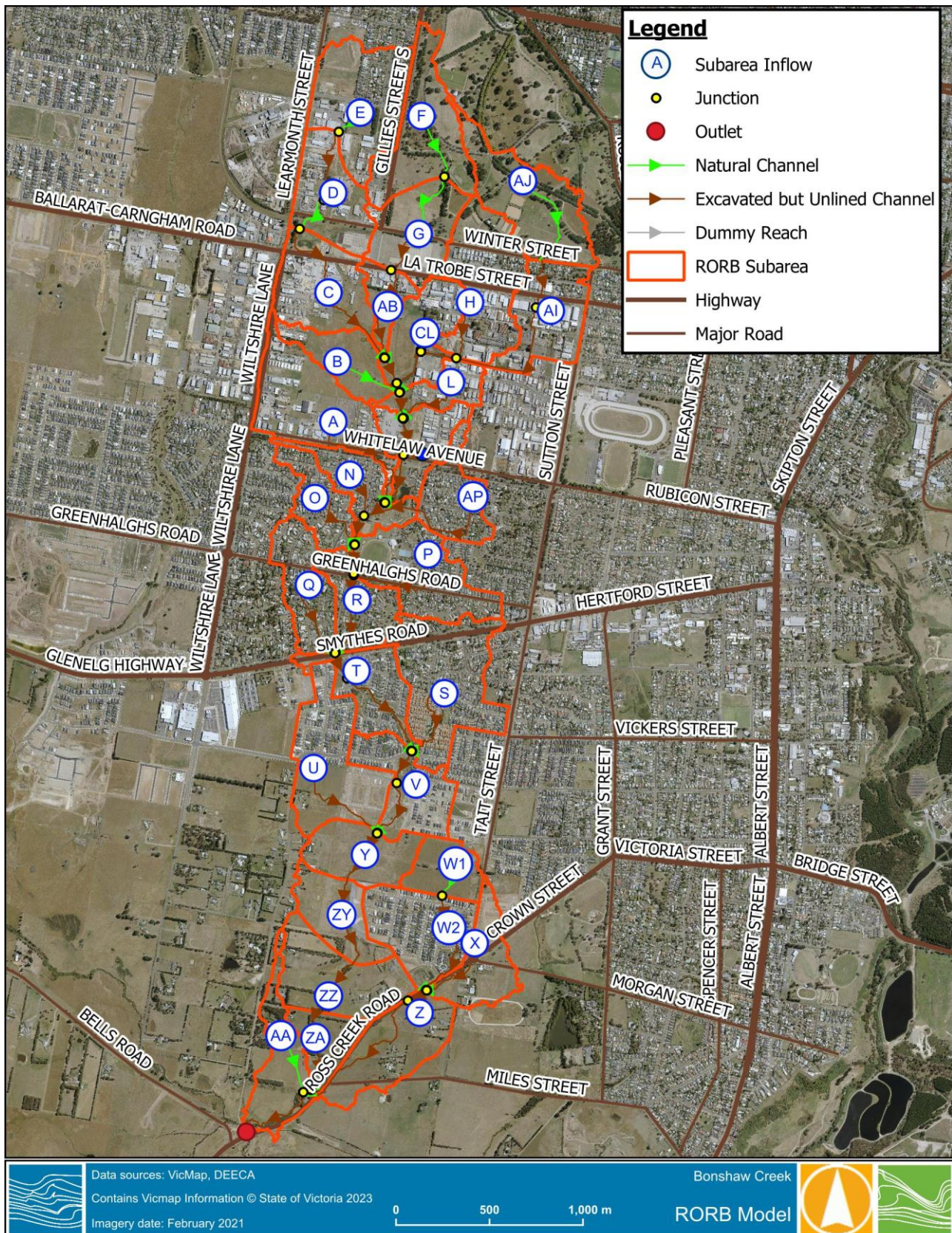


Figure 3-1 Example RORB Sub-Catchment and Reach Delineation – Bonshaw Creek



3.4.2.2 Fraction Impervious

The estimated impervious surface within each sub-catchment was represented by a Fraction Impervious (FI) value. The varying FI throughout each sub-catchment was determined using both recent satellite and aerial imagery and the City of Ballarat Planning Zones. A range of land uses were adopted throughout each catchment, with the main three being open space (including farming and greenspace), residential and industrial. Roadways and carpark areas were also delineated. Table 1 shows the adopted FI value for each land use. To determine the most appropriate FI value for each sub-catchment, an area weighted average was used. The FI values also consider future development as advised by City of Ballarat.

Typically Farming Zone would have a FI of 0; however, given the number of constructed drains, roads and buildings identified within the farming area, 0.1 was determined as a more appropriate value.

Table 1 Adopted FI Values for the Bonshaw Creek RORB Model

Land Use Description	Fraction Impervious
Business/Commercial/Industrial Zone	0.9
Road Reserves	0.7
Residential Zones	0.7
Rural Living Zones	0.2
Farming Zones	0.1

3.4.2.3 Rainfall Depths

Design rainfall depths for each catchment were determined with the use of the ARR2019 recommendations. Areal reduction factors and temporal patterns were sourced from the ARR data hub⁴, while Intensity Frequency Duration (IFD) rainfall depths were sourced from the Bureau of Meteorology (BoM) online IFD tool⁵. Both datasets were based on the coordinates of each catchment centroid.

3.4.2.4 RORB Kc

Kc is the routing parameter in RORB which attenuates the flow along model reaches. In gauged catchments the kc value is one of the major parameters used to calibrate the RORB model, varying peak flow and timing. In ungauged catchments, there are several ways to estimate the kc value. These include empirical equation-based estimates of kc and the adoption of a kc value based on nearby calibrated RORB models. There are several different equation-based estimates available for Victoria, these are outlined in Table 2, with the equations largely based on catchment area (A) and average reach distance (D_{av}).

Table 2 Empirical equation based Kc estimates

Description	Equation
Victoria (Mean Annual Rainfall <800mm)*	$k_c = 0.49 \times A^{0.65}$
Victorian based data (Pearse et al, 2002)	$k_c = 1.25 \times D_{av}$
Australian based data (Dyer, 1994)	$k_c = 1.14 \times D_{av}$
Australian based data (Yu, 1989)	$k_c = 0.96 \times D_{av}$

*Ballarat has a mean annual rainfall of 689.9 mm

⁴ <http://data.arr-software.org/>

⁵ <http://www.bom.gov.au/water/designRainfalls/revised-ifd/?year=2016>



3.4.2.5 Calibration of Yarrowee River and Gnarr Creek Model

Modelling Approach

Calibration of the Gnarr Creek and Yarrowee River RORB model was completed using the Leigh River at 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 was extended to the gauge. Figure 3-2 shows the Mount Mercer RORB model catchment extent.

The available flow record for the Leigh River at Mount Mercer gauge extends from 1957 to current day.

The kc and loss values determined during the model calibration were adopted during design modelling along with ARR2019 rainfall IFD data, as outlined in Section 3.4.2.3.

Flood Frequency Analysis (FFA) of annual peak flows was used to establish design peak flows at the streamflow gauge, as discussed in Section 3.4.2.4.

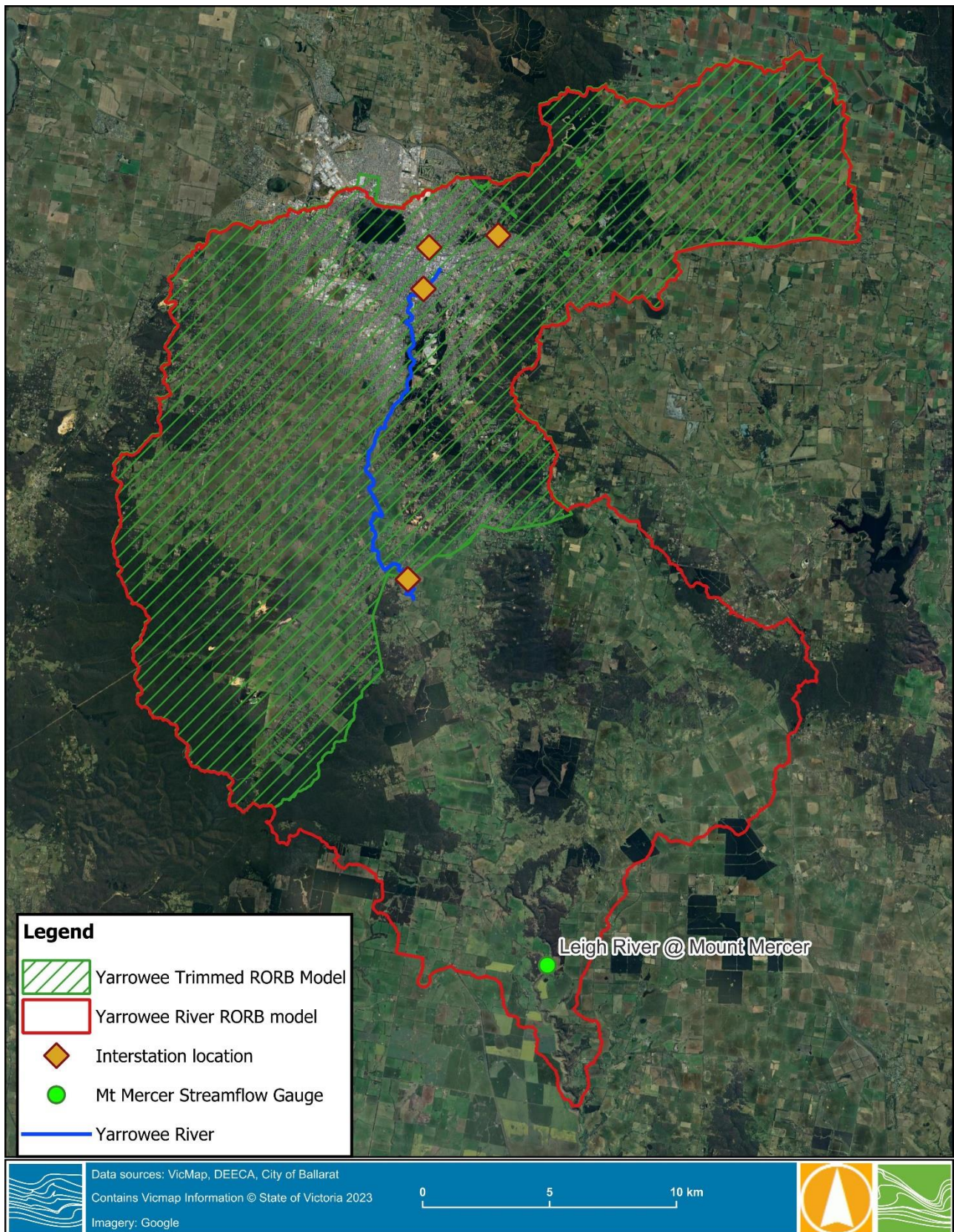


Figure 3-2 Yarrowee/Leigh River Catchment to Mount Mercer for RORB Calibration



Calibration Events

Three events were used for calibration of the Gnarr Creek and Yarrowee River RORB model; August 2010, January 2011 and September 2016. These events were chosen because of their varying magnitude and relatively recent occurrence, limiting catchment changes since the events. Temporal and spatial rainfall patterns were generated from local rainfall gauge records for each event and the outflow hydrographs from the RORB model were then compared to recorded stream gauge records at Mt Mercer.

Calibration of RORB Parameters

The Gnarr Creek and Yarrowee River RORB model was run using an initial loss/continuing loss model. The RORB kc, initial loss and continuing losses were fitted for each calibration event to give the best fit to the observed hydrograph at Mt Mercer. The routing parameter kc was calculated from the empirical equations outlined earlier in Section 3.4.2.4. The exponent m was set to 0.8 as per the RORB recommended value.

The final calibration model parameters for each event are summarised in Table 3. The fit of the RORB modelled hydrographs to the gauged hydrographs for August 2010, January 2011 and September 2016 are shown in Figure 3-3, Figure 3-4 and Figure 3-5 respectively. The shape, peak and timing of the fitted hydrographs generally agrees well with gauged flows for all events.

The initial losses tend to be higher than expected design values; however, with an initial loss of 150 mm for the January 2011 event. The losses for this study aligned closely with the calibration losses adopted in the Leigh River Flood Study⁶ for the 1973 and 2011 flood events. The variable losses for each interstation area were selected to provide not only a match to the streamflow hydrograph at Mount Mercer but also to match observed flood levels at various locations throughout the catchment in the TUFLOW model.

