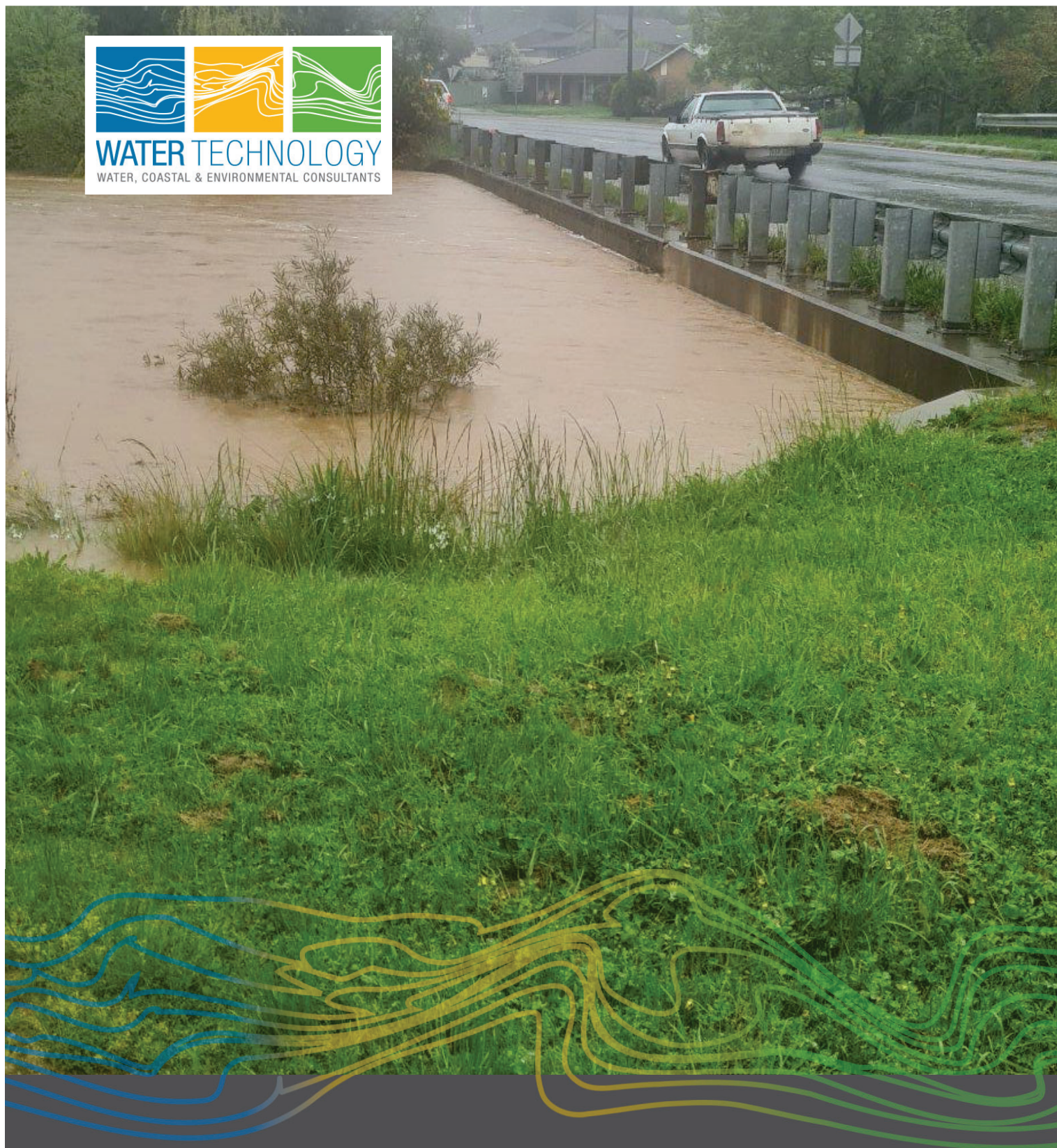




Final Report

Creswick Flood Mitigation Study

Hepburn Shire Council

9 April 2026



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Client	Hepburn Shire Council
Client Project Manager	Tim Powell
Water Technology Project Manager	Lachlan Inglis
Water Technology Project Director	Ben Tate
Authors	Lachlan Inglis, Abi Satria Praga
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Cover Image: October 2022 Flood Event

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51 Little Fyans Street
Geelong VIC 3220
Telephone (03) 8526 0800
ACN 093 377 283
ABN 60 093 377 283





GLOSSARY OF TERMS

Afflux	Refers to the difference in water level (or depth) between two modelling scenarios, usually measured in metres and a change in extent (e.g. “was wet now dry”)
Annual Exceedance Probability (AEP)	Refers to the probability or risk of a flood of a given size occurring or being exceeded in any given year. A 90% AEP flood has a high probability of occurring or being exceeded; it would occur quite often and would be relatively small. A 1% AEP flood has a low probability of occurrence or being exceeded; it would be fairly rare but it would be of extreme magnitude.
Australian Height Datum (AHD)	A common national surface level datum approximately corresponding to mean sea level. Introduced in 1971 to eventually supersede all earlier datums.
Cadastre, cadastral base	Information in map or digital form showing the extent and usage of land, including streets, lot boundaries, water courses etc.
Catchment	The area draining to a site. It always relates to a particular location and may include the catchments of tributary streams as well as the main stream.
Design flood	A design flood is a probabilistic or statistical estimate, being generally based on some form of probability analysis of flood or rainfall data. An average recurrence interval or exceedance probability is attributed to the estimate.
Discharge	The rate of flow of water measured in terms of volume over time. It is to be distinguished from the speed or velocity of flow, which is a measure of how fast the water is moving rather than how much is moving.
Flood	Relatively high stream flow which overtops the natural or artificial banks in any part of a stream, river, estuary, lake or dam, and/or overland runoff before entering a watercourse and/or coastal inundation resulting from elevated sea levels and/or waves overtopping coastline defences.
Flood Frequency Analysis (FFA)	A statistical analysis of observed flood magnitudes to determine the probability of a given flood magnitude.
Flood hazard	Potential risk to life and limb caused by flooding. Flood hazard combines the flood depth and velocity.
Floodplain	Area of land which is subject to inundation by floods up to the probable maximum flood event, i.e. flood prone land.
Flood storages	Those parts of the floodplain that are important for the temporary storage, of floodwaters during the passage of a flood.



Geographical information systems (GIS)	A system of software and procedures designed to support the management, manipulation, analysis and display of spatially referenced data.
Hydraulics	The term given to the study of water flow in a river, channel or pipe, in particular, the evaluation of flow parameters such as stage and velocity.
Hydrograph	A graph that shows how the discharge changes with time at any particular location.
Hydrology	The term given to the study of the rainfall and runoff process as it relates to the derivation of hydrographs for given floods.
Intensity frequency duration (IFD) analysis	Statistical analysis of rainfall, describing the rainfall intensity (mm/hr), frequency (probability measured by the AEP), duration (hrs). This analysis is used to generate design rainfall estimates.
LiDAR	Spot land surface heights collected via aerial light detection and ranging (LiDAR) survey. The spot heights are converted to a gridded digital elevation model dataset for use in modelling and mapping.
Peak flow	The maximum discharge occurring during a flood event.
Probability	A statistical measure of the expected frequency or occurrence of flooding. For a fuller explanation see Average Recurrence Interval.
Probable Maximum Flood	The flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in a particular drainage area.
RORB	A hydrological modelling tool used in this study to calculate the runoff generated from historic and design rainfall events.
Runoff	The amount of rainfall that actually ends up as stream or pipe flow, also known as rainfall excess.
Stage hydrograph	A graph that shows how the water level changes with time. It must be referenced to a particular location and datum.
Topography	A surface which defines the ground level of a chosen area.



EXECUTIVE SUMMARY

Water Technology were engaged by Hepburn Shire Council to deliver the Creswick Flood Mitigation Study. The project funding was sourced from a combination of Government opportunities and budget allocations from Council.

The study reviewed the available flood data for Creswick Creek and produced flood modelling and mapping in line with current industry best practices and the recommendations of Australian Rainfall and Runoff 2019. Flood modelling and mapping was produced for the 20%, 10%, 5%, 2%, 1%, 0.5%, 0.2%, 0.1% and Probable Maximum Flood (PMF) events.

In addition to the flood modelling and mapping, mitigation options and flood intelligence products detailing the flood behaviour and impacts in Creswick was developed and included in a draft update to the Hepburn Shire Municipal Flood and Storm Emergency Sub Plan (MFSEP).

