Bridgewater Flood Management Plan

Study Report

March 2016

DOCUMENT STATUS

Version	Doc type	Reviewed by	Approved by	Distributed to	Date issued
v01	Draft	Ben Tate	Ben Tate	Jolene Goulton	5/11/2015
v02	FINAL	Ben Tate	Ben Tate	Jolene Goulton	16/3/2016

PROJECT DETAILS

Project Name	Bridgewater Flood Study
Client	North Central CMA
Client Project Manager	Leila Macadam & Jolene Goulton
Water Technology Project Manager	Alison Miller
Report Authors	Alison Miller
Job Number	3524-01
Report Number	R06
Document Name	3524-01R06v01_StudyReport_DRAFT.docx

Cover Photo: Aerial photograph of Bridgewater on Loddon during January 2011 flood event (Bendigo Advertiser)

15 Business Park Drive
Notting Hill VIC 3168

Telephone (03) 8526 0800
Fax (03) 9558 9365

ACN No. 093 377 283
ABN No. 60 093 377 283

GLOSSARY OF TERMS

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 relatively large.
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.
Average Recurrence Interval (ARI)	Refers to the average time interval between a given flood magnitude occurring or being exceeded. A 10 year ARI flood is expected to be exceeded on average once every 10 years. A 100 year ARI flood is expected to be exceeded on average once every 100 years.
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	An event to be considered in the design process; various works within the floodplain may have different design standards. A design flood will generally have a nominated AEP or ARI (see above). 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.
Flash flooding	Flooding which is sudden and often unexpected because it is caused by sudden local heavy rainfall or rainfall in another area. Often defined as flooding which occurs within 6 hours of the rain which causes it.
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 damage	The tangible and intangible costs of flooding.
Flood frequency analysis	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.
Flood mitigation	A series of works to prevent or reduce the impact of flooding. This includes structural options such as levees and non-structural options such as planning schemes and flood warning systems.
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.
Freeboard	A factor of safety above design flood levels typically used in relation to the setting of floor levels or crest heights of flood levees. It is usually expressed as a height above the level of the design flood event.
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.
Ortho-photography	Aerial photography which has been adjusted to account for topography. Distance measures on the ortho-photography are true distances on the ground.
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.
Risk	Chance of something happening that will have an impact. It is measured in terms of consequence and likelihood. For this study, it is the likelihood of consequences arising from the interaction of floods, communities and the environment.
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	Equivalent to 'water level'. Both are measured with reference to a specified datum.
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.
TUFLOW	A hydraulic modelling tool used in this study to simulate the flow flood water through the floodplain. The model uses numerical equations to describe the water movement.

EXECUTIVE SUMMARY

Introduction

Following the recent flood events affecting Bridgewater during September 2010 and January 2011, Water Technology was commissioned by the North Central CMA to undertake the Bridgewater Flood Management Plan. This plan included detailed hydrological and hydraulic modelling of the Loddon River and Bullabul Creek, flood mapping of the study area and investigations into potential flood mitigation works, and recommendations regarding improving the total flood warning system and planning scheme

Study Area

Bridgewater is situated on the Loddon River in Central Victoria, approximately 40 km north-west of Bendigo. The River has a catchment area upstream of Bridgewater of over 1,600 km^2, with significant upstream storages including Cairn Curran, Tullaroop and Laanecoorie Reservoirs.

A number of small creeks feed into the Loddon River between Laanecoorie and Bridgewater, including: Murphy Creek; Little Creek and Bradford Creek. Bullabul Creek flows into the Loddon River immediately downstream of Bridgewater.

In large flood events, the Loddon River breaks away from its usual course approximately 7 km to the south of Bridgewater and heads north-west, spreading onto the wide flat floodplain towards Bullabul Creek. Breakouts also occur immediately upstream of Bridgewater, with water escaping from the river on both banks, with the easterly breakout flooding the township. Downstream of Bridgewater significant breakouts occur as the Loddon River capacity diminishes and a large portion of the flow is distributed across the floodplain and into anabranches.

The flood mapping area for this study included the Loddon River and Bullabul Creek floodplains from upstream of the Loddon River breakout to the Bullabul (approximately 7 km upstream of Bridgewater), to downstream of the Bullabul Creek confluence with the Loddon River (approximately 4 km north of Bridgewater).

Data Collation and Review

As part of the initial scoping work, the data required for modelling and mapping was collated and reviewed. This included:

- Streamflow data for the Loddon River at Laanecoorie Reservoir and Serpentine, and older gauges no longer in service at Laanecoorie and Bridgewater.
- Rainfall data at 18 nearby daily rainfall stations and 3 pluviograph stations (instantaneous rainfall data).
- Digital elevation models of the study area (i.e. LiDAR topography).
- Bathymetric survey of the Loddon River, feature survey of key hydraulic structures, and floor level survey (commissioned during the study).
- Surveyed flood marks from the January 2011 flood event, September 2010 flood event and September 1983 flood event.

The data was supplemented by a significant amount of anecdotal evidence provided by the steering committee and community members.

An initial site visit was undertaken by Water Technology on 4th September 2014 through the townships of Bridgewater, Inglewood, Newbridge and Laanecoorie and parts of the surrounding floodplain. A number of subsequent site visits were carried out during the study to capture further detail of floodplain features and potential mitigation sites.

Community Consultation

Throughout the study, a range of community consultation activities were undertaken, including community drop-in sessions, media releases and questionnaires to ensure that community issues were heard and the ideas of the community were considered in the development of potential flood mitigation options. The community participation was very helpful, with flood observations, local information and feedback on the study greatly improving the outcomes for the study.

Model Schematisation/Development

A preliminary coarse model of the Loddon River floodplain from Laanecoorie to the Waranga Channel was developed to assess the location and magnitude of breakout flows within the catchment. The model was run with steady state flows ranging from 10,000 ML/d to 100,000 ML/d. Results showed that flow remains largely within the banks of the Loddon River for flows up to 50,000 ML/d. At flows of 70,000 ML/d flood flows break out to the north-west towards Bullabul Creek. At 80,000 ML/d water begins to breakout to the east, near Peppercorn Lane and around the back of the Bridgewater Township. This modelling was also used to develop an understanding of the flow distribution to the floodplain and anabranches from the Loddon River downstream near Serpentine. This showed that in large flood events like the January 2011 flood, 89% of the Loddon River flow leaves the river upstream of Serpentine and is distributed into Pompapiel Creek and Bullock Creek

Based on the results of this preliminary modelling, a detailed hydrological model of the catchment was developed for the purpose of estimating historic flood flows for calibration, and the development of design event flows. The modelling comprised of a flood frequency analysis of the Laanecoorie gauge data, and a RORB model of the remainder of the catchment downstream of Laanecoorie (with incorporated flow split relationships along the Loddon River). Output from the model was used as boundary conditions to the TUFLOW hydraulic model which comprised of a two dimensional (2D) representation of the Loddon River, Bullabul Creek and the broader floodplain as well as key hydraulic structures.

The hydraulic model was well calibrated to available flood marks and flood photography across the study area, and received good feedback from the community during consultation sessions.

Design Event Modelling

Following on from the successful hydrology and hydraulic model calibration, a series of design events were modelled. This required the adoption of various design parameters to be included within RORB to generate design hydrographs for input to the hydraulic model. For this study, the 20%, 10%, 5%, 2%, 1%, 0.5%, and 0.1% AEP events were required.

The model considered temporal and spatial distributions of rainfall. A sensitivity analysis was undertaken on the model parameters adopted, and resulting flows were compared against estimates using other methods. A panel of technical experts from the Department of Environment, Water, Land and Planning reviewed and approved the methodology undertaken by Water Technology to derive the design flood estimates.

Results indicated that flood magnitudes rarer than a 10% AEP were sufficiently large to cause breakout flow from the eastern side of the Loddon River, travelling north east across farmland and through the township, over the Calder Highway. This inundation through the town centre results in a large portion of the flood damages that occur.

Table 0-1 summarises the damages assessment results for existing conditions. The 1% AEP flood extent can be seen in Figure 0-1.

The flood intelligence gained from this modelling exercise, including flood extents, travel times, and impacted residences/businesses, and has been incorporated into the Municipal Flood Emergency Plan. This will assist in emergency response planning.