Table 3 RORB Calibration Parameters – Mount Mercer

RORB Model Interstation	Kc	m	IL (mm)	CL (mm/hr)
September 2016				
Yarrowee at Little Bendigo Confluence	30.0	0.8	5.0	2.0
Gnarr Creek	2.9		9.90	1.65
Ballarat CBD	6.7		12.40	1.65
US Mt Mercer	30.0		40.0	2.0
January 2011				
Yarrowee at Little Bendigo Confluence	30.0	0.8	5.0	1.0
Gnarr Creek	2.96		9.9	1.65
Ballarat CBD	6.67		9.9	1.65
US Mt Mercer	30.0		150	1.0
August 2010				
Yarrowee at Little Bendigo Confluence	30.0	0.8	1.0	0.0
Gnarr Creek	2.96		1.0	1.65
Ballarat CBD	6.7		1.0	1.65
US Mt Mercer	30.0		30.0	1.0

⁶ Corangamite CMA (2017), Leigh River Flood Study

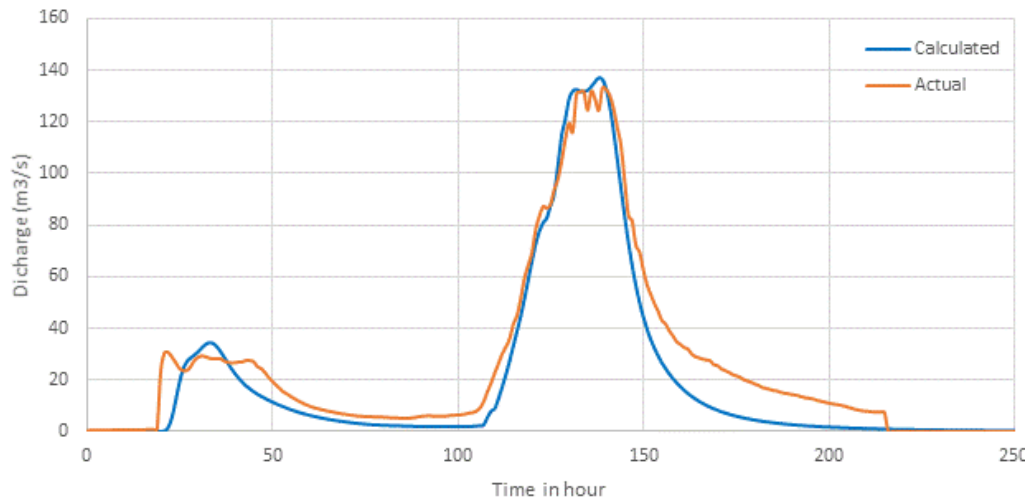


Figure 3-3 Modelled and Gauged Hydrographs – September 2016

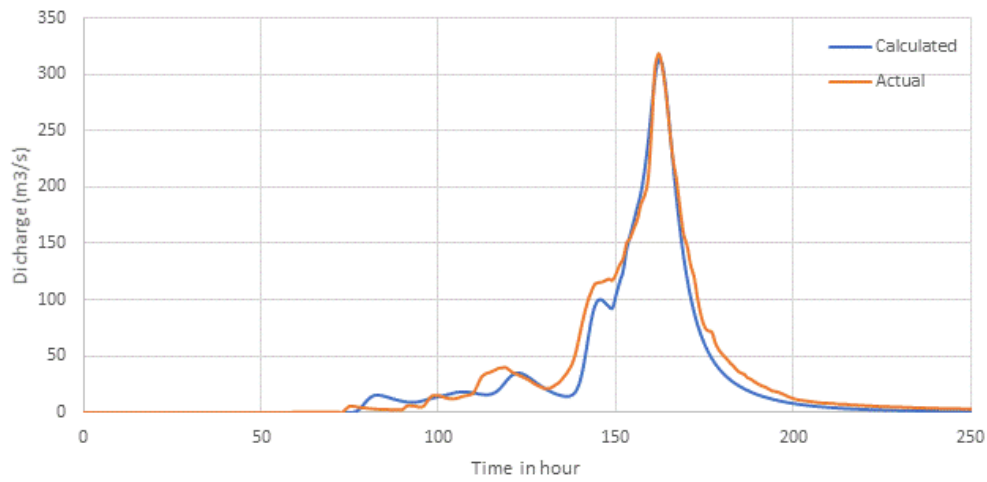


Figure 3-4 Modelled and Gauged Hydrographs – January 2011

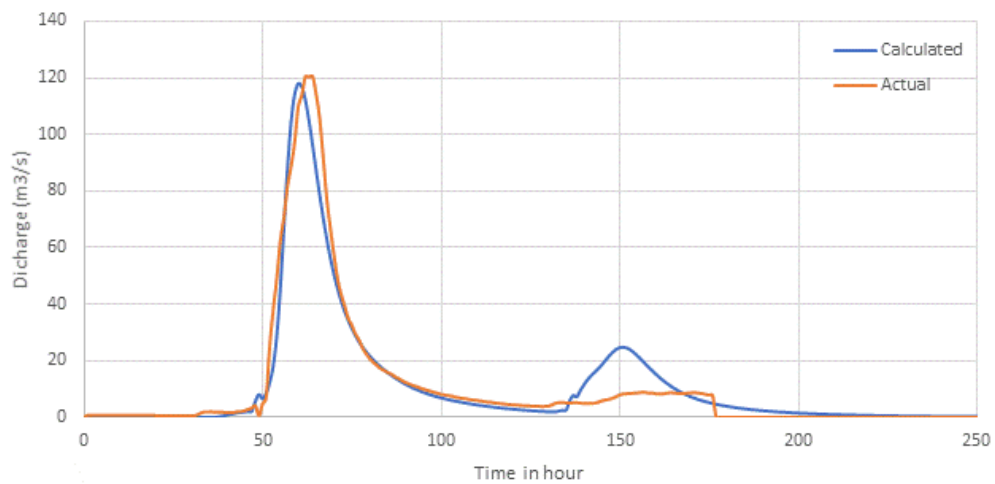


Figure 3-5 Modelled and Gauged Hydrographs – August 2010



3.4.3 Design Modelling

3.4.3.1 Overview

Monte Carlo and Ensemble analysis can be used to determine the design peak flows at key locations within each project catchment. The flow chart outlined in Figure 3-6 demonstrates the modelling process used to determine the representative design event to be simulated in the hydraulic model.

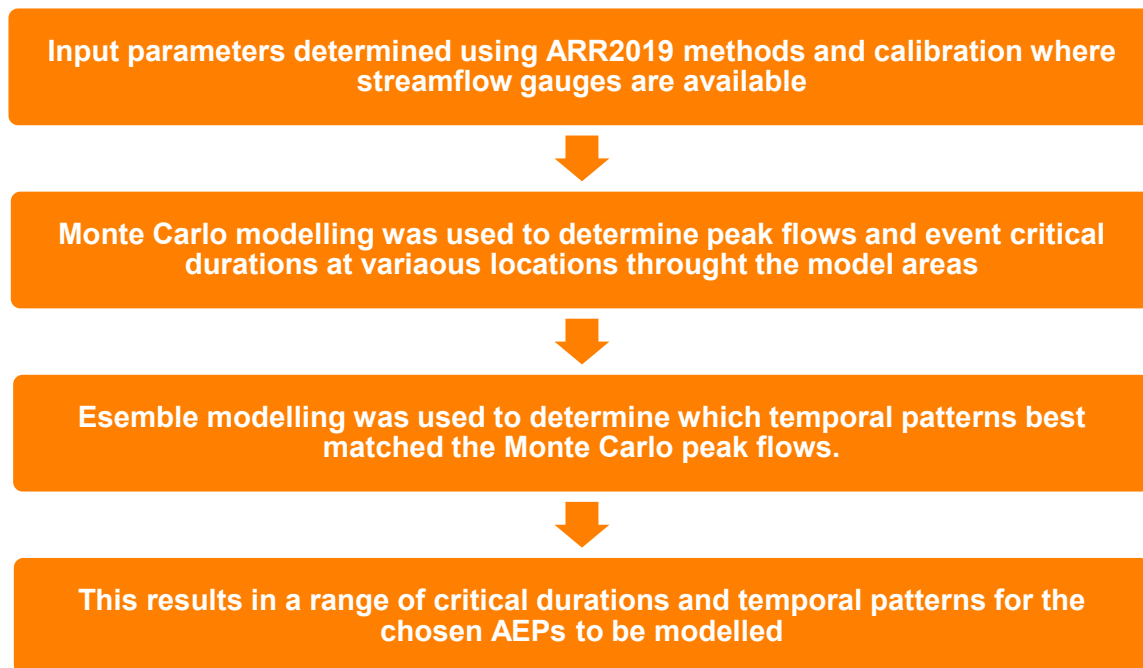


Figure 3-6 Design Modelling Process Diagram

3.4.3.2 Monte Carlo Analysis

The RORB Monte Carlo analysis was undertaken for each waterway catchment. During a Monte Carlo analysis, the RORB model is run 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. Key locations were selected within each catchment to output data from the RORB model.

3.4.3.3 Ensemble Analysis

The RORB model was also run using the Ensemble Analysis, using the determined k_c values for each catchment and calibrated losses. The RORB Ensemble Analysis was run for all 10 ARR2019 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 throughout each project area.

To reduce the potential number of hydraulic model runs, critical durations and temporal patterns at key locations for design events were chosen that closely matched the Monte Carlo results.



3.4.3.4 Design Modelling Verification

Flood Frequency Analysis

As discussed in Section 3.4.2.5, a Flood Frequency Analysis (FFA) at the Leigh River at Mt Mercer streamflow gauge was used to verify the adopted RORB model design parameters. The FFA was undertaken using an annual maximum peak flow series within each water year (1 July to 30 June⁷). The extracted annual series was checked for missing data to ensure the peak flow within each year was captured. Review of the data indicated the November 1978 event had an unusually flat top that may indicate an equipment malfunction. This was also reported in the Leigh River Flood Study, where the CMA study estimated a peak flow of 352 m³/s. The amended peak flow was included in the current analysis.

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 ARR2019.

A continuous record of flow and water level data exists at the gauge, available from 1956 to 2018 (at the time of the initial study), 63 years of complete annual record. The annual peak flow series was extracted from the gauge record and is listed in Table 4.

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 m³/s, removing 26 years from the 63-year record during the censored assessments. A Log Pearson Type 3 (LP3) distribution was chosen to fit best, with Generalised Extreme Value (GEV), Generalised Pareto GP) and Gumbel distributions all tested.

Table 4 Summary of Annual Peak Flows for Mount 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 [#]	88
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	2024 [#]	19
1969	22	1983	112	1997	13	2011	313		

* Amended based on Leigh River Flood Study

[#]Data not used in FFA

⁷ <http://www.bom.gov.au/water/awid/product-water-status-water-market-reports.shtml>



An LP3 probability distribution of the annual series resulted in a 1% AEP peak flow estimate of 477 m³/s at Mount Mercer, as shown in Figure 3-6.

Table 5 Summary of FFA Estimate 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

Design Flow Verification

To confirm the design parameters to be adopted, the Gnarr Creek and Yarrowee River RORB model design peak flows were compared to those determined in the FFA. The RORB modelling adopted the parameters as shown in Table 6. The k_c and continuing losses were adopted from the calibration, with the continuing loss also consistent with the calibration. The initial loss of a storm can vary depending on antecedent catchment conditions; therefore a design initial loss was selected to be consistent with values from ARR2019 as well as a value that provides suitable alignment between the RORB model and the FFA design flows.

A comparison of the Gnarr Creek and Yarrowee River RORB model and FFA determined flows at Mount Mercer is shown in Table 7. The flows match very closely, verifying the adopted design RORB model parameters with the flood frequency analysis.

Table 6 Gnarr Creek and Yarrowee River Adopted RORB Model Parameters at Interstation's for Design Flood Modelling

Parameter	Adopted value			
	Yarrowee at Little Bendigo Creek	Gnarr Creek	Ballarat CBD	US outlet
m	0.8			
k_c	30	2.96	6.70	30
Median initial loss (mm)	25			
Continuing loss (mm/h)	2.0	1.65	1.65	2.0

Table 7 Comparison of Peak Flows at Mount Mercer

AEP	FFA	RORB	Difference	Difference
	(m ³ /s)			%
10%	214	235	21	9%
5%	290	301	11	4%
2%	395	393	-2	-1%
1%	477	473	-4	-1%

The k_c and m parameters adopted for design modelling in each study area is outlined in Table 8, it should be noted calibration data was available for the Yarrowee River and Gnarr Creek catchment which resulted in a



calibrated RORB model and determination of k_c . This was completed separating the catchment into four interstation areas.

