Summary Report

Ballarat Mapping Updates

Ballarat City Council

15 March 2019

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15 March 2019

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Via email sarahauld@ballarat.vic.gov.au

Dear Jack/Neil

Ballarat Mapping Updates

Please see the attached report summarising our work on the numerous flood mapping projects we have been completing within the City of Ballarat management area.

If you have any queries, please don't hesitate to give me a call.

Yours sincerely

Ben Hughes
Principal Engineer

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WATER TECHNOLOGY PTY LTD

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1 OVERVIEW AND PURPOSE

City of Ballarat (CoB) has identified the need to update their flood mapping throughout their municipality. The update has been driven by the continued expansion of Ballarat and new modelling standards outlined in Australian Rainfall and Runoff 2016[1]. Modelling of the CoB municipality was undertaken during the Ballarat Flood Risk and Opportunity Mapping Project[2]; however, it was largely strategic and used the methodology and parameters outlined in Australian Rainfall and Runoff 1987[3].

CoB commissioned Water Technology to undertake flood modelling and mapping of several catchments. The ultimate purpose of this work was to produce Land Subject to Inundation Overlay (LSIO), Flood Overlay (FO) and Special Building Overlay (SBO) layers for implementation via a planning scheme amendment. Each catchment has been the focus of a separate study undertaken by Water Technology. Modelling and mapping focused on waterway inundation along each waterways main reach where flooding is caused by the capacity of the pipe of channel system is exceeded (opposed to stormwater inundation where overland flow causes flooding as it flows toward the main waterway reach).

The studies have had a relatively consistent methodology with small variants based on the specific constraints of each catchment. The projects have been completed in draft form with feedback being sought from the community comparing their recollections of flooding to the model results. The catchments covered by these studies includes:

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

These catchments are highlighted in Figure 1-1.

[1] Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I (Editors) (2016), Australian Rainfall and Runoff: A Guide to Flood Estimation, Commonwealth of Australia
[2] Water Technology (2014), Ballart Flood Risk and Opportunity Mapping Project
[3] Institution of Engineers, Australia (1987), Australian Rainfall and Runoff: A Guide to Flood Estimation , Vol. 1, Editor-in-chief D.H. Pilgrim, Revised Edition 1987 (Reprinted edition 1998), Barton, ACT

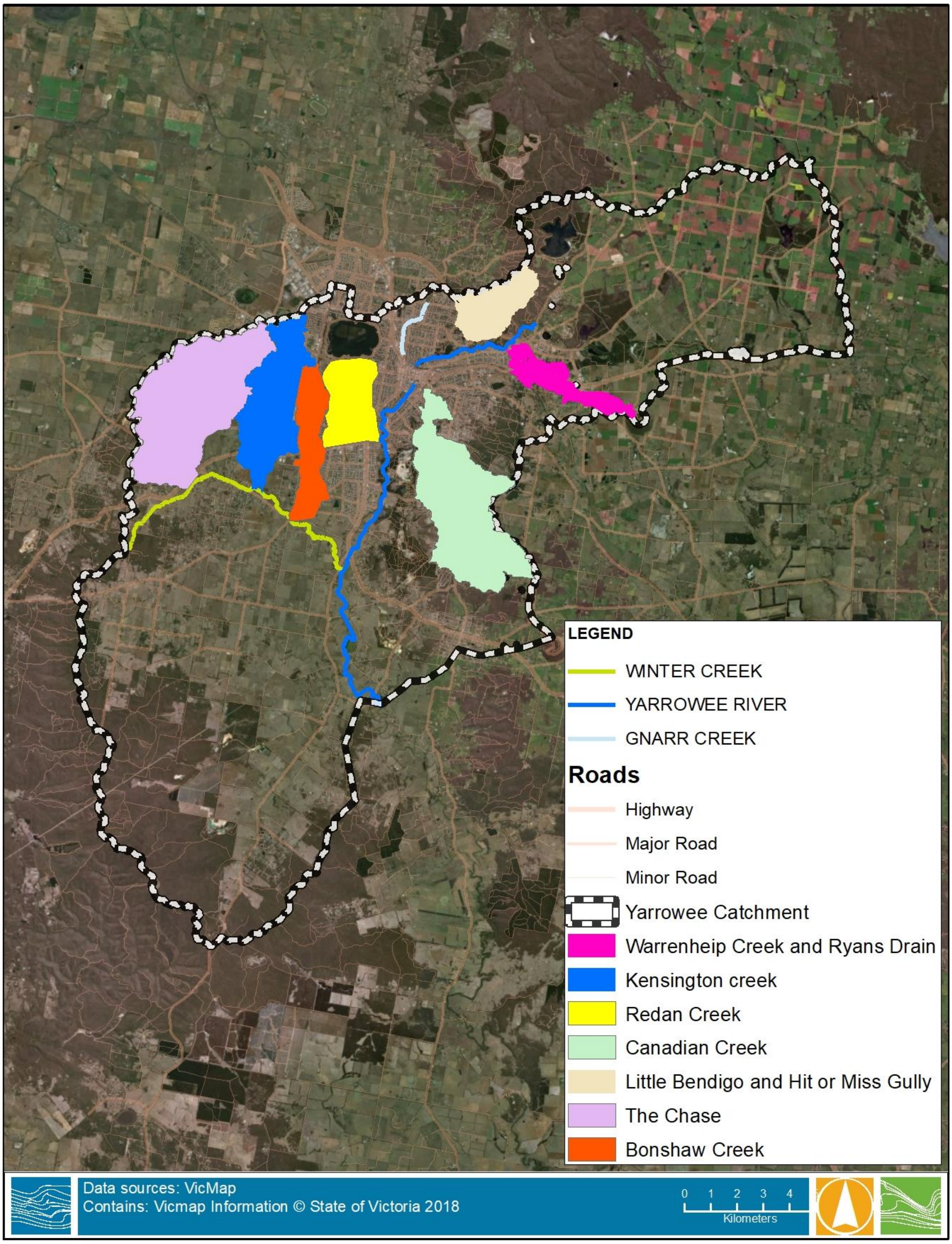

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FIGURE 1-1 CATCHMENTS COVERED BY THIS PROJECT

2 PREVIOUS REPORTING

There have been several previous flood mapping projects completed across Ballarat. The modelling and mapping completed during this project supersedes these along the modelled waterways. All previous studies were undertaken using recommendations set out in Australian Rainfall and Runoff (1987)[3], the revised studies have updated all modelled inputs and methodologies to in Australian Rainfall and Runoff (2016)[1]. There are some areas where the previous mapping will still be appropriate for use, predominantly modelling completed during the Ballart Flood Risk and Opportunity Mapping Project which focused on direct catchment runoff and used a different modelling methodology than used in this project.

Projects previously completed within the area covered by this project 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).

3 METHODOLOGY

3.1 Overview

This section details the methodology used to determine 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 runoff routing program RORB, while the hydraulics was completed in TUFLOW.

3.2 Modelling focus, exclusions and assumptions

The modelling completed during this project focused on inundation along the main waterway within each catchment. Inundation was mapped where the main waterway reach exceeded its bank or pipe capacity. Mapping excluded the following types of inundation:

- Overland flow paths or tributaries of the main waterway.
- Areas of stormwater inundation away from the main waterway.
- Low areas where water pools disconnected from the main waterway.

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

- Winter Creek.
- Ross Creek.
- Dog Trap Creek.
- Union Jack Creek.

Each waterway was modelled and mapped separately over late 2017 and 2018 and it is likely some infrastructure has been constructed since the modelling was completed. This will be reviewed in consultation with City of Ballarat and updated in the final version of the modelling and the infrastructure in place at a single point in time will be adopted across each model.

3.3 Third Party Review

As part of the modelling third party review was undertaken in two components. The hydrologic and hydraulic modelling methodology was reviewed as well as individual review of each study report. These reviews are summarised as follows:

- The hydrologic and hydraulic modelling report completed during the Kensington Creek catchment project (this was the first project 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 relatively new ARR2016 recommendations it was considered prudent to confirm the applied methodology given the streamlined approach. The reviewer found the reporting to be technically sound.
- 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 till after community consultation and potential changes to model results.

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 covered Gnarr Creek and the Yarrowee River.

Section 3.4.2 details general RORB model construction methodology and parameter choices for design modelling while Section 3.4.3 specifically discusses calibration of the Gnarr Creek and Yarrowee River RORB model.

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.
- kc – RORB's calibration parameter.
- m – RORB's 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) data captured in 2007, 2011 or 2012, the 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 The Chase, as shown in Figure 3-1.

The objective of the delineation was to ensure the even distribution of similar sized catchments and a detailed representation of flow along each waterway. Generally, three sub catchments are used prior to each inflow point into the main stream. However, in some areas a single sub catchment inflow was used, this was usually to represent direct catchment inflows along the main waterway.

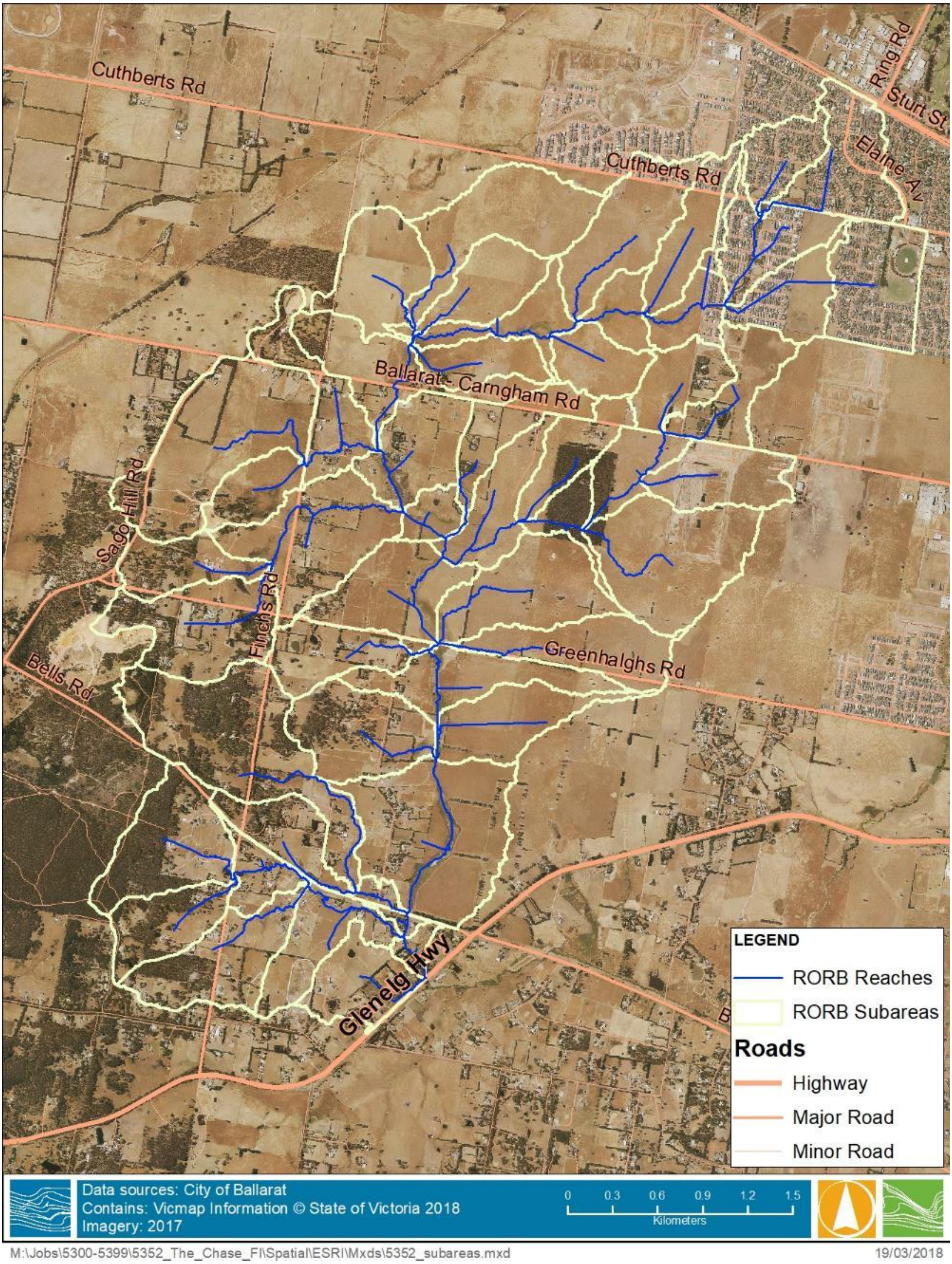

FIGURE 3-1 RORB SUBCATCHMENT AND REACH DELINATION FOR THE CHASE CATCHMENT

3.4.2.2 Fraction Impervious

The estimated impervious surface within each sub catchment was represented by a Fraction Impervious (FI). The varying FI throughout each catchment was determined using both recent satellite imagery and the CoB 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. Figure 3-1 shows the adopted FI value for each land use. To determine the most appropriate FI value for each sub area, an area weighted average was used. The FI values also take into account future development as advised by CoB.

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

TABLE 3-1 ADOPTED FI VALUES FOR THE CHASE RORB MODEL

ZONE DESCRIPTION	FRACTION IMPERVIOUS
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

3.4.2.3 Rainfall Depths

Design rainfall depths for each project catchment were determined with the use of the Australian Rainfall and Runoff (2016) recommendations. Areal reduction factors and temporal patterns were sourced from the ARR data hub[4], while Intensity Frequency Duration (IFD) rainfall depths were sourced from the Bureau of Meteorology (BoM) online IFD tool[5]. Both datasets were based on the coordinates of each catchment centroid.

Rainfall depths for rare events (less than 0.5% AEP) are only supplied for storm durations greater than 24 hours. To estimate design rainfalls for AEPs between 1% and 0.2% for short duration depths a growth factor was applied, as outlined in ARR 2016[6].

3.4.2.4 Losses

Deign losses for the uncalibrated RORB models (all but the Yarrowee River and Gnarr Creek model) were determined using ARR2016 Book 5, Chapter 3 methods[7]. This included both mapped regional estimates and equation-based estimates. The project area is in Region 3 for loss prediction equations, as outlined in ARR2016, Book 5, Chapter 3 (Figure 5.3.16), and shown in Figure 3-2.

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[4] http://data.arr-software.org/
[5] http://www.bom.gov.au/water/designRainfalls/revised-ifd/?year=2016
[6] Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors), 2016, Australian Rainfall and Runoff: A Guide to Flood Estimation, Commonwealth of Australia, Book 8, Chapter 3
[7] http://arr.ga.gov.au/arr-guideline

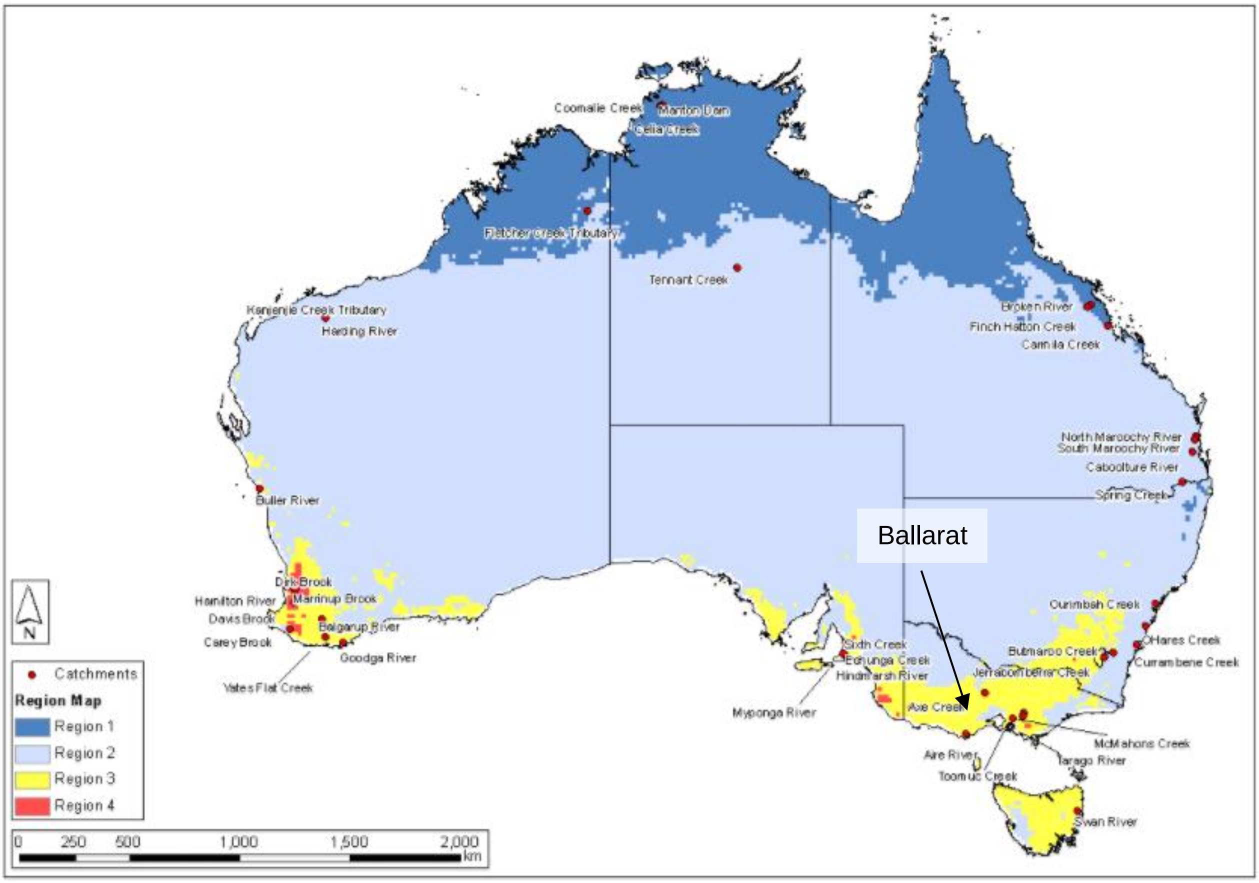

FIGURE 3-2 REGIONS ADOPTED FOR LOSS PREDICTION EQUATIONS

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

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

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

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.

ARR2016, 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 3-3 and Figure 3-4.