Table 0-1 Flood Damage Assessment Costs for Existing Conditions

Parameter	Annual Exceedance Probability					
	0.5%	**1%**	**2%**	**5%**	**10%**	**20%**
Buildings Flooded Above Floor	81	52	39	17	1	0
Properties Flooded Below Floor	75	78	65	47	27	6
Total Properties Flooded	**156**	**130**	**104**	**64**	**28**	**6**
Direct Potential External Damage Cost	$536,000	$444,000	$377,000	$248,000	$68,000	$13,000
Direct Potential Residential Damage Cost	$3,403,000	$1,541,000	$825,000	$183,000	$48,000	$0
Direct Potential Commercial Damage Cost	$1,720,000	$1,082,000	$716,000	$185,000	$0	$0
Total Direct Potential Damage Cost	**$5,659,000**	**$3,067,000**	**$1,917,000**	**$616,000**	**$116,000**	**$13,000**
Total Actual Damage Cost *(0.8*Potential)*	**$4,527,000**	**$2,454,000**	**$1,534,000**	**$493,000**	**$93,000**	**$10,000**
Infrastructure Damage Cost	**$1,892,000**	**$1,294,000**	**$1,021,000**	**$479,000**	**$276,000**	**$23,000**
Total Damage Cost	**$6,419,000**	**$3,747,000**	**$2,555,000**	**$972,000**	**$369,000**	**$33,000**
Average Annual Damage	**$164,000**					

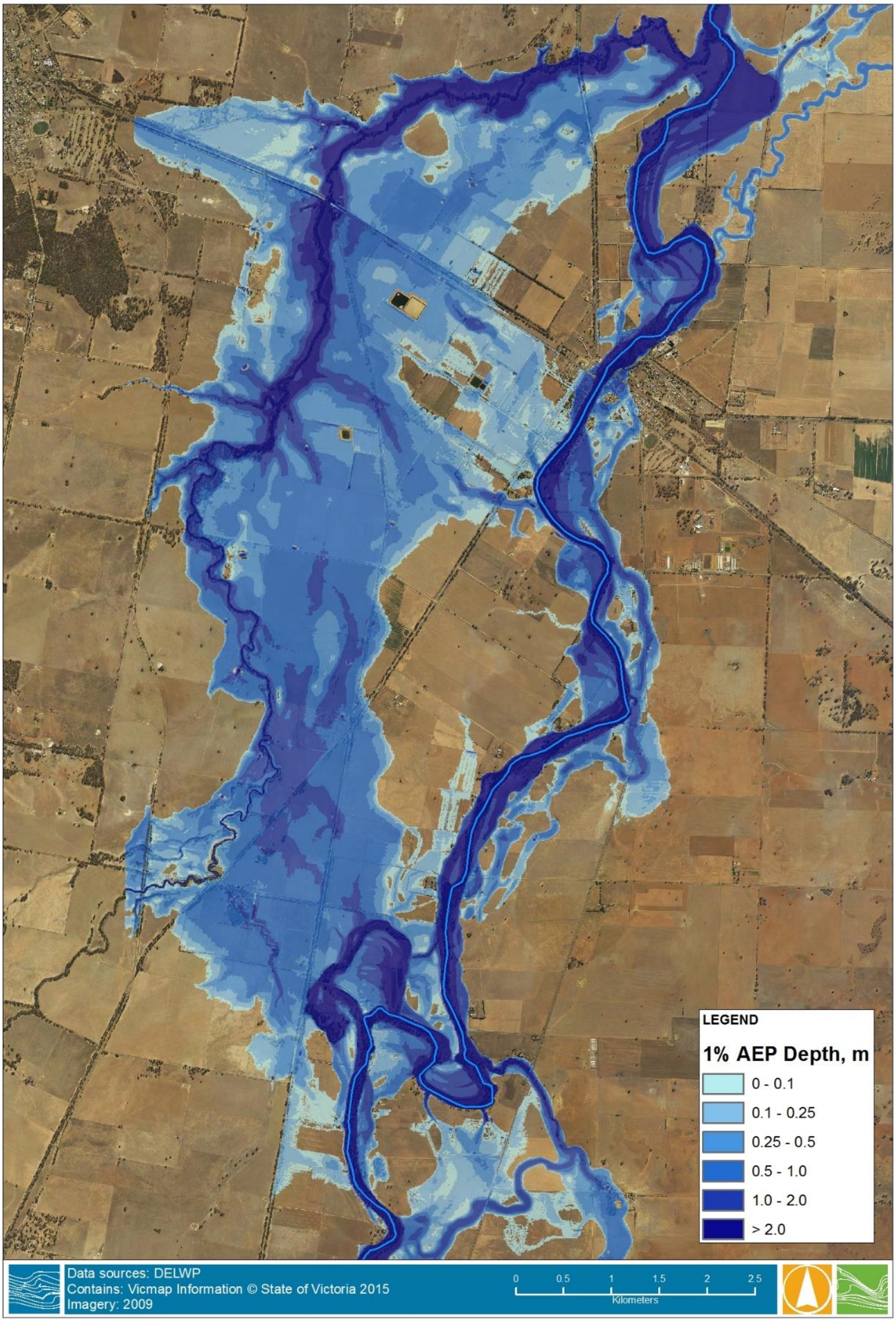


Figure 0-1 Modelled 1% AEP Flood Depth

Flood Mitigation

An initial prefeasibility assessment of 8 structural mitigation options was undertaken. From this assessment, three options were selected for further analysis using the developed hydraulic model. These included: diversion of waters from Loddon River to Bullabul Creek; improved conveyance across the Calder Highway and railway; and a levee around the Caravan Park and along Peppercorn Lane. These three broad options were run iteratively many times with slight changes to arrive at a solution that best mitigates flooding for the Bridgewater township.

Diverting water to Bullabul Creek was found not to be effective as it only shifted the problem elsewhere. Similarly, any additional capacity under the Calder Highway and Railway Bridge was not sufficient to reduce flood levels and extents within the township. The levees were found to be the most effective option for mitigation, and a number of refinements were made to the size, location and alignment of levees.

The final refined mitigation package included:

- 1,350 m of levee along the eastern side of the Loddon River, upstream of the pub (note that some sections of this levee will be temporary) as well as around 150 m of levee from the Calder Highway to the railway embankment across Eldon Street;
- 640 m of raised walkway along the western bank of the Loddon River.

This package of works was found to be cost effective, providing a substantial reduction in flood risk across a range of design events. The package reduced the Average Annual Damage to $136,000, a reduction of $27,000 per year. Three costing options were considered, depending on the configuration of the levee (e.g. earthen embankments, temporary levees and/or raised roads). The total capital cost of the refined package was estimated at between $146,500 and $305,124 (for the various options) and provides a benefit-cost ratio of between 1.02 and 2.4.

Despite a positive cost-benefit ratio, there was strong opposition to this mitigation option from the community with 70% of respondents indicating that they did not support any of the three levee configurations presented. The opposition was not limited to those who were adversely impacted by the levee, but resonated throughout the whole community. It was generally felt that while the levee provided protection to the majority, some would be adversely impacted and that this was not an equitable solution.

There was strong community support for developing an improved flood warning system for the township of Bridgewater focusing on the message dissemination.

Recommendations

Following significant consultation with the community, the Bridgewater Flood Management Plan Steering Committee recommends the following actions:

- Amendment of the planning scheme for Bridgewater to reflect the flood risk identified by this project;
- Adopt the design flood levels for existing conditions for use in future planning related decisions
- The adoption of the Municipal Flood Emergency Plan to improve emergency response;
- Regular education/information sessions regarding the management of reservoirs to address community concerns regarding reservoir management;
- Investigation and development of a total flood warning system, with particular emphasis on the dissemination of information.

The refined mitigation option outlined in this report is not a recommended outcome of this study, given the lack of community support. Details of this mitigation option can be reviewed at a later date should the level of interest change.

It should be noted that this document does not represent policy of North Central CMA, Loddon Shire Council or State Government. This is a technical report produced as part of the Bridgewater Flood Management Plan. There are many considerations that must be made following the completion of this study by all stakeholders and Government prior to implementing any of the recommendations.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Background

Following the flood events of September 2010 and January 2011, with the later significantly impacting on Bridgewater, Water Technology was commissioned by the North Central CMA to undertake the Bridgewater Flood Management Plan. This plan includes detailed hydrological and hydraulic modelling of the Loddon River and Bullabul Creek, flood mapping of the Bridgewater Township and recommendations for flood mitigation works.

As part of the investigation process there were several reporting stages to ensure the study was reviewed and approved by the Steering Committee. This report is the Study Report, a compilation of all previous staged reports:

- Inception Report and Project Plan (22 August 2014)
- Data Collation, Review and Model Scoping (24 November 2014)
- Hydrology Analysis (28 January 2015)
- Hydraulic Analysis (18 May 2015)
- Preferred Mitigation Package Detailed Results Memo (11 May 2015)

A Municipal Flood Emergency Plan has also been produced. This report has been submitted to VicSES and North Central CMA independently of this report.