Flood Mitigation Options focusing on riverine and stormwater inundation were investigated at six key flooding hotspot areas as part of a pre-feasibility assessment. The mitigation options were then refined and ranked against each of the options assessed. The options investigated at each of the six locations were:

- Location 1: Building a 1.8-hectare retarding basin upstream of Pasco Street and redirecting overland flow along Johns Road using new culverts and a levee. It also involves upgrading drainage from Clunes Road to Davies Street and adding a new pipe between 1 and 1A Davies Street.
- Location 2: Enhance the existing Cambridge Retention Basin by increasing its volume, testing a pumped outlet and adding a one-way outlet to Creswick Creek. An additional scenario assessed connecting the Pearman Street drain directly to the basin.
- Location 3: Constructing a 0.5m levee on an existing bluestone wall and an upstream retarding basin with twin outlets. Additionally, Hyde Park Road was lowered further upstream.
- Location 4: Upgrading the existing 525mm culvert north of Bald Hills Road to a twin 900x600mm box culvert. Constructing an upstream embankment to function as a retarding basin at near Cassels Lane.
- Location 5: Council pumping station at North Parade to reduce stormwater inundation behind the Creswick Creek Levee.
- Location 6: Installing new pipes and pits to direct stormwater from White Hills Road, Caddy Drive, and Wright Court to Nuggetty Gully. A cutoff drain behind 31 Gardiner Street to divert runoff into the drainage network.

Modelling and assessment for each mitigation options suggest that Mitigation 6 and Mitigation 1 would provide the best value to mitigate flooding, followed by Mitigation 3 and 5. Mitigation 2 and 4 ranked as the lower of the options assessed, however refinement options and further work may indicate them as feasible strategies to improve flood risk in Creswick.



Non-structural mitigation in the form of planning scheme mapping was also developed (in draft format) and is recommended for inclusion in the Hepburn Shire Planning Scheme. The mapping is based on the 1% AEP flood with projected increased rainfall intensity to 2100 under a Shared Socioeconomic Pathway (SSP) 5 -8.5 Climate Scenario. The extent of the mapping extends on the current flood related controls within Creswick.

Flood intelligence products developed throughout the study include the following:

- A rating table for the existing manual read gauge on Creswick Creek at the Water Street bridge;
- Summaries of flood behaviour and impacts in concise tables for design flood events and gauge heights at the Water Street gauge;
- Flood peak timing estimates from the beginning of rainfall;
- A simple tool to link rainfall to potential flood impacts, and;
- Recommended Flood Class Levels for the Water Street gauge in line with the Bureau of Meteorology's Flood Class definitions.

Additional components to improve the flood warning capability for Creswick were recommended, with a sub-daily rainfall gauge within the catchment and a streamflow gauge along Slaty Creek upstream of the confluence with Creswick Creek proposed to improve the town's flood monitoring capacity.

The study outputs aim to support drainage and floodplain management in Creswick into the future by providing a sound basis for the implementation of riverine and stormwater flooding mitigation options. The extension of the current planning controls aims to ensure development within the town is appropriate and responds to the risk. Future flood events can be responded to in a more proactive way through utilisation of the intelligence products produced.



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1 INTRODUCTION

1.1 Overview

Water Technology was commissioned by Hepburn Shire Council (Council) to undertake the Creswick Flood Mitigation Study. The investigation area covers the Creswick Creek and tributaries in the township of Creswick, as shown in Figure 1-1. The study was to produce updated draft planning controls, and complete a detailed investigation into drainage issues in Creswick as identified as a High Priority in the North Central Regional Floodplain Management Strategy (2018).

The outcomes of the Creswick Flood Mitigation Study are documented in a series of reports detailing each stage of the analysis:

- R01 – Return Brief
- R02 - Hydrology & Hydraulic Modelling Report.
- R03 - Priority Project Mitigation Evaluations Assessment Report.
- R04 – Flood Intelligence and Warning Report
- **R05 - Final Study Report - This Report**

Further to these reports and as part of the emergency management deliverables, Water Technology produced flood intelligence and consequence information for use by emergency services.

Previous flood investigations covering Creswick include Council and NCCMA investigations undertaken in 2012. The 2012 study focussed on the flood behaviour along Creswick Creek and Nuggetty Gully and used the Australian Rainfall and Runoff (ARR 1987) guidelines¹. This project also investigated stormwater inundation across the town, not just riverine flooding associated with these creeks. The hydrology parameters developed for the urban stormwater mitigation assessments are discussed in an earlier report (R03).

As recommended in the Return Brief (R01), the hydrology model was updated in line with the current Australian Rainfall and Runoff Guidelines² (ARR 2019), considering the Victorian Specification Information³ commissioned by Melbourne Water and DEECA regarding application of pre-burst rainfall. A thorough review of the hydrology model was undertaken, particularly focusing on the design rainfall and storm losses. Design flows were compared with the previous investigation flows and validated against a long-term streamflow gauge record (at Clunes) and several empirical estimation methods. Additional investigation into the rating curve of the Creswick Creek at Clunes gauge was undertaken to provide justification for the use of a rating curve prior to 2015 which saw a significant change in flow ratings following a rating curve update. The development of a hydraulic model at Clunes was undertaken to provide further validation of this approach. The report also provides details of the hydrology model, selection of representative temporal patterns and discussion on the design results.

¹ Water Technology 2012, Creswick Flood Study, developed for North Central CMA.

² ARR 2019 - Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors) Australian Rainfall and Runoff: A Guide to Flood Estimation, C Commonwealth of Australia (Geoscience Australia), 2019.

³ Victorian Specification Information: http://data.arr-software.org/vic_specific



Further to the initial scope of the project and the details in the return brief, an assessment of the design hydrology under different climate change scenarios was completed, responding to the release of ARR v4.2 during the delivery of this study. This involved updates to the design baseline rainfall IFDs to assess the current day/near-term risk in 2024, as well as a future year 2100 scenario. Design modelling referring to 'existing conditions' throughout the report is in reference to scaled up rainfall IFDs for the current day/near-term (2024). Where the baseline IFDs were used to verify design flows, these were referred to as 'baseline' conditions.

The modelling completed in 2012 is the basis for the current Land Subject to Inundation Overlay (LSIO1 and LSIO2) in the Hepburn Planning Scheme. The modelling within this study was carried out to ensure that the planning scheme mapping accurately reflects flood hazard and to ensure that growth in Creswick is managed appropriately into the future and considers climate change.

In addition, the study produced flood intelligence information for use in emergency management situations, assessed the current flood impact/exposure in terms of annual average damages caused by flooding in Creswick, investigated structural and non-structural mitigation options to reduce damages, investigated and made recommendations for establishing a flood warning system for the town.

1.2 Objectives and Outputs

The Creswick Flood Mitigation Study outputs are required to meet several floodplain management objectives as highlighted in the project brief prepared by Hepburn Shire Council. The objectives of the investigation are described below:

- Evaluate and re-model the areas of the catchment where flood risks have been identified by either formal or empirical observations.
- Identify other areas of flood risk and evaluate mitigation methods;
- Evaluate (inclusive of calculations, high-level design, costings, and prioritisations) mitigations measures identified across several known flooding hotspots;
- Assist in the preparation of community flood awareness and education products; and
- Assess feasibility for improved flood warning arrangements.
- The priority areas for the current investigation are shown in Figure 1-2.



1.3 Modelling Approach

This study focusses on both the riverine flood risk through Creswick as well as the stormwater flood risk from runoff of local catchments throughout the town. Within the town and peri-urban areas, a rain on grid modelling approach was adopted. This compliments the direct inflow approach used for Creswick Creek and several other tributaries which used flow hydrographs developed in RORB. This approach also allowed for investigation of mitigation options related to stormwater inundation to be assessed within the same model. Details of the hydrology and hydraulic models are provided in the following sections.

Local stormwater inundation was observed across Creswick in the January 2022 storm event. This was largely due to an isolated storm burst to the south-west of the Creswick township within the Nuggety Gully catchment. Stormwater runoff impacted the Caddy Drive and Wright Street area significantly, as runoff made its way towards Nuggety Gully and the Creswick township.