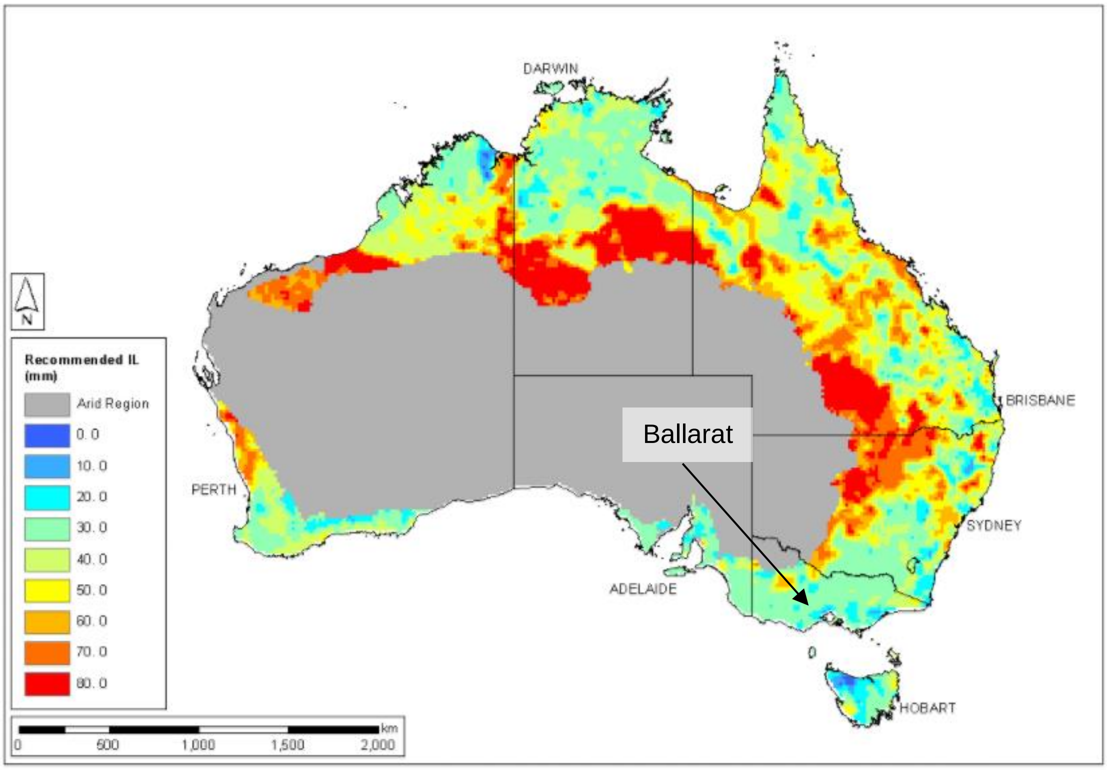

FIGURE 3-3 ARR RECCOMENDED MEDIAN ILs VALUES

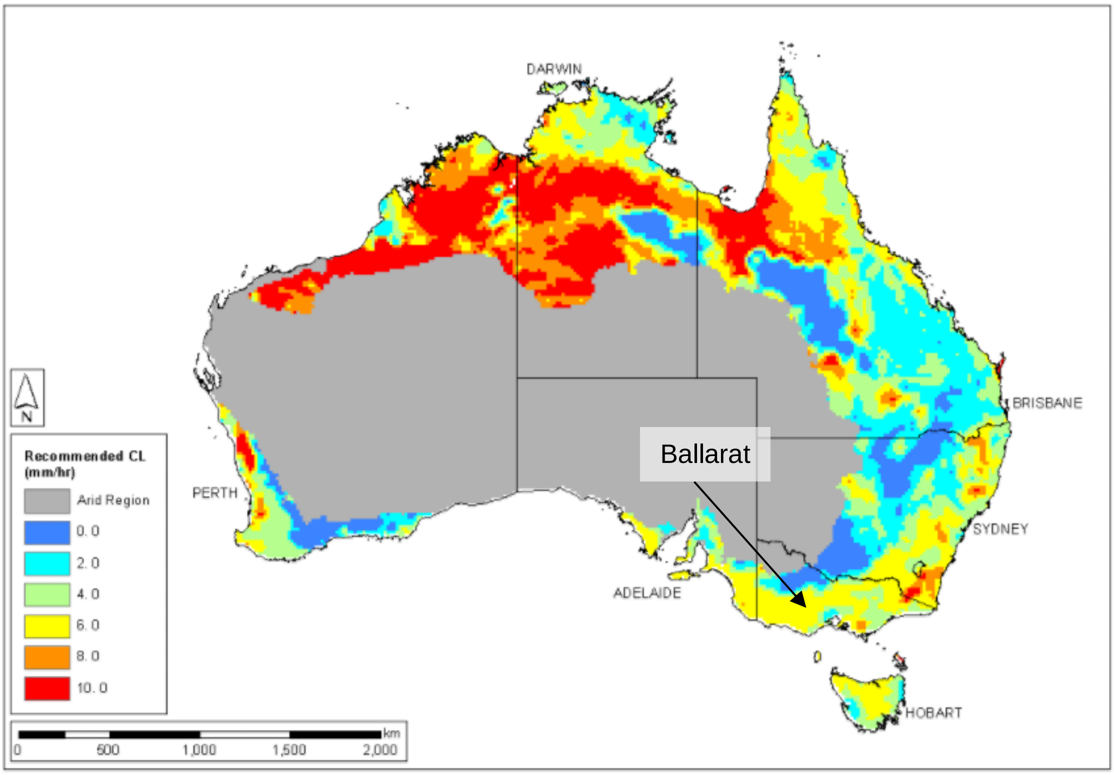

FIGURE 3-4 ARR RECCOMENDED MEDIAN CL VALUES

To take into account the pre-rainfall losses, a 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 ARR2016, Book 5, Chapter 3, Figure 5.3.29. This results in a continuing loss of 4.65 mm/hr.

The ARR online datahub suggests the use of 24 mm initial loss and 4.5 mm/hr continuing loss. Given no stream gauge is present in any of these catchments, these values were adopted across all studies.

TABLE 3-2 ADOPTED LOSSES FOR BALLARAT CATCHMENTS

Loss Type	Loss
Initial Loss	24 mm
Continuing Loss	4.5 mm/hr

3.4.2.5 RORB Kc

Kc is RORB's model routing parameter, dictating attenuation 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, such as the project area, 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 3-3. The parameters utilised within these equations are as follows:

$$A = Area\ (km^2)$$

$$D_{av} = Average\ reach\ distance\ (km)$$

TABLE 3-3 EQUATION BASED KC ESTIMATES

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

* Ballarat has a mean annual rainfall of 689.9mm.

The kc and m parameters across each study area is outlined in Table 3-4, 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 kc. This was completed separating the catchment into four interstation areas.

TABLE 3-4 RORB MODEL PARAMETERS

<table>
<tr><th colspan="2">Catchment</th><th>Kc</th><th>m</th></tr>
<tr><td colspan="2">Canadian Creek and tributaries</td><td>17.8</td><td rowspan="11">0.8</td></tr>
<tr><td colspan="2">Bonshaw Creek</td><td>5.4</td></tr>
<tr><td colspan="2">Kensington Creek</td><td>5.6</td></tr>
<tr><td colspan="2">The Chase Catchment</td><td>6.1</td></tr>
<tr><td colspan="2">Warrenheip Creek and Ryans Drain</td><td>3.0</td></tr>
<tr><td colspan="2">Redan Creek</td><td>3.5</td></tr>
<tr><td colspan="2">Little Bendigo Creek and Hit or Miss Gully</td><td>2.2</td></tr>
<tr><td rowspan="4">Yarrowee River and Gnarr Creek</td><td>Yarrowee US Little Bendigo Creek confluence</td><td>30.0</td></tr>
<tr><td>Gnarr Creek</td><td>3.0</td></tr>
<tr><td>Ballarat CBD</td><td>6.7</td></tr>
<tr><td>US outlet</td><td>30.0</td></tr>
</table>

3.4.3 Model calibration

3.4.3.1 Modelling Approach

Calibration of the Gnarr Creek and Yarrowee River RORB model was completed using the Mount Mercer streamflow gauge, the only available flow record within the catchment. As the Mount Mercer stream-gauge is outside the Yarrowee River flood mapping extent, the RORB model was extended to the Mount Mercer location. Figure 3-5 shows the Mount Mercer RORB model catchment extent. The available flow record for the 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 ARR2016 rainfall IDF data, as outlined in Section 3.4.2.3.

A statistical Flood Frequency Analysis (FFA) of annual peak flows was also used to establish design peak flows the site, as discussed in Section 3.4.4.4.

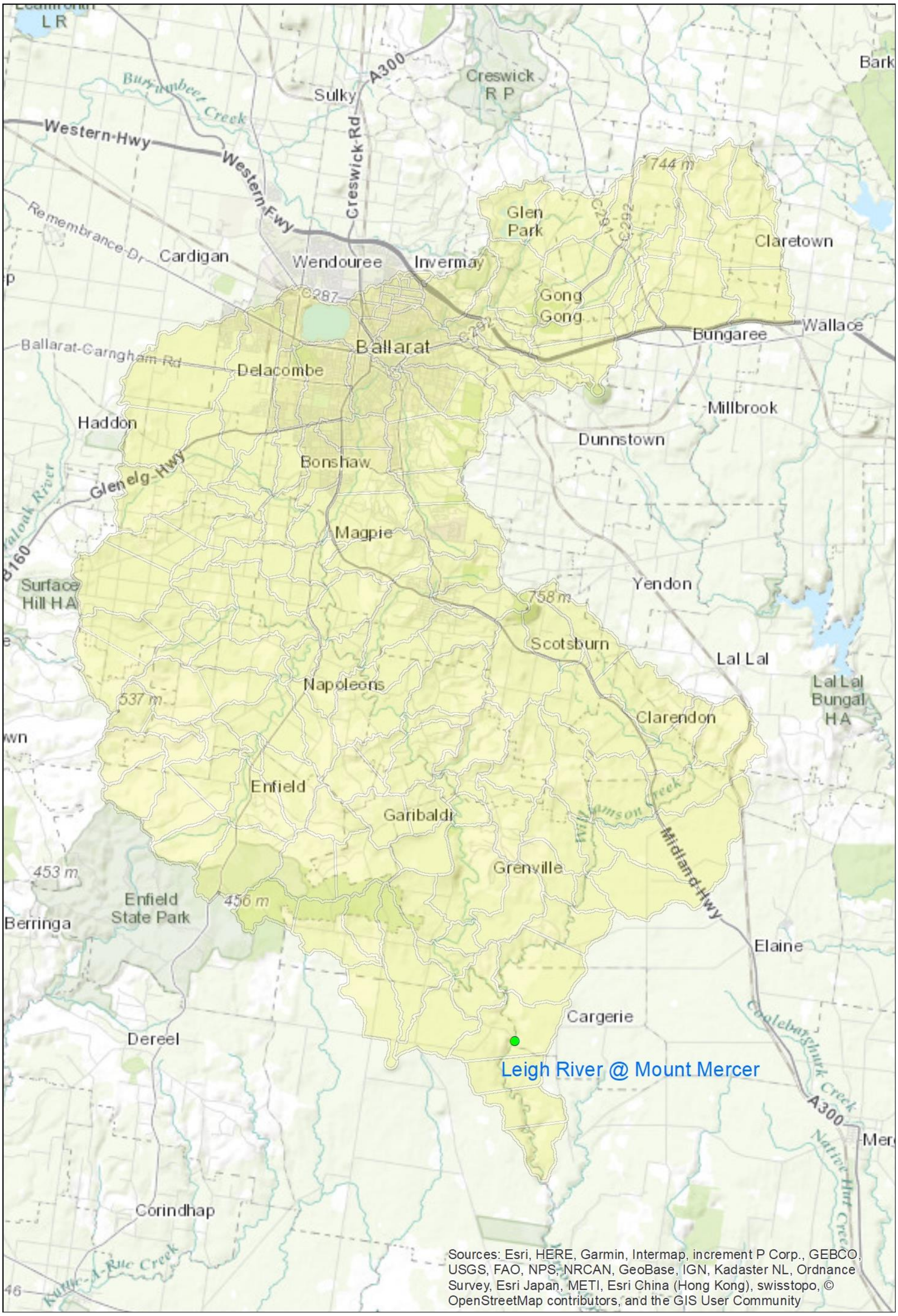

FIGURE 3-5 MT MERCER RORB CATCHMENT FOR CALIBRATION

3.4.3.2 Calibration Events

Three recorded events were used for calibration of the Gnarr Creek and Yarrowee RORB model; August 2010, January 2011 and September 2016. These events were chosen because of their size and relatively recent occurrence, limiting catchment changes since the events and increasing community and agency recollection of the events. More recent rainfall and streamflow data is also considered to be generally more accurate than historic data. 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.

3.4.3.3 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 varied within the range as calculated from Pearse et. al. (2002). The exponent m was set to 0.8 as per RORB recommended value.

The final calibration model parameters for each of event are summarized in Table 3-5. 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 3-6, Figure 3-7 and Figure 3-8 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.

TABLE 3-5 RORB CALIBRATION PARAMETER, MOUNT MERCER

	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

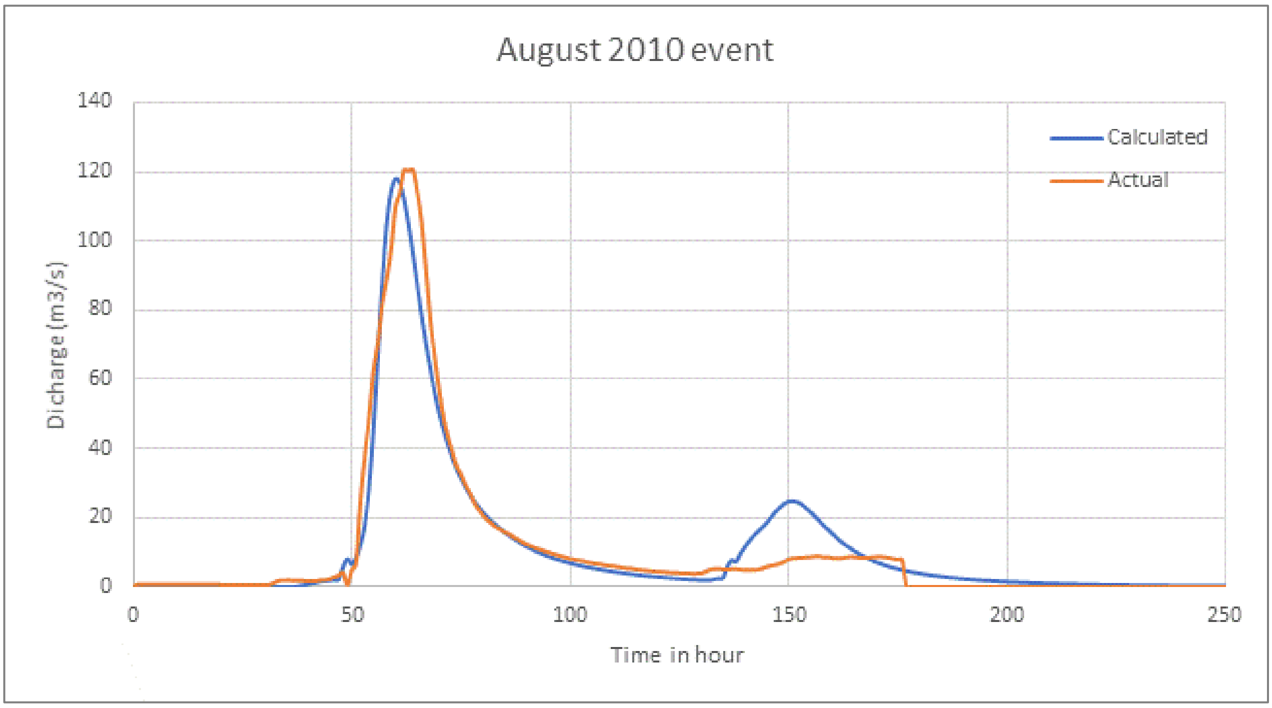

FIGURE 3-6 AUGUST 2010 - MODELLED AND GAUGED HYDROGRAPHS

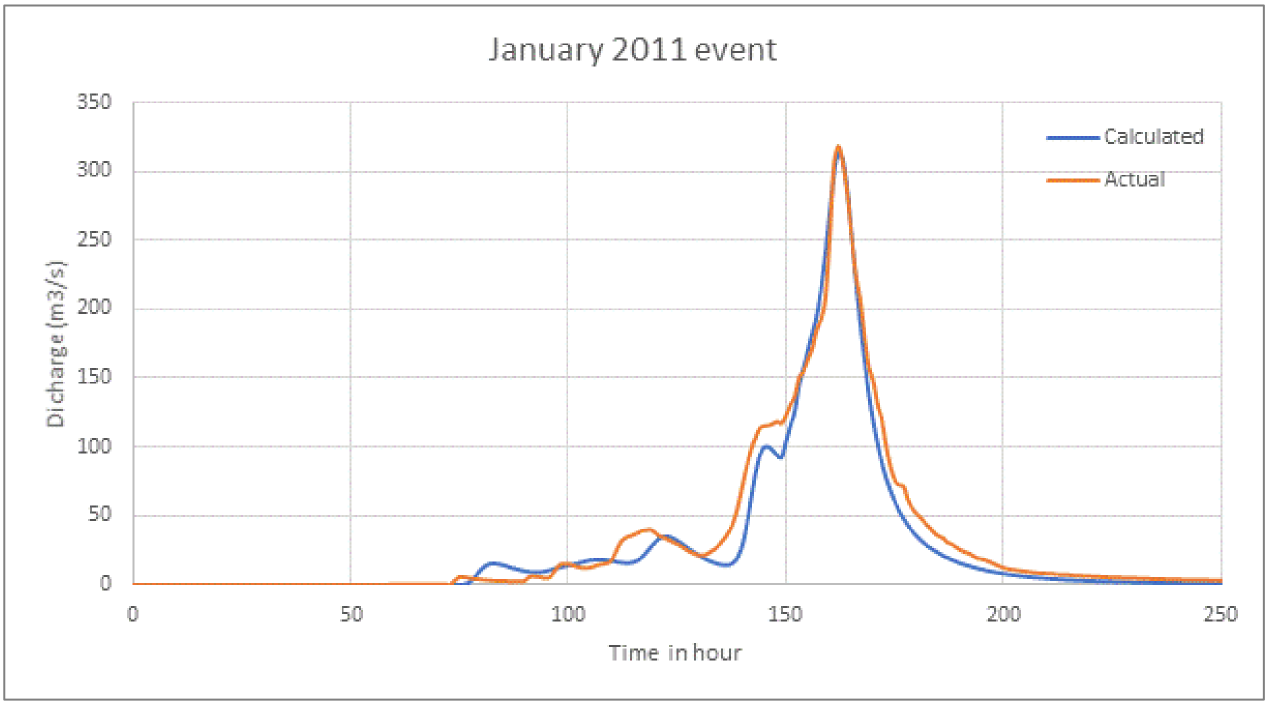

FIGURE 3-7 JANUARY 2011 - MODELLED AND GAUGED HYDROGRAPHS

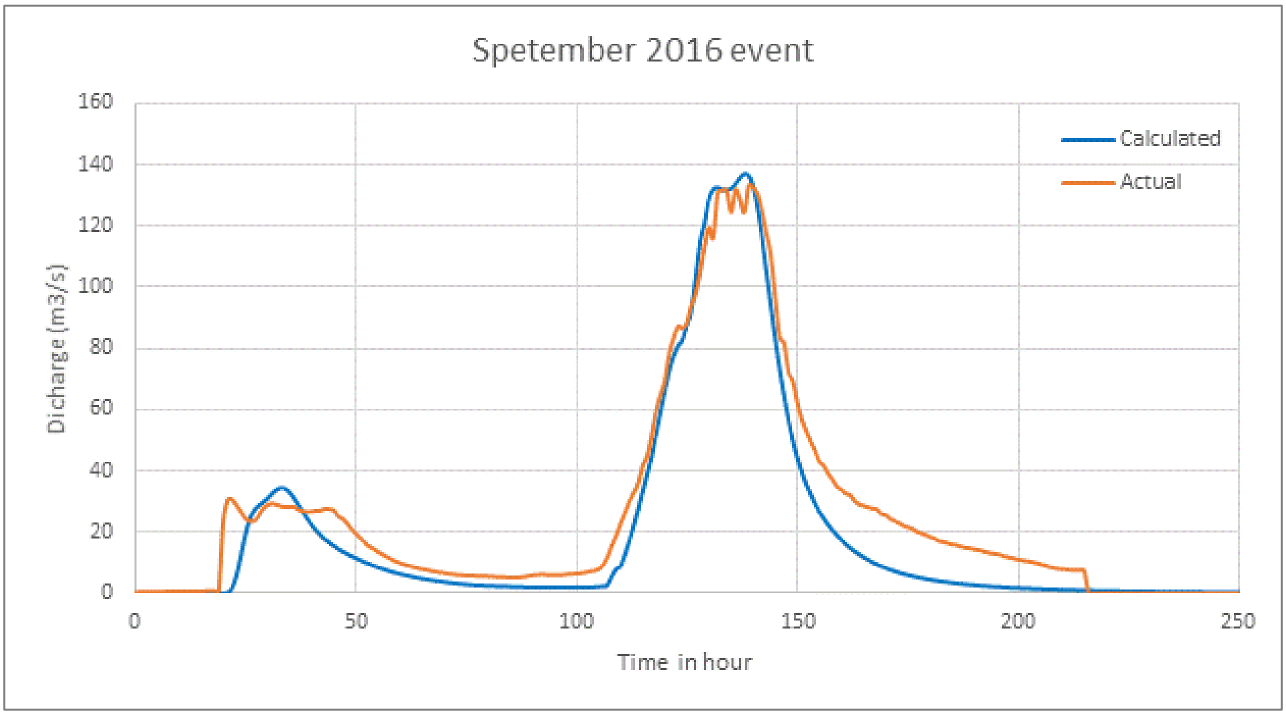

FIGURE 3-8 SEPTEMBER 2016 - MODELLED AND GAUGED HYDROGRAPHS

3.4.4 Design Modelling

3.4.4.1 Overview

As outlined in ARR2016, a Monte Carlo analysis was used to determine the design peak flows at key locations within each project catchment. RORB was run using the ensemble approach (modelling ten temporal patterns per AEP), with the pattern which most closely matches the Monte Carlo results chosen for each AEP event. The flow chart outlined in Figure 3-9 demonstrates the modelling process.