1.2 Study Area

Bridgewater is situated on the Loddon River in Central Victoria, approximately 40 km north west of Bendigo. The River has a catchment area upstream of Bridgewater of over 1,600 km^2, with significant storages including Cairn Curran, Tullaroop and Laanecoorie Reservoirs.

A number of small creeks feed into the Loddon River between Laanecoorie and Bridgewater, including: Murphy Creek; Little Creek and Bradford Creek. The Bullabul Creek flows into the Loddon River immediately downstream of Bridgewater as shown in Figure 1-1.

In large flood events the Loddon River breaks away from its usual course and spreads onto the wider floodplain. The study area was extended beyond that described in the brief to approximately 15 km upstream and 6 km downstream of Bridgewater to include these breakout flows. The original and revised study areas are overlayed on Figure 1-1.

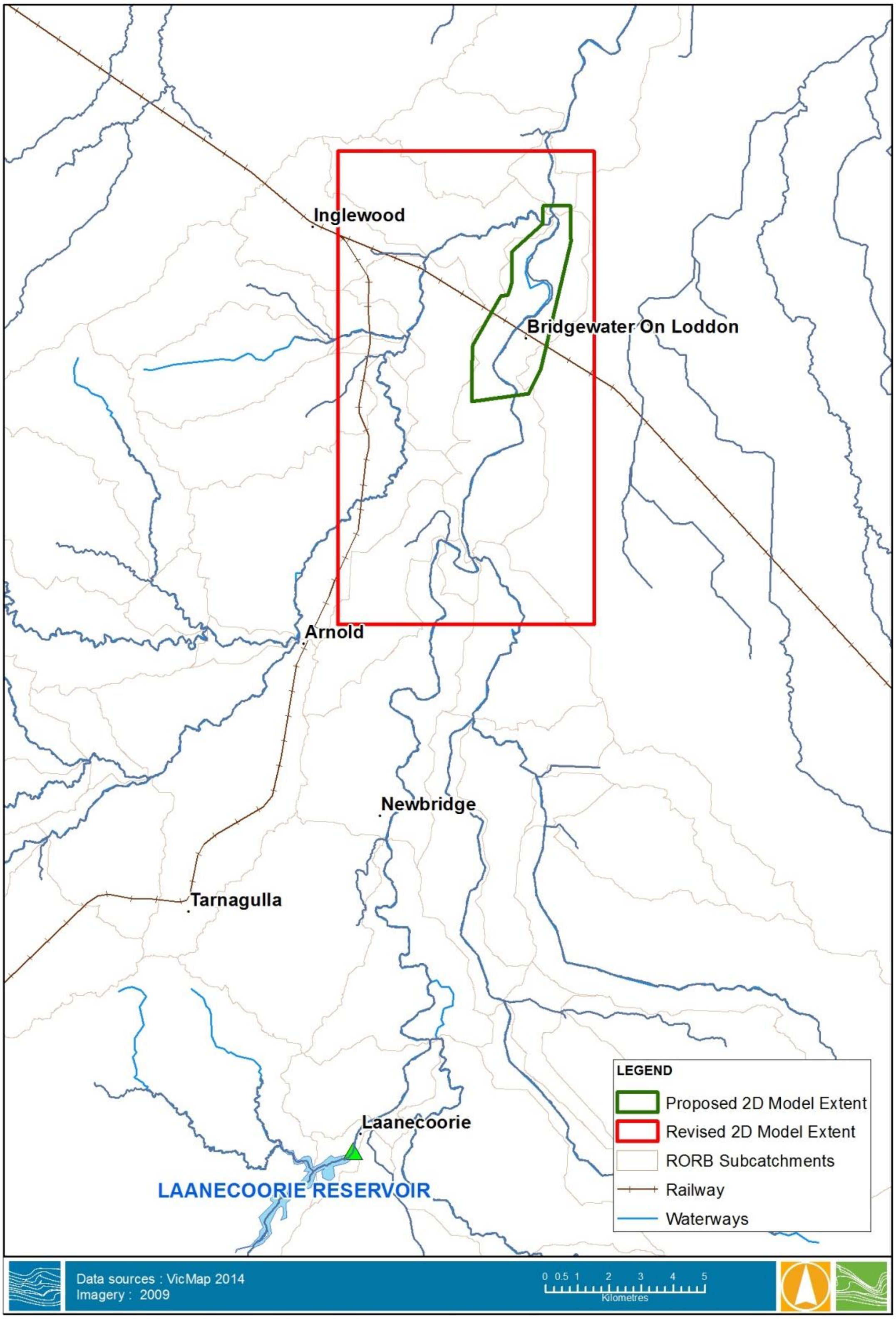


Figure 1-1 Contributing inflows to the study area

2. DATA COLLATION AND REVIEW

2.1 Flood Related Studies

A number of flood investigations exist for the Loddon River, however there were no recent flood studies carried out for Bridgewater. The 1% annual exceedance probability (AEP) flood levels were estimated in 1996 by the Department of Natural Resources and Environment, based on the 1% AEP flood profile of the Loddon River[1]. This study assumed the flood of 1909 to be representative of the 1% event, with a peak flow of 213,000 ML/d from Laanecoorie Reservoir. This exceeds the estimated January 2011 peak flow of 195,000 ML/d. The resulting peak water level at the Calder Highway was estimated to be 137.66 m AHD.

Bridgewater is known to be prone to flooding, with a Land Subject to Inundation overlay (LSIO) in the Planning Scheme, Figure 2-1. The LSIO shows the eastern side of the town as prone to flooding.

Note that the January 2011 flooding resulted in a greater extent than that of the LSIO. The North Central CMA has used data from this flood (and other historical floods) to develop a 1% AEP flood extent and 'flood feature' extent, highlighting areas that were inundated during the September 2010 and January 2011 flood events.

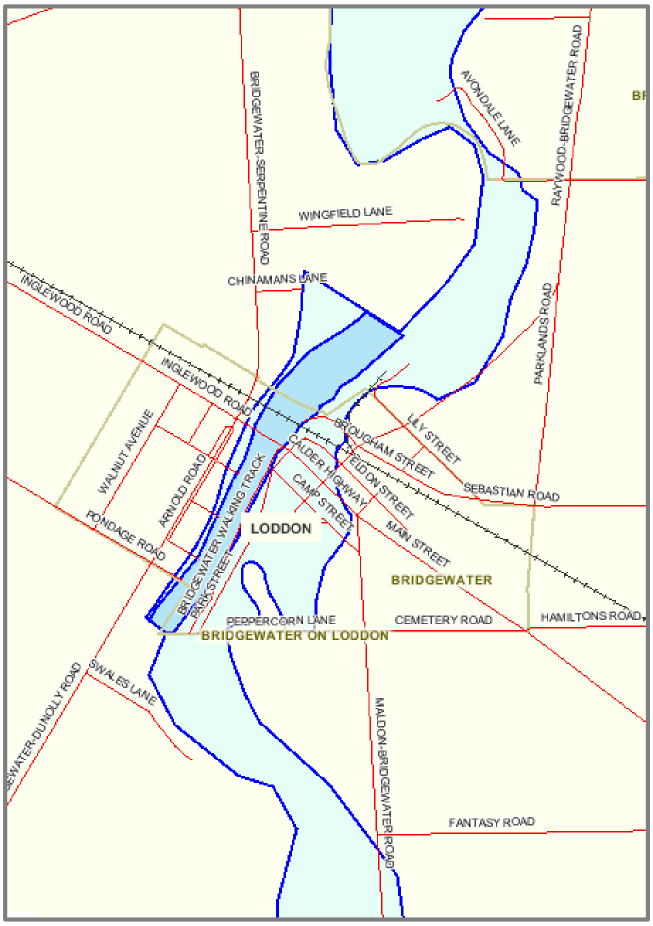


Figure 2-1 Land Subject to Inundation Overlay in Bridgewater

[1] Department of Natural Resources and Environment, 1996. The Estimation of the 1% Flood Profile of the Loddon River from Laanecoorie to Bridgewater Township and the Declaration of 1% Flood Levels in Bridgewater Township. <http://www.ga.gov.au/flood-study-web/download/resource/269>

2.2 Hydrological Data

2.2.1 Streamflow

There are a number of streamflow gauges on the Loddon River, both upstream and downstream of Bridgewater.