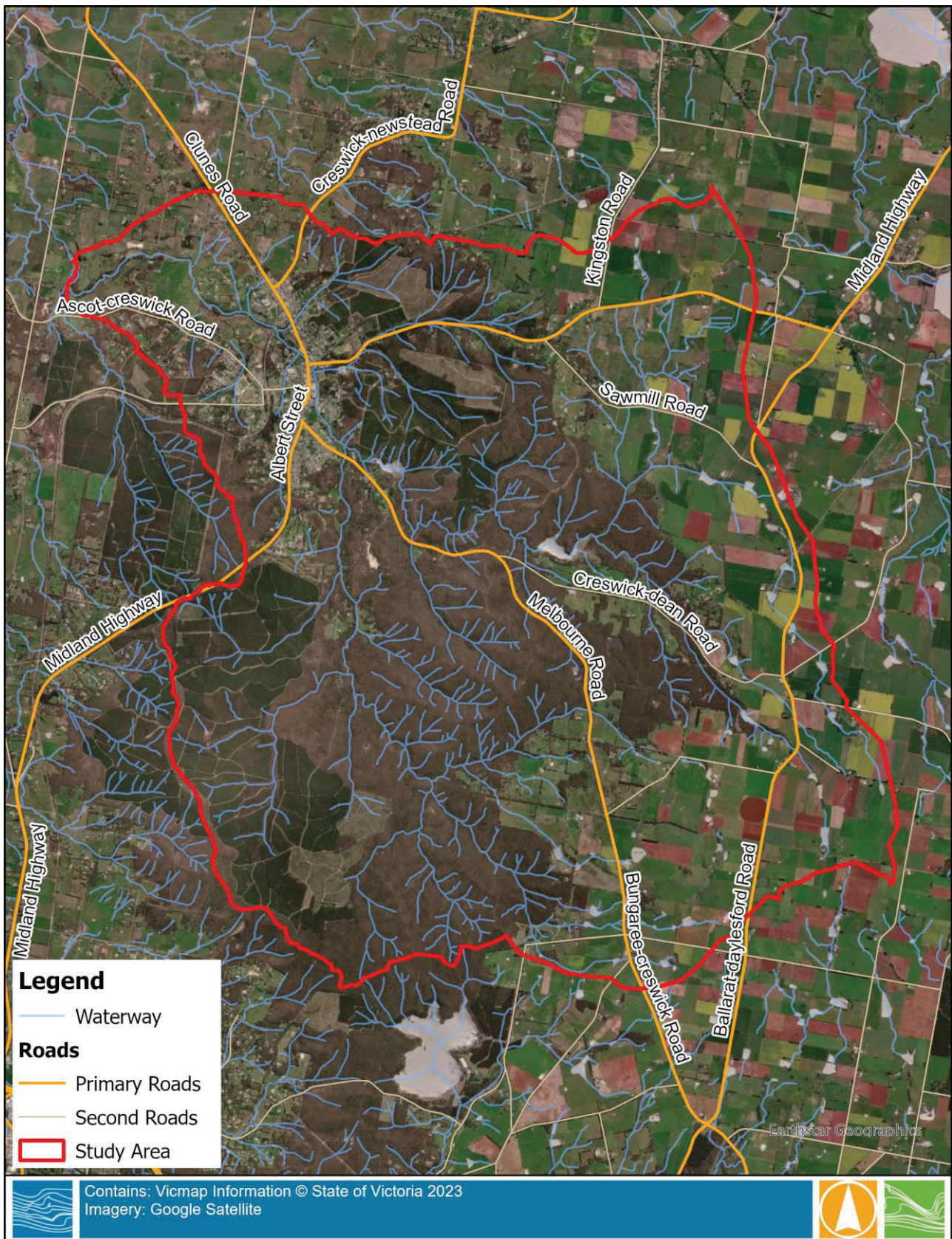
The hydrology approach was undertaken in line with the latest ARR guidelines as well as the latest Climate Change modelling recommendations released during the project (ARRV4.2). A summary of the modelling approach is listed below.

- Existing RORB model review and updates
- Joint Calibration
 - September 2016, January 2022, October 2022
 - September 2010 and January 2011 (hydrology calibration only)
- Update hydrology to ARR2019 (including 2016 IFDs and temporal patterns)
- Verification to FFA
 - Rating Table Review due to gauging discrepancy
- Climate Change Modelling
 - Near Term/Present Day Scenario
 - Long Term (2100) Scenario

1.4 Study Area

The township of Creswick is located in central Victoria, approximately 18 km north of Ballarat. Creswick is within the North Central CMA boundary and is a major town within Hepburn Shire Council.

Creswick Creek is the main watercourse flowing through the township. Slaty Creek, Sawpit Gully (also known as Spring Gully) and Nuggety Gully are major tributaries of Creswick Creek. Other tributaries within the upper catchment include Adekate Creek, Slattery Creek, Glendonald Creek, Reedy Creek, Glendaniel Creek and Kilkenny Creek, alongside numerous small streams and gullies which also feed into Creswick Creek. Two notable water storages are located upstream of Creswick on Creswick Creek, these include Cosgrave Reservoir and St Georges Lake. The Creswick Creek catchment and other waterways are shown in Figure 1-1.



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Figure 1-1 Creswick Creek Catchment

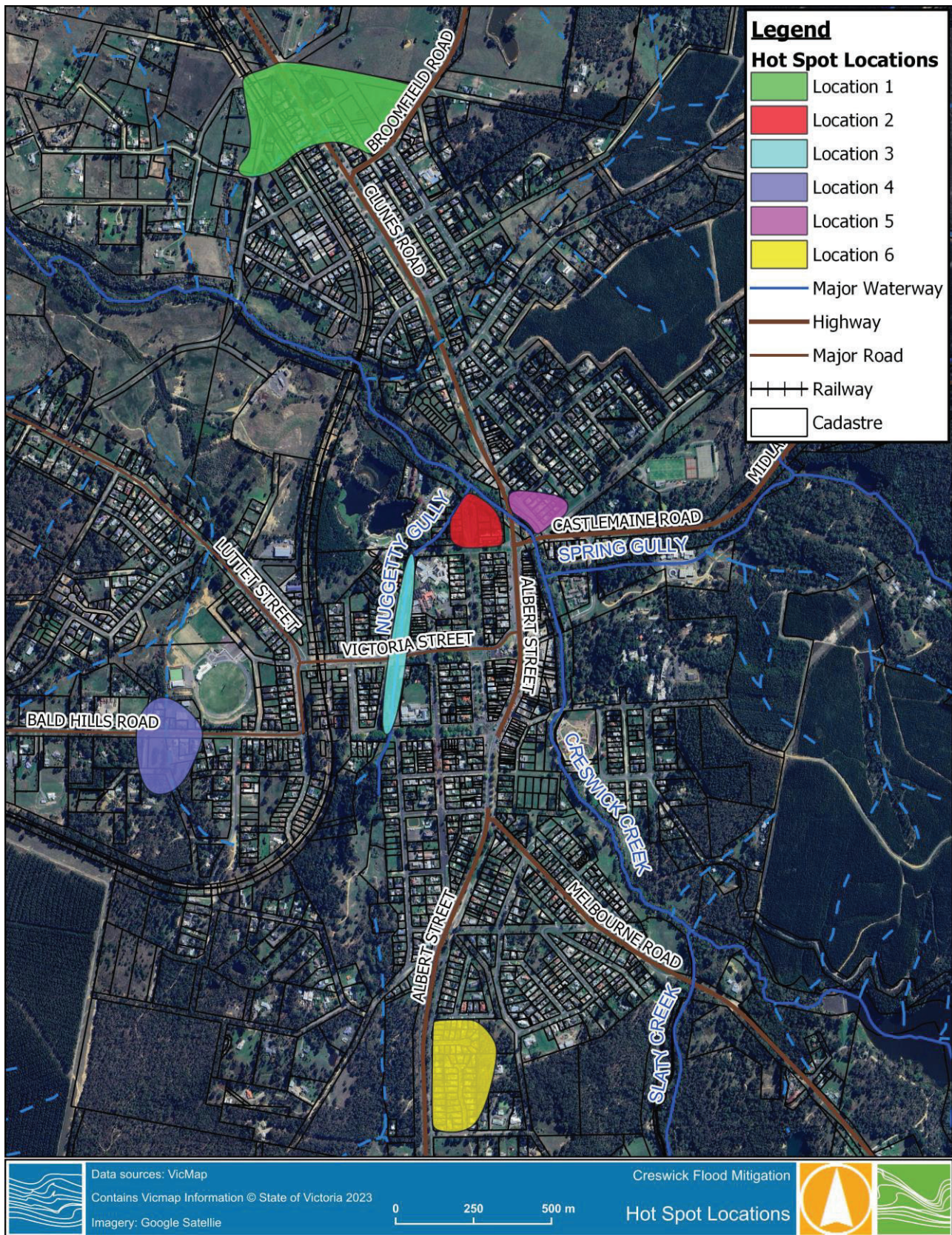


Figure 1-2 Priority Investigation Areas



2 DATA COLLATION AND REVIEW

The first stage of the project included the collation and review of available data relevant to flooding in Creswick. This included the following:

Previous flood studies and reports covering the area (see Table 2-1 below)

Table 2-1 Flood related studies completed in Creswick and Creswick Creek Region

Related Studies	Author	Year
Victorian Flood Data Transfer Project (2001)	DNRE/SKM	2001
<i>Creswick Flood Mitigation and Urban Drainage Plan</i>	Water Technology	2012
<i>Creswick Flood Mitigation and Urban Drainage Plan Summary</i>	Water Technology	2011

Historical flood events and accompanying anecdotal evidence:

- The NCCMA captured flood heights following the January and October 2022 flood events.
- Water Technology, Council and NCCMA also gathered anecdotal evidence from the two 2022 flood events. This information was used in the validation modelling based on the information available.