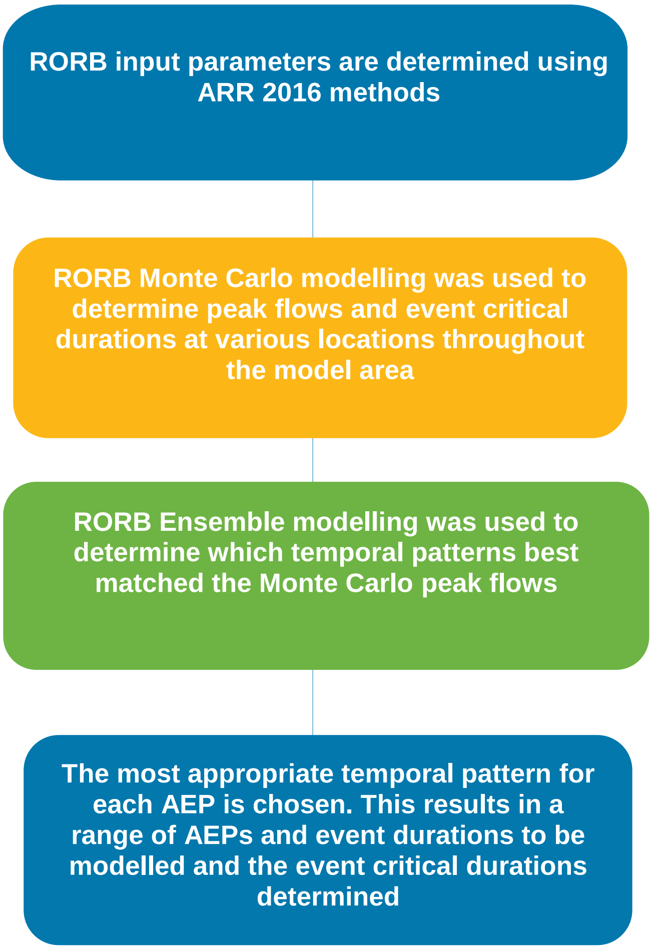

FIGURE 3-9 DESIGN MODELLING PROCESS DIAGRAM

3.4.4.2 Monte Carlo Analysis

The RORB Monte Carlo analysis was undertaken for each catchment, adopting the recommended losses from ARR2016 (or calibrated losses in the case of Gnarr Creek and the Yarrowee River). 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, kc 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 range of locations were selected along the catchment to output data from the RORB model.

3.4.4.3 Ensemble Analysis

The RORB model was also run using the Ensemble Analysis, using the determined kc value and recommended ARR2016 loses. The RORB Ensemble Analysis was run for all 10 ARR2016 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.

The Ensemble Analysis model results showed several temporal patterns in combination with design event and duration provided the best match to the Monte Carlo Analysis peak flows. To reduce the potential number of hydraulic model runs a single temporal pattern for each AEP was chosen.

3.4.4.4 Design Modelling Verification

3.4.4.4.1 FLOOD FREQUENCY ANALYSIS

As discussed in Section 3.4.3.1, a Flood Frequency Analysis (FFA) at the Leigh River at Mt Mercer was used to verify the adopted RORB model design parameters. The FFA was undertaken using the annual maximum peak flow within each using the water year definition, 1 July to 30 June[8]. 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 ARR2016.

A continuous record of flow and water level data exists at the gauge, available from 1956 to current day, 60 years of complete annual record.

A series of annual maxima were extracted from the gauge record and are listed in Table 3-6.

TABLE 3-6 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	3
1963	152	1977	134	1991	45	2005	121		
1964	109	1978	352	1992	102	2006	7		
1965	192	1979	72	1993	95	2007	20		
1966	73	1980	27	1994	13	2008	16		
1967	4	1981	115	1995	133	2009	26		
1968	87	1982	5	1996	123	2010	127		
1969	22	1983	112	1997	13	2011	313		

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

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 Leigh River Flood Study[9]. The recorded data shows 212 m^3/s, where the CMA study estimated 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. A Log Pearson Type 3 (LP3) distribution was chosen with Generalised Extreme Value (GEV), Generalised Pareto GP) and Gumbel distributions all tested.

An LP3 probability distribution of the annual series resulted in a 1% AEP peak flow estimate of 477 m^3/s at Mount Mercer, as shown in Table 3-7.

TABLE 3-7 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

3.4.4.4.2 COMPARISON

The Gnarr Creek and Yarrowee River RORB determined peak flows were compared to those determined in the FFA. The RORB modelling adopted parameters based on those determined during the design modelling, as shown in Table 3-8.

TABLE 3-8 GNARR CREEK AND YARROWEE RIVER ADOPTED RORB MODEL PARAMETERS AT INTERSTATIONS 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	6.7	30
Median initial loss (mm)	25			
Continuing loss (mm/h)	2.0	1.65	1.65	1.0

A comparison of the Gnarr Creek and Yarrowee River RORB and FFA determined flows is shown in Table 3-9. The flows match very closely verifying the adopted design RORB model parameters.

[9] Corangamite CMA (2017), Leigh River Flood Study

TABLE 3-9 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 verified Gnarr Creek and Yarrowee River RORB model parameters were compared to those determined for the remaining catchments which did not have gauge data to verify to, as shown in Table 3-10. The comparison shows the adopted initial losses across all projects are very consistent; however, the adopted ungauged catchment losses are 2-2.5 mm/hr lower than the gauge verified losses.

TABLE 3-10 COMPARISON OF RORB MODEL PARAMETERS AND LOSSES

Catchment	Parameter			
	m	k_c (relative to D_{av})	Initial Loss (mm)	Continuing Loss (mm/hr)
Bonshaw Creek	0.8	2.4	24	4.5
Kensington Creek		4.1	24	4.5
Redan Creek		1.2	24	4.5
The Chase Catchment		1.3	24	4.5
Canadian Creek and tributaries		1.1	25	4.5
Warrenheip Creek and Ryan's Drain		1.3	25	4.4
Little Bendigo Creek and Hit or Miss Gully		1.0	25	4.4
Yarrowee River and Gnarr Creek		0.5-3.1	24	1-2

3.5 Hydraulics

3.5.1 Overview

Hydraulic modelling undertaken as part of this project covers main waterways flowing through and/or away from Ballarat. A detailed combined 1D – 2D hydraulic modelling approach was adopted for each study, consisting of one dimensional (1D) drainage lines and structures and a broader two dimensional (2D) floodplain.

The 1D and 2D hydraulic model components are required to accurately model the interaction between in bank/pipe flows (1D) and overland floodplain flows (2D).

The hydraulic modelling suite TUFLOW was utilised in this study. TUFLOW is a widely used hydraulic model that is suitable for the analysis of overland flows in urban and rural areas. TUFLOW has four main inputs:

- Topography and drainage infrastructure data.
- Inflow data (based on catchment hydrology).
- Roughness.
- Boundary conditions.

3.5.2 Boundary Conditions

3.5.2.1 Model Inflows

Each TUFLOW model contained various inflow regions. Inflow regions simulated flow into the main channel within the catchment. Inflows were extracted from each RORB model at each RORB defined sub catchment.

An example of how this was carried out is shown in Figure 3-10, demonstrating the catchment up and downstream of The Chase Estate.

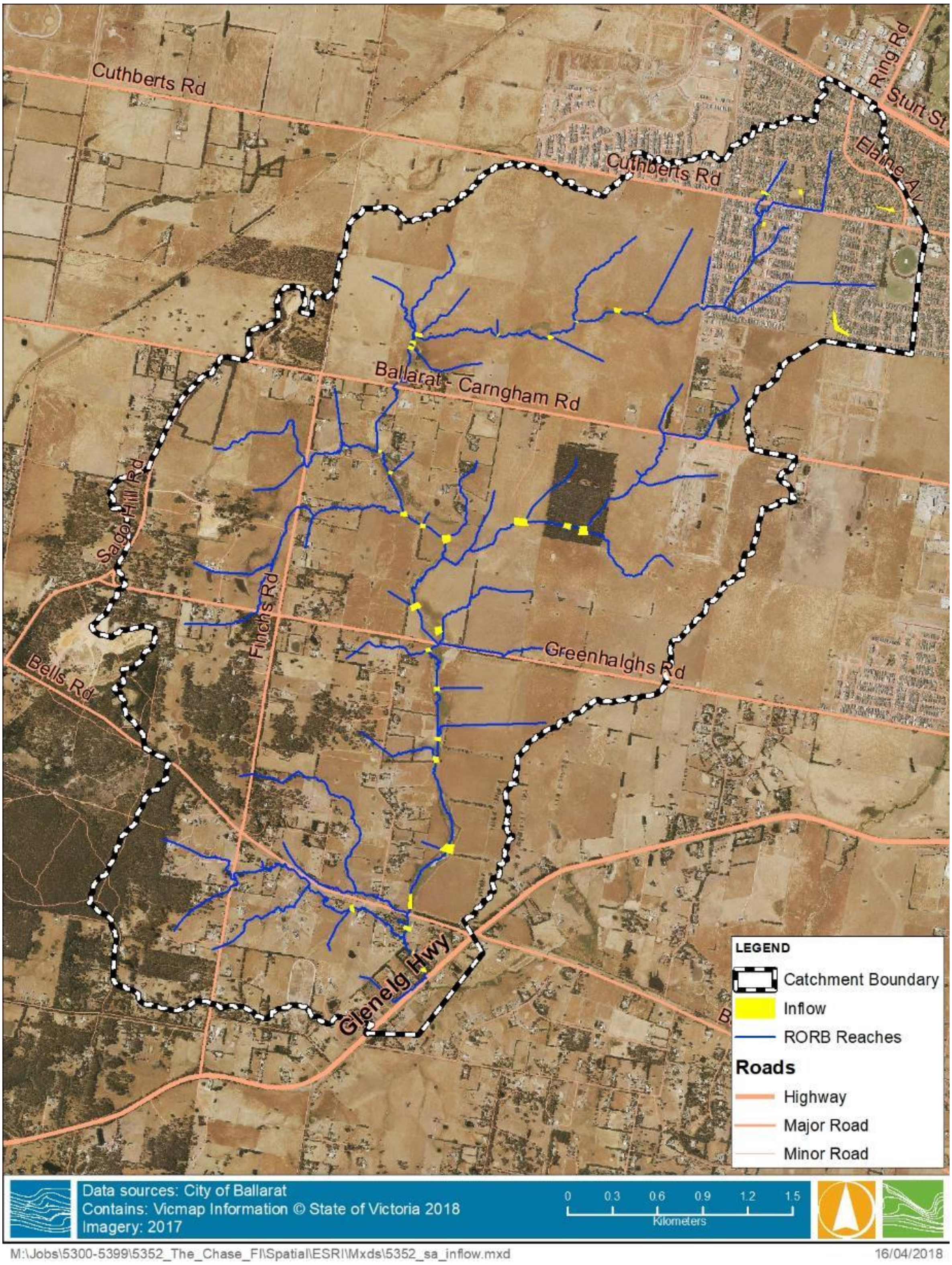

FIGURE 3-10 INFLOW LOCATIONS FOR THE CHASE

3.5.2.2 Model Outflows

Each hydraulic model had at least one hydraulic outflow at the end of the main steam, or at the confluence to another stream. Outflows were modelled as flowrate/height boundaries (HQ), these boundaries allow water to exit the model based on a stage discharge curve generated by TUFLOW.

3.5.3 Grid Extent and Resolution

The model topography was largely based on LiDAR data captured in 2011-12 through the Central Highlands Photography & Elevation Project. The LiDAR datasets was provided as a 1m resolution Digital Elevation Model (DEM), which was resampled to 3 m grid resolution for input into the hydraulic model.

A key consideration in determining the grid size was the trade-off between accurate representation of the streamflow paths and reasonable model run times. Although smaller grid sizes can provide higher resolution results, they also significantly increase the run times. A 3m grid was found to well represent the catchment in an acceptable run time.

An example topography is shown in Figure 3-11, demonstrating the topography used to model The Chase Estate.

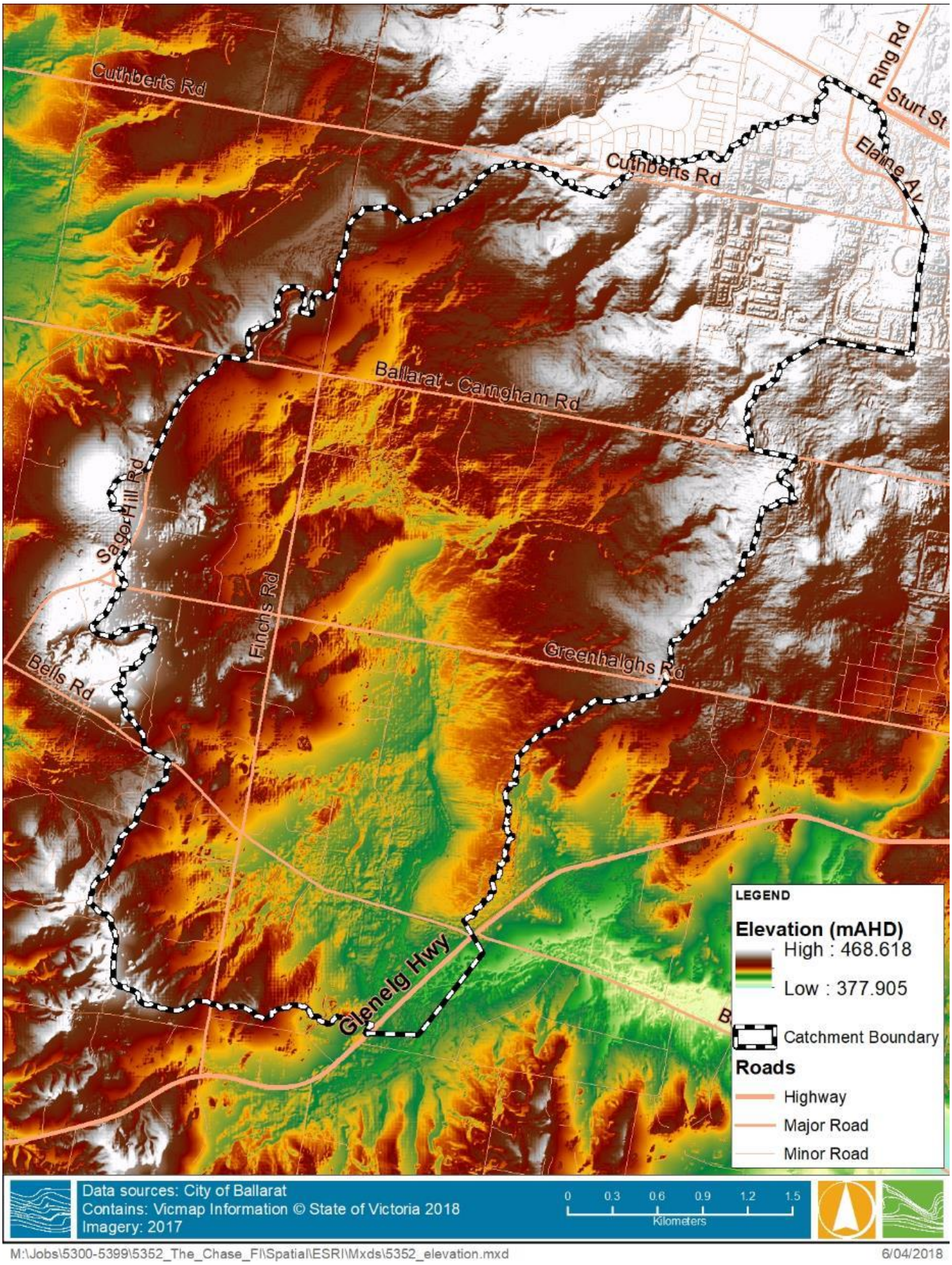

FIGURE 3-11 DIGITAL ELEVATION MODEL IN THE CHASE

3.5.4 Hydraulic Roughness

Hydraulic model roughness was determined using CoB planning layers, along with aerial imagery for verification. Table 3-11 outlines the generalised (before aerial image verification) Manning's 'n' roughness values adopted within project area. These values were adopted for use in the hydraulic model and are shown in Table 3-11. The adopted roughness' were based on standard industry accepted values (VicRoads Road Design Guidelines).

TABLE 3-11 MANNINGS 'N' VALUES FOR LAND USE TYPES

Land Use	Manning's 'n'
Residential - Urban (higher density) - when building footprints and remainder of parcel are modelled together (with one roughness value)	0.35
Residential - Rural (lower density) - when building footprints and remainder of parcel are modelled together (with one roughness value)	0.15
Residential Footprint - Urban (higher density) - when building footprints are modelled separately to remainder of parcel	0.40
Residential - Urban (higher density) - when building footprints are modelled separately to remainder of parcel	0.10
Residential Footprint - Rural (lower density) - when building footprints are modelled separately to remainder of parcel	0.40
Residential - Rural (lower density) - when building footprints are modelled separately to remainder of parcel	0.05
Industrial/Commercial or large buildings on site	0.30
Significant Drainage Easement (regardless of zone type)	0.05
Open Space or Waterway - minimal vegetation	0.04
Open Space or Waterway - moderate vegetation	0.06
Open Space or Waterway - heavy vegetation	0.09
Open water (with reedy vegetation)	0.06
Open water (with submerged vegetation)	0.02
Car park/pavement/wide driveways/roads	0.02
Railway line	0.13
Concrete lined channels	0.01

3.5.5 Key Hydraulic Structures

Key hydraulic structures were included in the hydraulic model using a 1D pipe network or 1D layered flow restrictions. This enables features such as road decks and culvert spans to be accounted for accurately. 1D structures were linked to the 2D floodplain domain allowing water to flow through the structures. All structures were tested for stability. The structures modelled include the pipe network throughout model, and any culverts traversing hydraulic model area.

4 RESULTS/MAPPING

Results of each project are presented in the following sections. Reporting largely focuses on 1% AEP modelled depths; however, velocities, pipe capacities etc. can all be extracted from the model outputs. Modelling of 20%, 10%, 5%, 2% and 1% AEP events was completed, with durations ranging from 15mis to 72 hours depending on the characteristics of the catchment.

1% AEP depths for each waterway is shown in the following figures:

- Bonshaw Creek
  - Figure 4-1 – Upper catchment
  - Figure 4-2 – Mid catchment
  - Figure 4-3 – Lower catchment
- Kensington Creek
  - Figure 4-4 – Full extent
  - Figure 4-6 – Wensleydale Drive
  - Figure 4-7 - Greenhalghs Road
- Redan Creek
  - Figure 4-8 – Full extent
  - Figure 4-9 – Latrobe Street to Kent Street
  - Figure 4-10 – South of Rubicon Street
  - Figure 4-11 – Between Winter Street and Rubicon Street
- The Chase Waterway
  - Figure 4-12 – Full extent
  - Figure 4-13 – Upper catchment
  - Figure 4-14 – Mid catchment
  - Figure 4-15 – Lower catchment
- Canadian Creek
  - Figure 4-17 – Northern tributaries
  - Figure 4-18 – Lower catchment
  - Figure 4-19 – Mid catchment
  - Figure 4-20 – Upper catchment
- Warrenheip Creek and Ryan's Drain
  - Figure 4-22 – US Humffray Street
  - Figure 4-23 – Finlay Street
  - Figure 4-24 – DS Old Melbourne Road
- Yarrowee River and Gnarr Creek
  - Figure 4-25 – Gnarr Creek, upper catchment

- Figure 4-26 – Gnarr Creek, lower catchment
- Figure 4-27 – Yarrowee River, DS Western Freeway
- Figure 4-28 – Yarrowee River, US railway line
- Figure 4-29 – Yarrowee River, CBD
- Figure 4-30 – Yarrowee River, DS Bridge Street
- Figure 4-31 – Yarrowee River, DS Midland Highway
- Figure 4-32 – Yarrowee River, east of Colac-Ballarat Road
- Figure 4-33 – Yarrowee River, US Scotchmans Lead Road