Table 8 RORB Model Parameters for each Catchment

Catchment		K_c	m
Bonshaw Creek		3.39	0.8
Kensington Creek		5.60	
The Chase Waterway		6.10	
Redan Creek		5.60	
Warrenheip Creek and Ryans Drain		3.39	
Little Bendigo Creek and Hit or Miss Gully		3.39	
Canadian Creek and Tributaries	Canadian Creek	14.76	
	Tributaries	8.46	
Yarrowee River and Gnarr Creek	Yarrowee US Little Bendigo Creek Confluence	30.00	
	Gnarr Creek	2.96	
	Ballarat CBD	6.70	
	US Mt Mercer	30.00	

ARR Data Hub Regional Design Losses

A review of the ARR Data Hub Design losses for the study area was undertaken as part of the Gnarr Creek and Yarrowee River study. The regional losses were determined using ARR2019 Book 5, Chapter 3 methods¹⁰. This included both mapped regional estimates and equation-based estimates. The project area is in Region 3 for loss prediction equations, (Book 5, Chapter 3, Figure 5.3.16), and shown in Figure 3-7.

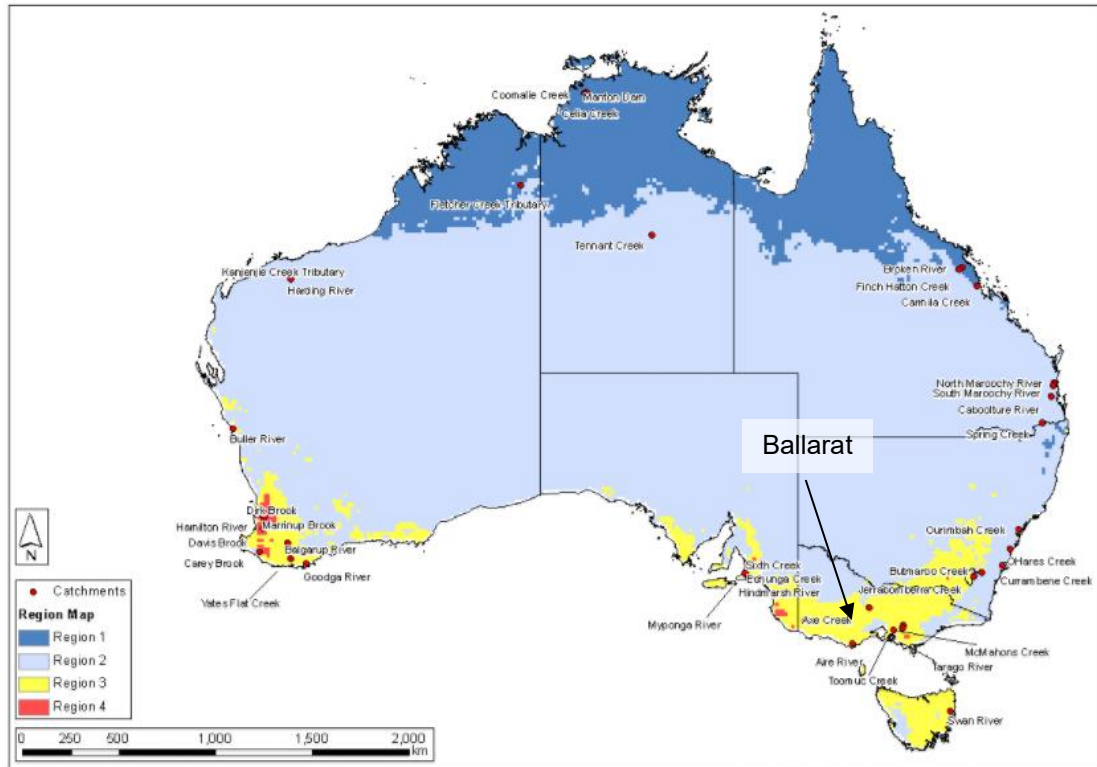


Figure 3-7 Regions Adopted for Loss Prediction Equations

IL_s (Storm Initial Loss) and CL (Continuing Loss) equations are outlined below.

$$IL_s = -1.57 * s0_{wtr} + 0.14 * DES_{RAIN_{24HR}} + 18.8$$

$$CL = 0.03 * DES_{RAIN_{24HR}} + 0.06 * SO_{max} + 5.1$$

Where:

IL_s is the storm Initial Loss (mm)

CL is the Continuing Loss (mm/h)

s0_{wtr} is the soil moisture in the surface store in winter season (mm)

DES_{RAIN_24HR} is the design Rain Intensity (I24,50) (mm)

SO_{max} is the maximum storage of the surface soil layer (mm)

Based on median input values these equations determined an ILs value of 27.5 mm and a CL of 3.1 mm/hr.

ARR2019, Book 5, Chapter 3, Figure 5.3.18 and Figure 5.3.19 also outline median ILs and CL values of 30 mm and 6 mm/hr respectively for the region, as shown in Figure 3-8 and Figure 3-9.

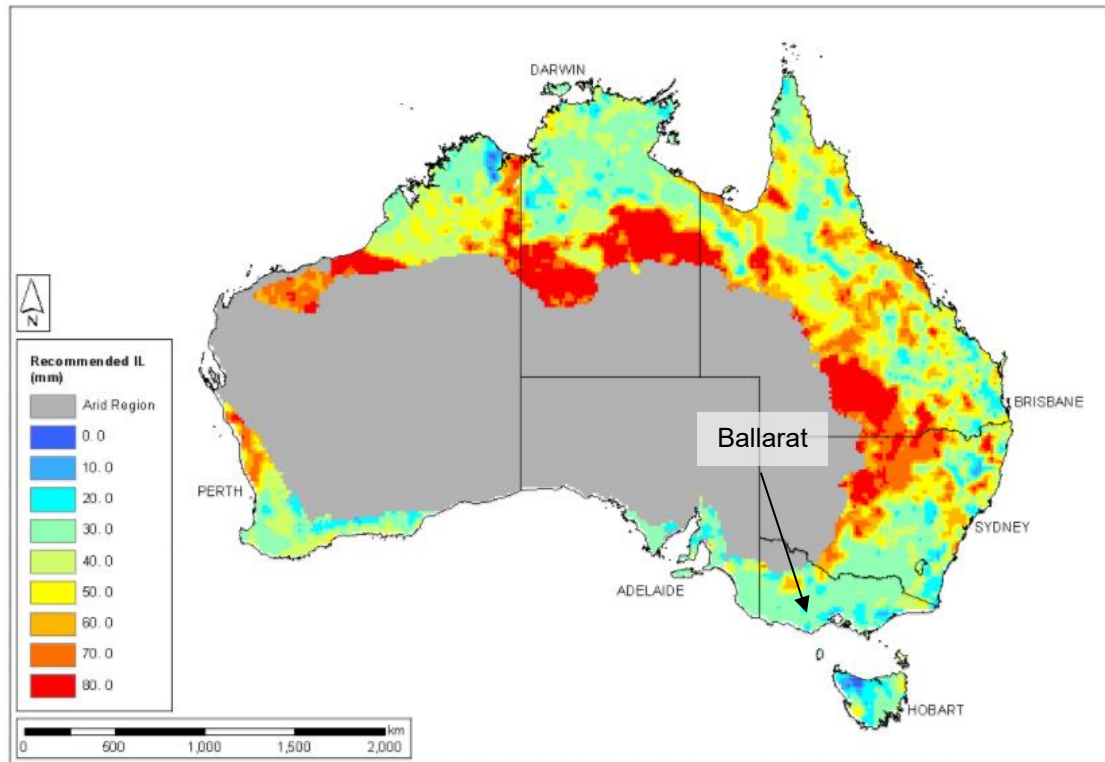


Figure 3-8 ARR Recommended Median ILs Values

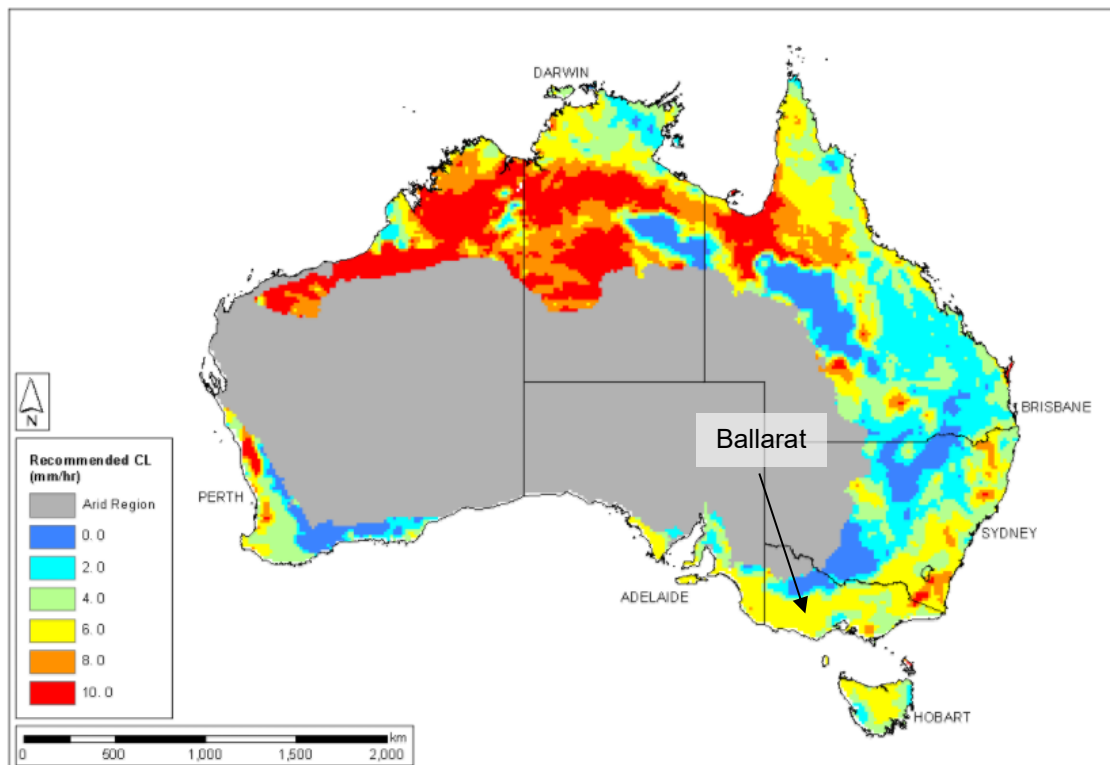


Figure 3-9 ARR Recommended Median CL Values



To ensure the complete storm design losses were compatible with the burst rainfall from the Bureau of Meteorology, the pre-burst rainfall depth was subtracted from the IL_s (Storm Initial Loss). The ARR Data Hub gives a median pre-burst rainfall depth of 1.3-4.1 mm for events from 50% AEP to 1% AEP for the three-hour duration. This results in a final median loss of between 26.2 mm and 23.4 mm using the upper and lower estimates of IL_s and pre-rainfall loss.

CL values must be factored up for models running at a timestep of less than 1 hour, in this case the model timestep was 5 mins. This corresponds with a 1.5 factor increase as outlined in ARR2019, Book 5, Chapter 3, Figure 5.3.29. This results in a continuing loss of 4.65 mm/hr.

Given the close match between the recommended initial loss value and the calculated values, the ARR recommended initial loss value was adopted.

The ARR online datahub suggests the use of 24 mm initial loss and 4.5 mm/hr continuing loss.

Ungauged Catchments

Following the release of ARR2019, DELWP (now DEECA) commissioned a study with Melbourne Water to validate the performance of datahub values in the state of Victoria. A summary of the Victorian Specific Information was added to the ARR datahub page⁸ where six methods of determining design losses estimates were listed out in order of defensibility. These are listed below.

1. *Reconciliation with at-site flood frequency quantiles*: initial and continuing losses are varied within their expected range to achieve a reasonable level of agreement between estimates derived from rainfall-based modelling and flood frequency analysis.
2. *Reconciliation using within-catchment transposed flood quantiles*: streamflow observations are commonly available at gauging stations upstream or downstream of the site of interest, and flood quantiles derived from these sites can be transposed to the site of interest and used for reconciliation as described in approach 1.
3. *Event-based calibration*: continuing losses obtained from calibration of historical events provide some indication of typical design values, noting that past historical events are biased towards wet catchment conditions; initial losses from historical events are highly variable and information from a small sample of events are of low utility (and therefore some form of reconciliation with other sources of information is recommended).
4. *Reconciliation using nearby catchment transposed flood quantiles*: regional flood quantiles derived using RFFE and other procedures (Section 3, Book 3, ARR2019) can be used for reconciliation as described in approach 1.
5. *Transposition of losses*: initial and continuing loss estimates validated on nearby catchments which are considered to be hydrologically similar.
6. *Regional losses (ARR Data Hub)*: unmodified initial and continuing loss estimates obtained from the Data Hub losses can be adopted in data poor areas, noting that in loss region 3 these should be combined with 75th percentile pre-burst values.