Recorded streamflow:

- There are no streamflow gauges along the Creswick Creek through Creswick. There are four active streamflow gauges located within the Creswick Creek catchment (three relatively short record gauges upstream around the major storages and a long-term gauge downstream of the study area at Clunes) as shown in Table 2-2. The Creswick at Clunes gauge was previously used to calibrate hydrology models within the study area. The gauges upstream of Creswick, at and upstream of Cosgrave Reservoir gauge, are relatively new with a short period of record and have primarily been used to provide information for the 2022 floods.

Table 2-2 Streamflow Gauge Data

Station Name	Station No.	Start
Creswick Creek at Clunes	407214	11/08/1943
Creswick Creek at Cosgrave Reservoir	407324	04/09/2018
Creswick Creek U/S Cosgrave Reservoir	407237	14/04/2010
Adekate Creek at Creswick	407238	14/04/2010

Recorded rainfall

- Historic daily and sub daily rainfall data was used for the hydrologic and hydraulic model calibration. Daily rainfall gauges were used to provide a representation of spatial rainfall variation while sub daily gauges provide a representation of timing of the rainfall distribution.
- Table 2-3 summarises the active daily rainfall information available within or near the Creswick Creek catchment. The locations of the rainfall gauges and several non-active gauges are shown in Figure 2-1.
- There are no sub daily rainfall gauges located within the Creswick Creek catchment. The closest sub-daily gauges are located at Mt Hope (located southeast of the catchment) and Ballarat Aerodrome (southwest of the catchment).



Table 2-3 Daily Rainfall Station Information

Station Name	Dist. From Creswick	Station No.	Start	End
Creswick	0 km	088019	1949	Current
Glen Park	10.17 km S	089048	1953	Current
Ballarat Aerodrome	12.61 km SW	089002	1908	Current
Smeaton	13.16 km N	088113	1968	Current
Ballarat Hopetoun Rd	13.72 S	089111	2004	Current
Bungaree	13.9 km S	087014	1881	Current
Wilsons Reservoir	14.58 km SE	087067	1896	Current
Clunes	17 km NW	088015	1879	Current
Addington	19.23 km W	089106	1956	Current
Moorabool Reservoir	19.35 km SE	087045	1912	Current

Road and drainage infrastructure

- Drainage data was supplied by council with gaps infilled by survey for major structures and site visits for minor structures with a key focus on capturing culvert/pipe diameters.

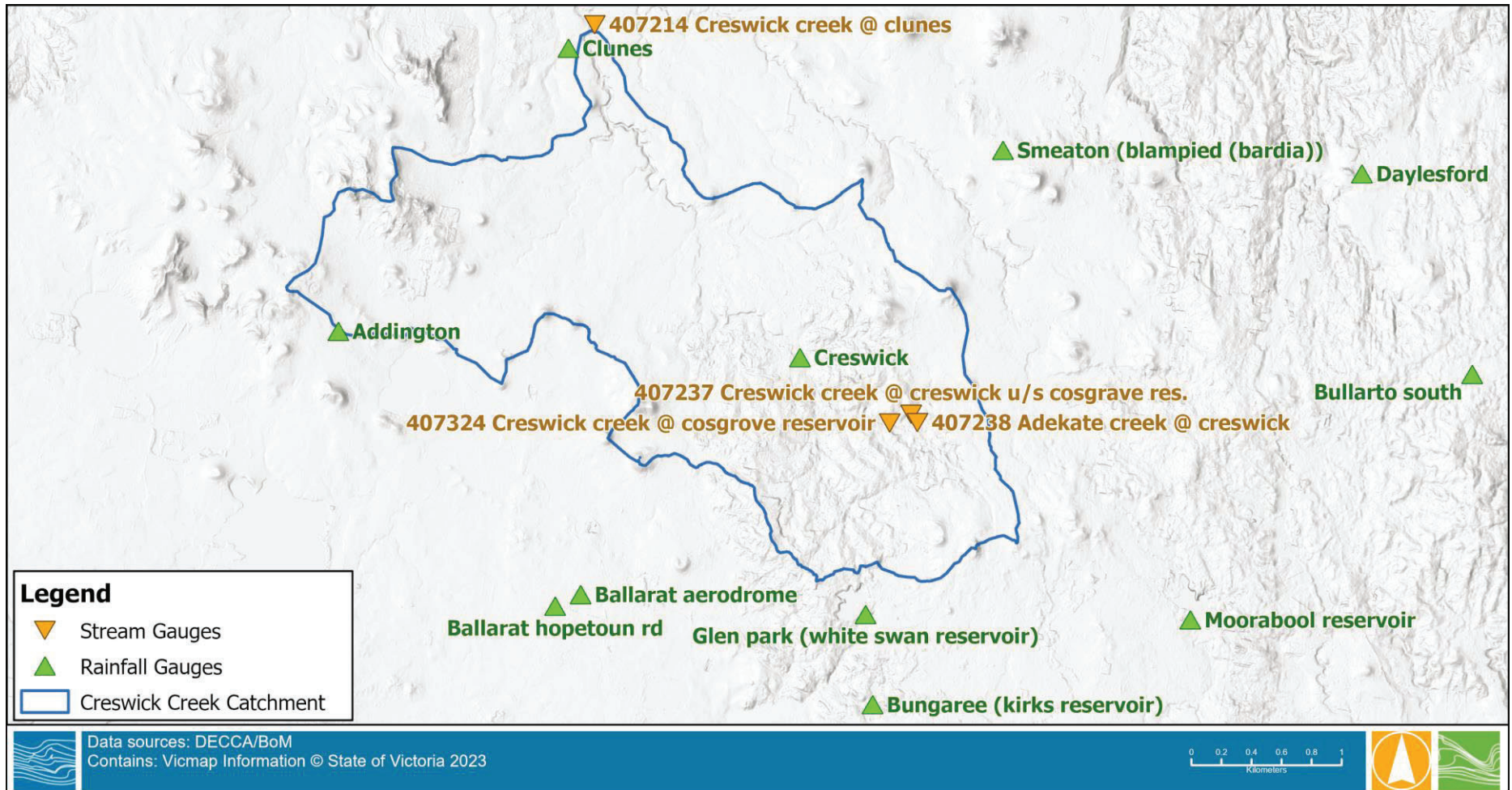
Topographic data

Multiple LiDAR data sets were available and were verified against survey captured for the project. The key dataset used in the development of the hydraulic model DEM and catchment delineation was the **2020-21 Golden Plains LiDAR Data – DEECA**. This dataset covers the entire study area with a reported Vertical accuracy 0.1m.

LiDAR data was verified in order to ensure the hydraulic model can accurately replicate flood behaviour within the study area. The capture of ground survey at three locations within the study area was commissioned to assist with verification of the available LiDAR datasets. The survey captured transects along the crest of roadways. The 2021 Golden Plains LiDAR was verified with comparison to surveyed road transects (captured at three road locations). Comparison to cross section survey was completed in two ways; on a point by point basis to create a statistical distribution of the differences, and as transects to get a visual comparison of the reliability of the data. A total of 62 surveyed crest points were available across the road transects, each of the surveyed levels was compared to the level determined in the LiDAR data with the difference between the two calculated. Of the 62 points compared, all were within 0.05m while 57 were within 0.03m. The average difference across the three transects is less than 1cm and indicates a high degree of accuracy and that the LiDAR is suitable for use in the development of the Digital Elevation Model (DEM) for the hydraulic modelling.

Additionally, floor level survey of 102 properties was captured to complement the existing 131 floor level surveyed in 2012. The top and toe of several levees within Creswick were captured and incorporated into the hydraulic model.

The Data Collation Report (R01) also confirmed and detailed the modelling methodology for the following stages of the project.



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3/10/2023

Figure 2-1 Streamflow and Rainfall Gauge Locations



2.1 Rating Curve Review

When investigating the calibration of the 2016 and 2022 flood events as well as undertaking the Flood Frequency Analysis (FFA), it was noted that the reported streamflow discharges for mid to high flows were significantly higher than values previously reported for similar water levels (particularly for 2016 and 2022 flood events). The rating curve which was updated around 2015 suggests the peak flow at Clunes in the October 2022 flood event (344 m³/s) was double the peak flow rate in September 2010 (177 m³/s) and significantly higher than January 2011 (222 m³/s). The 2011 flood event resulted in over 50 buildings flood above floor in Clunes. In the October 2022 flood event, it is understood no above floor flooding occurred in Clunes.