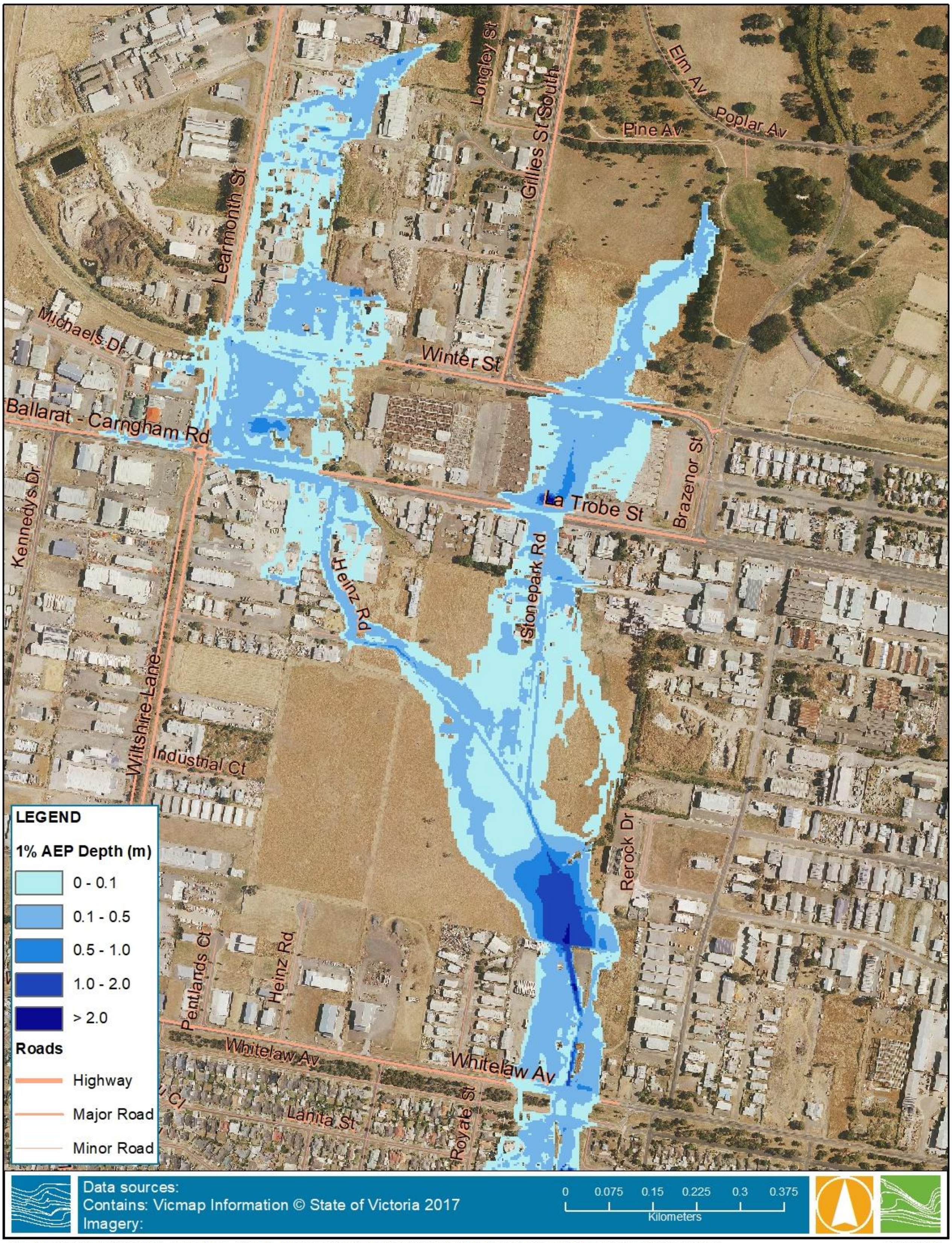

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FIGURE 4-1 BONSHAW CREEK – 1% AEP FLOOD DEPTHS, UPPER CATCHMENT

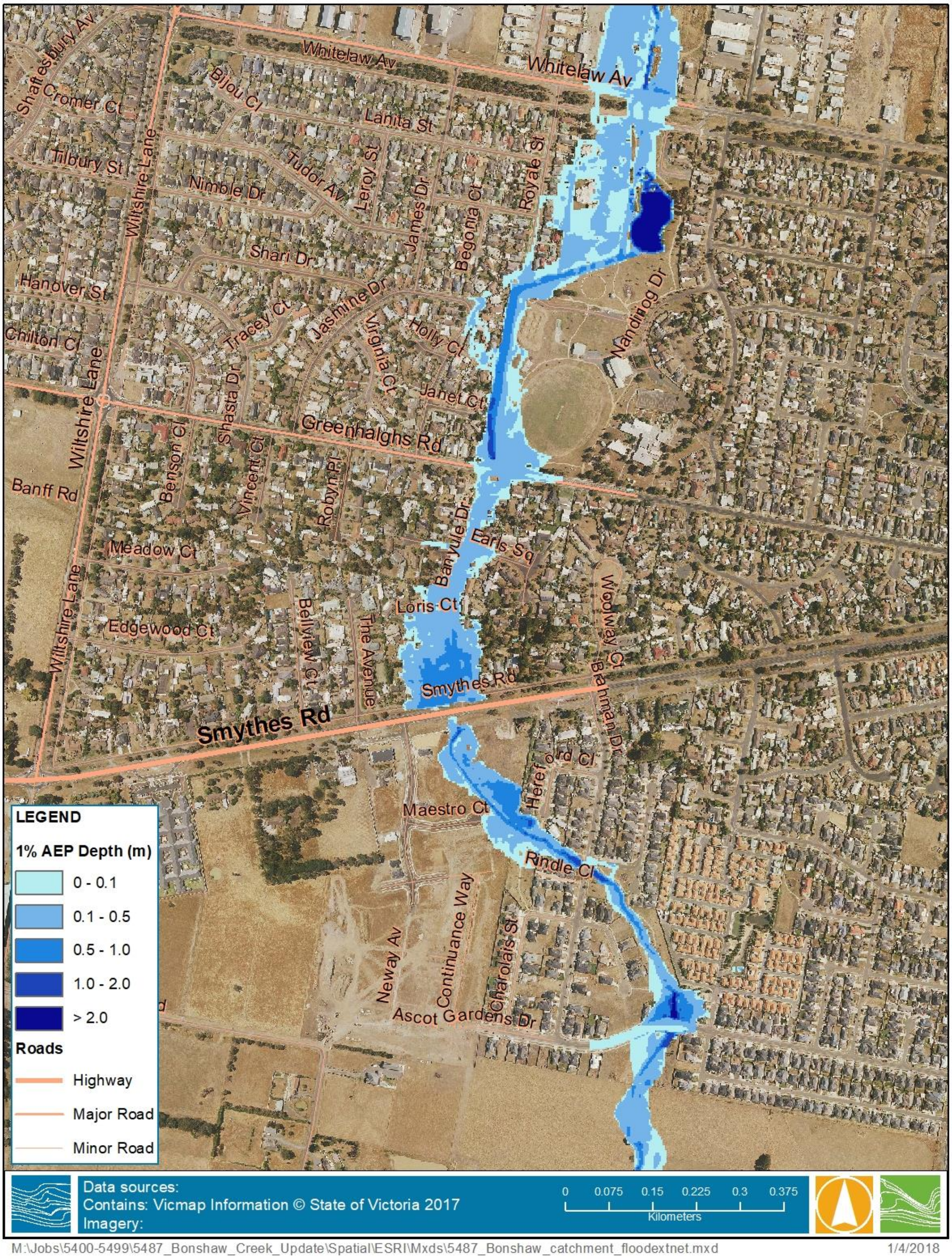

FIGURE 4-2 BONSHAW CREEK – 1% AEP FLOOD DEPTHS, MID CATCHMENT

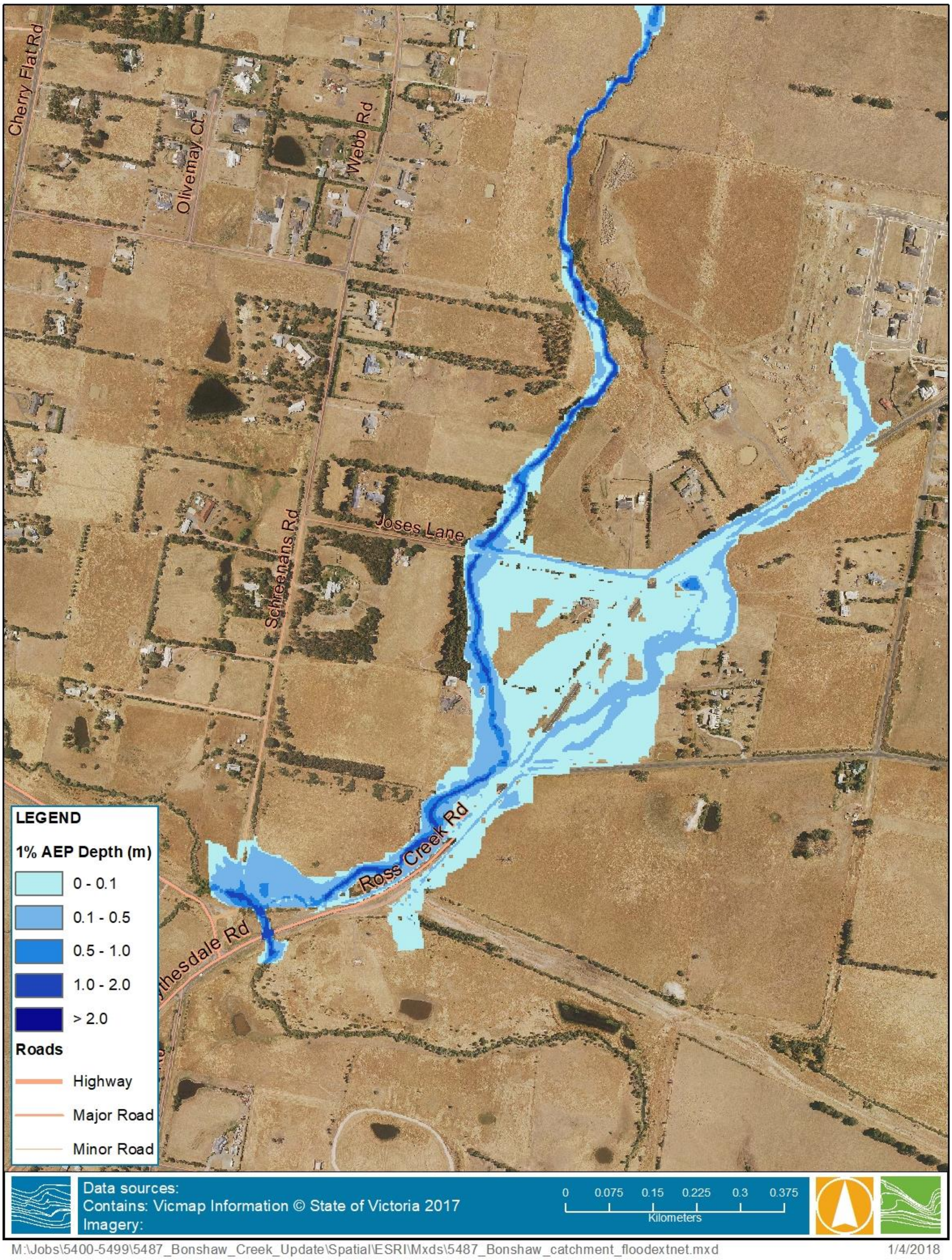

FIGURE 4-3 BONSHAW CREEK – 1% AEP FLOOD DEPTHS, LOWER CATCHMENT

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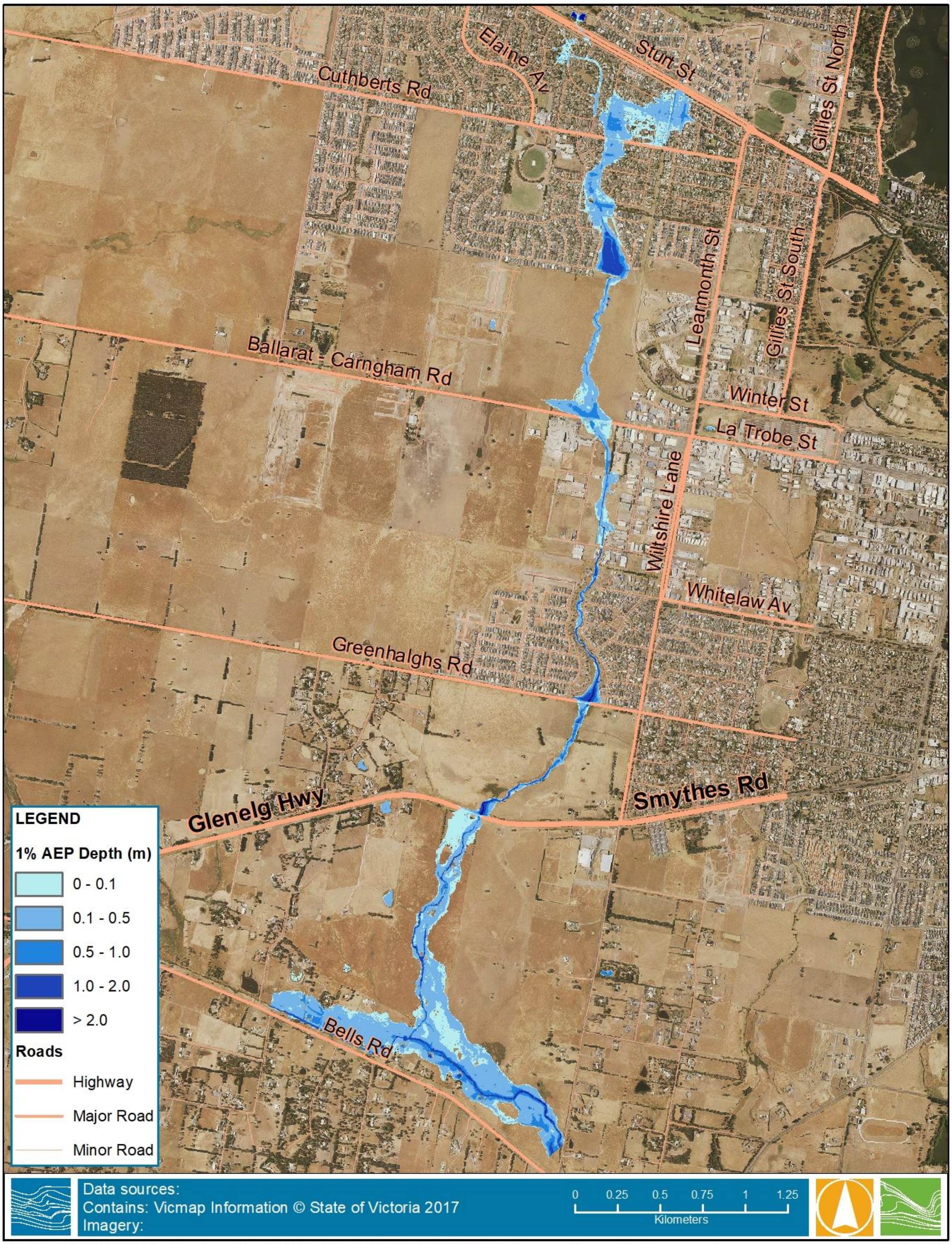