The Gnarr Creek Yarrowee River model could be said to have adopted a combination of method 1 and 3. For the ungauged catchments which ultimately outfall to the Yarrowee River a design initial loss of 24 mm was adopted, this is consistent with the initial loss adopted in the calibrated design modelling of the Yarrowee River and Gnarr Creek model. For the design continuing loss, the ungauged catchments all adopted a loss of 2 mm/hr, consistent with that of the calibrated and verified design modelling of the Yarrowee River and Gnarr

⁸ Victorian Specific Information from ARR Datahub accessed from https://data.arr-software.org/vic_specific



Creek model. This approach was reviewed as part of the 2019 Tony Ladson third party review and incorporates method 2 in preference to the adoption of method 6 (ARR data hub regional losses).

3.4.4 Climate Change Assessment

The impact of increased rainfall intensity associated with climate change was investigated for the 1% AEP event, with three RCP (Representative Concentration Pathway) scenarios modelled:

- Projected flows to 2100 under RCP 4.5
- Projected flows to 2100 under RCP 6
- Projected flows to 2100 under RCP 8.5

These RCP's are models that predict the potential climate in the future due to CO₂ emissions and the possible reduction in atmospheric concentration through this century. Multiple scenarios are available to model, each representing a global rise in temperature that is linked to the implementation of climate policies across the world. A brief overview of the predicted global temperature increases for each RCP is as follows:

- RCP 4.5
 - Global temperature rise of between 1.7 and 3.2°C
- RCP 6
 - Global temperature rise of between 2.0 and 3.6°C
- RCP 8.5
 - Global temperature rise of between 3.2 and 5.4°C

Current projections from the ARR2019 Data Hub only go up to the year 2090, meaning projected flows to 2100 needed to be extrapolated. Recommended climate change projection for the years 2030 to 2090, and the linearly extrapolated factors for 2100, are shown in Figure 3-10 and Table 9.

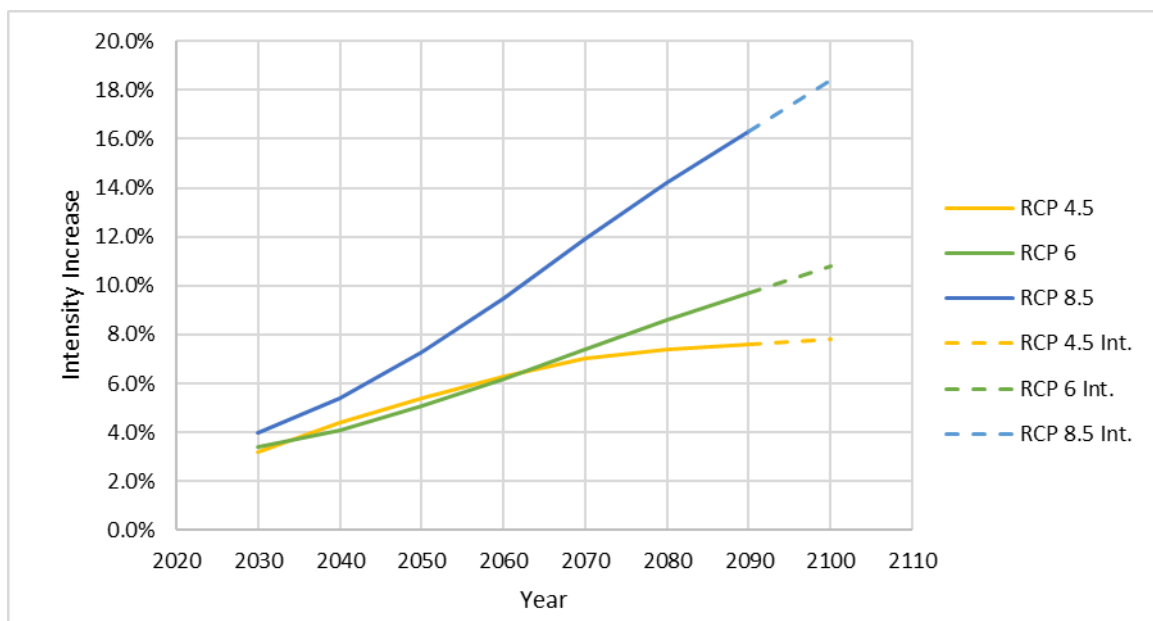


Figure 3-10 Extrapolation of Rainfall Intensity for Climate Change



Table 9 Rainfall Intensity Increase for the Bonshaw Creek Under Climate Change Factors

Projected Year	RCP 4.5	RCP 6	RCP 8.5
2030	3.20%	3.40%	4.00%
2040	4.40%	4.10%	5.40%
2050	5.40%	5.10%	7.30%
2060	6.30%	6.20%	9.50%
2070	7.00%	7.40%	11.90%
2080	7.40%	8.60%	14.20%
2090	7.60%	9.70%	16.30%
2100	7.80%	10.80%	18.40%

3.5 Hydraulics

3.5.1 Overview

Model runs were performed with a Heavily Parallelised Compute (HPC) solution scheme using the 2023-03-AB build of TUFLOW. HPC technology enables 2D models to utilise the parallel processing ability of GPU graphics cards, with many thousand processors operating in unison, significantly speeding up simulation run times compared to TUFLOW Classic. Sub-Grid-Sampling (SGS) was included for two of the study areas, Redan Creek and Yarrowee River/Gnarr Creek. These studies included SGS modelling as they both feature extensive constructed channels within their catchments. The Canadian Creek and Tributaries model also features and extensive network of constructed channels, however, its channels have been modelled using cross-sections and a 1D network.

Design flood modelling included the 20%, 10%, 5%, 2%, 1% and 0.5% AEP events with the inclusion of climate change scenarios for the year 2100 under RCP 4.5, RCP 6 and RCP 8.5 for the 1% AEP event.

3.5.2 Boundary Conditions

3.5.2.1 Model Inflows

Each TUFLOW model contained multiple inflow locations. Inflow regions simulated flow into the main waterway or key channels within the catchment and/or directly into stormwater pits. Inflows were extracted from each RORB model at print locations. An example of how this was carried out is shown in Figure 3-11 and Figure 3-12, showing the inflow locations within Upper Bonshaw Creek and Lower Bonshaw Creek model areas.

3.5.2.2 Model Outflows

Each hydraulic model had at least one hydraulic outflow boundary at the end of the main waterway, or at the confluence to another waterway. Outflows were modelled as height-discharge boundaries (HQ), these boundaries allow water to exit the model based on a stage discharge curve generated by TUFLOW based off the floodplain or channel slope exiting the model.