Of interest to this study are the gauges at: Laanecoorie Reservoir (#407240) at the Laanecoorie head gauge; Laanecoorie (#407203) located downstream of the reservoir; Serpentine (#407229), and a closed stream level gauge at Bridgewater (#407200) which operated from 1884 to 1985. The location of these gauges can be seen in Figure 2-2. A summary of the annual maximum flow recorded at these gauges during their period of record can be seen in Figure 2-3. This provides a summary of the availability of data over time. Some years may not be complete and may have missing data.

Quality codes provided from the Department of Environment and Primary Industries (DEPI) water monitoring database[2] showed the streamflow records for the Loddon system contained generally good quality data for the periods observed.

In large flood events the Loddon River breaks away from its usual course and spreads onto the wider floodplain. These breakout flows result in several of the gauges located on the Loddon River misrepresenting the actual flow, with flow bypassing the gauges. For example, the use of the gauge at Serpentine Weir for calibration data is limited, due to a number of breakout flows upstream of the gauge. Historical data indicates the gauge has a maximum capacity of around 21,000 ML/d, however the rating table is only valid for flows up to 5,200 ML/d (flows greater than this are extrapolated).

Preliminary rapid assessment modelling using flows from the Laanecoorie reservoir input into a coarse scale hydraulic model has allowed for the identification of the breakout locations at high flows, as seen in Figure 2-4 and Figure 2-5. The methodology for deriving these flow splits is discussed further in Section 3.2.

[2] Department of Environment and Primary Industries (2014). < http://data.water.vic.gov.au/monitoring.htm>

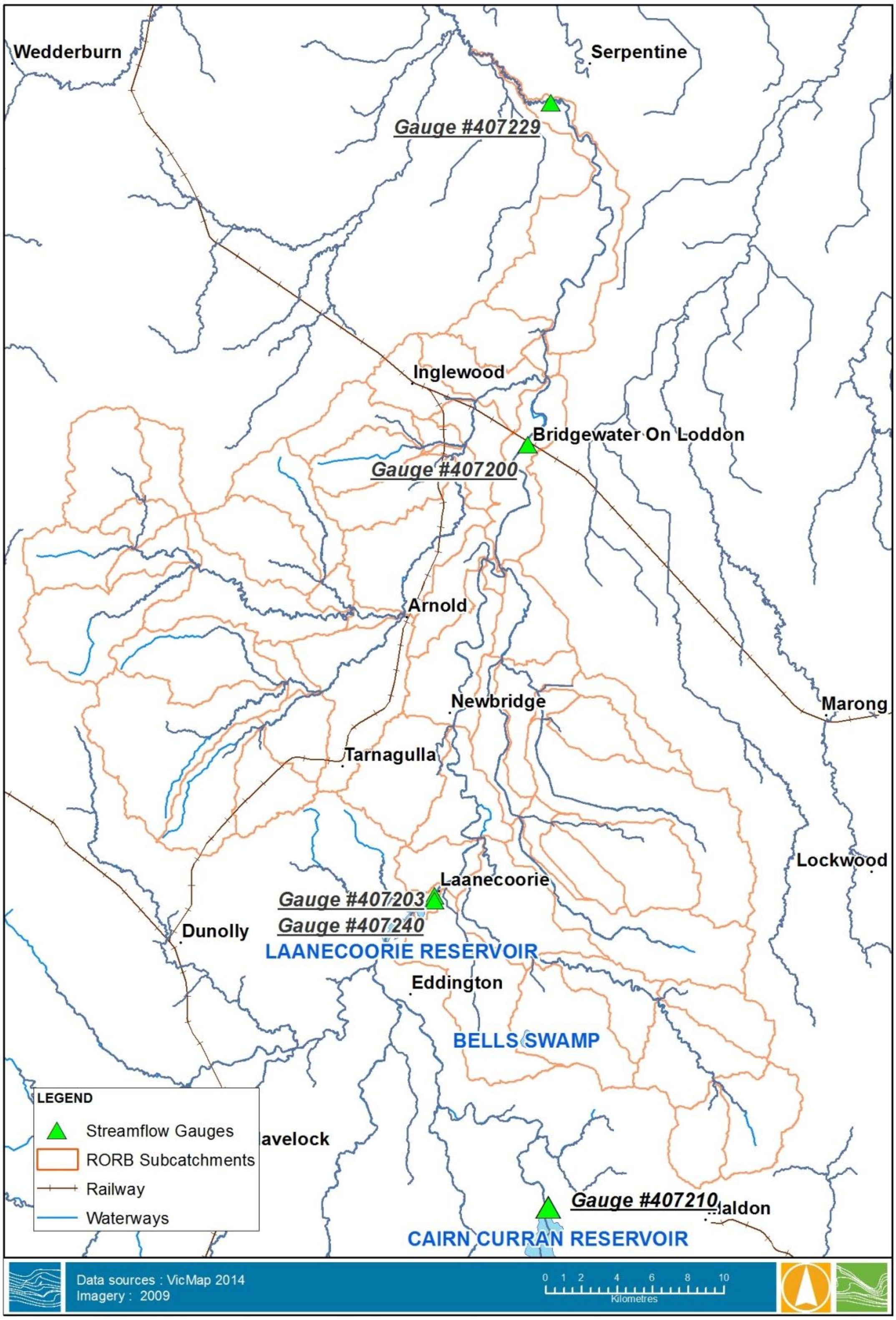


Figure 2-2 Streamflow Gauges throughout the catchment

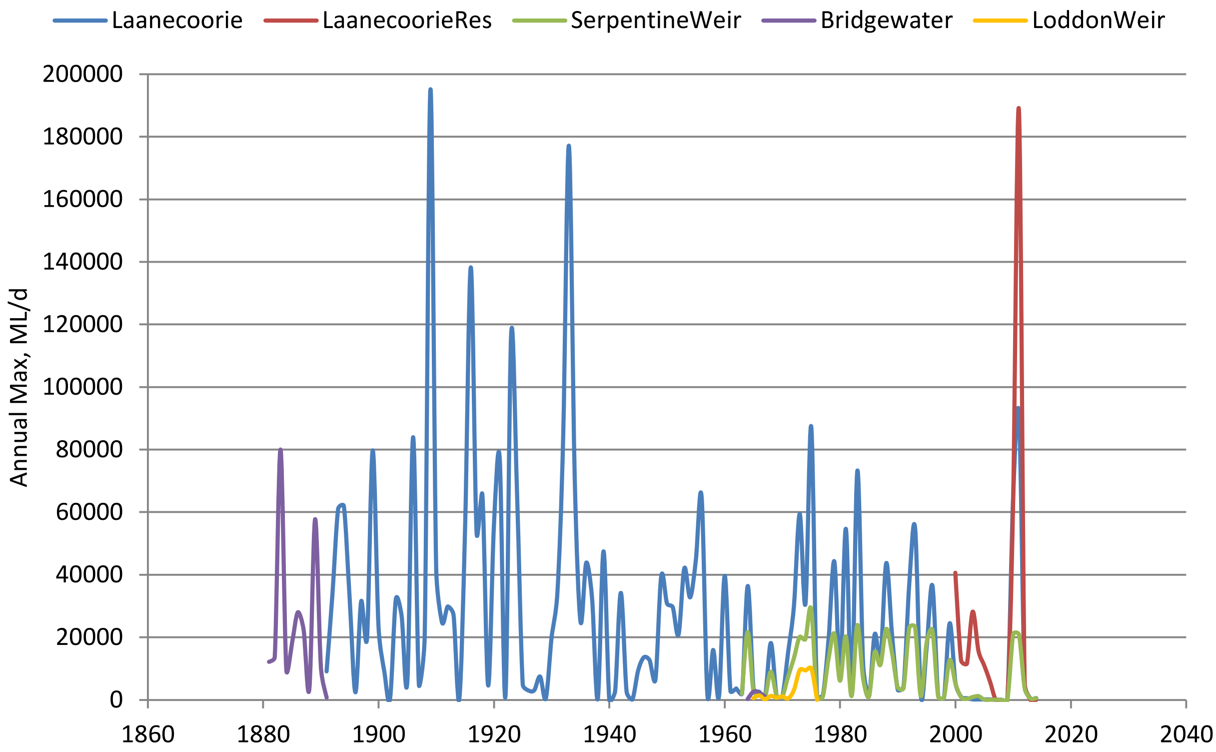


Figure 2-3 **Recorded annual maximum discharge at streamflow gauges of interest**