FIGURE 4-4 KENSINGTON CREEK – 1% AEP FLOOD DEPTHS, FULL EXTENT

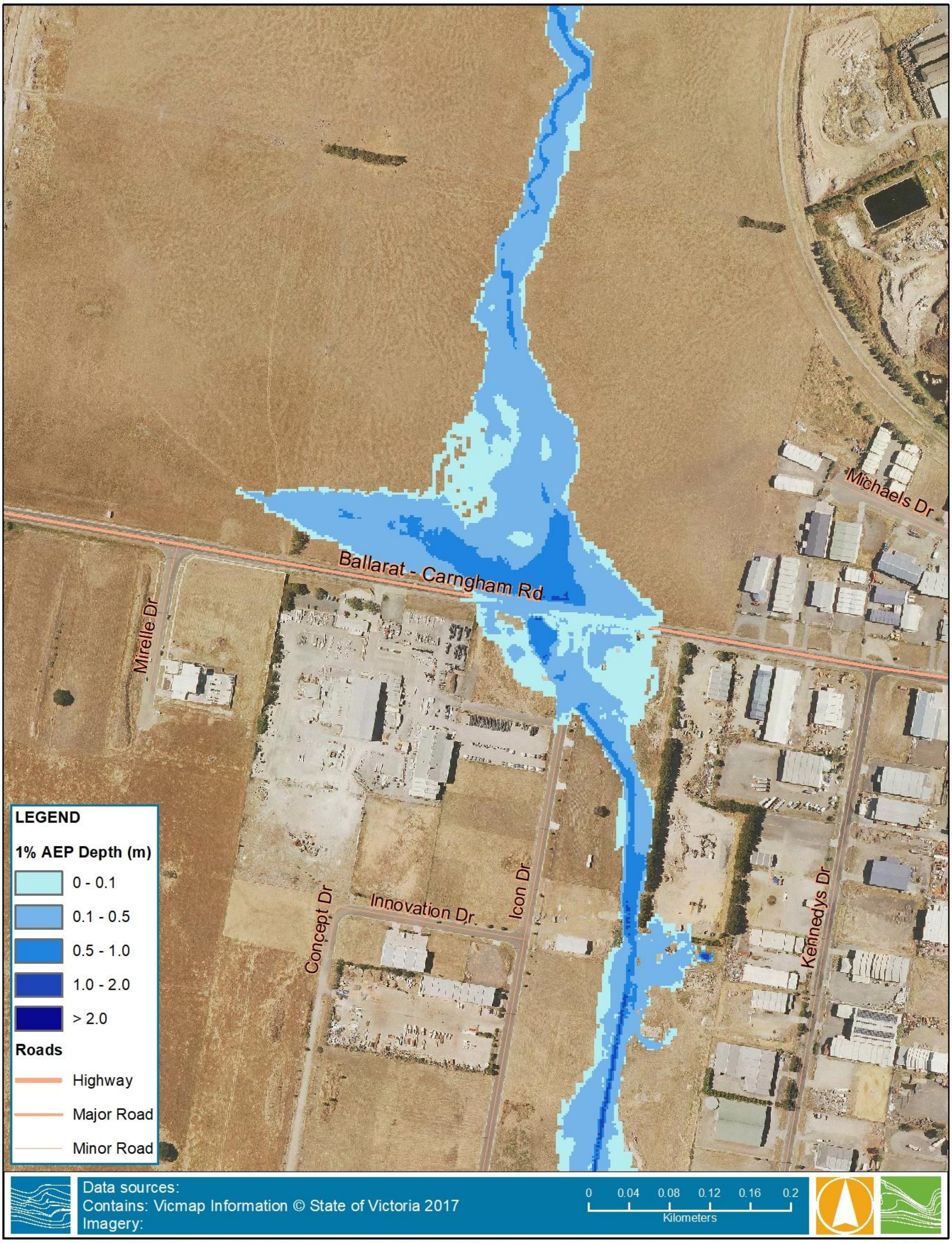

FIGURE 4-5 KENSINGTON CREEK – 1% AEP FLOOD DEPTHS, BALLARAT-CARNGHAM ROAD

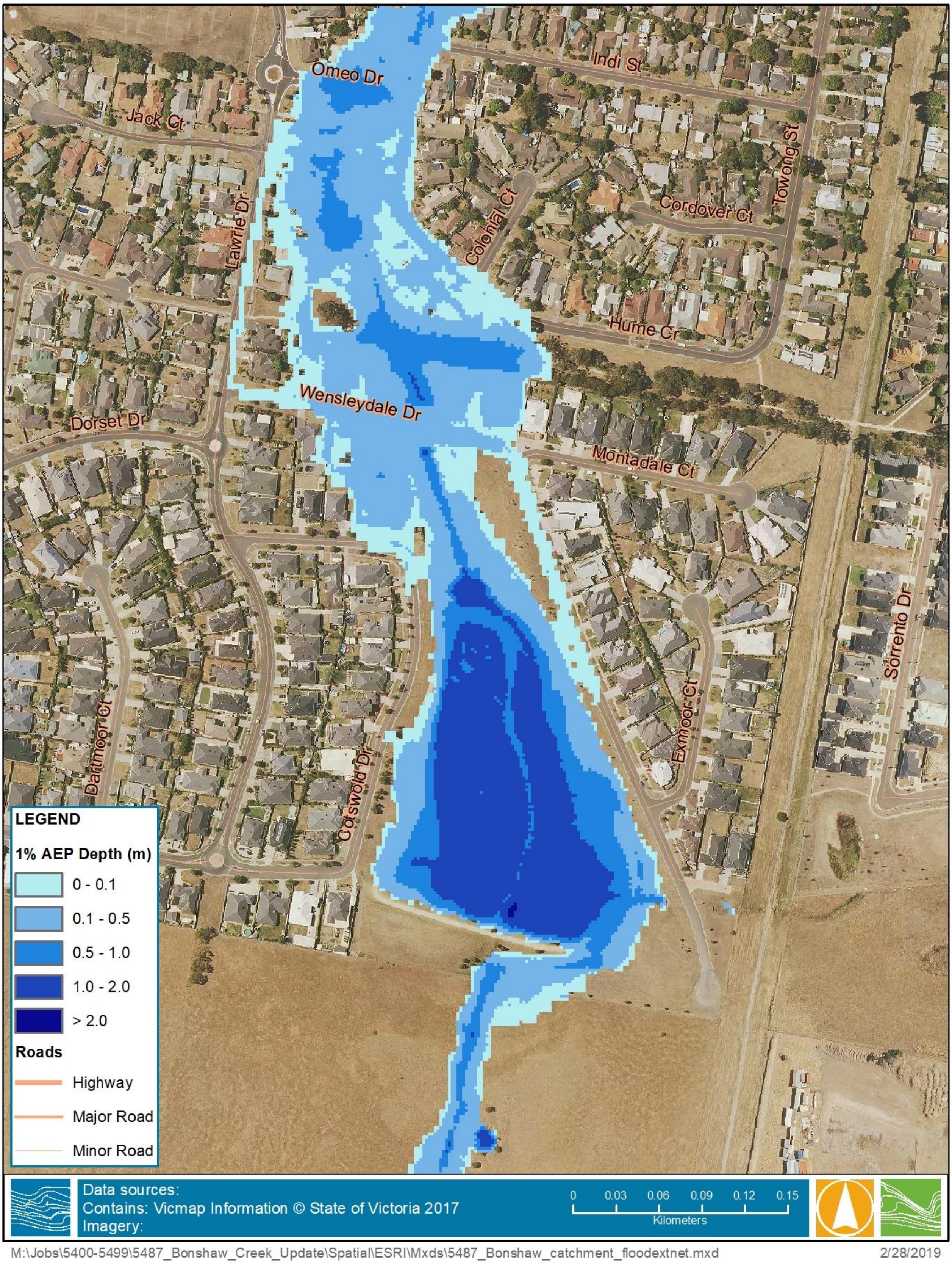

FIGURE 4-6 KENSINGTON CREEK – 1% AEP FLOOD DEPTHS, WENSLEYDALE DRIVE

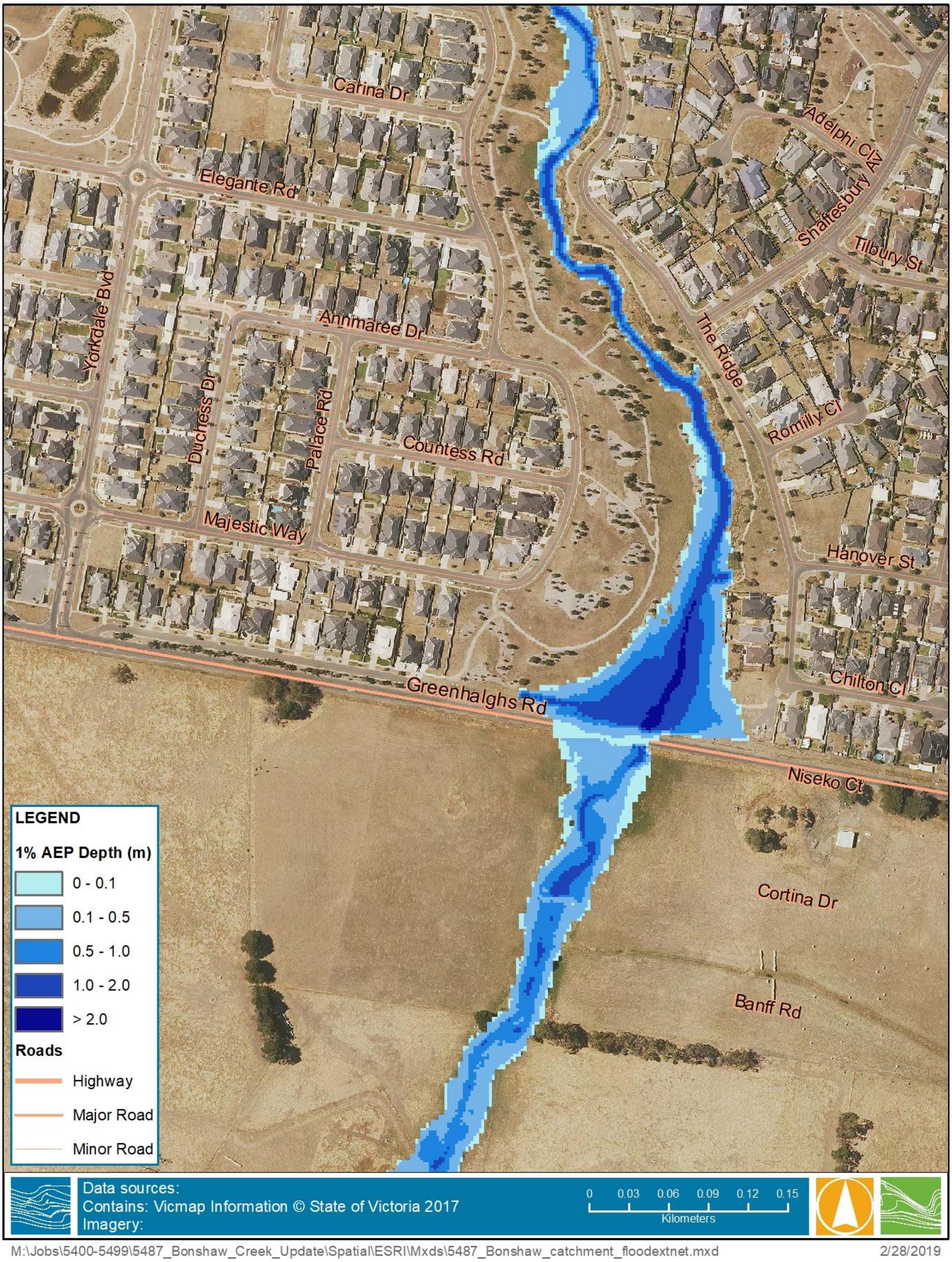

FIGURE 4-7 KENSINGTON CREEK – 1% AEP FLOOD DEPTHS, GREENHALGHS ROAD

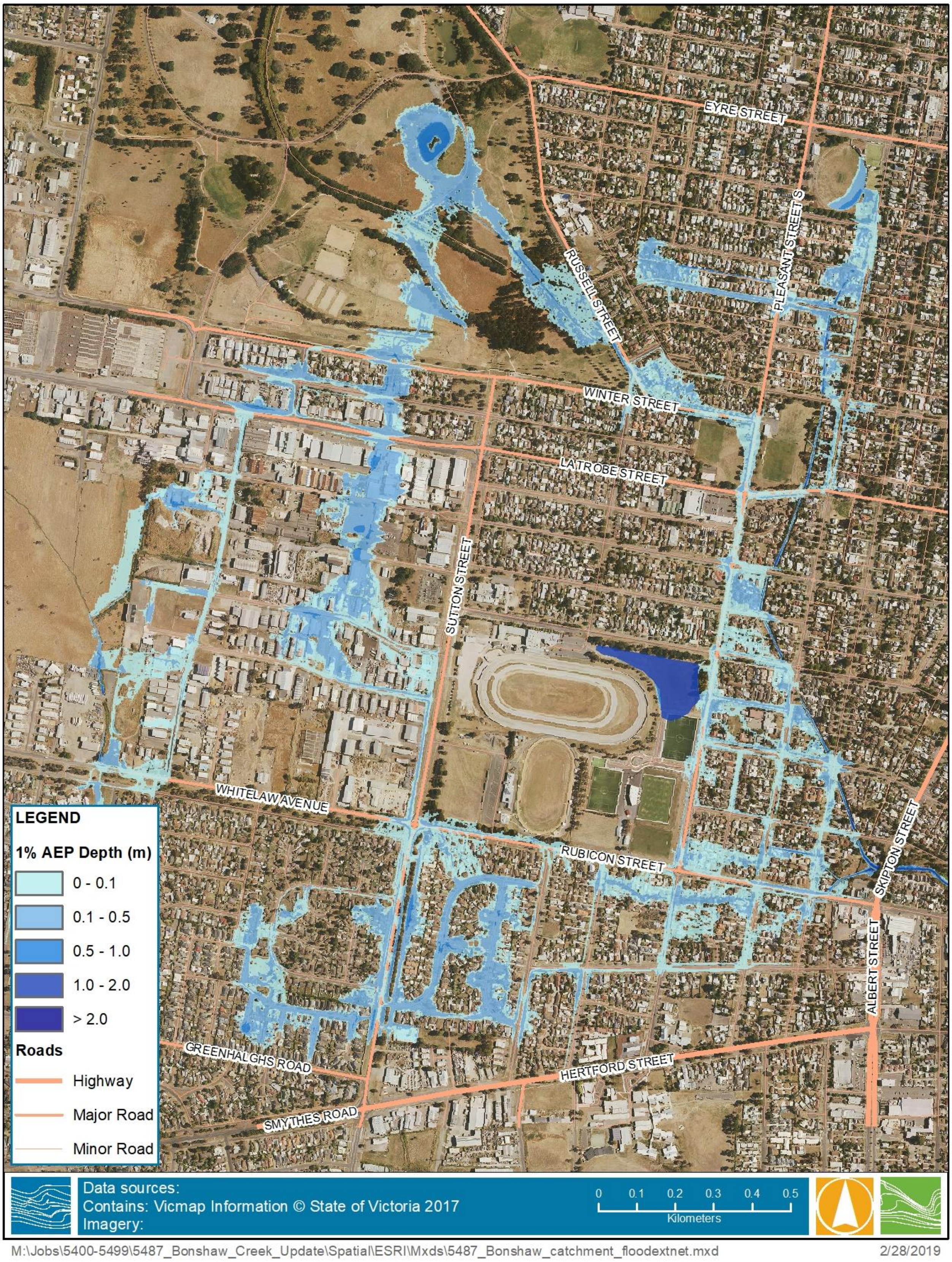

FIGURE 4-8 REDAN CREEK - 1% AEP FLOOD DEPTHS, FULL EXTENT

FIGURE 4-9 REDAN CREEK - 1% AEP FLOOD DEPTHS, LATROBE STREET TO KENT STREET

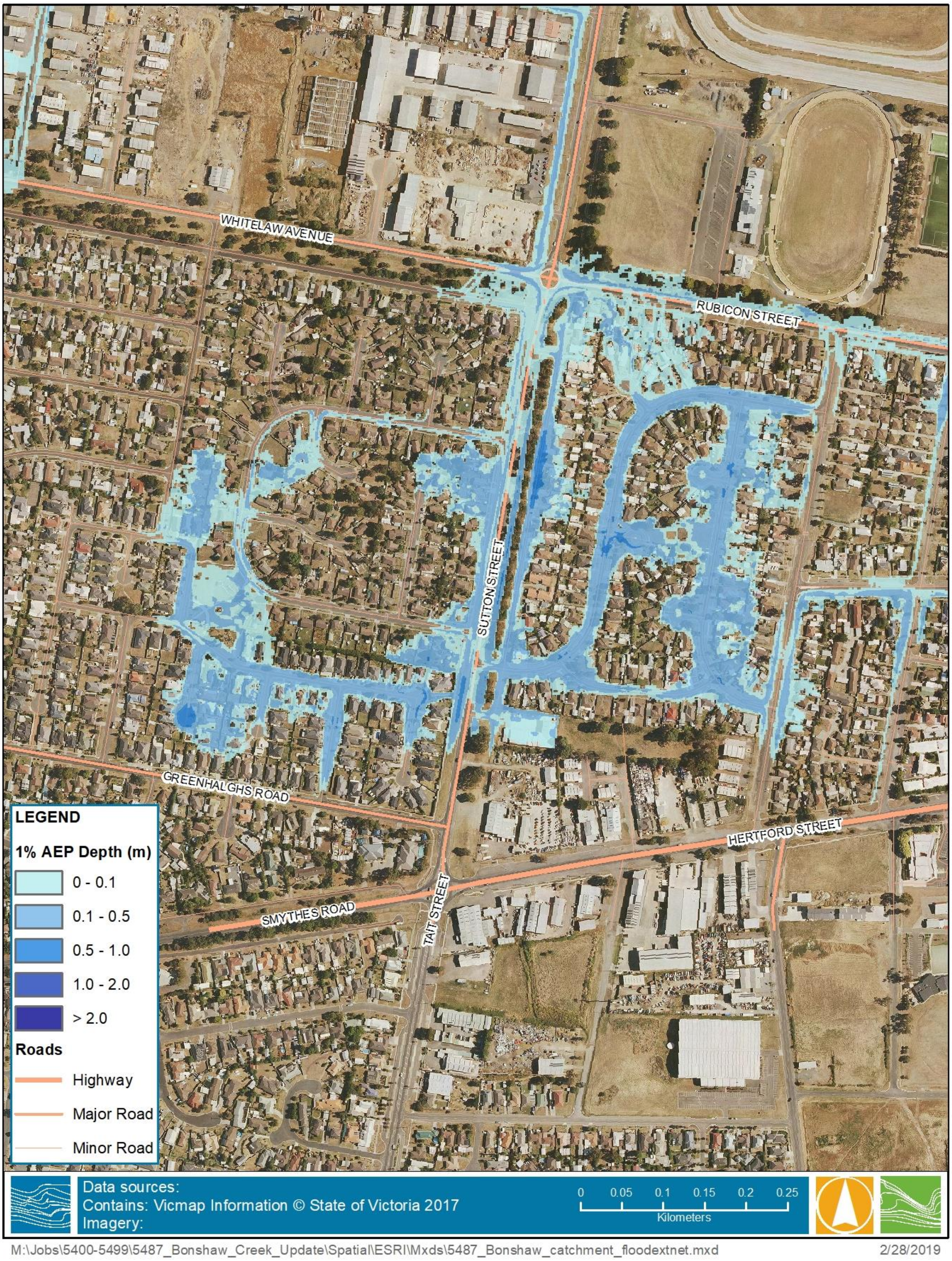

FIGURE 4-10 REDAN CREEK - 1% AEP FLOOD DEPTHS, SOUTH OF RUBICON STREET

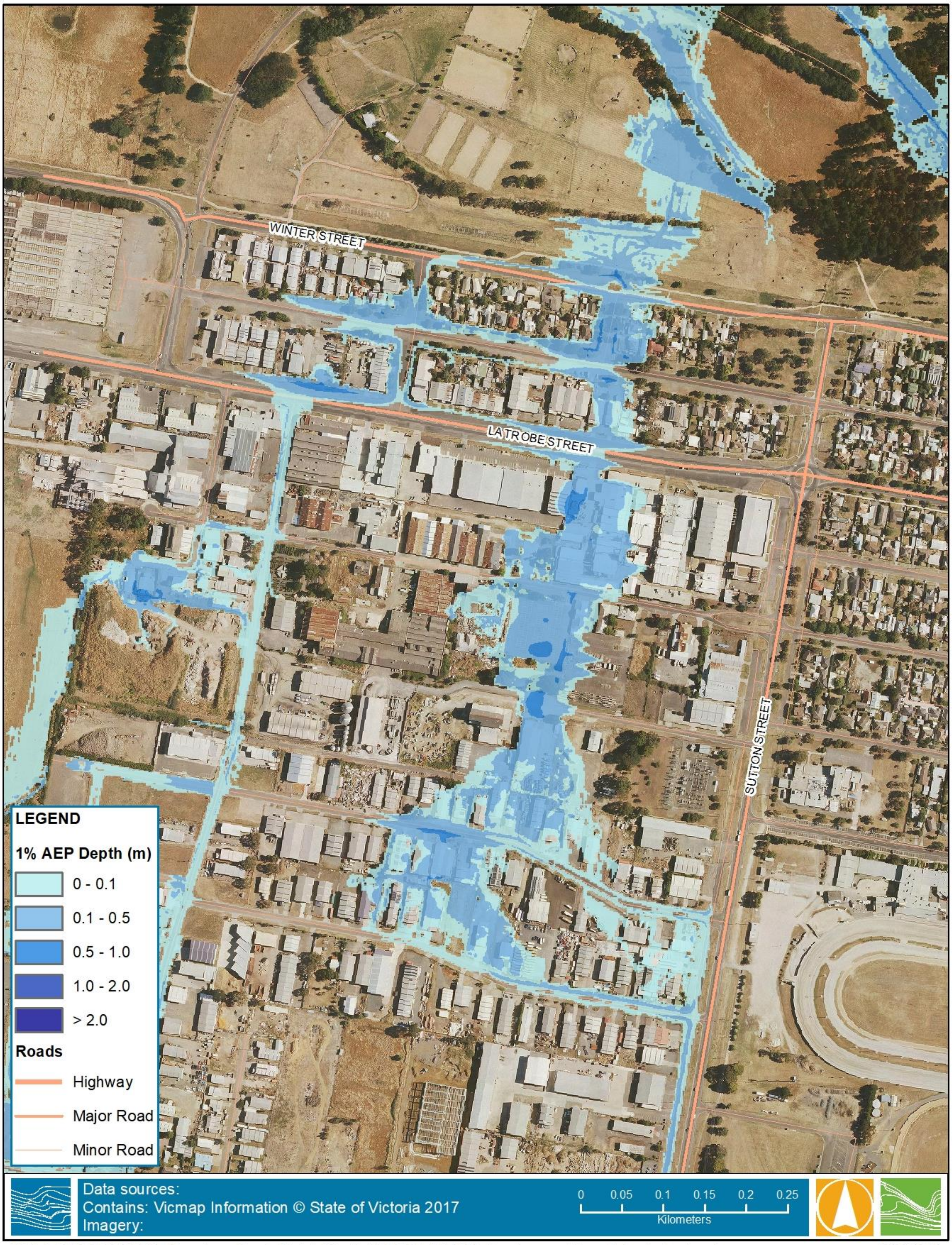

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FIGURE 4-11 REDAN CREEK - 1% AEP FLOOD DEPTHS, BETWEEN WINTER STREET AND RUBICON STREET