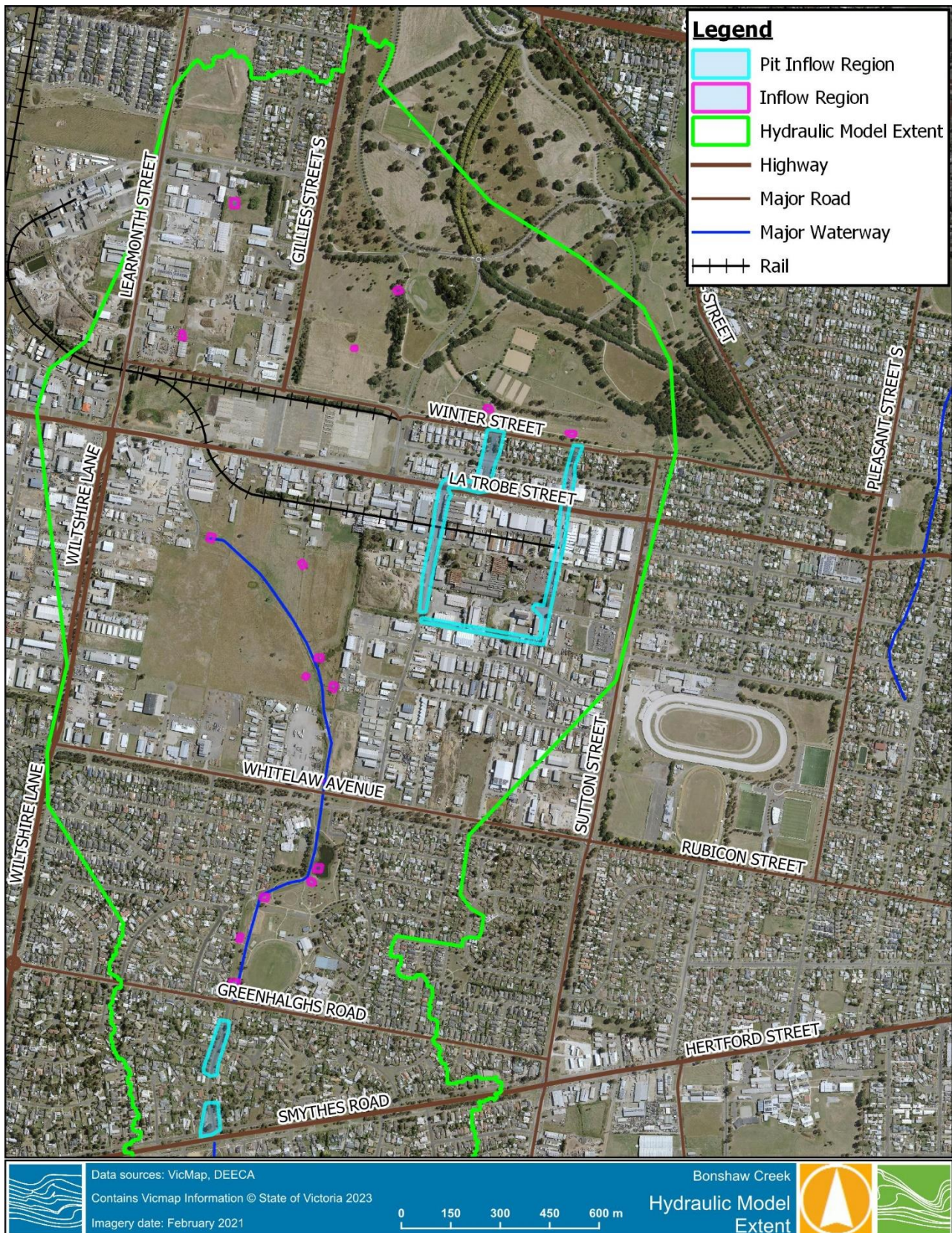


Figure 3-11 Inflow Locations for the Upper Bonshaw Creek

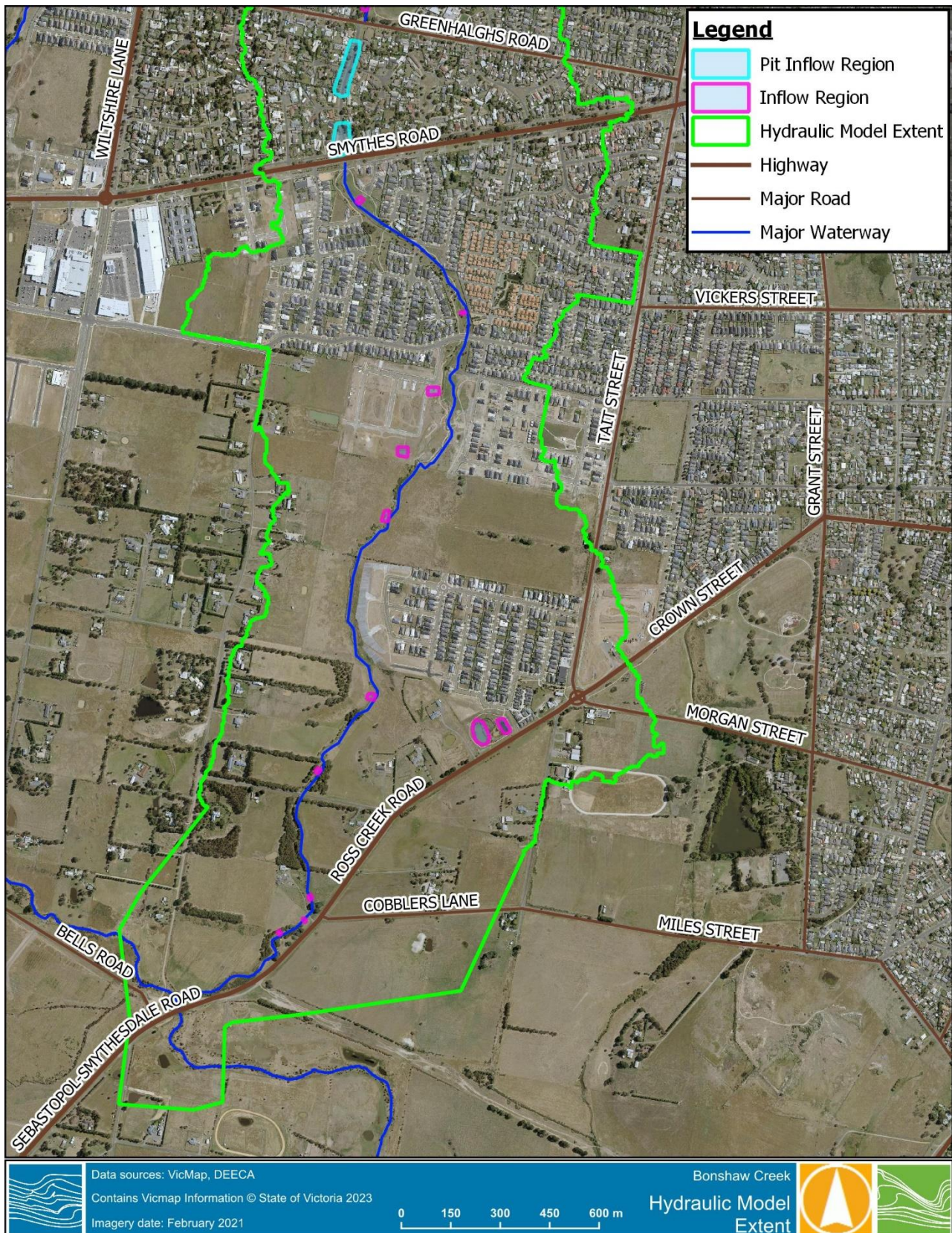


Figure 3-12 Inflow Locations for the Lower Bonshaw Creek



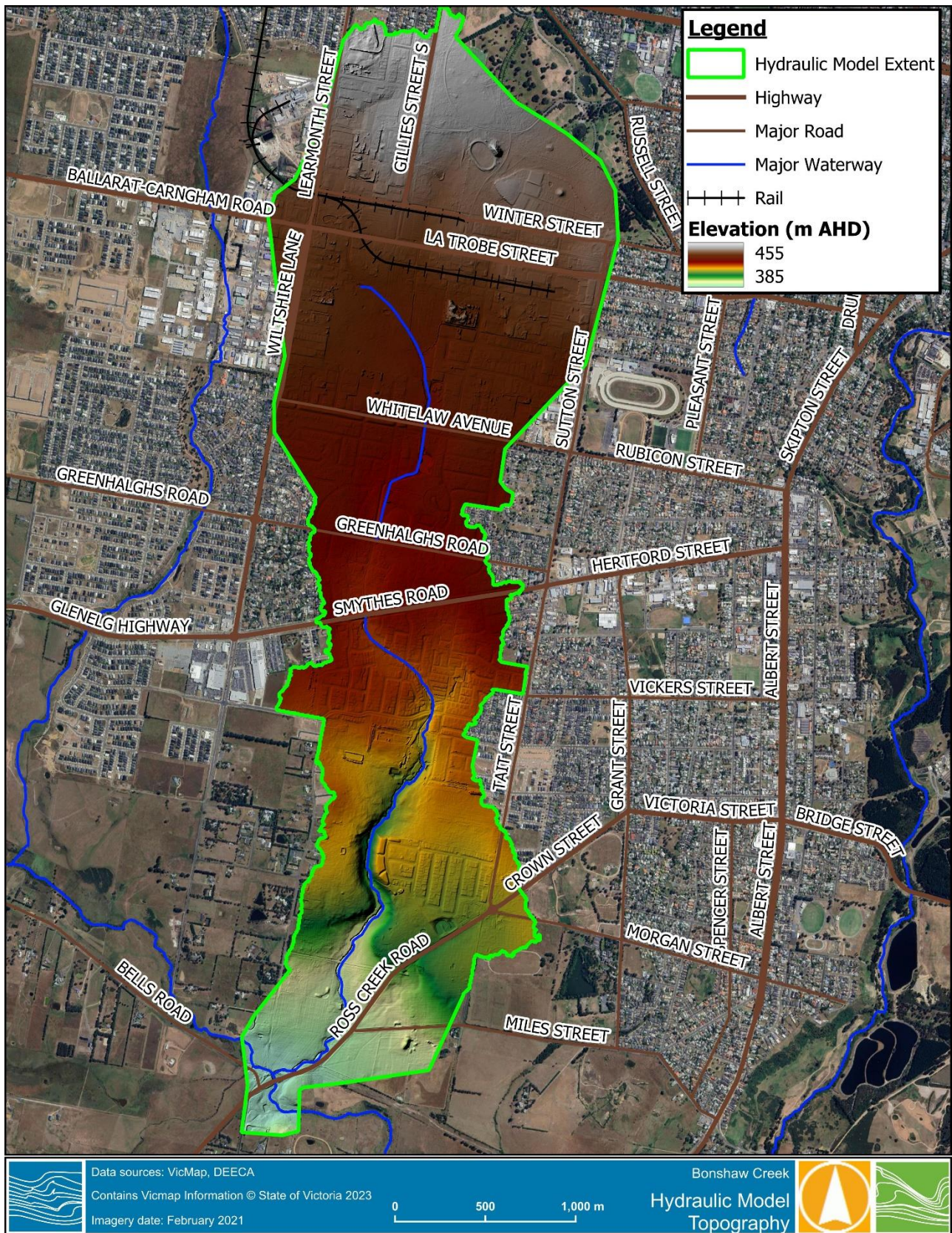
3.5.3 Model Extents and Resolution

The model topography was largely based on the LiDAR data captured in October 2019, which featured a grid cell size of 1-metre and a vertical accuracy of $\pm 10\text{cm}$. A key consideration in determining the grid size in the hydraulic model is the trade-off between accurate representation of flow paths and reasonable model run times. Although smaller grid sizes can provide higher resolutions, they also significantly increase the model run time and do not guarantee a significant difference in model results. For the Bonshaw Creek model, a 2-metre grid cell size was found to represent the catchment characteristics throughout most of the modelling areas while maintaining suitable simulation times. Grid cell sizes for each model varied between 2-metres and 3-metres, depending on the overall size of the hydraulic model and the size/quantity of overland flow paths. For the Canadian Creek and Tributaries hydraulic model, flows in constructed channels were represented using a 1D network feature for open channel flow. This gave a more accurate representation of flows in the channels than a 2D grid resolution. An overview of what grid size was adopted for each model is shown in Table 10 below.

An overview of the hydraulic model terrain for the Bonshaw is shown in Figure 3-13 below.

Table 10 Adopted Grid Cell Size for each Hydraulic Model

Hydraulic Model	Adopted Grid Size (m)
Bonshaw Creek	2
Redan Creek	2
Warrenheip Creek & Ryans Drain	2
Little Bendigo & Hit or Miss Gully	2
Yarrowee River & Gnarr Creek	3
Canadian Creek & Tributaries	3
Kensington Creek	3
The Chase Waterway	3



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Figure 3-13 Hydraulic Model Topography for the Bonshaw Creek



3.5.4 Hydraulic Roughness

Hydraulic model roughness was determined using City of Ballarat planning layers, along with aerial imagery for verification. Table 11 outlines the generalised (before aerial image verification) Manning's 'n' roughness values adopted within the Bonshaw Creek catchment area. The adopted roughness' were based on standard industry accepted values (VicRoads Road Design Guidelines and Melbourne Water recommendations). A delineation of the roughness extents is shown in Figure 3-14 below.

Table 11 Mannings 'n' Values for Land Types in Bonshaw Catchment Area

Land Use	Manning's 'n'
Residential - Urban (higher density)	0.35
Industrial/Commercial or large buildings on site	0.30
Open Space or Waterway - minimal vegetation	0.04
Open Space or Waterway - moderate vegetation	0.06
Car park/pavement/wide driveways/roads	0.02

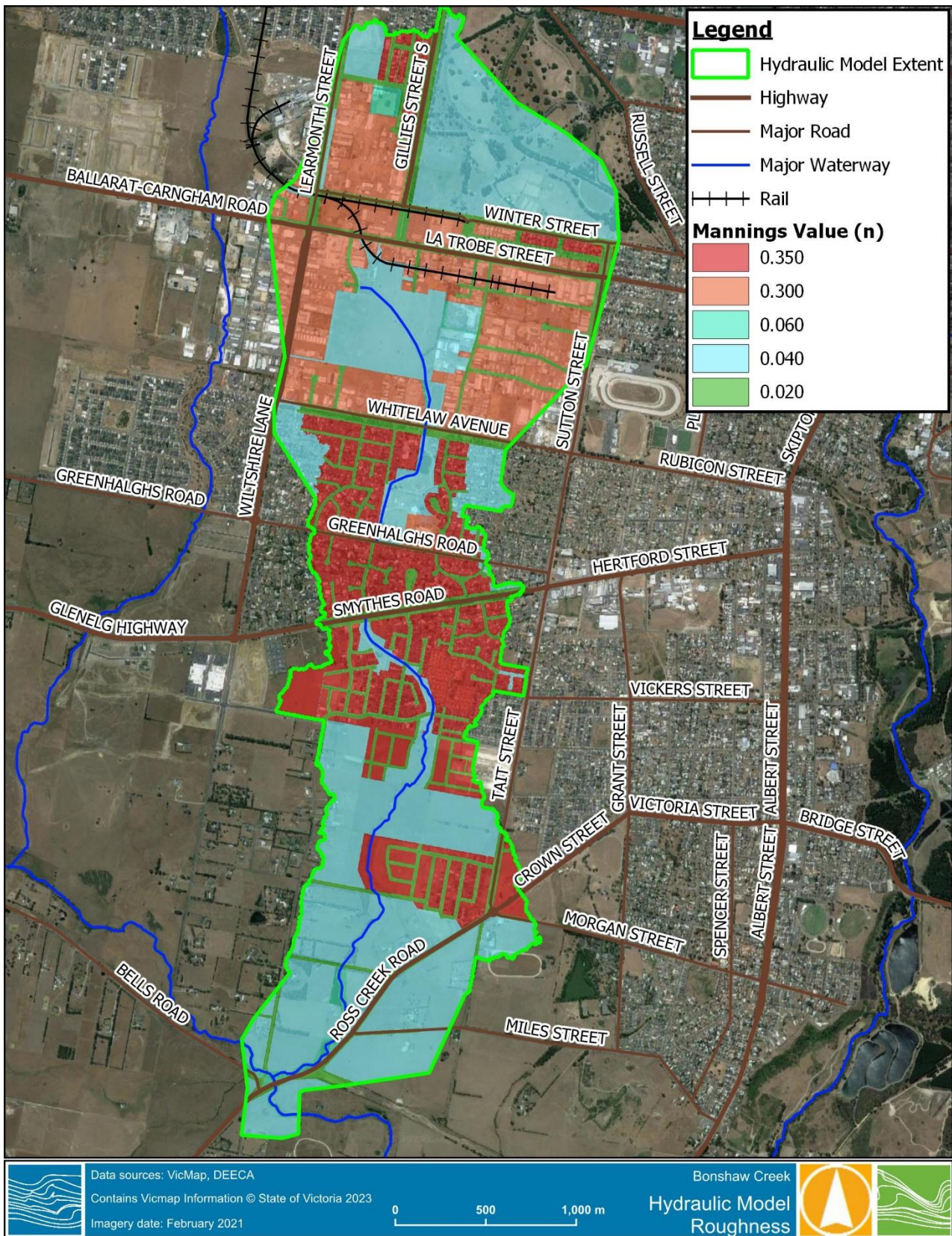


Figure 3-14 Surface Roughness Values for the Bonshaw Creek Catchment



3.5.5 Key Hydraulic Structures

Underground drainage infrastructure (culverts, pipes and pits) was modelled as 1D network features. City of Ballarat provided a GIS database containing information of Council drainage assets in the municipality. All relevant GIS databases were reviewed and combined into two GIS databases; one for pipes and one for pits. Pipes with diameters less than 300mm were typically excluded from the hydraulic model as they are not normally a part of any major drainage networks.

During the review process, gaps in the provided drainage network datasets were found and, in some instances, it was possible to infer the missing culvert diameter information based on a site visit or engineering judgement. Missing invert level information was inferred from topographical information and assumed to maintain a similar gradient to the network upstream or downstream of the missing information.

Pits were incorporated in the 1D network as 'weir' or 'rectangular' type pits which was based on the pit being either a grated pit or side entry pit, respectively. 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.