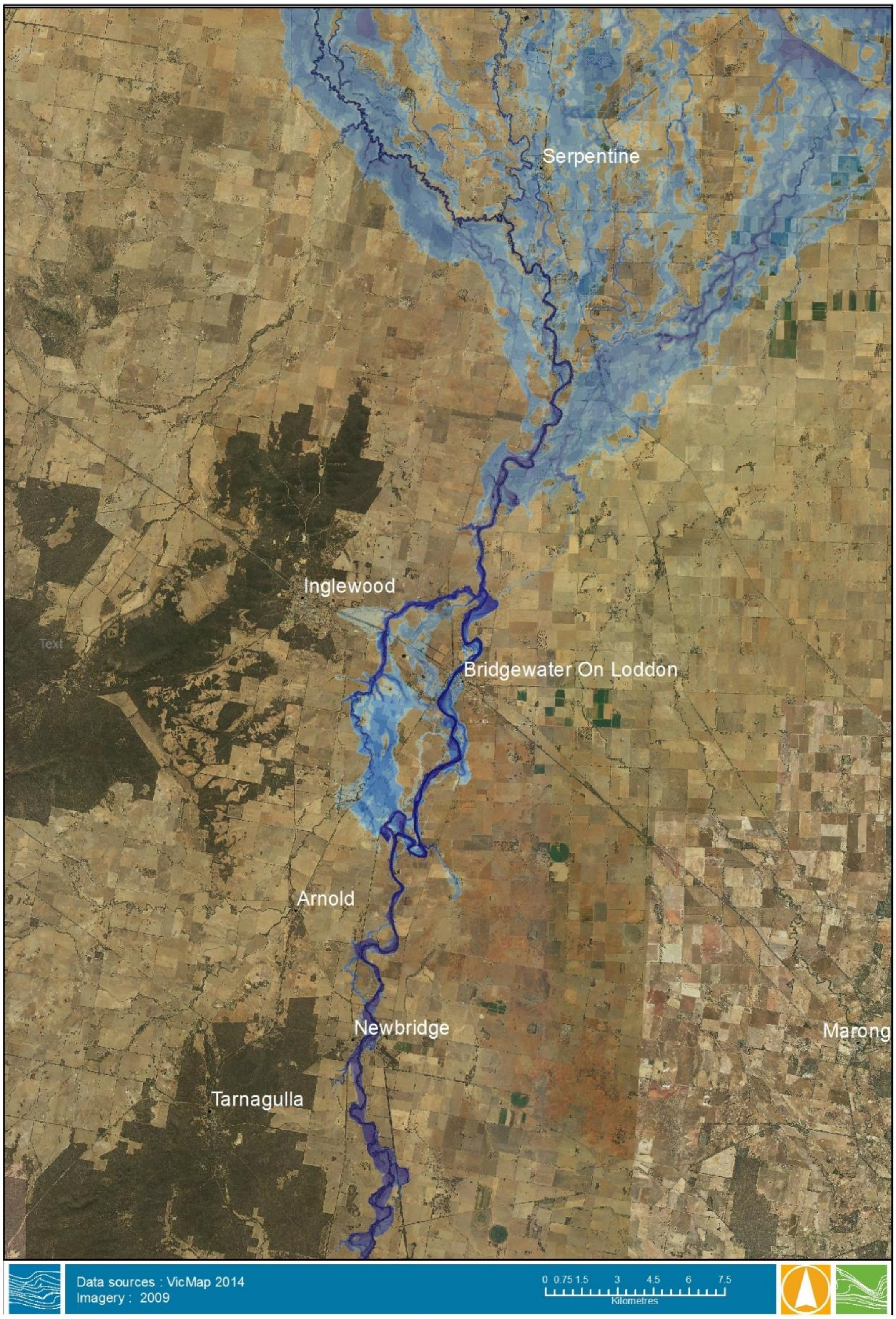


Figure 2-4 Modelled breakout flows from the Loddon River (whole model extent)

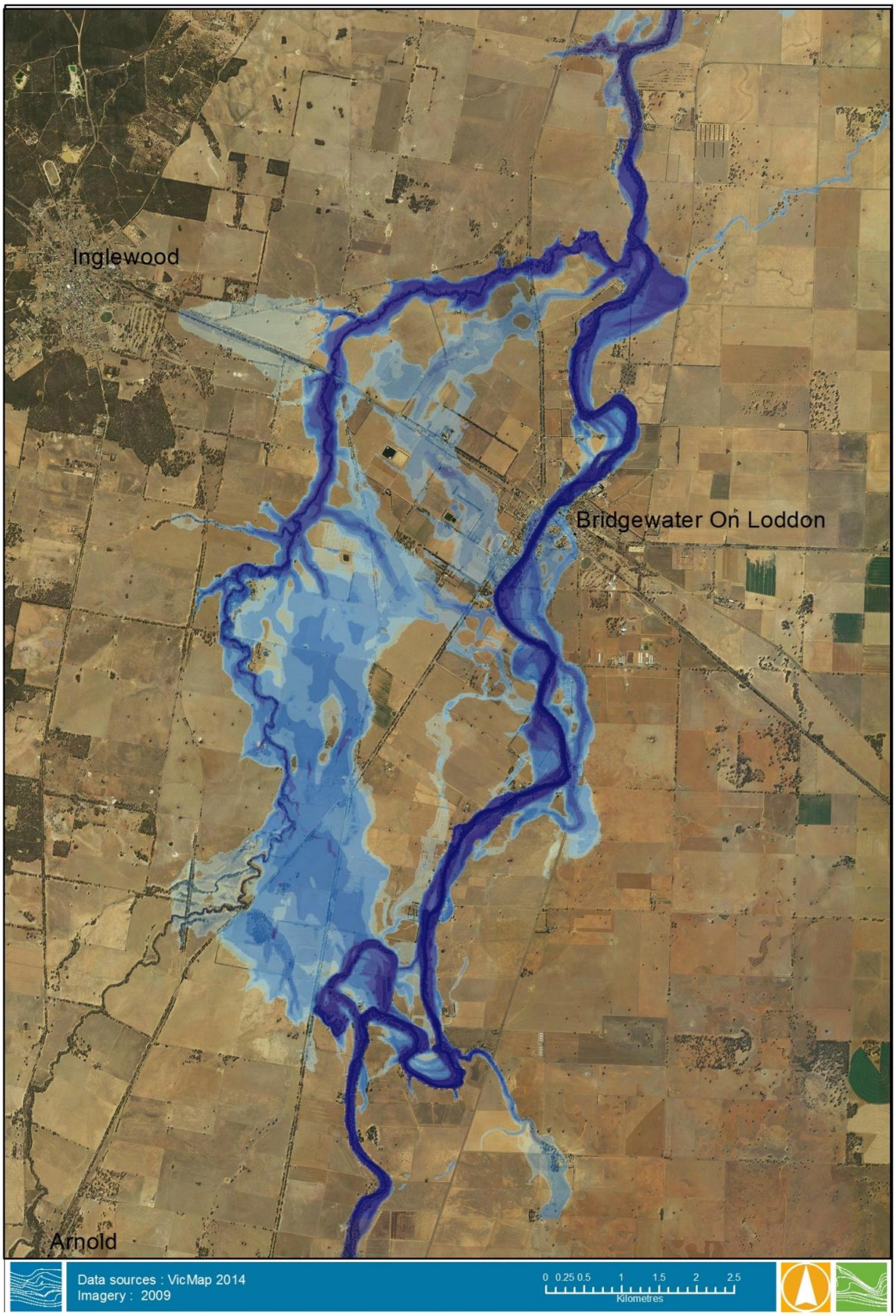


Figure 2-5 Modelled breakout flows from the Loddon River surrounding Bridgewater

Rating Curve Review

The tail gauge at the Laanecoorie Reservoir (407203), approximately 40 km upstream of Bridgewater, was used to provide historic flows and develop design flow estimates of Loddon River flows. As flooding in Bridgewater is dominated by the Loddon River flows upstream of Laanecoorie, it is pertinent to understand the accuracy of the rating curve for the gauge.

Whilst it is commonly understood that a flow gauge with a long period of record is the best possible source of information for any flood study, the accuracy of the rating curve is often overlooked. Water Technology has demonstrated in previous flood mapping investigations across the State that it is not uncommon for a rating curve to overestimate or underestimate flows by up to 40% in the extrapolated zone of the rating curve. This is very important when estimating the flow of the January 2011 event because it is clearly the largest event on record and well beyond the reliable section of the rating curve.

Better understanding the rating curve ensures the correct amount of emphasis is put on matching the historical flow rates, and that the flow estimate is treated accordingly.