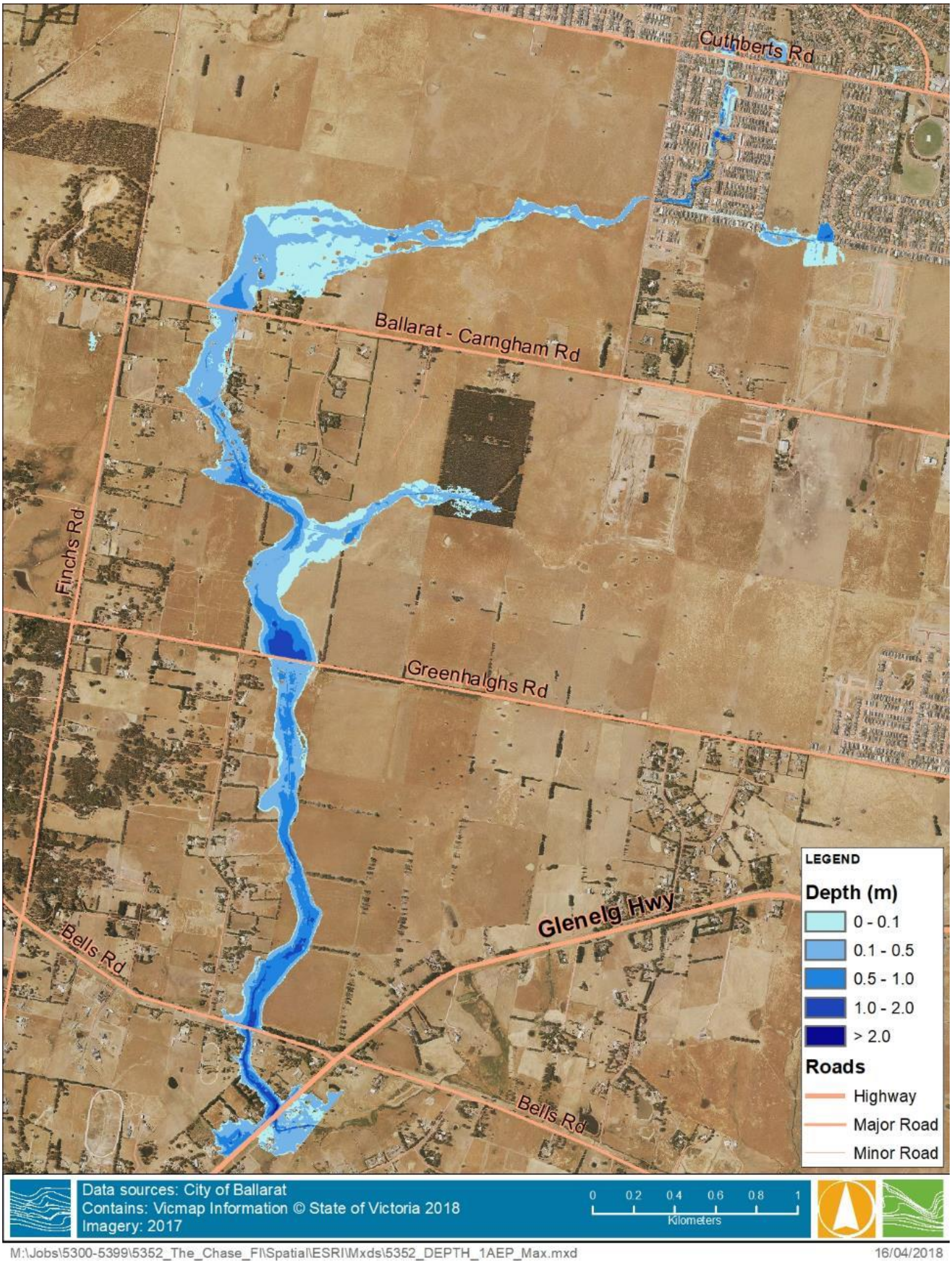

FIGURE 4-12 THE CHASE - 1% AEP FLOOD DEPTHS, FULL EXTENT

FIGURE 4-13 THE CHASE - 1% AEP FLOOD DEPTHS, UPPER CATCHMENT

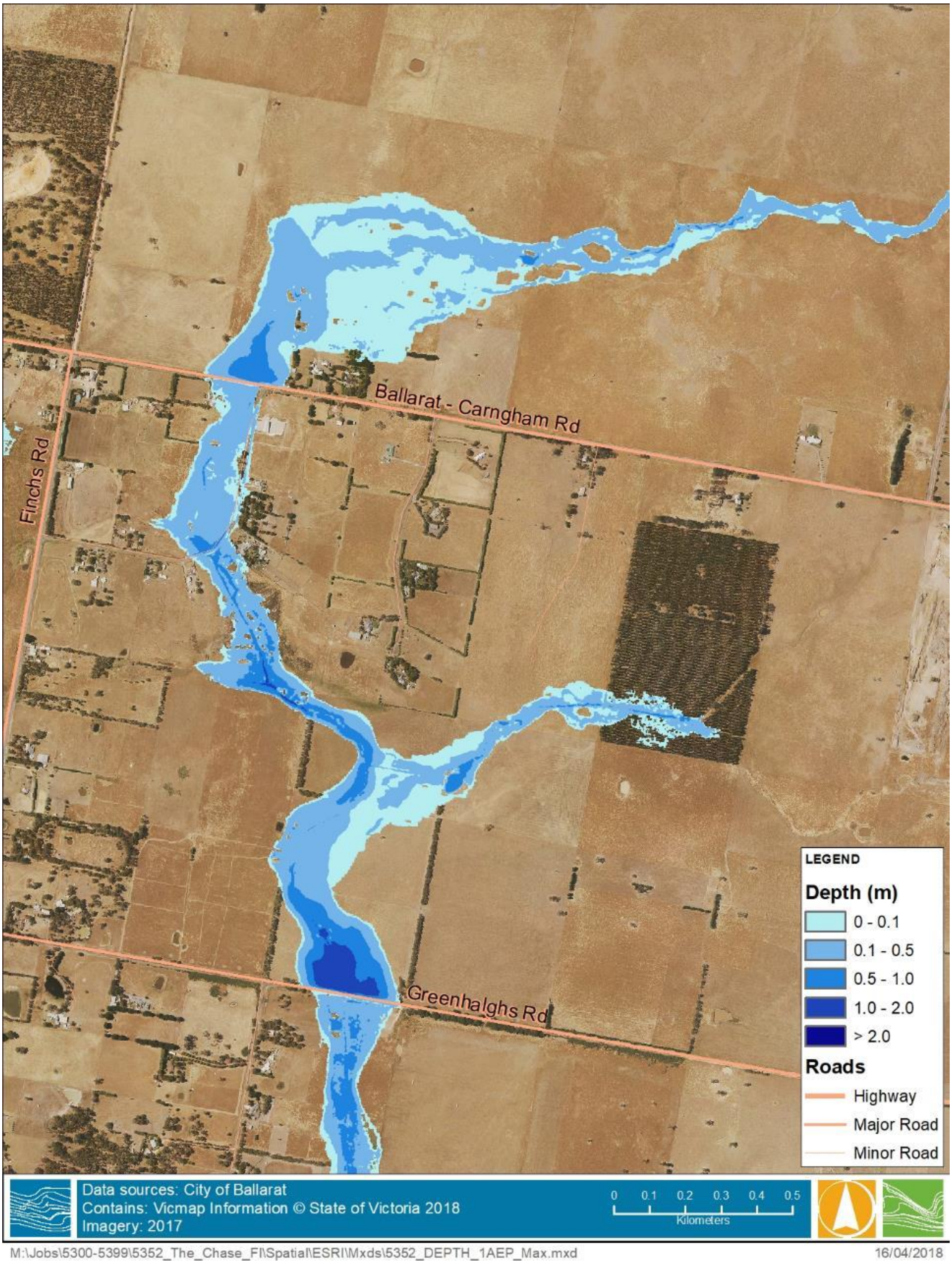

FIGURE 4-14 THE CHASE 1% - AEP FLOOD DEPTHS, MID CATCHMENT

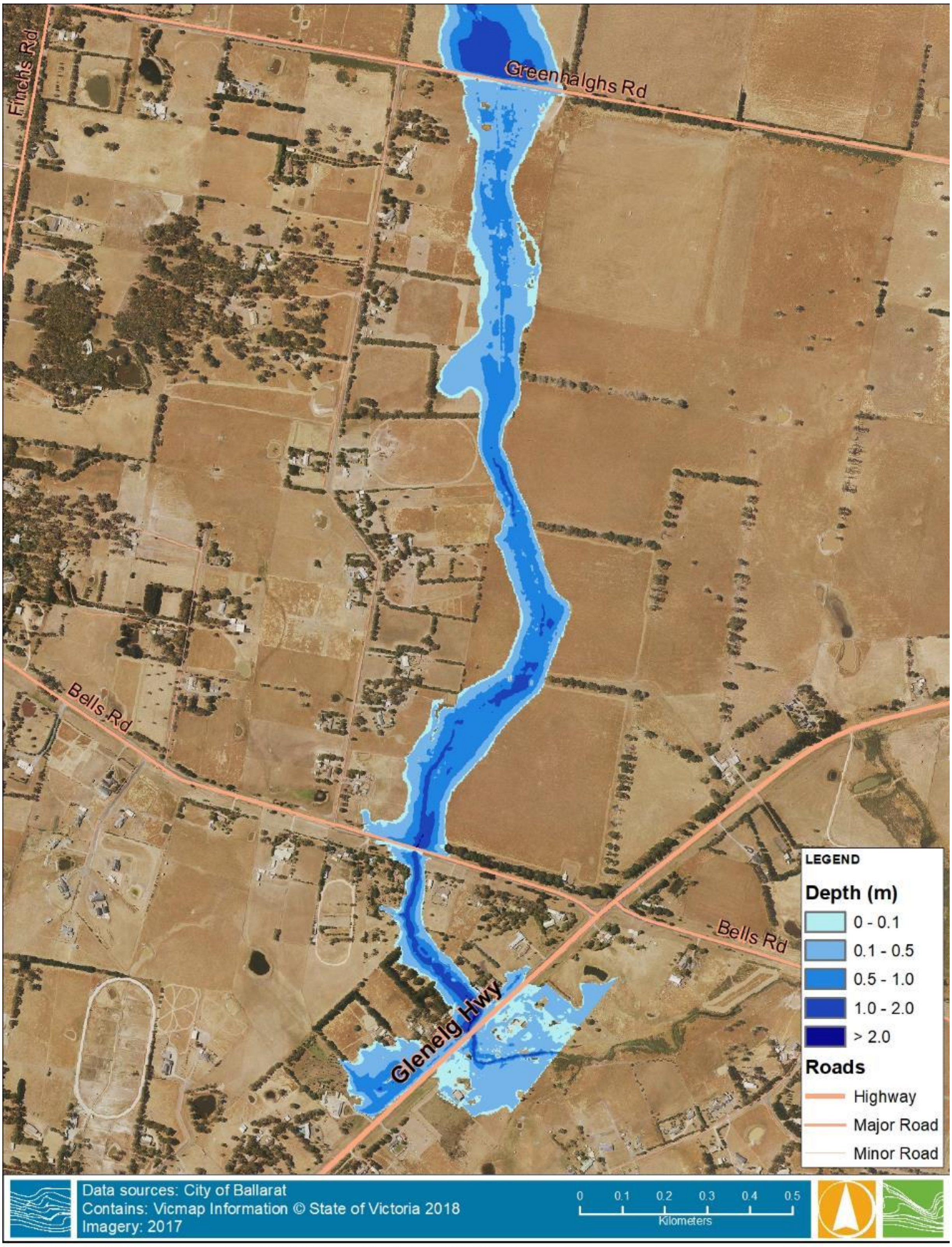

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FIGURE 4-15 THE CHASE - 1% AEP FLOOD DEPTHS, LOWER CATCHMENT

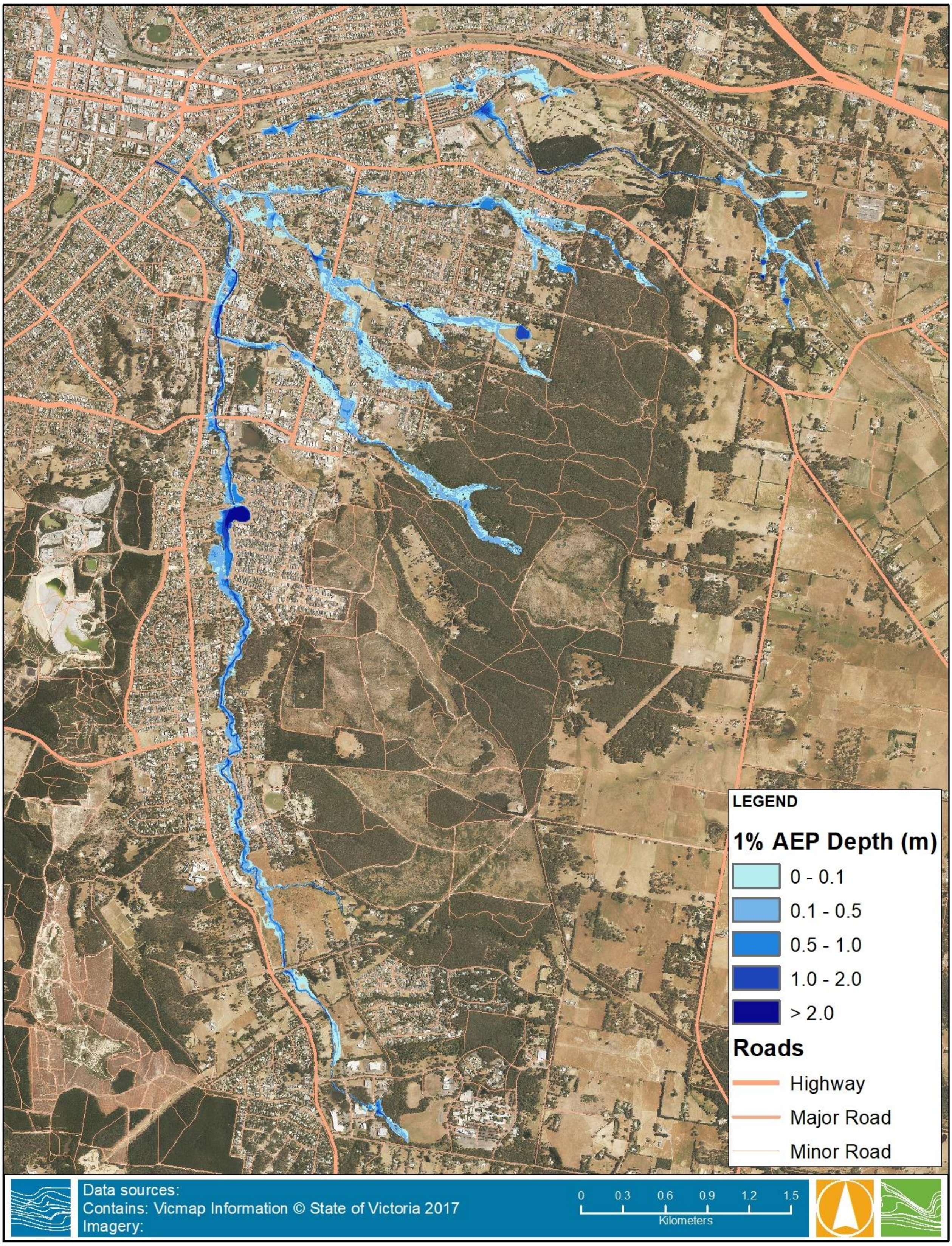

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FIGURE 4-16 CANADIAN CREEK - 1% AEP FLOOD DEPTHS, FULL EXTENT

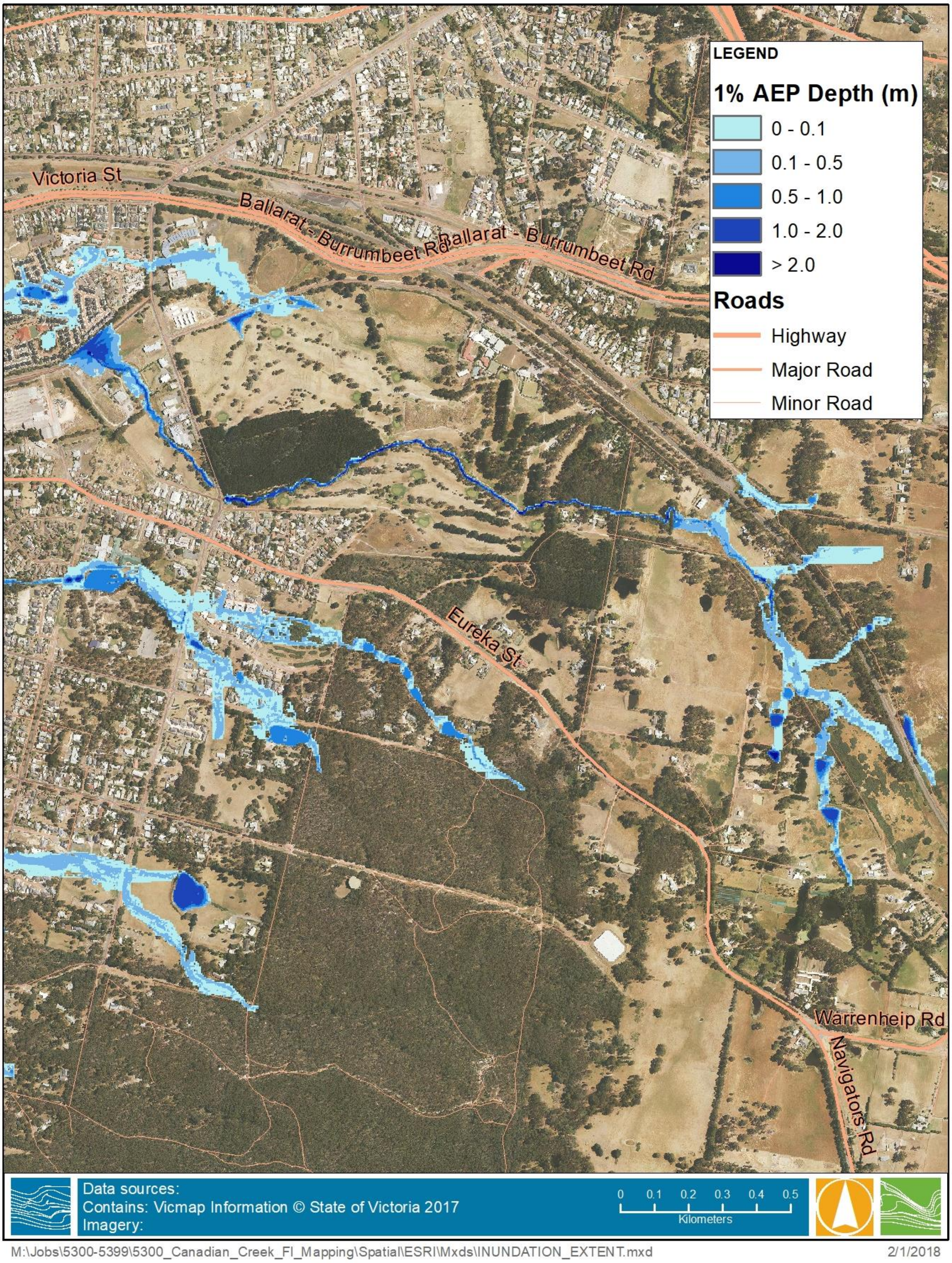

FIGURE 4-17 CANADIAN CREEK - 1% AEP FLOOD DEPTHS, UPPER TRIBUTARIES

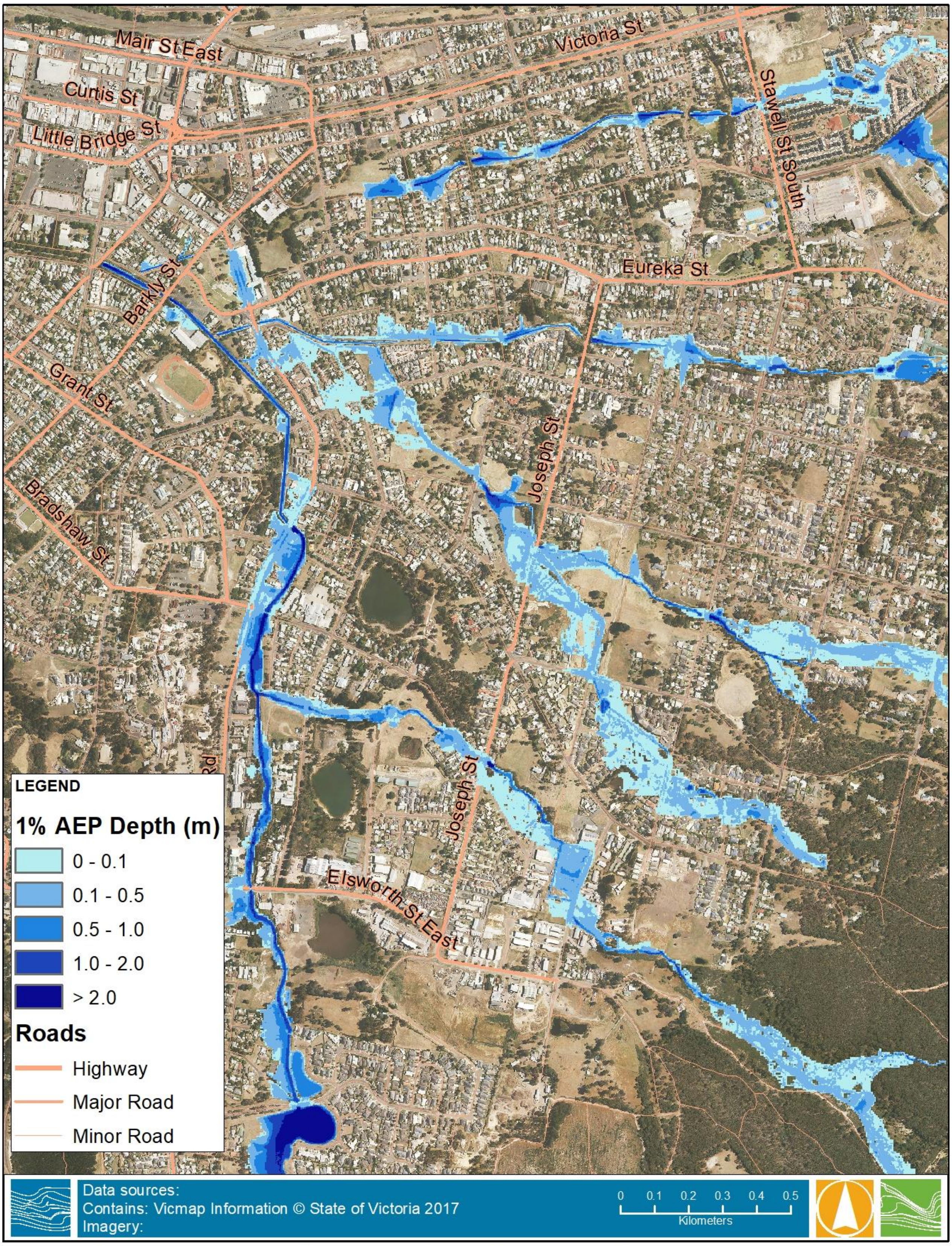

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FIGURE 4-18 CANADIAN CREEK - 1% AEP FLOOD DEPTHS, LOWER CATCHMENT

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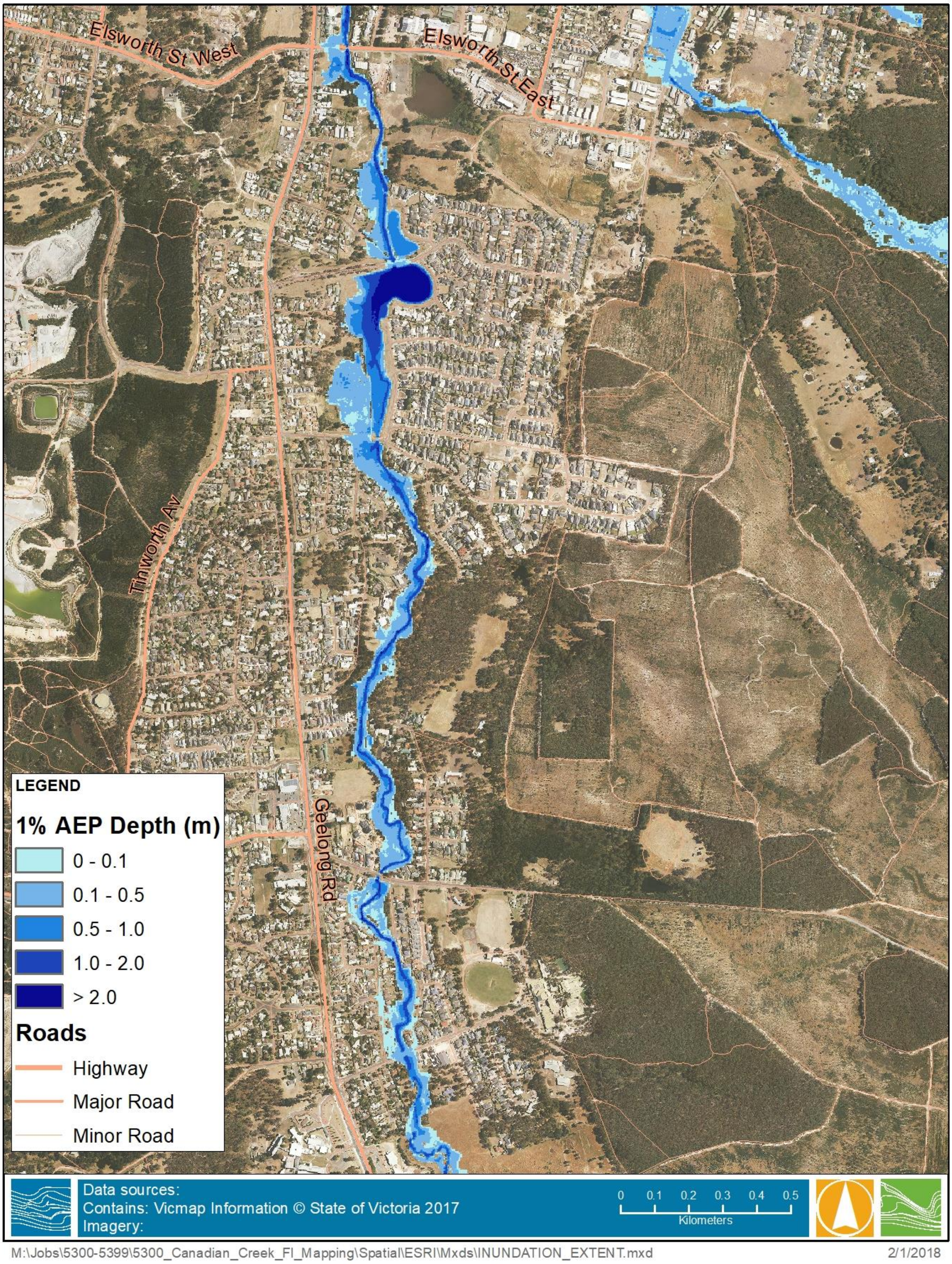