Based on the drainage network GIS database and the site visit, majority of pipes and culverts were modelled as reinforced concrete, with a Manning's 'n' of 0.013 adopted. A small network of culverts south of Victoria Park were modelled with a Manning's 'n' of 0.015, representing a composition of brickwork. The culvert, pipes and pits modelled in the Bonshaw Creek catchment are shown in Figure 3-15.

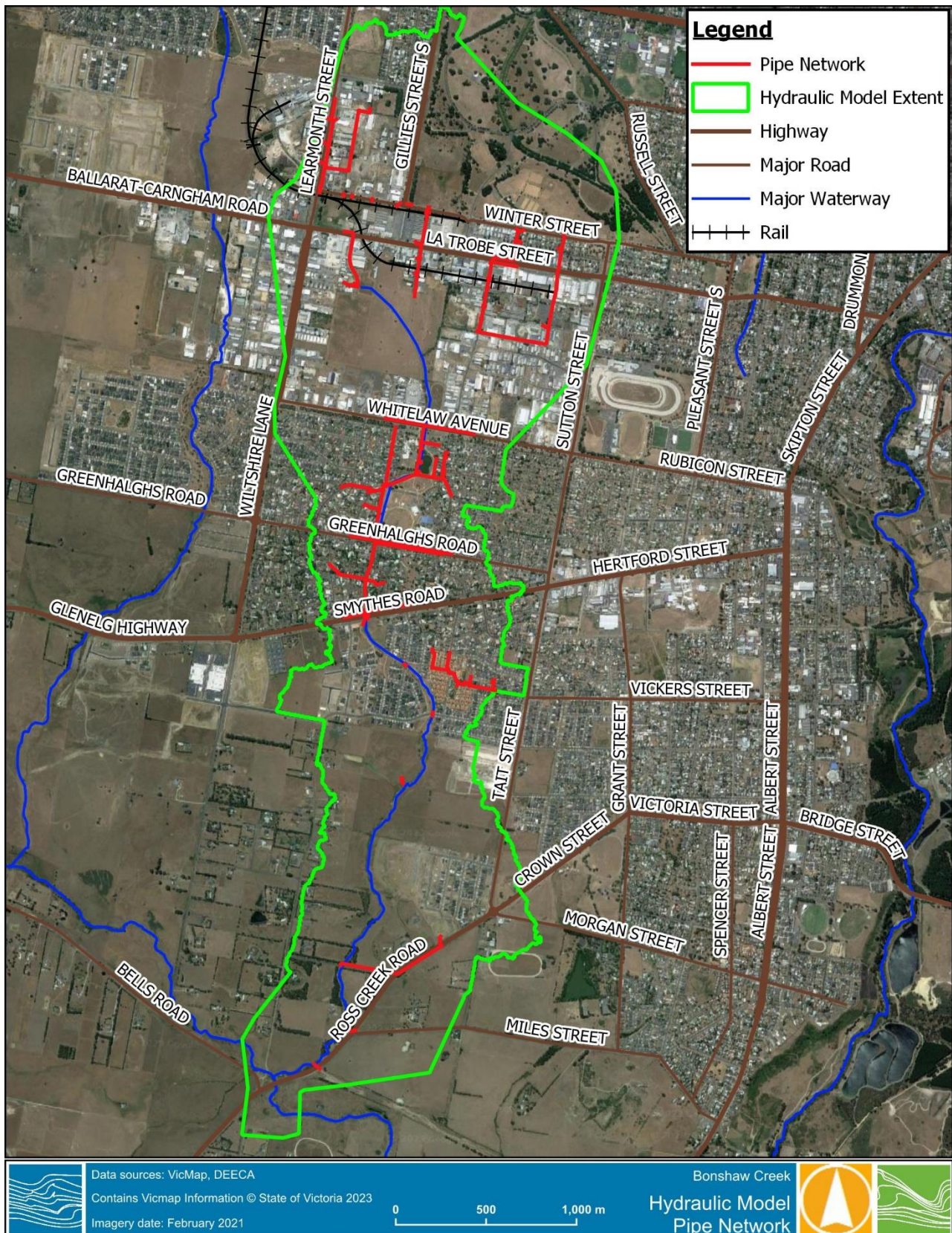


Figure 3-15 1D Pipe Network Throughout the Modelled Bonshaw Creek Catchment



4 FLOOD MAPPING RESULTS

Results of each catchment are presented in the following section. Mapping largely focuses on 1% AEP RCP 8.5 (2100) modelled flood depths; however, velocities, pipe capacities etc. can all be extracted from the model outputs. Modelling of the 20%, 10%, 5%, 2%, 1%, 0.5% AEP events and climate change for the year 2100 RCP 4.5 and RCP 6 events was also completed, with modelled durations ranging from 30-minutes to 72-hours depending on the characteristics of the catchment. Mapped results show the modelled durations for each AEP spliced together to provide a representative 1% AEP (RCP 8.5 for year 2100) output.

1% AEP RCP 8.5 for year 2100 maximum depths for each waterway are shown in the following figures:

- Bonshaw Creek
 - Figure 4-1
- Canadian Creek and Tributaries
 - Figure 4-2
- Chase Waterway
 - Figure 4-3
- Kensington Creek
 - Figure 4-4
- Little Bendigo Creek and Hit or Miss Gully
 - Figure 4-5
- Redan Creek
 - Figure 4-6
- Warrenheip Creek and Ryans Drain
 - Figure 4-7
- Yarrowee River and Gnarr Creek
 - Figure 4-8
 - Figure 4-9

The flood mapping data has been formatted into the Victoria Flood Database format and has been provided to the City of Ballarat and Corangamite CMA. Along with the flood mapping displayed in the report, the following will also be provided to the City of Ballarat and Corangamite CMA:

- Flood mapping grids for all design events, 20% to 0.2% AEP and 2100 RCP 4.5, RCP6 and RCP 8.5
 - Depth
 - Water Surface Elevation
 - Velocity
 - Velocity x Depths (VxD)
 - Hazard

The City of Ballarat will also receive all hydrological RORB models (inputs and outputs) and packaged TUFLOW models.