Information from the hydrographers indicated that changes to the Creswick Creek in the vicinity of the Clunes streamflow gauge (the significant removal of vegetation), were likely the result of the significant change in the rating table. While the changes to the vegetation within Creswick Creek may have reduced the associated drag/roughness and result in lower levels for equivalent flows prior to the works, it is not expected to impact flood levels as much as suggested by the hydrographers. An image of the Creswick Creek at Clunes gauge (captured in May 2024) is shown in Figure 2-2.



Figure 2-2 Creswick Creek at Clunes gauge (May 11, 2024)

Further investigation into the gauge discrepancies assessed streamflow gauges further down the catchment. Creswick Creek flows into Tullaroop Creek downstream of Clunes. The Tullaroop Creek at Clunes streamflow gauge located 10 km downstream of Clunes indicates the September 2016 (315 m³/s) and October 2022 (433 m³/s) flood events were of significantly less magnitude than September 2010 (544 m³/s) and January 2011 (573 m³/s). Creswick Creek contributes around 53% of the total catchment area to this point and flows at Clunes are likely to be generally reflective of the Tullaroop Creek at Clunes peak flows.

Additional testing of the changes at the Clunes gauge through the development of a small hydraulic model using TUFLOW software, indicated the application of the latest rating curve may over-estimates flows. The



hydraulic model initially utilised the January 2011 flow hydrograph based on pre 2016 rating table (Rating 978) and was modelled using three roughness scenarios.

- The first scenario adopted the surface roughness values and delineation used in the 2012 flood study.
- The second scenario adopted a uniform Mannings n value of 0.04 (used to represent a Main Channel with clean, winding, some pools and shoals⁴).
- The third scenario adopted a more detailed roughness assessment.

The results (Figure 2-3) plotted against the recorded gaugings and the two rating curves (pre and post 2016) show the current rating curve results in significantly higher flows in large events compared with model results for either the calibrated roughness or a smooth channel using a Mannings n value 0.04. This indicates the previous rating curve (pre-2016) better represents high flow events and should be adopted for the development of the annual series and hydrologic calibration. It is noted that the 2010 event is not well matched for either model and indicates further refinement of the rating table may be necessary. For the purposes of the investigation, we have adopted the previous rating table (Rating 978) for comparison of flows.

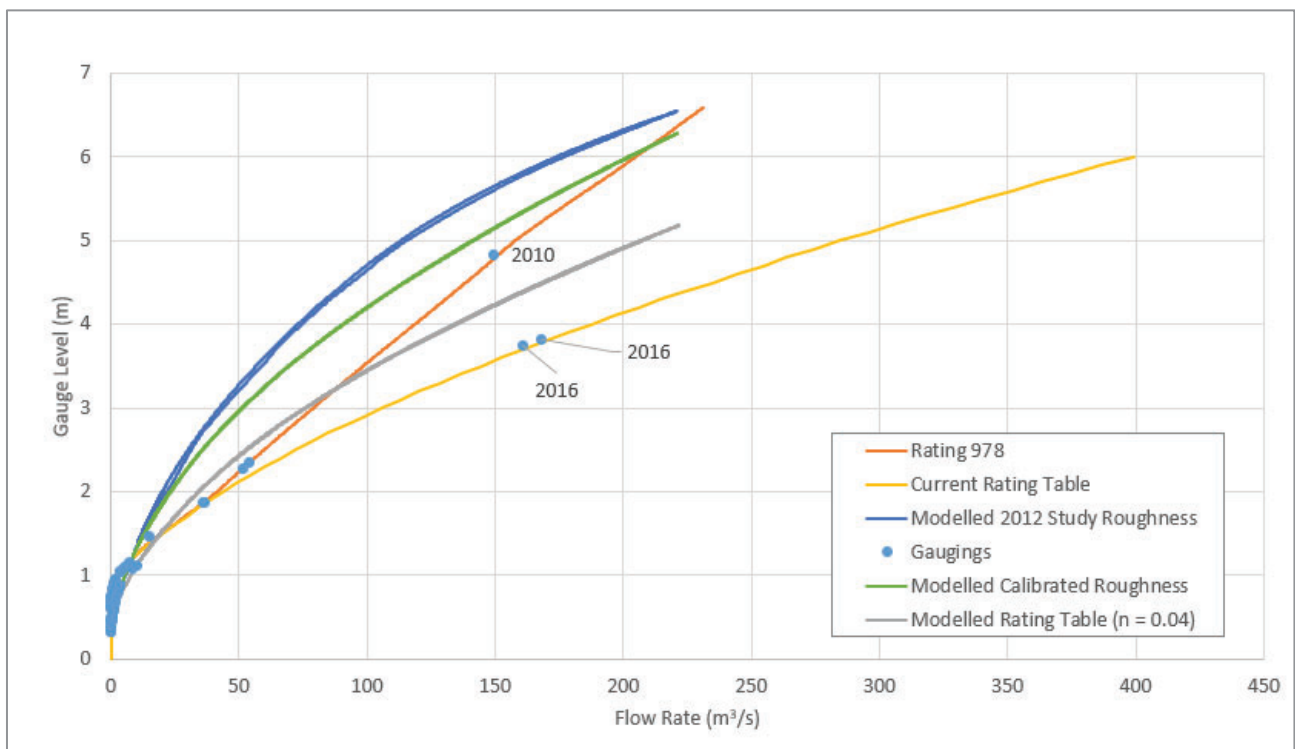


Figure 2-3 Modelled rating curves compared with gaugings and derived rating curves

As an additional verification, the October 2022 event was modelled using the flows from the pre 2016 rating table (Rating 978) and the latest rating table. The modelled water levels at the Clunes gauge were compared to the recorded water level shown in Figure 2-4. The revised flows based on the Rating 978 rating table show a good fit to the recorded levels, while the current published rating table flows show the modelled level is over two metres higher than the recorded levels. This provides further verification to adopt the pre 2016 rating table (Rating 978) for the hydrology assessment.

⁴ Chow (1958), Manning's n values for Channels, Closed Conduits Flowing Partially Full, and Corrugated Metal Pipes.

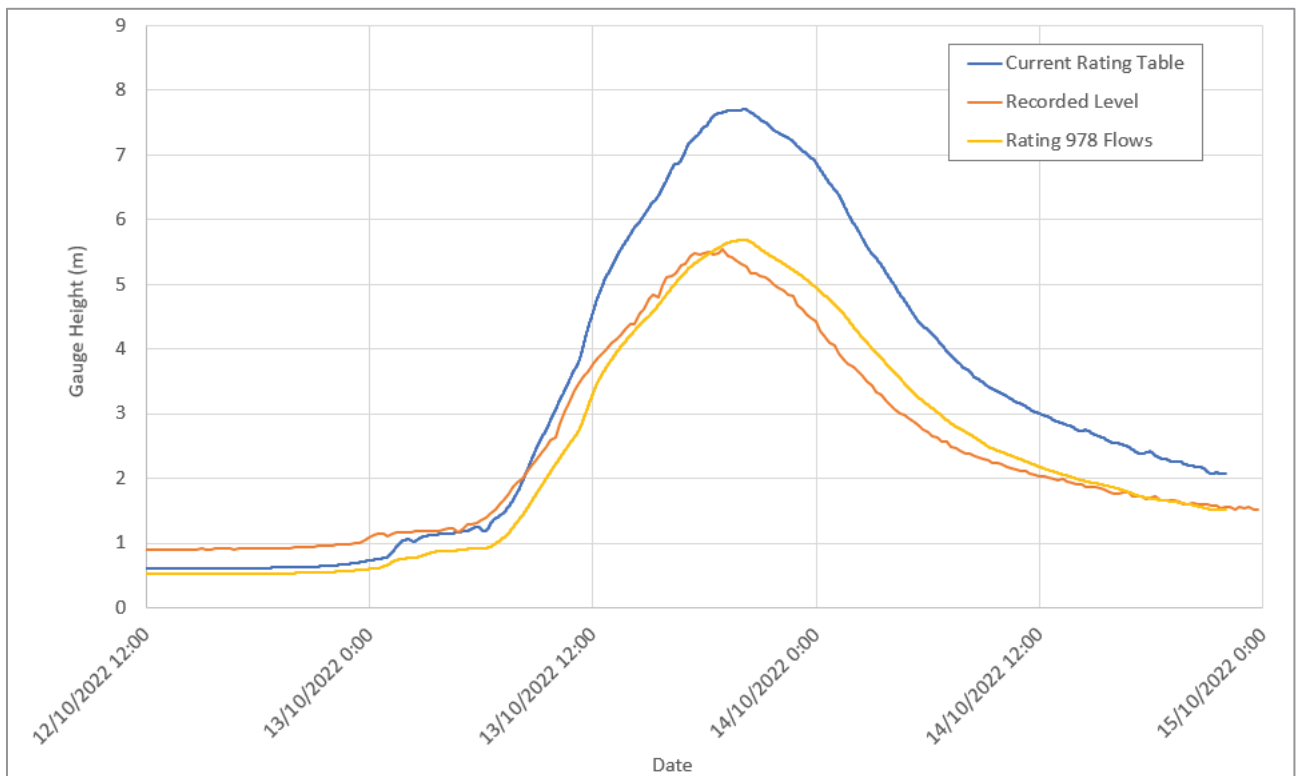


Figure 2-4 Modelled water levels compared with recorded water levels for the current published rating table (Rating 31.02) and Rating 978 for October 2022 event.