Discharge and water level readings for the Laanecoorie gauge were analysed over the period of record (1893 to 2014) as shown in Figure 2-6. The water level and flow relationship indicated several rating curves have been utilised throughout the gauge record. This may be a result of bathymetric changes or a changed/improved understanding of the relationship as more data is collated.

The current rating curve is shown in Figure 2-7, along with observed water level and flow records. The data shows good agreement to the rating curve for flows between 100 to 100,000 ML/d, however it should be noted that the rating curve is extrapolated for flows greater than 29,000 ML/d.

The current rating curve was developed as part of a report conducted in 2012 for DELWP ‘Rating Table Extrapolations for the Upper Loddon Catchments. Report 307.’ The report states that a relationship was developed by estimating releases from Laanecoorie Reservoir through a spillway rating, a cross sectional survey and historical measurements.

Given this recent investigation into the rating curve, it is considered to be the best estimate for Loddon River flows at Laanecoorie. Further hydraulic modelling may improve the rating curve somewhat in the extrapolated region of the curve, but through the hydrology and hydraulic modelling conducted for this study Water Technology has demonstrated that the rating curve provides reasonable estimates of flow from Laanecoorie resulting in a close match to observed flood levels in Bridgewater.

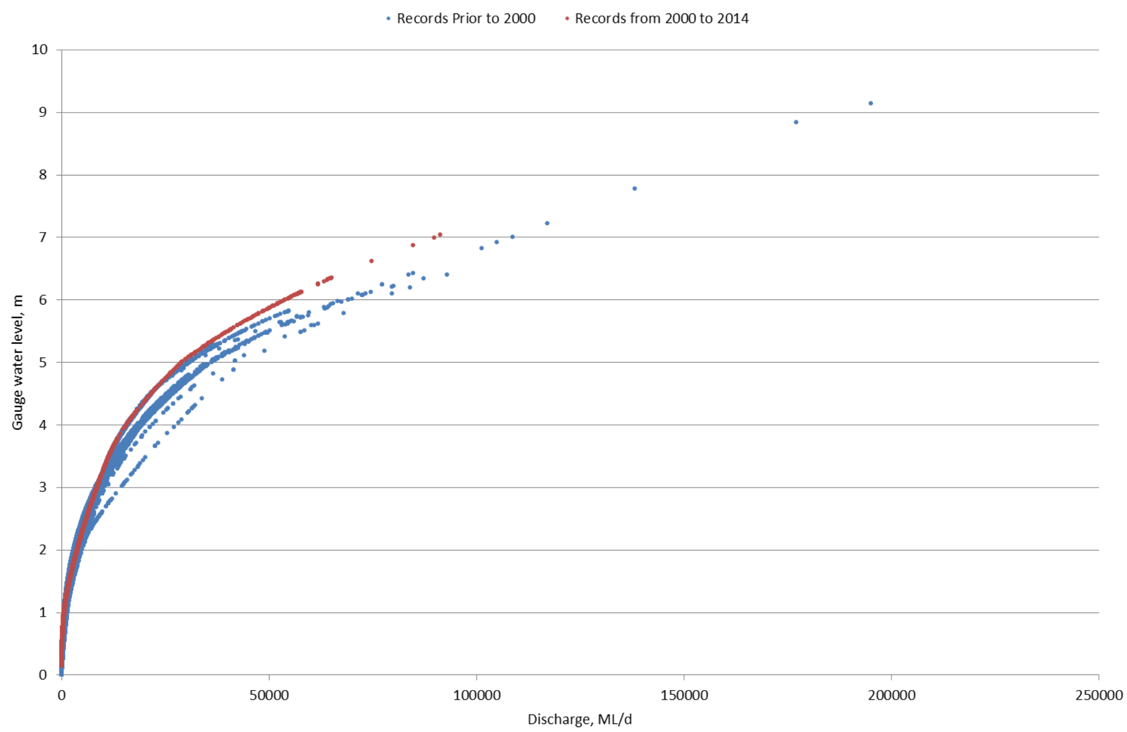


Figure 2-6 Water levels versus discharge at Laanecoorie tail gauge over the gauge record (DEPI, 2014)

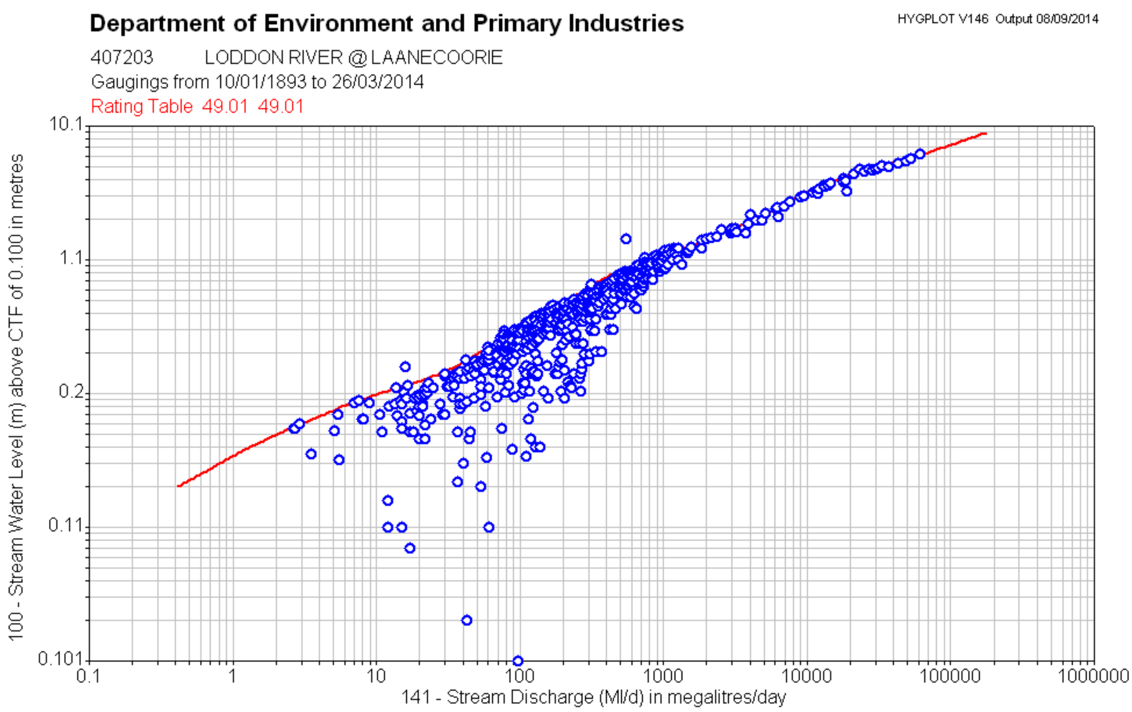


Figure 2-7 Observed and theoretical (rating curve) gaugings at Laanecoorie tail gauge

Data at the Laanecoorie tail gauge (provided by DELWP, 2014) has been compared to historical records compiled by the Rural Water Commission of Victoria (1990)[3] for the period 1892 to 1986 (5 years of record were missing within this period). A comparison of peak annual flows for each data set, presented in Figure 2-8, shows the data published by RWC (1990) to be slightly higher than that from DELWP (2014).

Of particular interest is the peak flows recorded in 1909, given as 252,000 ML/d and 195,140 ML/d for the RWC and DELWP data sets respectively. Discussions with residents of Bridgewater suggest that the 1909 flood was similar in magnitude to that observed in January 2011. It is known that the January 2011 peak flow was approximately 195,000 ML/d, suggesting that the data provided by RWC is too high. This further indicates that the DELWP data set is likely a more realistic representation of flows.