Figure 4-1 Bonshaw Creek – 1% AEP RCP 8.5 Flood Depths



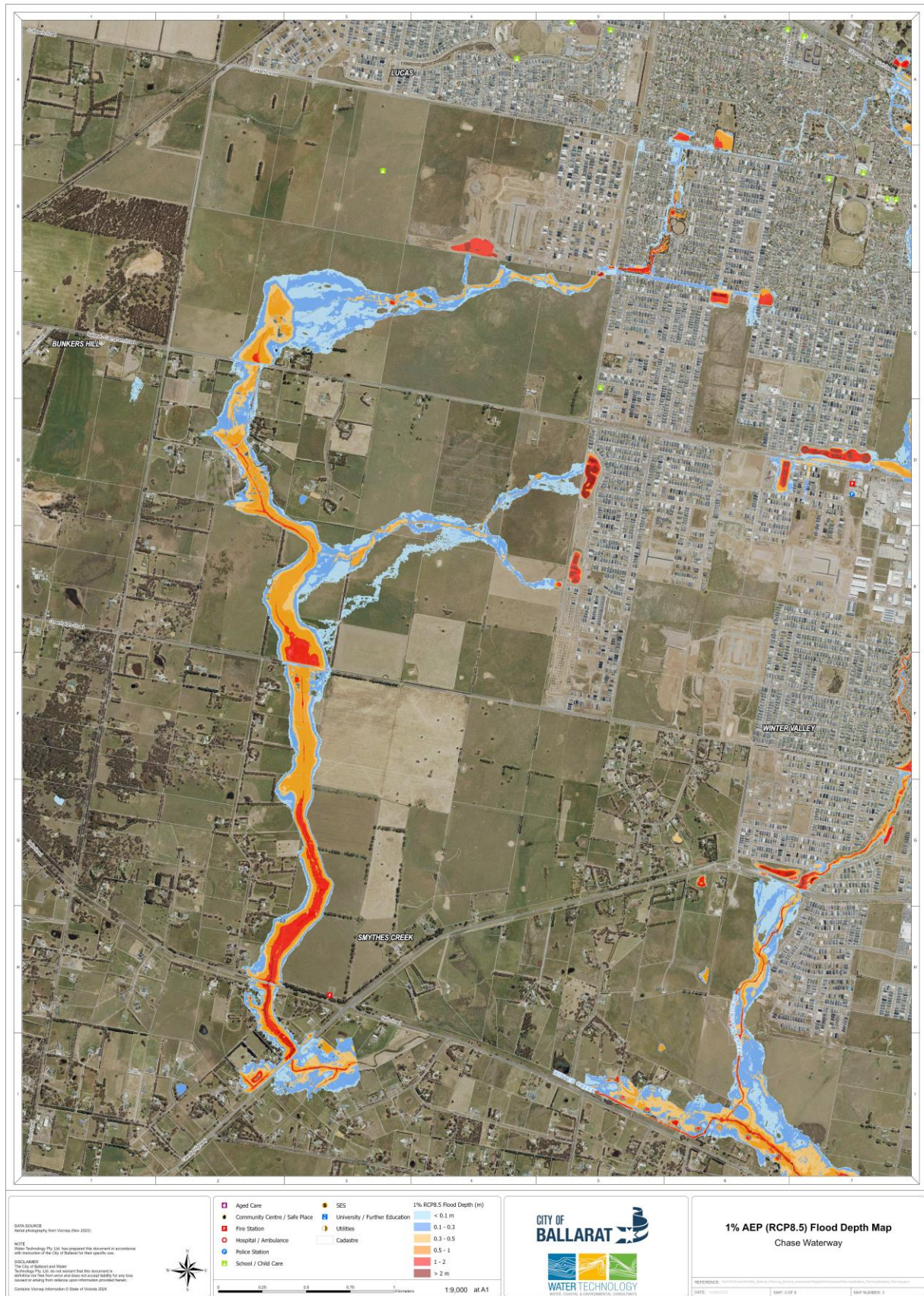


Figure 4-3 Chase Waterway – 1% AEP RCP 8.5 Flood Depths





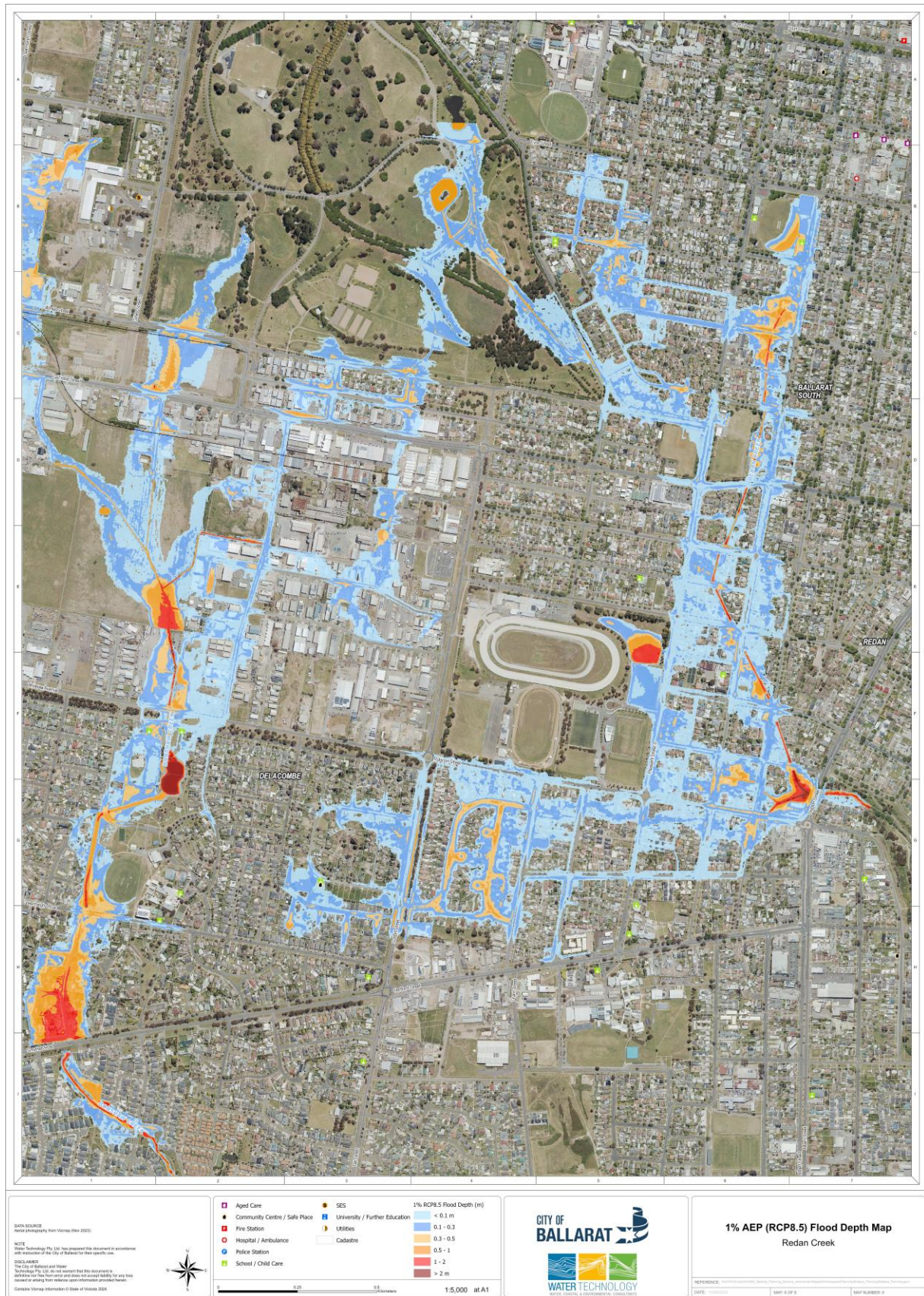


Figure 4-6 Redan Creek – 1% AEP RCP 8.5 Flood Depths

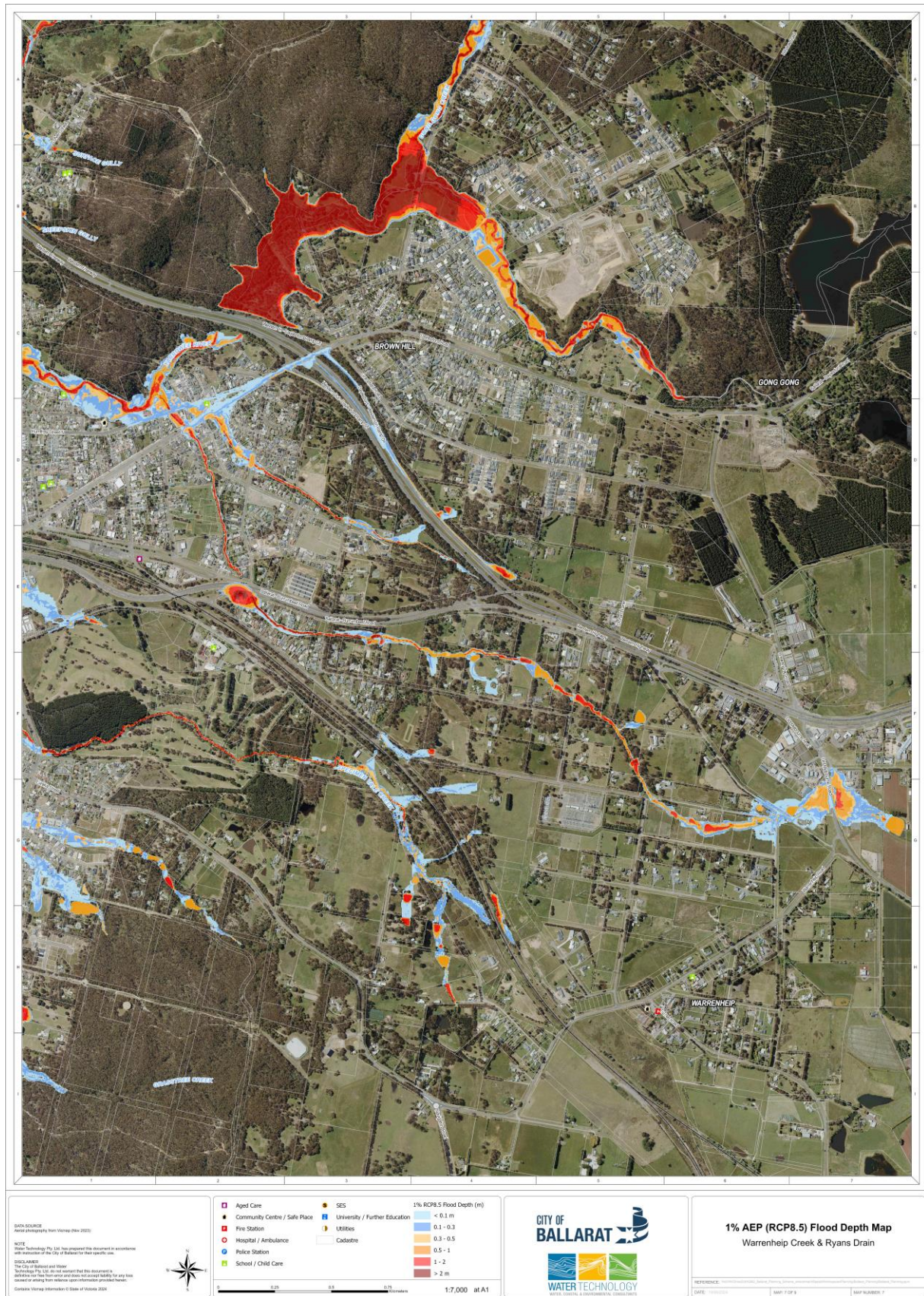


Figure 4-7 Warrenheip Creek and Ryans Drain – 1% AEP RCP 8.5 Flood Depths



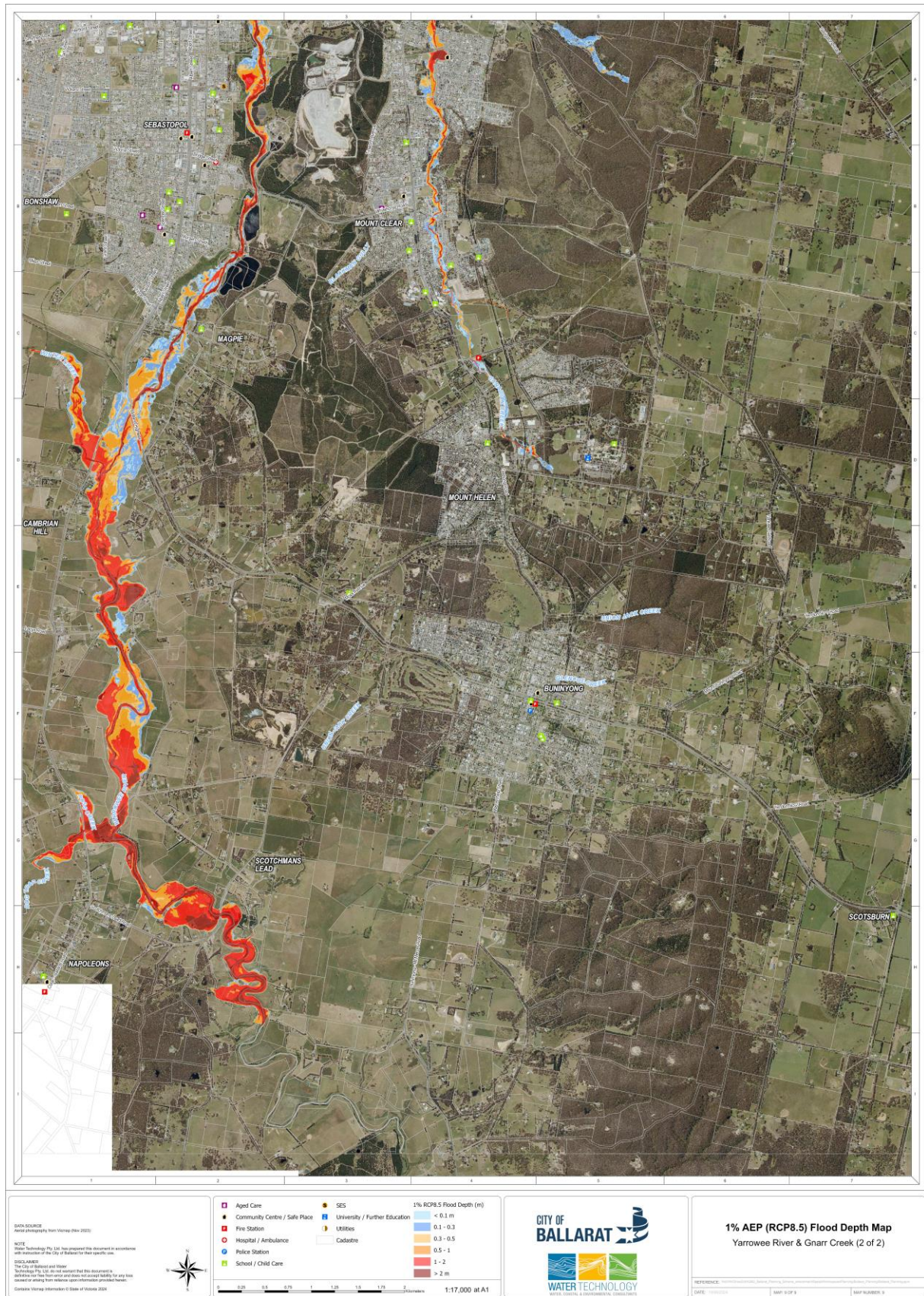


Figure 4-9 Yarrowee River and Gnarr Creek Lower Catchment – 1% AEP RCP 8.5 Flood Depths



5 FLOOD MAPPING FOR LAND USE PLANNING

5.1 Overview

Land use planning controls and building regulations provide mechanisms for ensuring appropriate use of land and building construction, given the flooding risks to a particular area. Land use planning controls are aimed at reducing the growth in flood damages over time. The controls balance the likelihood of flooding with the consequences (flood risk).

As part of ongoing municipal reform, the State Government introduced a consistent planning scheme format for application across the State. The Victorian Planning Provisions (VPPs) are employed by all Victorian municipalities.

Victorian Building Regulations specify that floor levels should be at least 300 mm above a nominated flood level. If land is subject to flooding, the municipal council may set conditions that require a particular type of construction or particular types of construction materials.

This section details the input data, methodology and outputs for the land use planning flood mapping. The following are discussed:

- Victorian Planning Provisions – outlines the flood related Victoria Planning Provisions (VPPs).
- Flood related planning zones and overlay – details the available flood related planning zone and overlays.
- Flood related planning zone and overlays delineation – details the delineation of the flood related planning zone and overlays for the study area

5.2 Victorian Planning Provisions

The Victoria Planning Provisions (VPPs) aim to achieve consistency in the application of planning controls for areas subject to flooding throughout the State. The stated objectives are to protect life, property and community infrastructure from flood hazard, and to preserve flood conveyance capacity, floodplain storage and natural areas of environmental significance.

The VPPs provide for three overlays and one zone associated with mainstream flooding as follows:

- Land Subject to Inundation Overlay (LSIO).
- Floodway Overlay (FO).
- Urban Floodway Zone (UFZ).
- Special Building Overlay (SBO).

Only the **LSIO**, **FO** and **SBO** overlays were considered relevant to the present study. The definitions of these overlays and their criterion are provided in the following sections.

For each of the overlays, the VPPs specify the appropriate types of land uses and developments which are to be regulated through a system of permits. These are intended to achieve consistency throughout the State, but local variations to these guidelines are allowed in planning permit exemptions through a schedule to a flood overlay and/or performance-based criteria through a local floodplain development plan that has been incorporated into the planning scheme.



5.3 Flood Related Zones and Overlays

5.3.1 Land Subject to Inundation Overlay (LSIO)

The LSIO identifies land liable to inundation by overland flow, in flood storage or in flood fringe areas affected by flooding. In this project the 1% AEP flood under a 2100 RCP8.5 climate change scenario was used.

The permit requirements of LSIO are intended:

- To ensure that development maintains the free passage and temporary storage of floodwaters.
- To minimise flood damage.
- To be compatible with the flood hazard and local drainage conditions.
- Not to cause any significant rise in flood level or flow velocity.
- To protect water quality in accordance with relevant State Environment Protection Policies (SEPPs).

In general, emergency facilities (hospitals, schools and police stations etc.) must be excluded from this area (refer Clause 15.02). Similarly, developments or land uses which involve the storage or disposal of environmentally hazardous chemicals or wastes, and other dangerous goods should not be located within LSIO.

Permit requirements as well as performance-based controls can be specified. A LSIO is recommended for each of the 11 waterways in this study.

5.3.2 Floodway Overlay (FO)

The FO identifies waterways, main flood paths, drainage depressions and high hazard areas. The identification of FO has been based on the below criteria:

- 1% AEP RCP8.5 depths ≥ 0.3 m
- 1% AEP RCP8.5 velocities ≥ 2.0 m/s
- 1% AEP RCP8.5 velocity x depth ≥ 0.3 m²/s

5.3.3 Special Building Overlay (SBO)

The SBO is used to define flooding from overland flows where stormwater infrastructure plays controlling role in the inundation (as opposed to water escaping from a waterway). The overlay is generally used within built up areas where the nature of flooding from stormwater has been identified. This planning control is used to ensure that development within these areas identified as flood prone can be undertaken with due regard for the flood risk and in accordance with appropriate conditions and floor level requirements.