3 HYDROLOGY MODELLING

3.1 Overview

The Hydrology and Hydraulic Modelling Report (R02) describes in detail the hydrologic (RORB) and hydraulic (TUFLOW) model builds and parameter selection adopted for the study. The report also details the hydrology calibration of historic flood events (2010, 2011, 2016, January 2022 and October 2022) along with hydraulic model calibration of the 2022 floods. Model performance and alignment with the calibration evidence was utilised to determine the RORB routing parameter k_c for the catchment. These parameters were selected based in consideration of values from nearby flood studies and regional approximations with a key focus in conjunction with local data.

3.2 RORB Summary

3.2.1 Model Build

The hydrologic model for the 2012 Study was developed using RORB, a non-linear rainfall runoff and streamflow routing model for calculating flow hydrographs in drainage and stream networks. The catchment was divided into 114 sub-areas, connected by the reach network presented in Figure 3-5.

Modifications to the RORB model setup for this study included:

- The addition of the gauging interstation areas for the following gauges for calibration to the October 2022 event:
 - Creswick Creek at Creswick US Cosgrave Reservoir and
 - Adekate Creek at Creswick
- The further delineation of several smaller sub-areas for Nuggety Gully and several unnamed tributaries around the Creswick township to allow for the mapping of these waterways as part of the flood study.
- The application of excavated unlined type reaches along Creswick Creek from just upstream of Creswick through to Clunes. This recognises the quicker routing of the waterway to provide an improved fit of historic flood events at Clunes.
- Flow hydrographs were extracted at the following locations for input into the hydraulic model:
 - Creswick Creek; (downstream of St Georges) Lake
 - Slaty Creek (upstream of Melbourne Road);
 - Spring Gully (at Sawpit Rd); and
 - Unnamed tributary, upstream of Pascoe St (flows into Creswick Creek upstream of the railway crossing).
- Additionally, design flow hydrographs were extracted along Creswick Creek at Creswick and Clunes (gauge location) for comparison of calibration and design flows as outlined in the reporting from the 2012 Study.

3.2.2 Calibration

The RORB model developed for the 2012 flood study was used to undertake a calibration of two major flood events that occurred between the studies as well as validation to a major storm event (January 2022) along with the events previously calibrated during the 2012 flood study.

As part of the hydrology calibration, further investigation was conducted on the Creswick Creek at Clunes Rating Table. As discussed in Section 2.1, the current rating table shows a significant discrepancy between



the rating table used in the 2012 Flood study, with peak flows increasing almost double that previously quoted for the same flood level. Flow rates quoted using the current rating table were not achievable in the RORB model when applying losses in the expected range at the Clunes gauge. As such, calibration to the previous rating table (rating 978) was undertaken.

Additionally, the October 2022 and January 2022 events were calibrated in the hydraulic model. The current day/near-term AEP for each calibration event based off the revised design event modelling for the Creswick Creek at Clunes streamflow gauge (discussed further in the report) is shown in Table 3-1.

Table 3-1 Calibration Event Magnitude for Creswick Creek at Clunes gauge

Calibration Event	AEP (approximation)
October 2022	2%
January 2022	5%
September 2016	5%
January 2011	1%
September 2010	4%