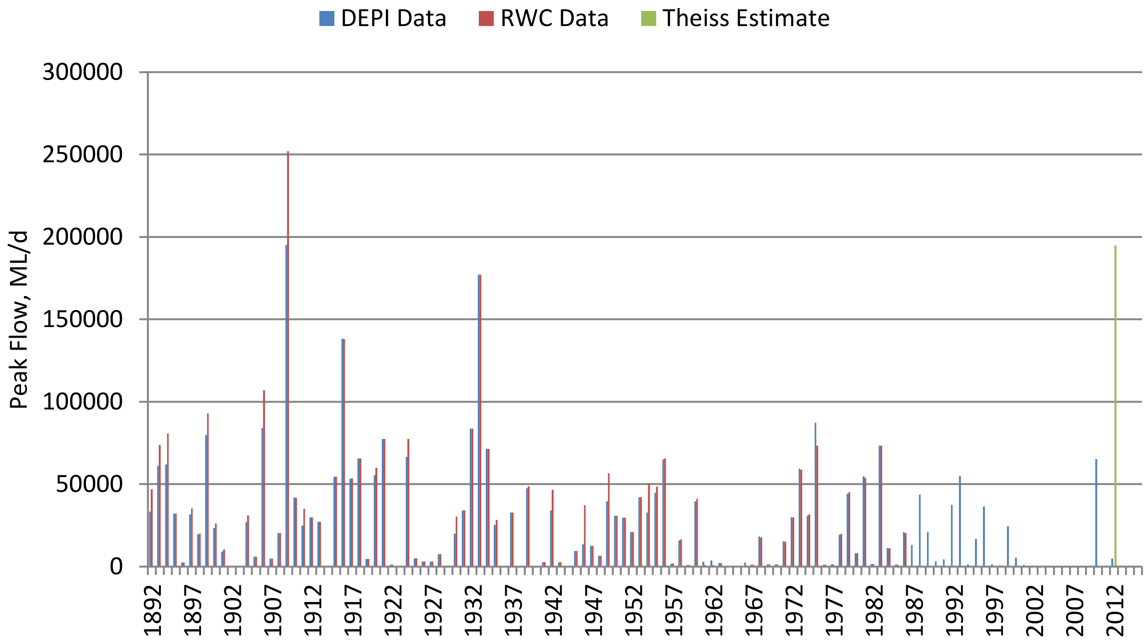


Figure 2-8 Annual maximum flow in the Loddon River at Laanecoorie (gauge # 407203)

It should be noted that the peak estimated flow during the January 2011 flood was approximately 195,000 ML/d, which is slightly beyond the extrapolated rating curve, as seen in Figure 2-9.

Further, the tail gauge was damaged to the point of being non-operational during the January 2011 flood event. The last streamflow recorded at the gauge was at 91,000 ML/d, taken at 12:30 pm on 12th January. A comparison of this data with the head gauge shows major discrepancies in the timing of the recorded flows, as seen in **Error! Reference source not found.**, with both gauges showing the same trend, but the Laanecoorie tail gauge reading approximately 24 hours earlier. This discrepancy in timing has only been observed in the January 2011 flood event. Timing of the peak flow recorded at the Laanecoorie head gauge is aligned with anecdotal evidence.

[3] RWC (1990). *Victorian Surface Water Information to 1987, Volume 5,* Rural Water Commission of Victoria.

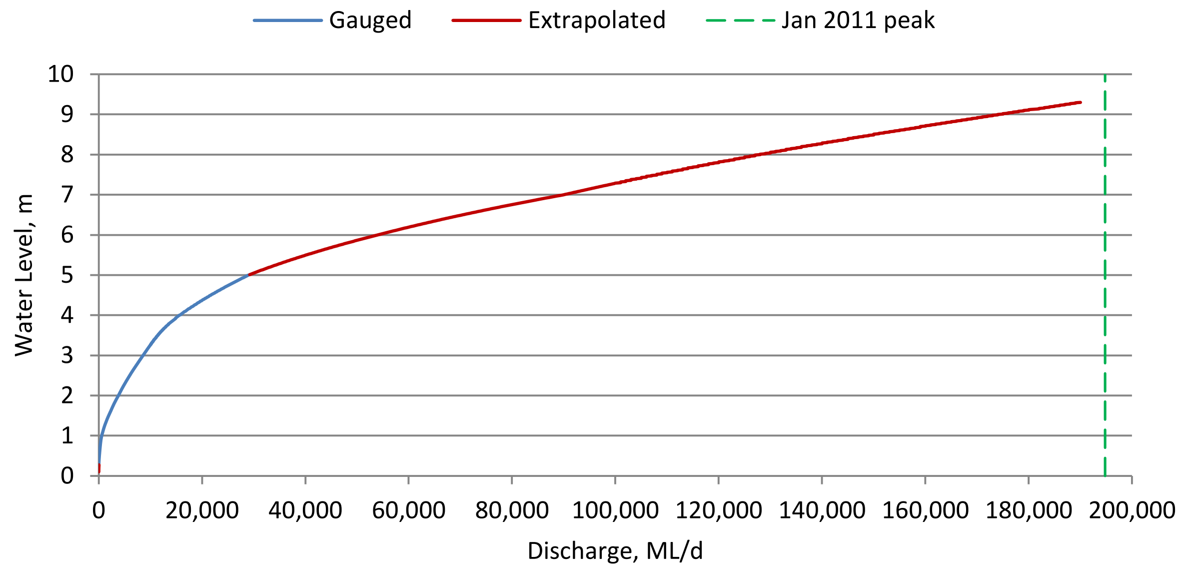


Figure 2-9 **Laanecoorie gauge rating curve and reported peak Jan 2011 flow**

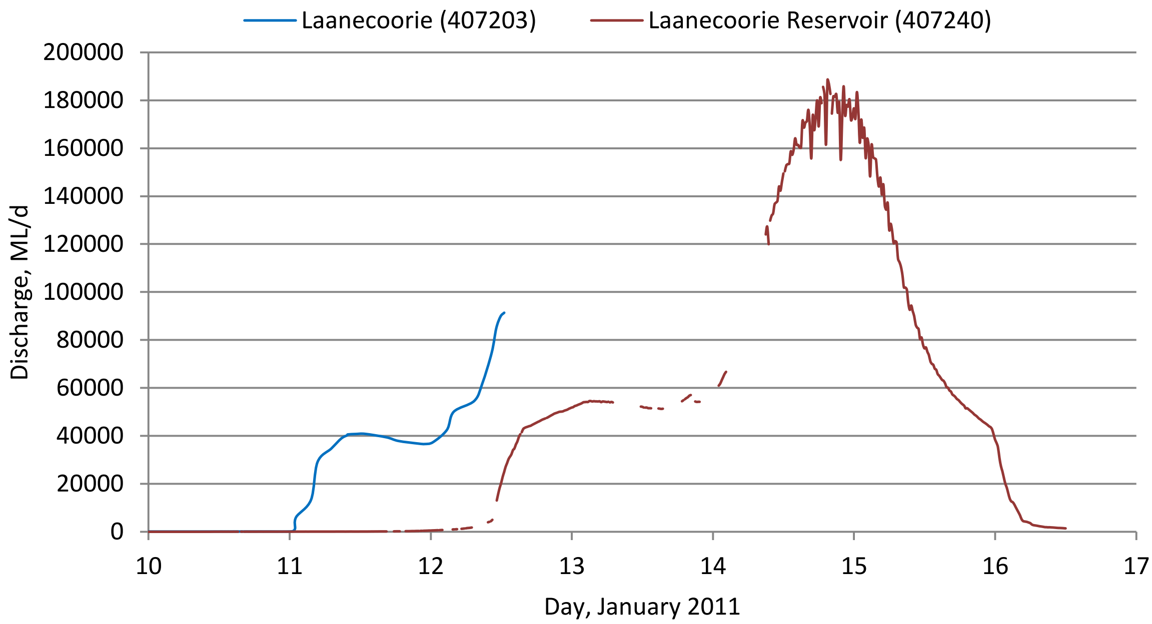


Figure 2-10 **Recorded streamflow at Laanecoorie gauges during the January 2011 flood event**

2.2.2 Rainfall

An extensive network of daily rainfall gauges exist across the wider study area, as well as three pluviographs, as shown in Figure 2-11.

Many of the daily rainfall stations have long term (more than 100 years) of rainfall records. A list of the daily rainfall stations and the rainfall totals for three historical events (which will be used in the calibration phase) is shown in Table 2-1.

The Cairn Curran Reservoir is considered to be the most suitable pluviograph for use in this study due to its proximity to the centre of the catchment. It will be used to develop the temporal pattern of rainfall for calibration events. The 6 minute rainfall totals and cumulative rainfall depths recorded at this gauge during the January 2011 event can be seen in Figure 2-12.