The primary objective of the SBO is:

- *“To ensure that development maintains the free passage and temporary storage of floodwaters, minimises flood damage, is compatible with the flood hazard and local drainage conditions and will not cause any significant rise in flood level or flow velocity.”*

SBO extents are recommended as part of this study and for only a select number of areas where inundation has been modelled outside of the designated waterways and infrastructure is a major controlling factor. This primarily inundation at the very top of catchments where a defined waterway is no longer present, i.e., urbanised catchments. Additionally, inundation in areas which have a catchment of 60 Ha or less were included in the delineation of SBO.



Further refinements to the extent of the proposed SBO were undertaken by assessing velocity vectors from the hydraulic model to determine where flows change from overland/stormwater flooding to riverine flooding. This determining factor was useful for delineating the Redan Creek and Chase Waterway SBO extents, as they both feature dense urbanisation around their defined waterways.

Filtering was applied to the generated SBO extent to remove shallow depths from the proposed overlay to account for any inaccuracies the catchment wide maps might have on a lot-by-lot scale. For this study, the SBO extents filtered out depths less than or equal to 5 cm.

5.4 Overlay Generation Criterion

In generating the draft overlays, the following principals and guidelines were developed and applied in consultation with the City of Ballarat and Corangamite CMA:

- Raw gridded model results were smoothed on their fringes to create plausible representation of the floodway and flood fringe boundaries. This removed the irregular 'saw tooth' edge.
- Irregularities in the floodway and flood fringe boundaries, such as small 'tongues' of flood-prone land extending out from the bulk of the identified flood extent were smoothed where necessary. Underlying Planning Scheme Zone is a consideration in doing this.
- Islands (high ground) within the Floodway Overlay (i.e. marooned by high hazard flooding) were in general covered by the Floodway Overlay due to access being cut. A planning permit application would be therefore triggered on such land which ensures flooded access hazards are accounted for.
- Thin slivers of low-hazard land identified on the fringe of high hazard areas were merged to remove the negligible sliver of land that is identified as low-risk.
- Clipping of boundaries was undertaken where trivial extents with areas of no more than 5 m² impeached on. This was done to remove unwarranted permit triggers that would not affect the overall integrity of the property.
- The removal of isolated patches (such as dams) mapped outside of the main floodplain area and not connected to any stormwater infrastructure were removed.

An overview of the proposed Flood Overlay (FO), Land Subject to Inundation Overlay (LSIO) and Special Building Overlay (SBO) are presented in Figure 5-1.

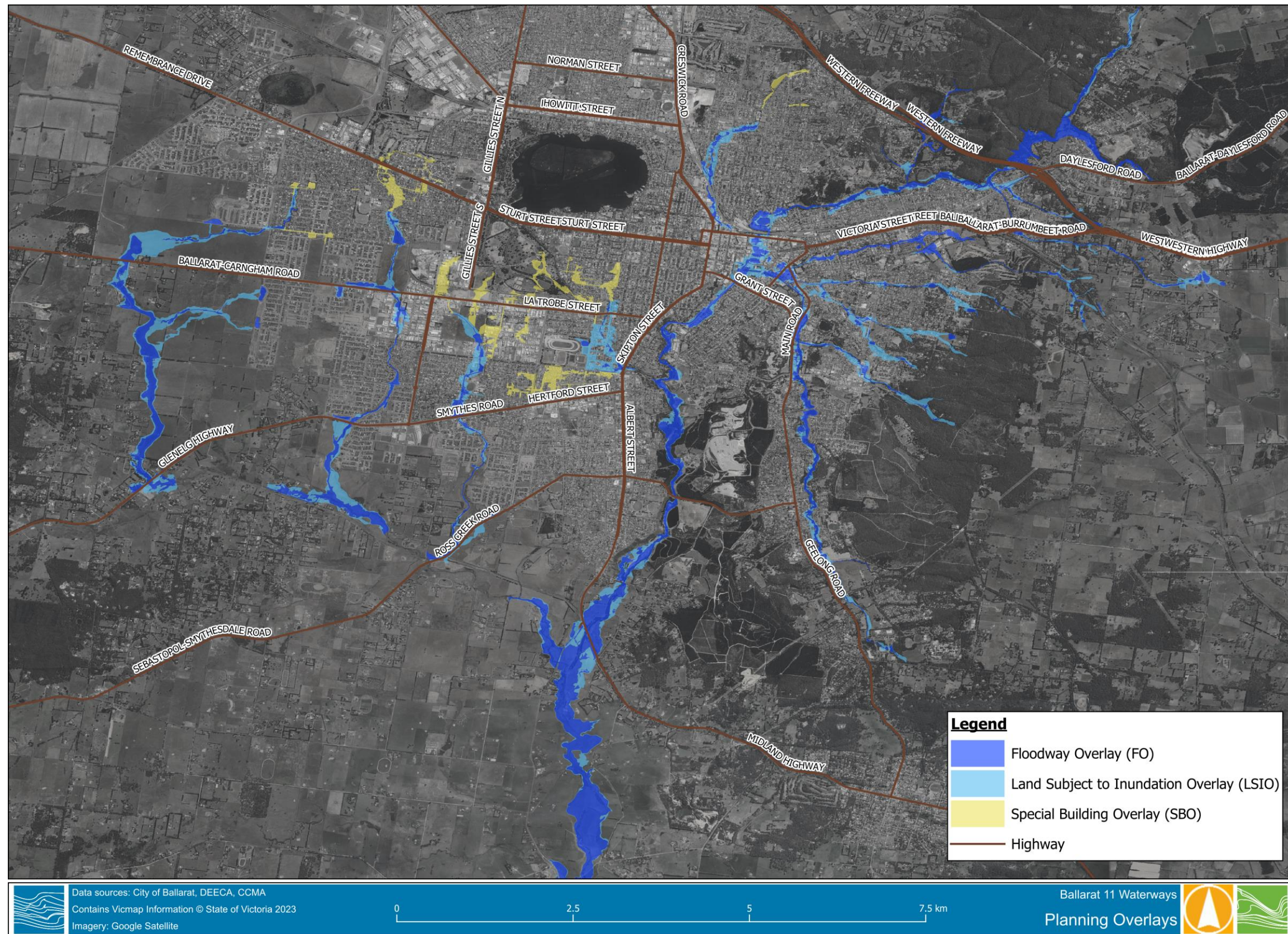


Figure 5-1 Proposed Planning Overlay Extent



6 SUMMARY

The establishment of detailed and consistent hydraulic modelling across Ballarat has been an extensive project for both the City of Ballarat and the Corangamite CMA, with the first study commissioned in 2004, *Design flood estimation for Ballarat Urban Waterways (Ecological Engineering)*. Between 2004 and 2017, studies on individual catchments and tributaries were completed using varying hydrological and hydraulic modelling methodologies, all with the aim of developing appropriate flood controls for the planning scheme.

In 2017, the City of Ballarat, with the support of the Corangamite CMA, undertook eight flood studies across 11 waterways across Ballarat using the latest, hydrological and hydraulic modelling approaches. With the aim to better understand areas potentially at risk of inundation. This mapping was intended to enable better planning and investment for City of Ballarat and developers.

With the continued development and expansion across Ballarat since 2017 and the release of terrain data (LiDAR) captured in 2019, the City of Ballarat opted to update all of the previous studies with the latest terrain and pit and pipe information. Other changes from the previous studies included the update to the latest TUFLOW software version, and the utilisation of HPC (Heavily Parallelised Compute), which was previously used by only two of the original studies. The project also considered the impacts of climate change on flooding, by modelling the impact of increased rainfall intensity by the year 2100 under multiple RCP's.

A major output of the study was the preparation of planning overlays. The overlays were developed using the 1% AEP flood event under a 2100 RCP8.5 climate change scenario. This is in line with the Victorian Planning Provisions Clause 13.01 & 13.03.

Modelling challenges were experienced during the project, the largest complication being the changes in topography conflicted with the open channel networks developed for the Redan Creek and Canadian Creek and Tributaries models. The decision was made to move away from an open channel approach for the Redan Creek and utilise SGS (Sub-Grid-Sampling), which stabilised the model and produced flood behaviour comparative to the original model.

The project aimed to ensure the mapping produced was suitable for informing flood risk, statutory and strategic planning decisions, and the implementation of flood overlays. To support this, a peer review of the adopted methodologies and assumptions was carried out by a third-party. The peer review disagreed with the methodology used to represent rainfall losses within the hydrological models (preferencing incorporation of Directly Connected and Indirectly Connected Areas). Sensitivity modelling was completed to quantify the likely differences between the two approaches, with the outcome being the adopted methodology determined flood levels marginally higher than the alternative method, with minor impacts to extents in the floodplain. Given the small differences, the methodology used in the 2017-19 studies was maintained.

Previous reviews undertaken as part of the original 2017-19 studies found the modelling approach to be in line with recommended guidelines. The modelling methodology adopted for this project has used the most practical and defensible of the design methodologies discussed in the ARR Victorian Specific Data, in line with ARR2019 recommendations (Section 3.3.3 of Book 5; Section 5 of Book 7).



Recommendations from the Ballarat 11 Waterways Flood Study Update have been separated into the agencies responsible for their fulfilment, these are as follows:

- **City of Ballarat**
 - Endorsement of the flood mapping update with aim of adopting the recommendations.
 - Undertake a planning scheme amendment to introduce flood related planning overlays, including, Land Subject to Inundation Overlay (LSIO), Floodway Overlay (FO) and Special Building Overlay (SBO) mapping.
 - Inclusion of climate change design modelling when considering and assessing flood risk.
 - Discuss with the Bureau of Meteorology and Corangamite CMA for the consideration of additional water level monitoring and rainfall gauges.
 - Seek to update the flood intelligence products of each catchment to be included in an update to the Ballarat Municipal Flood Emergency Plan (MFEP).
 - Development maintenance schedules for critical parts of the drainage network to reduce the likelihood of blockage in a storm event.
 - Identify opportunities to expand the flood mapping of the municipality through a stormwater flood mapping project.
- **Corangamite Catchment Management Authority**
 - Endorsement of the flood mapping update to inform floodplain risk management decisions.
 - Upload the mapping data to FloodZoom and the Victorian Digital Twin database.
 - Identify opportunities to increase flood warning products throughout the catchment.
- **Victoria State Emergency Service, with assistance from Corangamite CMA and City of Ballarat**
 - Continue to engage the community through regular flood awareness projects, such as the VICSES FloodSafe program.
 - Update the Ballarat CBD Local Flood Guide with the latest information.
 - Update the Golden Point, Canadian, Eureka and Ballarat East Local Flood Guide with the latest information.
 - Assist the City of Ballarat in updating the flood intelligence products and the MFEP.

Future flood events in Ballarat should be monitored carefully and compared to the results of this study, with the collection of flood level marks and survey where possible. Where flood behaviour appears to differ from the findings of this study, the reason for deviation should be investigated and an update to the study should be considered.

To ensure this information remains relevant to the growing catchment and changing environment, it is recommended that this study, or at the very least each of the waterways, be reviewed every 2-years. This review should focus on any development/changes in the catchment that would alter the defined overlays/flood extents. Updates to the study should be completed every 5-years, or when there is a substantial update Australian Rainfall & Runoff Guidelines that render the methodology adopted requiring an update, or if more information becomes available that could improve the accuracy of said study.



6.1 Deliverables

A list of the submitted deliverables as part of this project has been compiled and is described below in Table 12.

Table 12 Deliverables

<u>Deliverable</u>	<u>Items Delivered</u>
RORB & TUFLOW Models Yarrowee River & Gnarr Creek Canadian Creek & Tributaries Chase Waterway Kensington Creek Bonshaw Creek Redan Creek Little Bendigo Creek & Hit or Miss Gully Warrenheip Creek & Ryans Drain	RORB Files: ■ Catg Files ■ Parameter Files ■ Rainfall Files ■ RORB Result Files TUFLOW Files: ■ All required control files (.tcf, .tef, .ecf, .tgc, .tbc, .tmf) ■ Check Files ■ Result Files
Reports	■ Technical Reports for each model (Hydrology and Hydraulics Report) ■ Peer Review – Hydrology Sensitivity Testing Memorandum ■ Ballarat 11 Waterways Flood Study Summary Report (this report)
Peer Review	■ Peer Review Spreadsheets (with WT comments).
GIS Datasets	■ Flood depth, level, velocity and hazard grids. ■ Proposed Planning Overlays ■ Pipe capacity layers

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