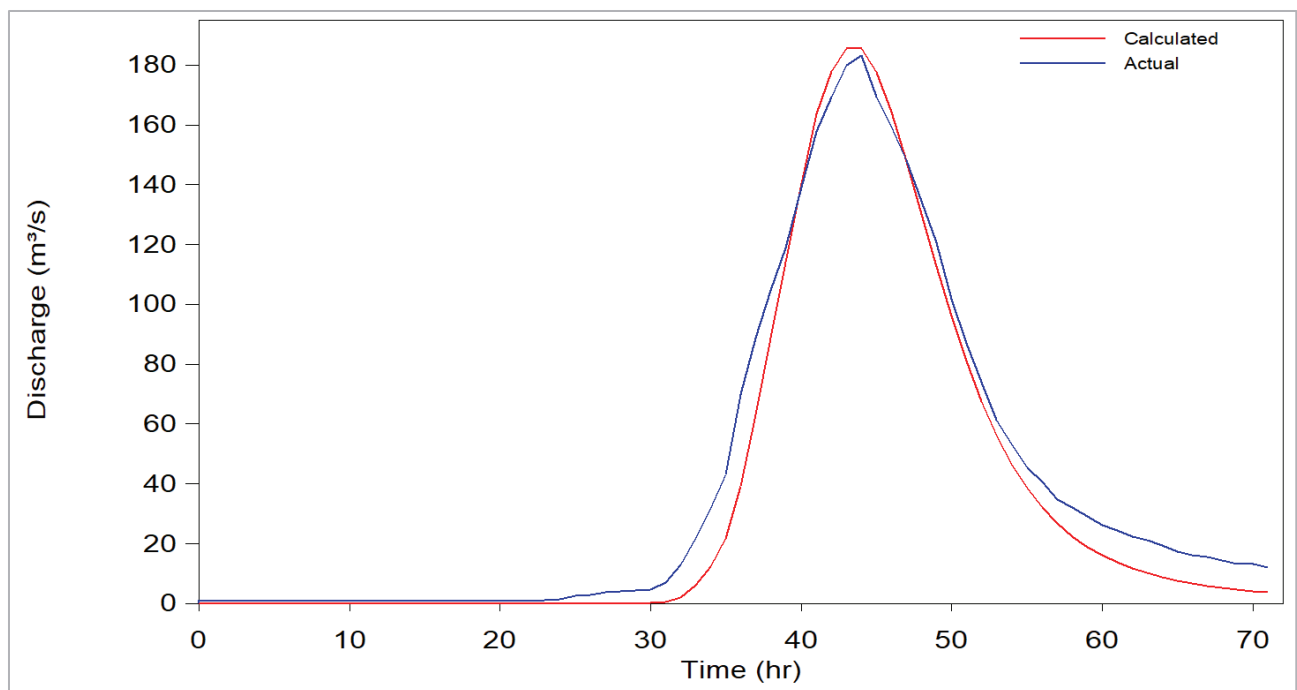


Figure 3-1 Creswick Creek at Clunes – October 2022

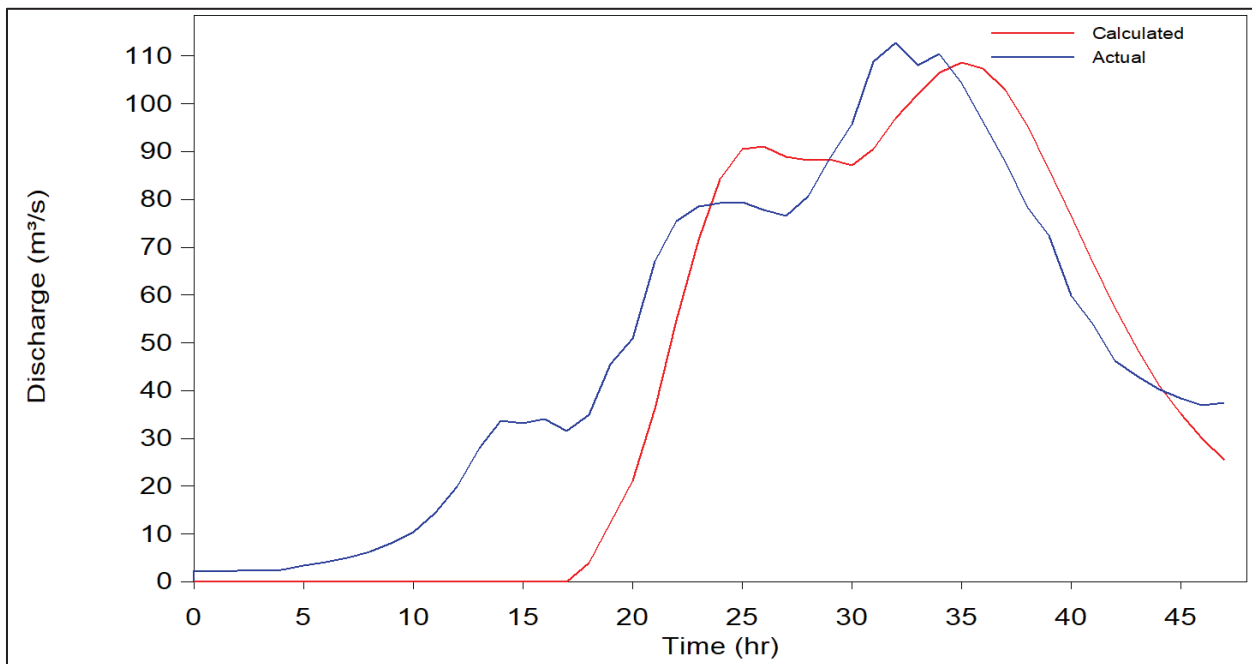


Figure 3-2 Creswick Creek at Clunes – September 2016

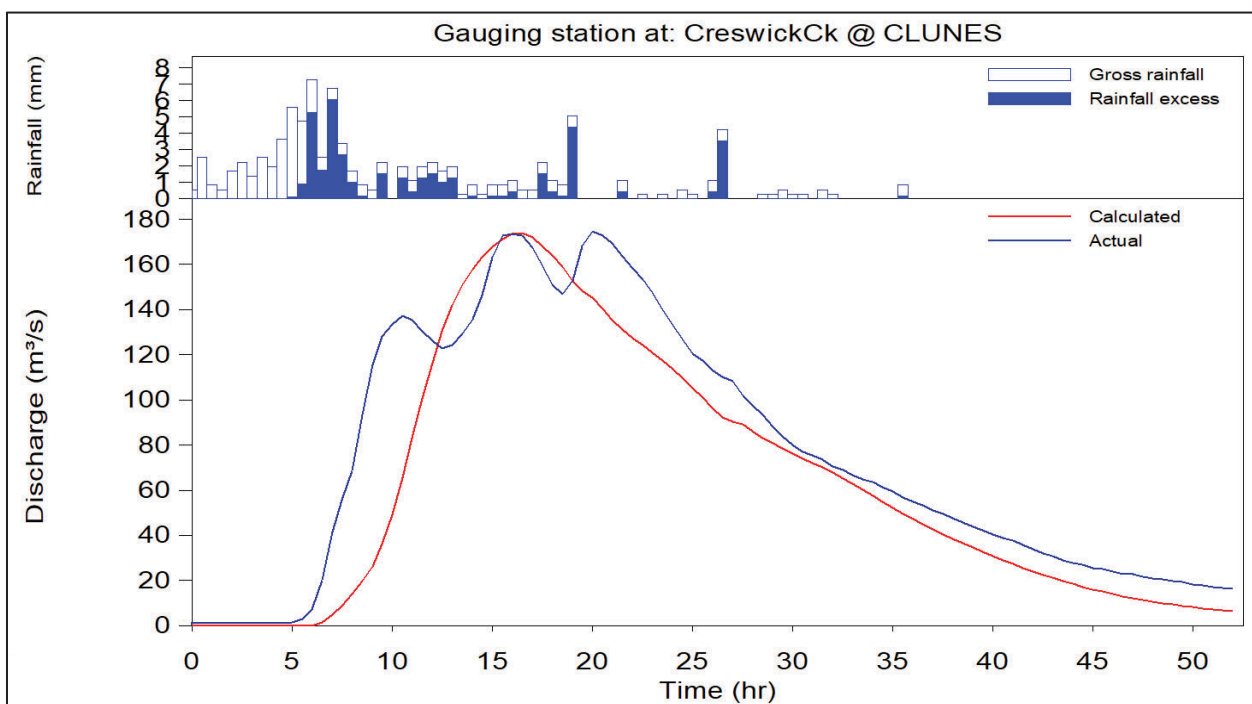


Figure 3-3 Creswick Creek at Clunes – September 2010

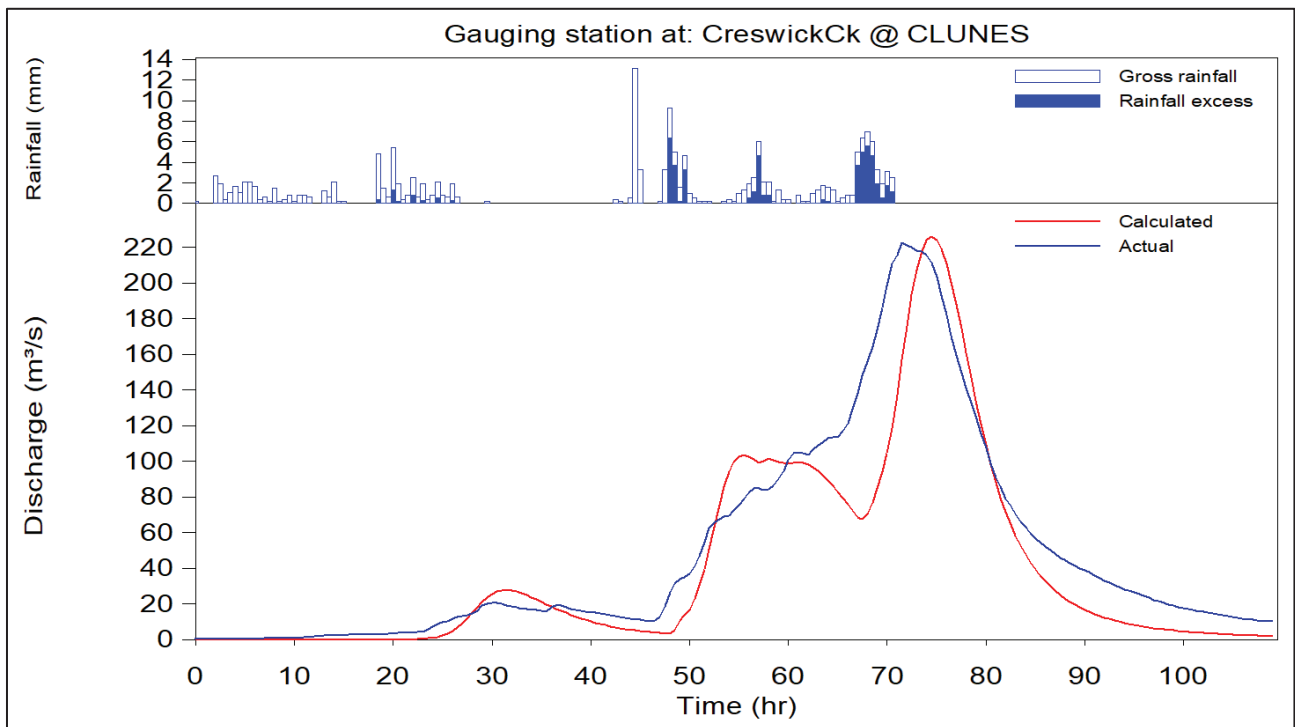


Figure 3-4 Creswick Creek at Clunes – January 2011

The hydrology model developed as part of the 2012 study was updated and calibrated to the October 2022 flood event at the Creswick Creek at Creswick US Cosgrave Reservoir, Adekate Creek at Creswick and the Creswick Creek at Clunes streamflow gauges. The parameters were then used to validate to the September 2016 and January 2022 flood event as well as the September 2010 and January 2011 events. The model parameters adopted for each of the calibration runs are provided in Table 3-2. The values are considered similar for each of the events allowing for the application of values within this range for design modelling.

The additional inter-stations included in the updated RORB model change the average distance (d_{av}) of the single interstation model (22.4 km), with multiple average routing distances from 1.2 km at Nuggetty Gully through to Clunes from down to 21.07 km. While not directly transferable due to changes to the RORB model setup, the k_c value was applied to fit calibration events showed a comparable k_c/d_{av} relationship.

The January 2022 event provided a reasonable match to the peak flow at Clunes (modelled flow of 113 m³/s compared to recorded flow 118 m³/s), however the timing and fit to the other gauges was not as well represented as the other events. This is likely due to the isolated bursts across the catchment that may not have been well represented at the daily rainfall gauges used for spatial variation. Overall, the RORB model was able to replicate several significant flood events well, with model parameters within an expected range of acceptable values. The flows developed in the RORB model were used as inflow boundaries for the hydraulic calibration.