FIGURE 4-19 CANADIAN CREEK - 1% AEP FLOOD DEPTHS, MID CATCHMENT

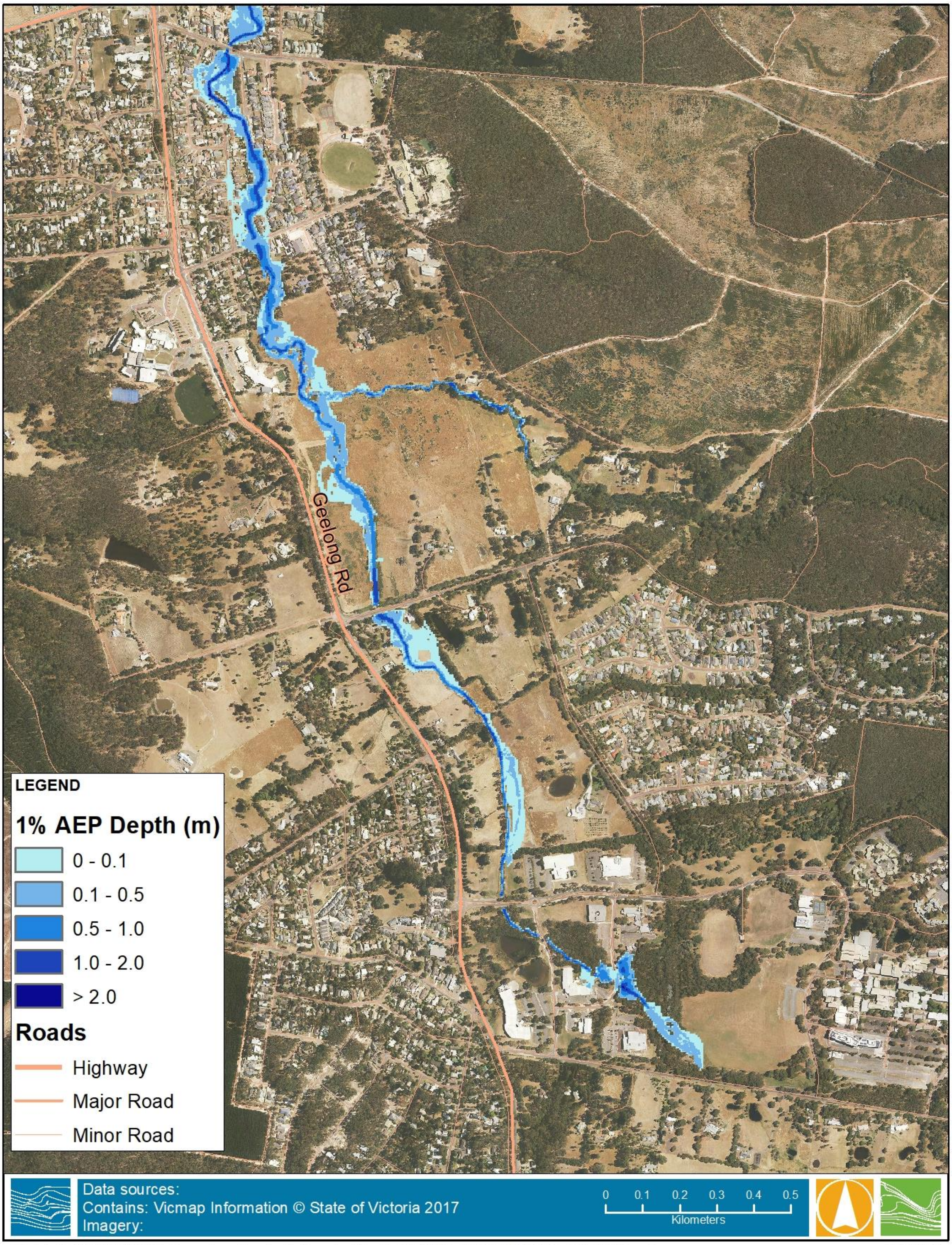

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FIGURE 4-20 CANADIAN CREEK - 1% AEP FLOOD DEPTHS, LOWER CATCHMENT

FIGURE 4-21 LITTLE BENDIGO CREEK – 1% AEP FLOOD DEPTHS, FULL EXTENT

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FIGURE 4-22 WARRENHEIP CREEK/RYANS DRAIN – 1% AEP FLOOD DEPTHS, US HUMFFRAY STREET

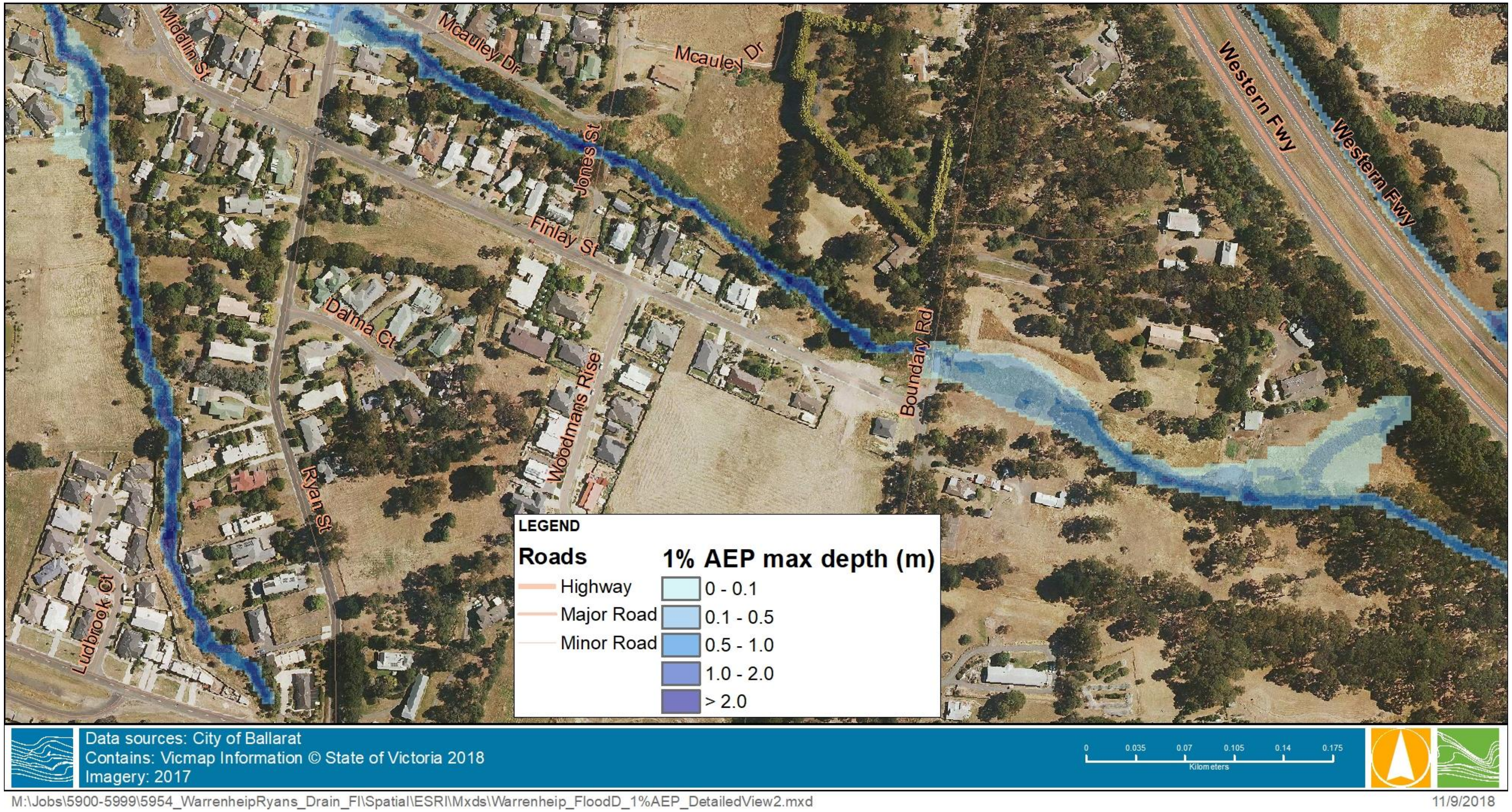

FIGURE 4-23 WARRENHEIP CREEK/RYANS DRAIN – 1% AEP FLOOD DEPTHS, FINLAY STREET

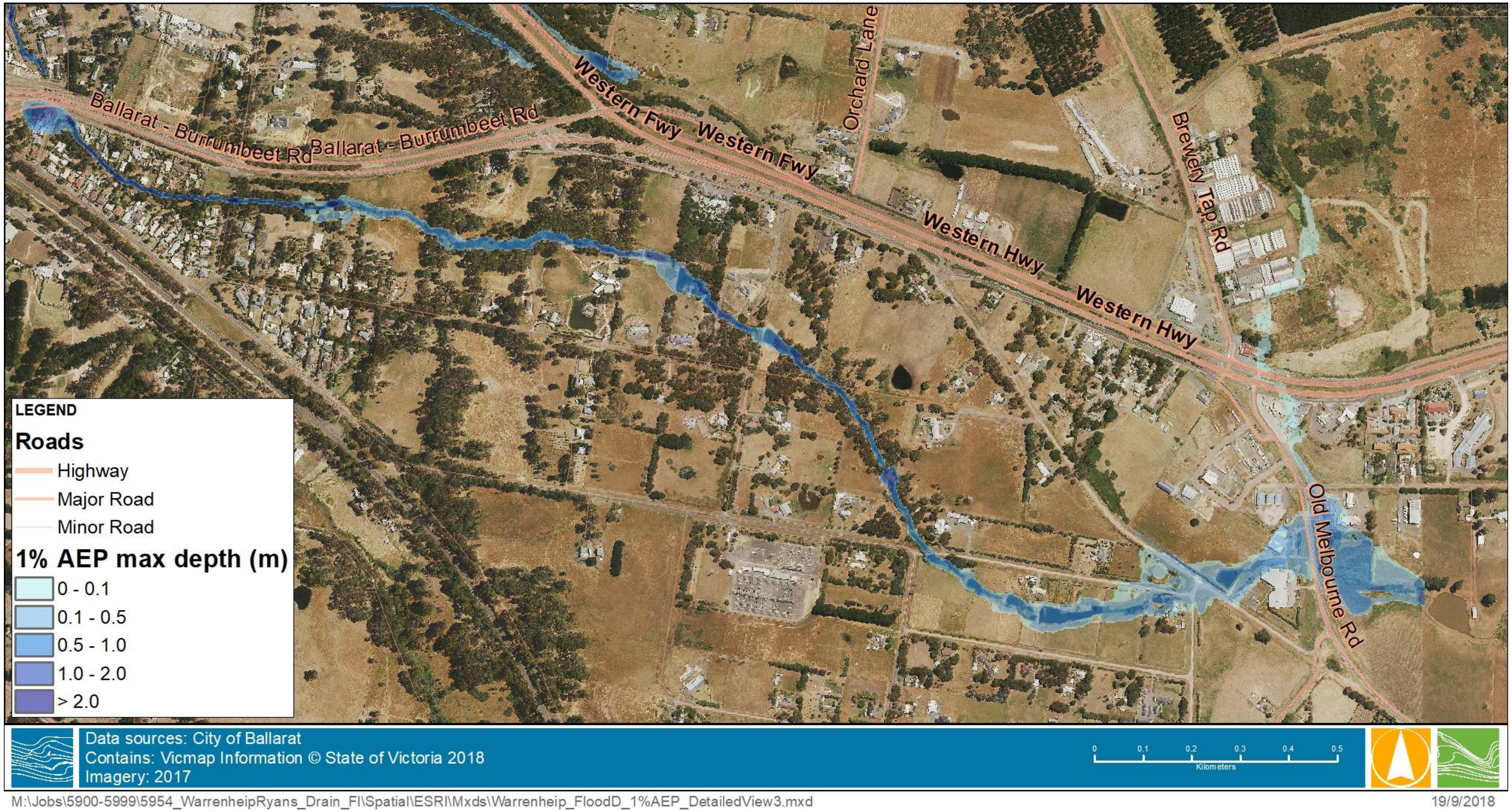

FIGURE 4-24 WARRENHEIP CREEK/RYANS DRAIN – 1% AEP FLOOD DEPTHS, DS OLD MELBOURNE ROAD

FIGURE 4-25 GNARR CREEK - 1% AEP FLOOD DEPTHS, UPPER CATCHMENT

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FIGURE 4-26 GNARR CREEK - 1% AEP FLOOD DEPTHS, LOWER CATCHMENT

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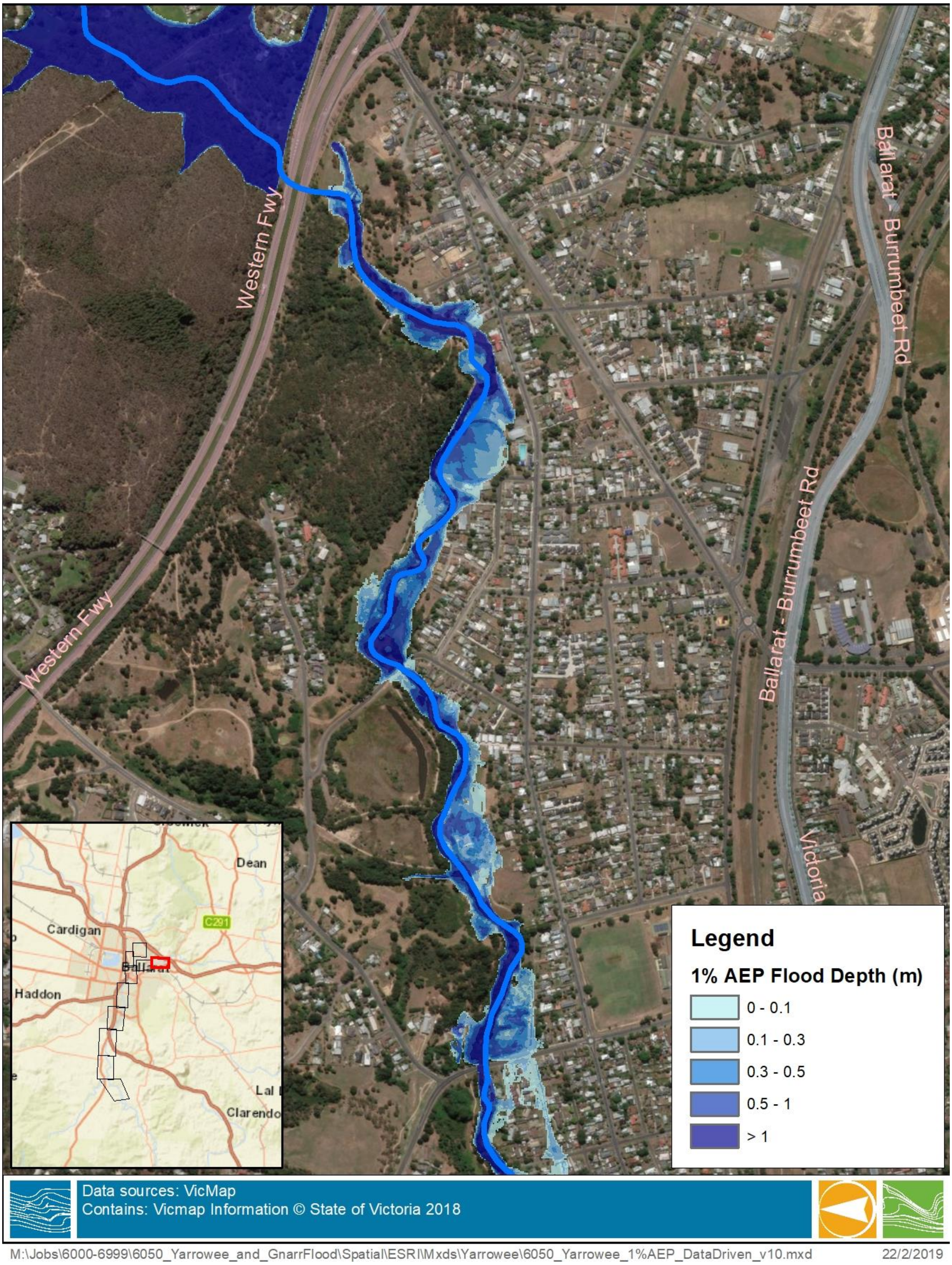