Table 3-2 Hydrology calibration parameters

Event	Interstation	k _c	m	IL (mm)	CL (mm/hr)
October 2022	Creswick Ck US Cosgrave	12.00	0.80	20.0	2.50
	Adekate Ck at Creswick	3.22	0.80	20.0	2.50
	Nuggetty Gully	1.63	0.80	20.0	2.00
	Bald Hills Road	1.48	0.80	20.0	2.00
	Creswick Ck at Clunes	24.60	0.80	20.0	2.10
September 2016	Creswick Ck US Cosgrave	12.00	0.80	25.0	2.00
	Adekate Ck at Creswick	3.22	0.80	25.0	2.00
	Nuggetty Gully	1.63	0.80	25.0	2.00
	Bald Hills Road	1.48	0.80	25.0	2.00
	Creswick Ck at Clunes	24.60	0.80	25.0	2.00
January 2022	Creswick Ck US Cosgrave	12.00	0.80	30.0	4.00
	Adekate Ck at Creswick	3.22	0.80	40.0	4.00
	Nuggetty Gully	1.63	0.80	30.0	4.00
	Bald Hills Road	1.48	0.80	30.0	4.00
	Creswick Ck at Clunes	24.60	0.80	30.0	4.00
September 2010	Creswick Ck US Cosgrave	12.00	0.80	31.5	1.5
	Adekate Ck at Creswick	3.22	0.80	31.5	1.5
	Nuggetty Gully	1.63	0.80	31.5	1.5
	Bald Hills Road	1.48	0.80	31.5	1.5
	Creswick Ck at Clunes	24.60	0.80	31.5	1.5
January 2011	Creswick Ck US Cosgrave	12.00	0.80	42 25*	3.5 3.0*
	Adekate Ck at Creswick	3.22	0.80	42 25*	3.5 3.0*
	Nuggetty Gully	1.63	0.80	42 25*	3.5 3.0*
	Bald Hills Road	1.48	0.80	42 25*	3.5 3.0*
	Creswick Ck at Clunes	24.60	0.80	42 25*	3.5 3.0*

* Dual burst applied. Value showing 1st burst initial/continuing loss | 2nd burst initial/continuing loss



3.2.3 Design Events

The RORB model was used to simulate a range of design storm events, namely the 20%, 10%, 5%, 2%, 1%, 0.5% and 0.1% Annual Exceedance Probability (AEP) as well as the Probable Maximum Flood (PMF) event. Design modelling was undertaken based on current day/near-term conditions to assess existing risk along with design modelling for a climate change scenario based on the year 2100 for climate scenario SSP5-8.5.

The design modelling process involved the use of event based calibration to provide a range of RORB model parameters. The RORB model losses were then reconciled to a flood frequency analysis (FFA) at the Creswick Creek at Clunes gauge. The reconciled design losses were then used with the scaled IFDs for current day/near-term risk assessment (2024) and 2100 under SSP5-8.5 in accordance with the equations supplied in the draft chapter. Scaled IFDs were checked to ensure that the curve of one duration does not cross the curve of another.

RORB was then run with the new IFDs and losses for both 2024 and 2100, and the resultant critical flows applied to TUFLOW. The 2024 flows were adopted as the present day and the 2100 SSP5-8.5 flows as the future climate change scenario to be run in TUFLOW. A PMP storm event was also modelled in RORB and the PMF flows run through TUFLOW. The ARR2019 temporal and spatial patterns and areal reduction factors from the ARR datahub were used for all design scenarios.

Baseline design rainfall depths for the range of AEPs and durations were downloaded from the Bureau of Meteorology's IFD (Intensity-Frequency-Duration) Design Rainfall Data System⁵. Given the size of the catchment, spatial variation in design rainfall was considered by deriving the spatial pattern in accordance with the method shown in section 6.5.4 of ARR2019 Book 2 Chapter 6.

3.2.4 Climate Change Design Rainfall (Current day/near-term 2024)

The baseline 2016 IFDs were scaled up to Current day/near-term totals based on the recently updated Climate Change ARR chapter. As outlined earlier, guidance on the increase in rainfall intensities is provided for four climate scenarios. SSP5-8.5 has been adopted for the Current-Day timelines to assess current day/near-term risk. This results in an increase in rainfall intensity of between 12% (24 hour and longer durations) up to 22% for durations shorter than 1 hour compared to the baseline 2016 IFDs.

3.2.5 Climate Change Design Rainfall (Long Term 2100)

The baseline 2016 IFDs were scaled up to totals reflecting a year 2100 timeline based on the recently updated Climate Change ARR chapter. SSP5-8.5 results in an increase in rainfall intensity of between 41% (24 hour and longer durations) up to 88% for durations shorter than 1 hour.

3.2.6 Design Temporal Patterns and Areal Reduction Factors

The temporal patterns used to distribute the design rainfall depths were obtained from the ARR Datahub⁶. Unlike in the 2012 Study, where a single design storm was used, 10 temporal patterns (point patterns) were used for storm durations up to 9 hours. Areal temporal patterns were adopted when the catchment area exceeds 75 km², 10 areal temporal patterns were added to the analysis for storms 12 hours in duration and longer. Areal Reduction Factors (ARF) convert point rainfall to areal estimates and are used to account for the variation of rainfall intensities over a large catchment. Several ARF's were applied to the RORB model when assessing and generating flow hydrographs throughout the model. This included an ARF of 0.94 for hydraulic model inflows, 0.92 for the RORB assessment at Creswick and 0.87 for the RORB assessment at Clunes.

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

⁶ <https://data.arr-software.org/>

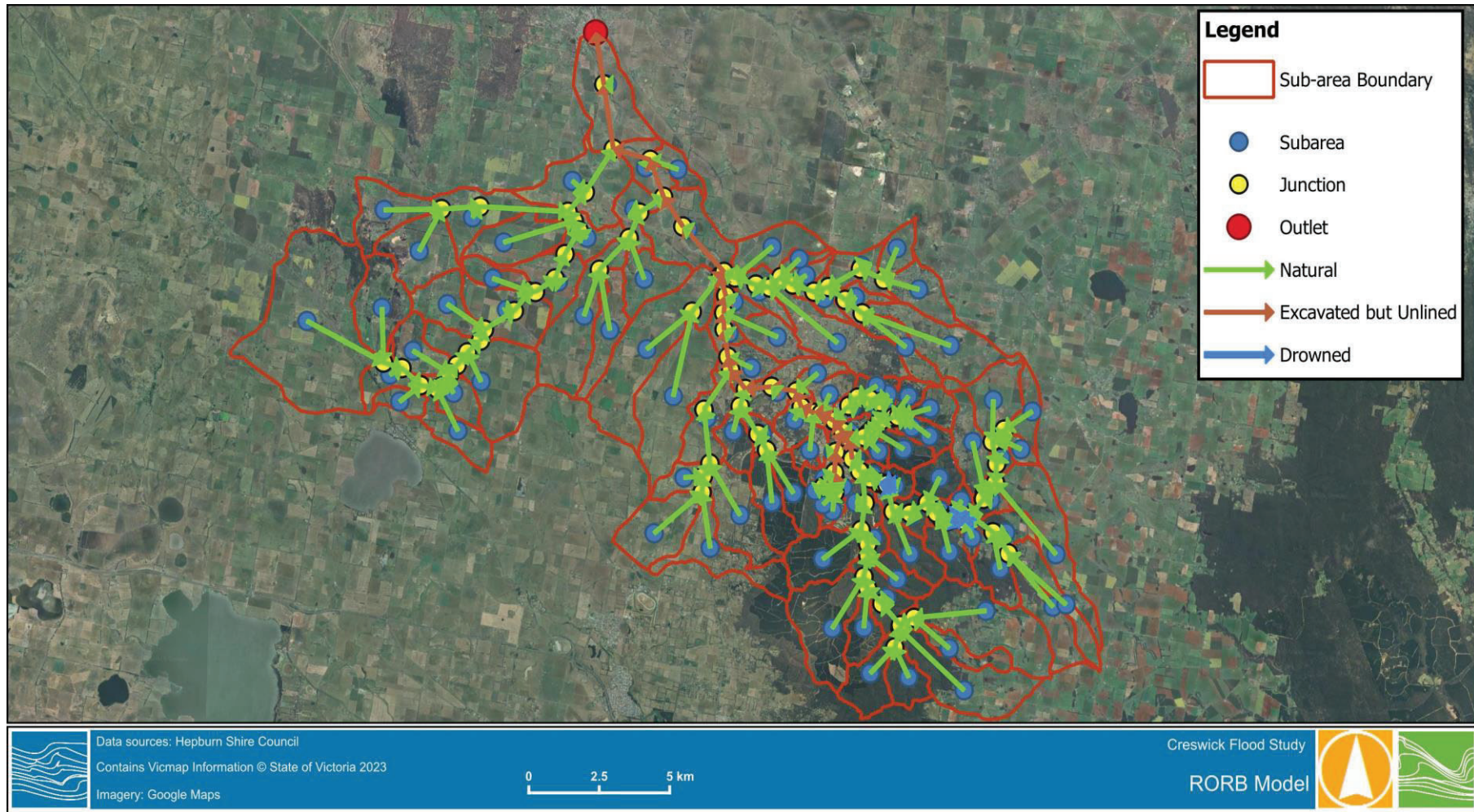


Figure 3-5 RORB model layout