FIGURE 4-27 YARROWEE RIVER - 1% AEP FLOOD DEPTHS, DS WESTERN FREEWAY

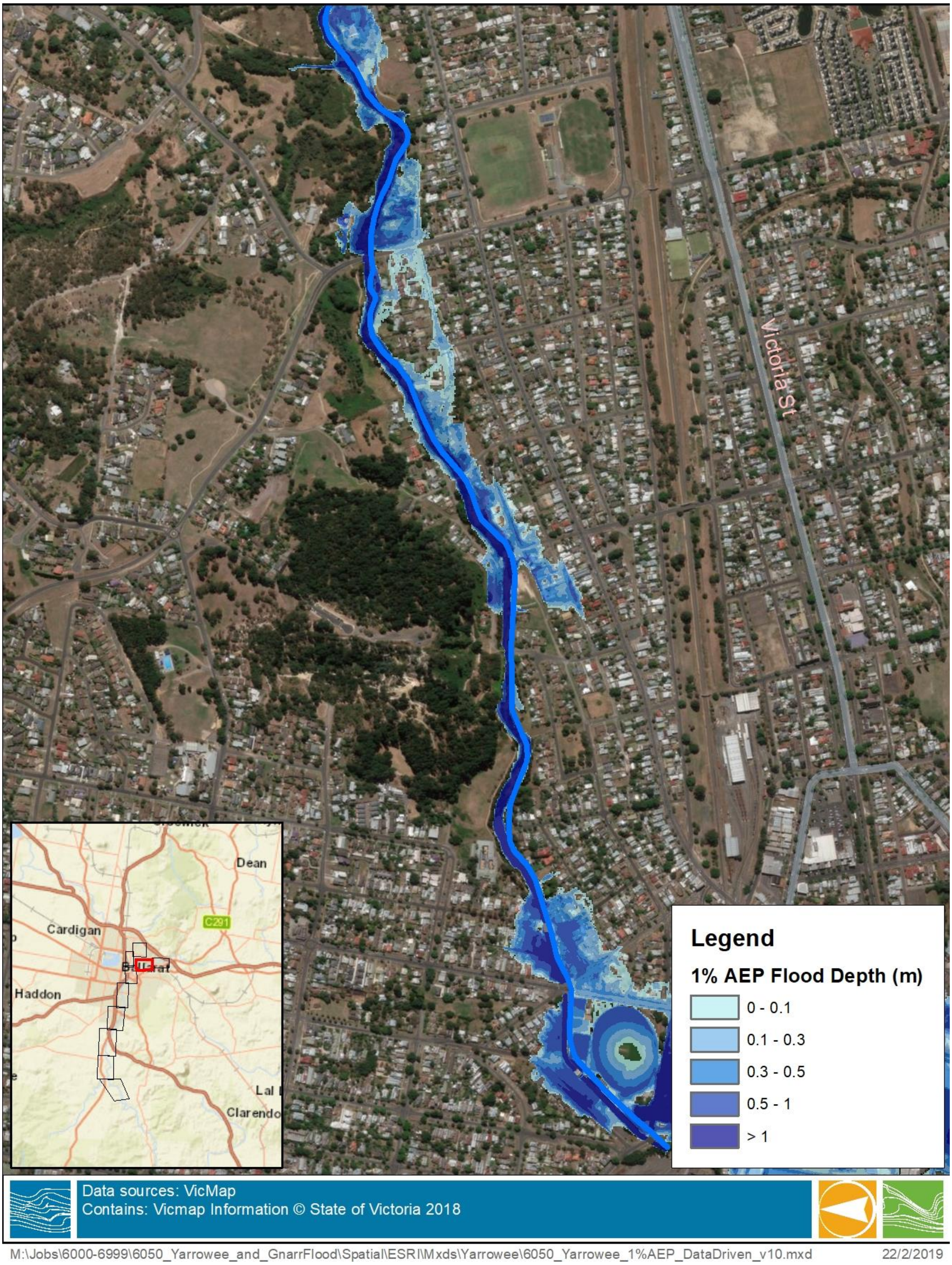

FIGURE 4-28 YARRWOEE RIVER - 1% AEP FLOOD DEPTHS, US RAILWAY LINE

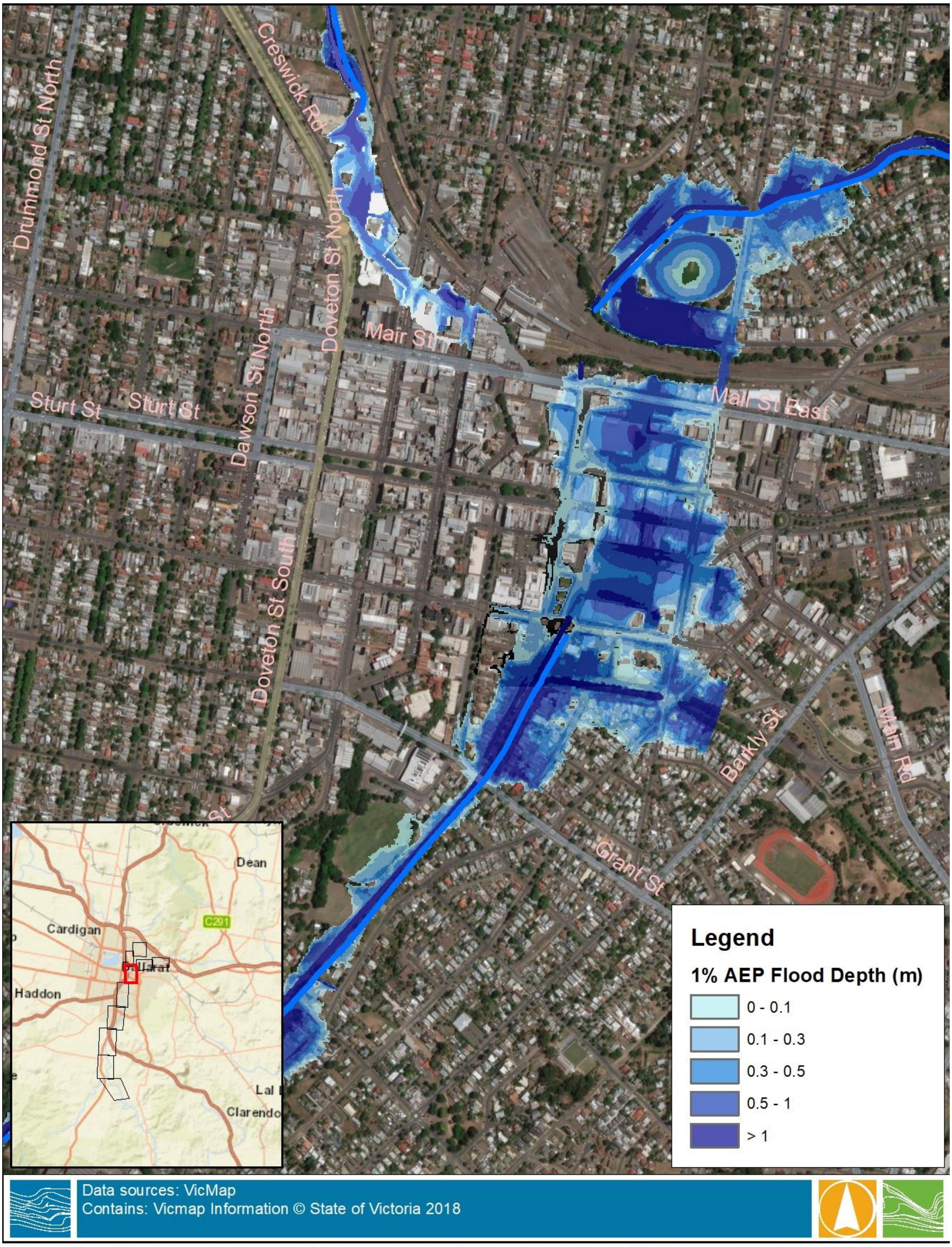

FIGURE 4-29 YARROWEE RIVER - 1% AEP FLOOD DEPTHS, CBD

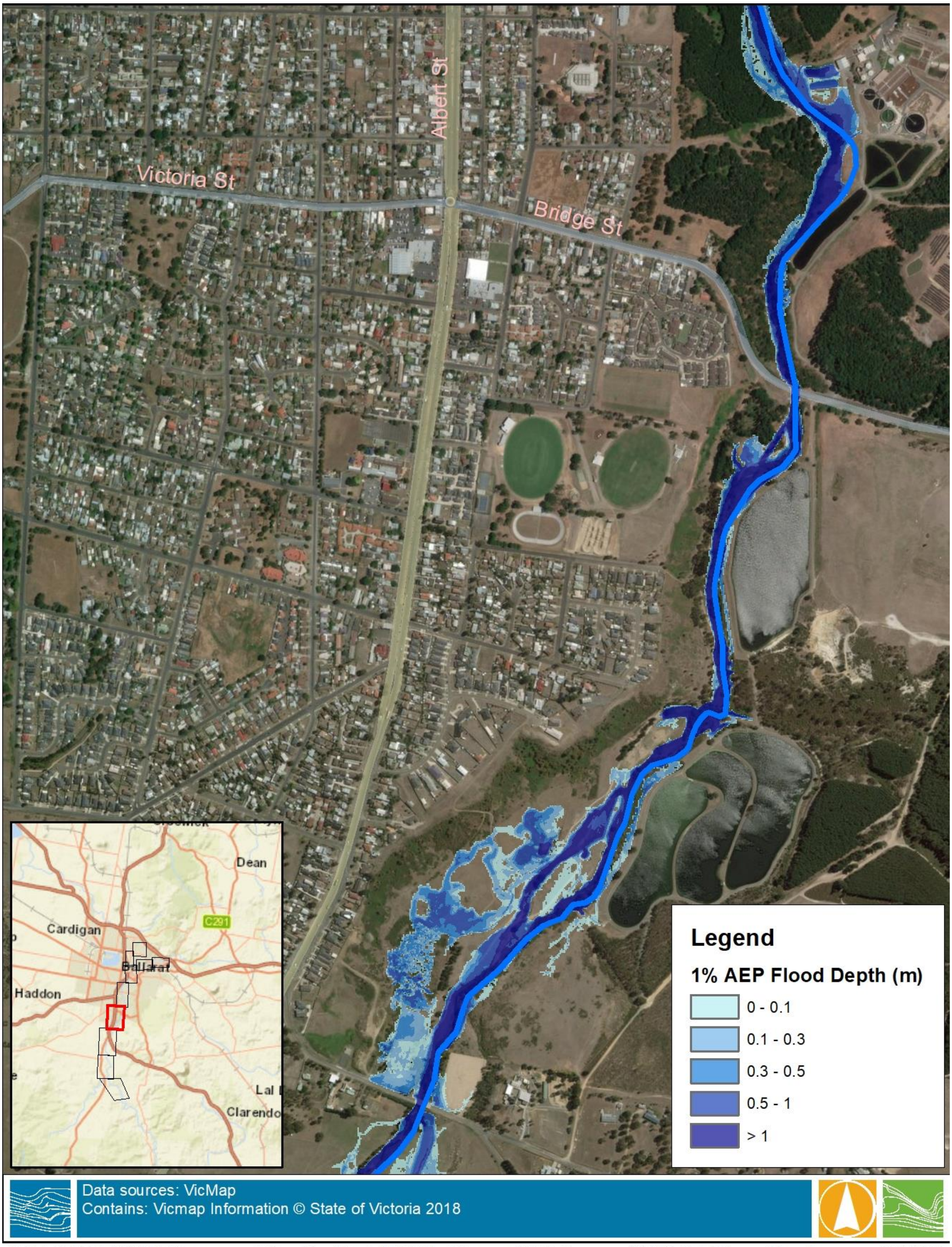

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FIGURE 4-30 YARROWEE RIVER - 1% AEP FLOOD DEPTHS, DS BRIDGE STREET

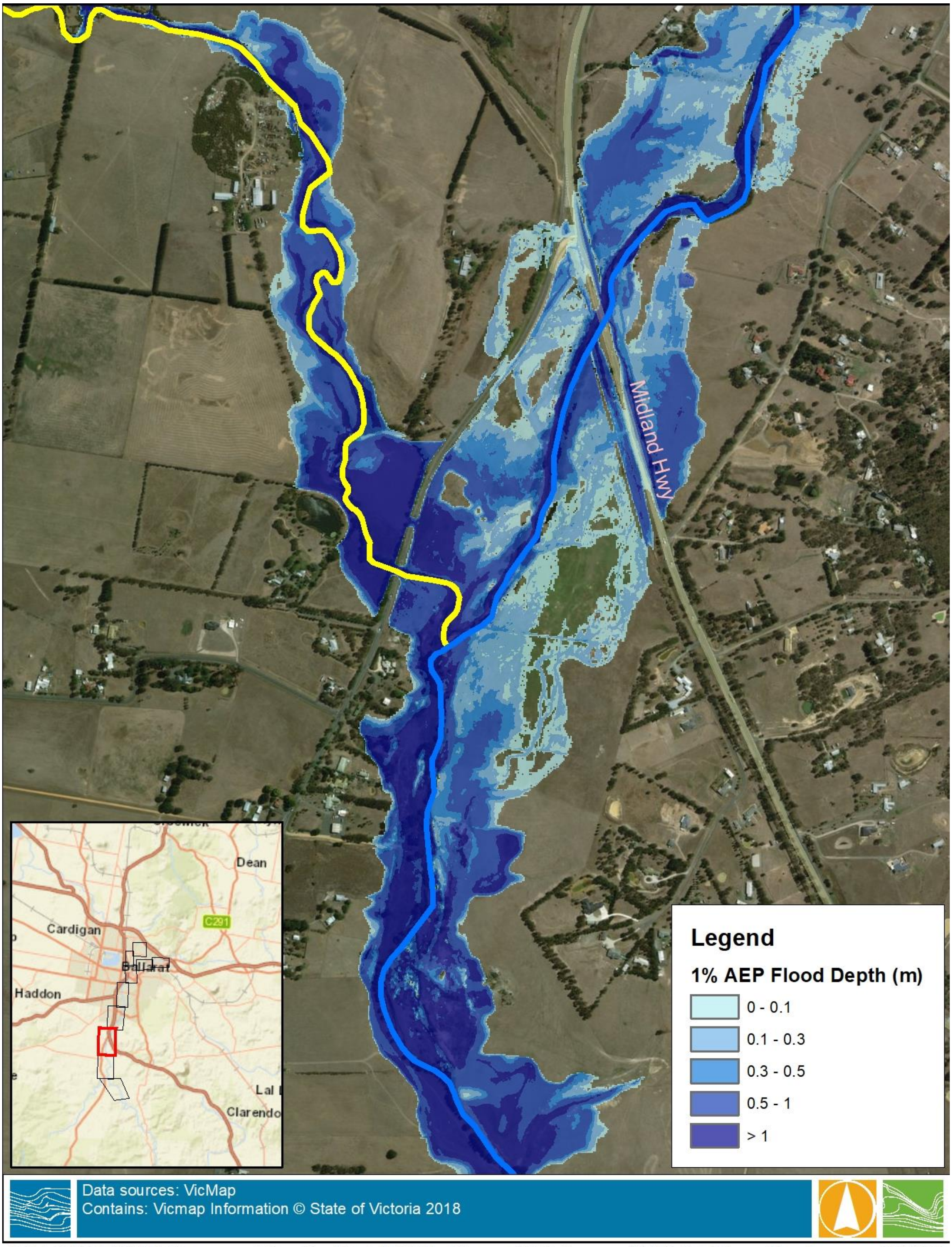

FIGURE 4-31 YARROWEE RIVER - 1% AEP FLOOD DEPTHS, DS MIDLAND HIGHWAY

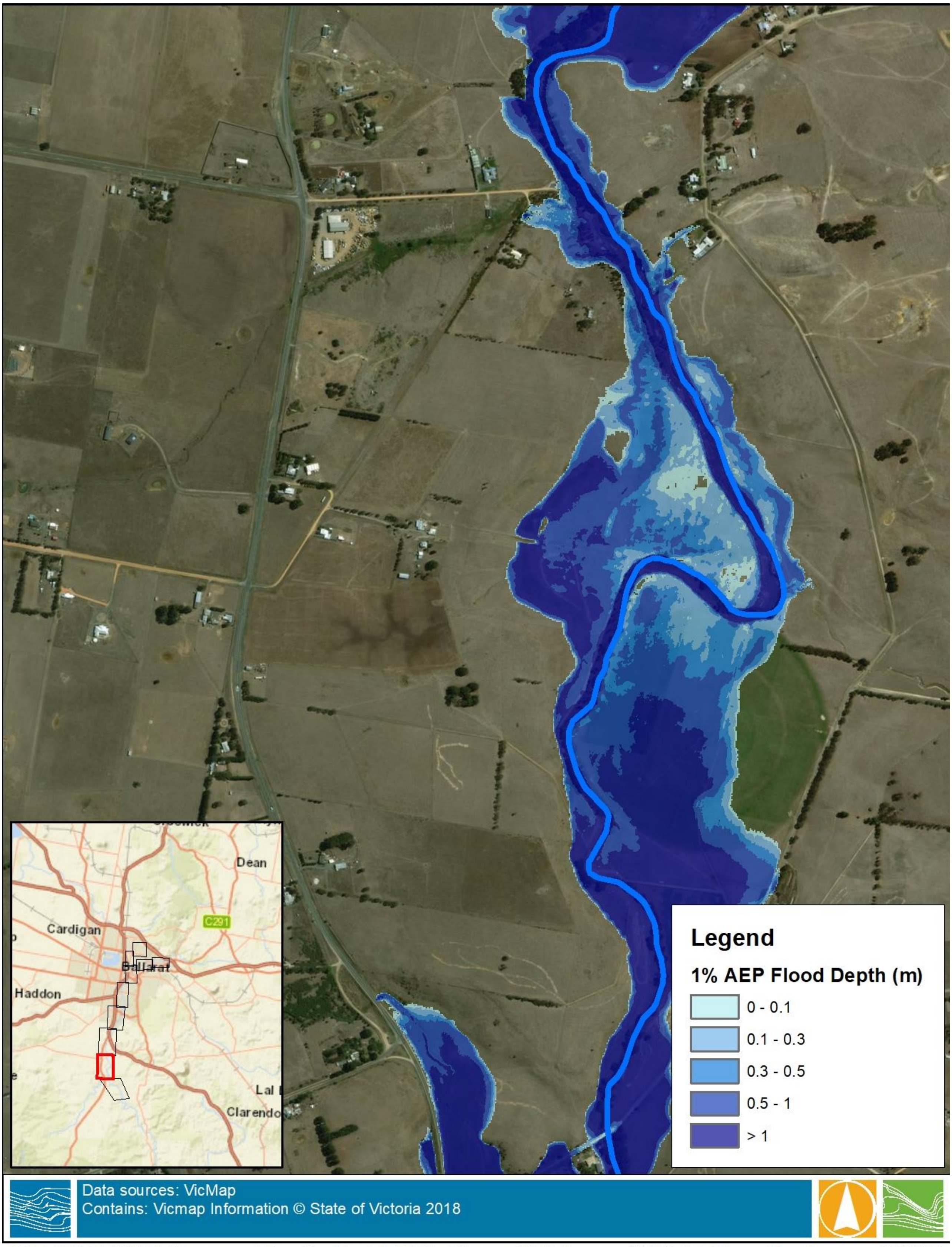

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FIGURE 4-32 YARROWEE RIVER - 1% AEP FLOOD DEPTHS, EAST OF COLAC BALLARAT ROAD

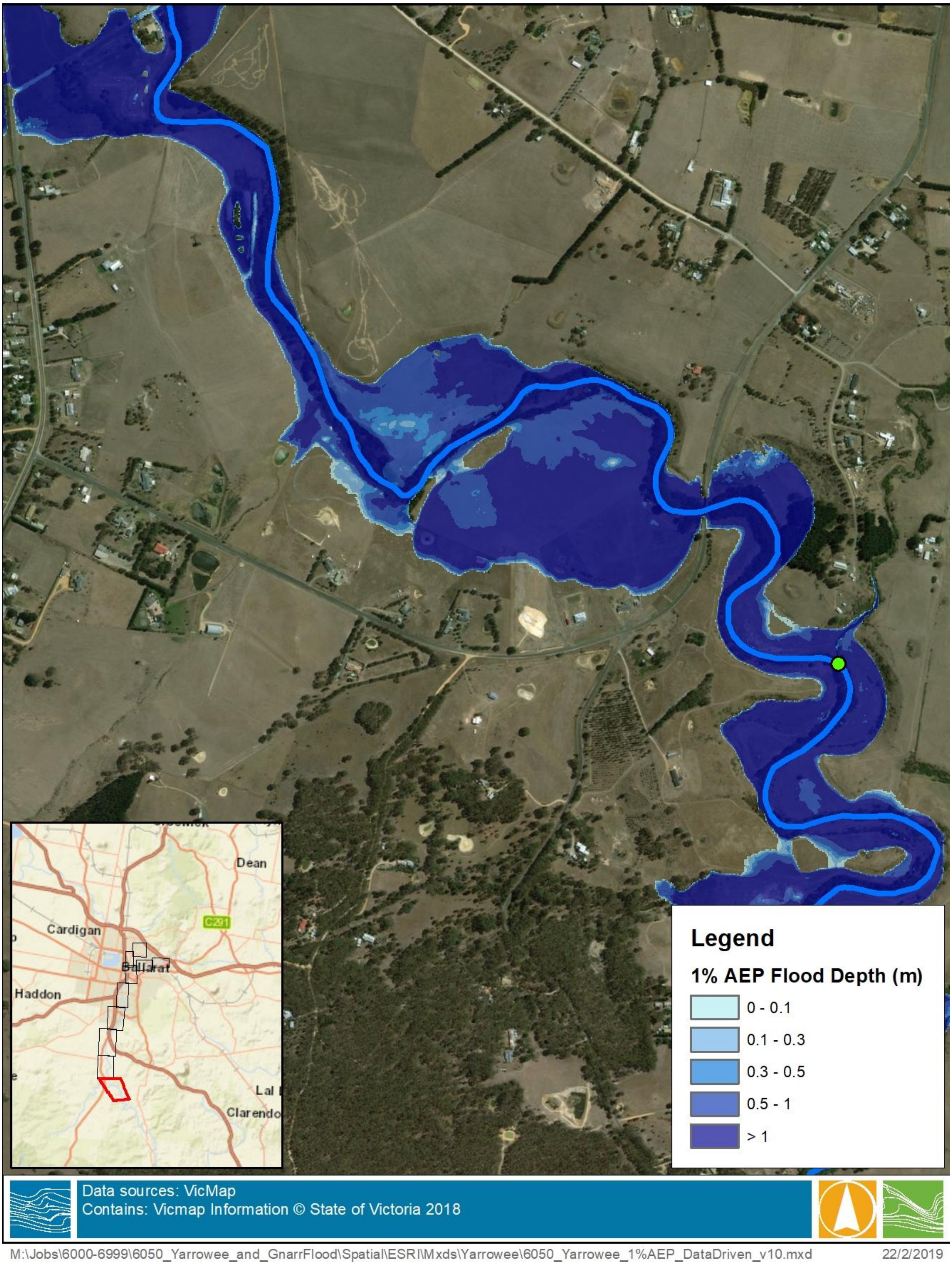

FIGURE 4-33 YARROWEE RIVER - 1% AEP FLOOD DEPTHS, US SCOTCHMANS LEAD ROAD

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