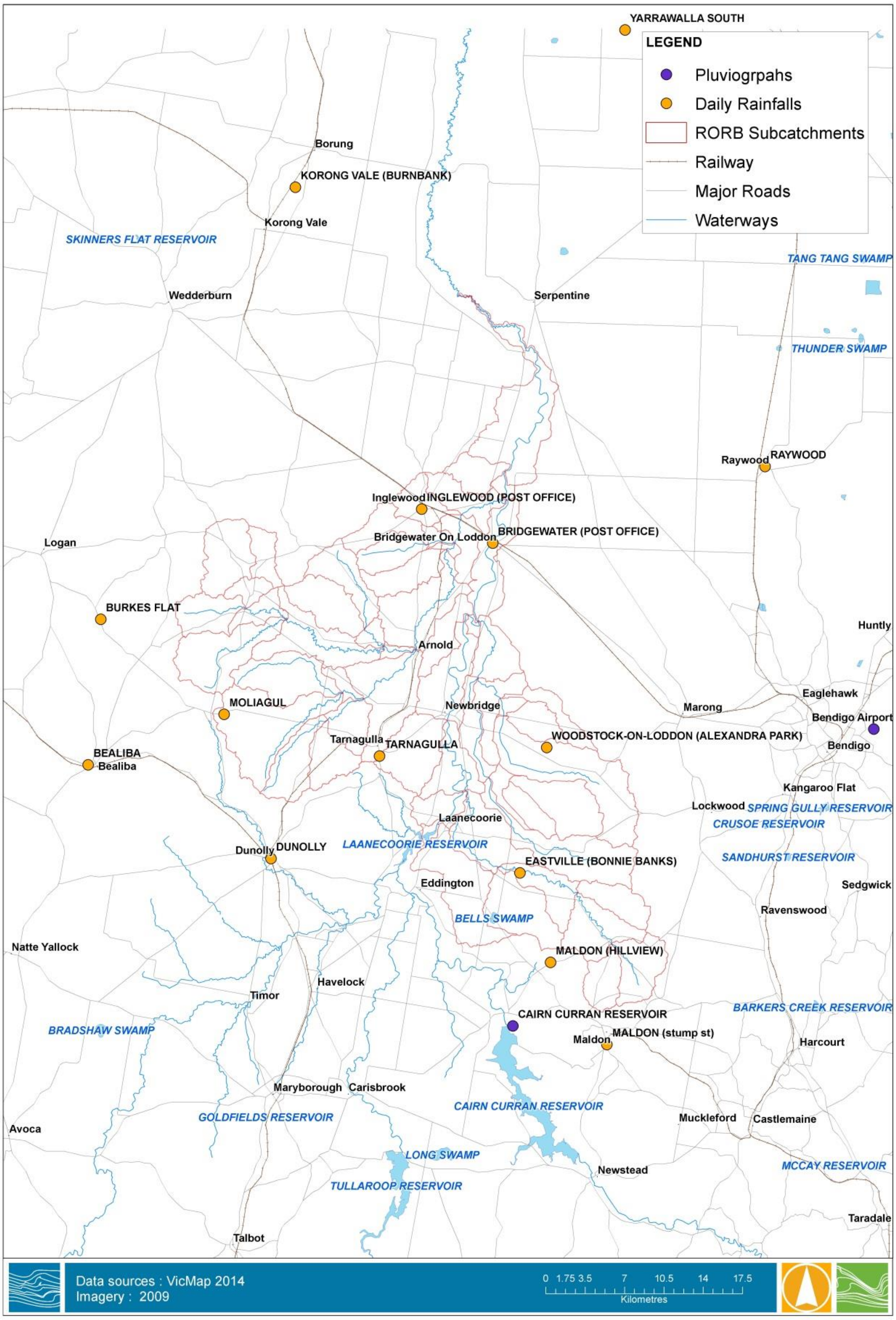


Figure 2-11 Rainfall Gauge Locations

Table 2-1 Daily Rainfall Data Records

Station ID	Station Name	Start Date	End Date	Jan-2011	Sep-2010	Sep-1983
81002	BEALIBA	1891	2014	206.8	77	64.7
81006	BURKES FLAT	1902	2014	178.8	69.4	81.2
81020	INGLEWOOD (POST OFFICE)	1880	2014	218.2	49.6	57.8
81041	RAYWOOD	1898	2014	162.8	42.2	64.4
81058	BRIDGEWATER (POST OFFICE)	1894	2014	207	43.2	55.2
81085	DUNOLLY	1882	2014	216.5	85.2	75.6
81090	MOLIAGUL	1968	2014	228.9	86	108.4
81092	EASTVILLE (BONNIE BANKS)	1969	2014	182.1	47.6	84.6
81100	WOODSTOCK-ON-LODDON (ALEXANDRA PARK)	1970	2014	199.4	48.4	81.8
88009	CAIRN CURRAN RESERVOIR	1949	2014	194.2	39	59.1
88132	MALDON (HILLVIEW)	1972	2014	186.4	42	71
80027	KORONG VALE (BURNBANK)	1942	2014	197	31.2	53.2
80039	YARRAWALLA SOUTH	1886	2013	145	26	58.8
80067	CHARLTON DONALD St	1951	2014	178.6	49.4	54.6
81089	CAMPBELLS FOREST (YARRABERB)	1889	1990	NA	NA	57.6
80099	SERPENTINE LODDON VALLEY H'WAY	1969	2006	NA	NA	53
81091	GLENALBYN (BRENANAH)	1968	2007	NA	NA	80.6
80061	WEDDERBURN (POST OFFICE)	1882	2014	184	66	60.4
80009	ST ARNAUD (COONOOER BRIDGE)	1880	2014	214.6	92.8	67.4
80026	KORONG VALE (POST OFFICE)	1889	2000	NA	NA	49.6
80029	LAKE MARMAL	1881	2014	179.3	32.8	45.6
80002	BOORT (POSTAL AGENCY)	1881	2014	202.8	22.2	48.6
80014	DURHAM OX	1937	2014	229	0	54
81003	BENDIGO PRISON	1863	1992	NA	NA	75.8
81026	LAANECOORIE WEIR	1892	2004	NA	NA	89.4

81047	TARNAGULLA	1888	2014	204	NA	79.4
81088	BIG HILL RESERVOIR	1878	1986	NA	NA	79.4
88118	HARCOURT	1968	2014	189.2	68.2	79.4
81123	Bendigo Airport	1991	2004	164	81.6	NA

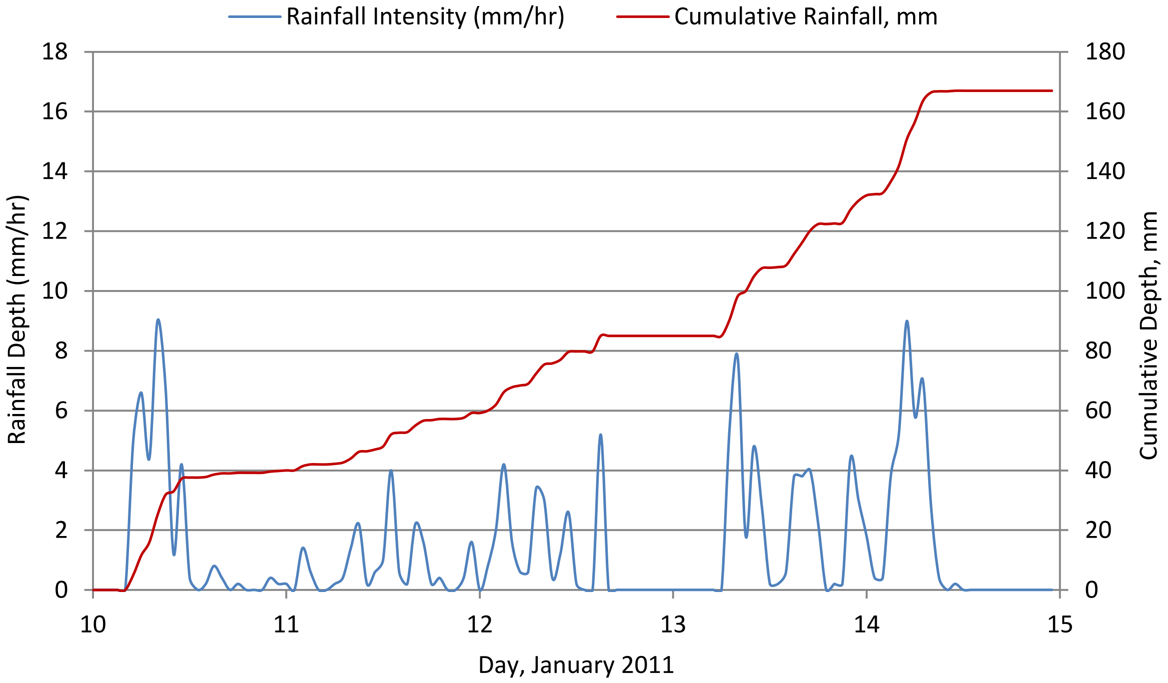


Figure 2-12 Cairn Curran Pluviograph Rainfall Temporal distribution January 2011

2.2.3 Storages

There are three major storages within the catchment upstream of Bridgewater: Cairn Curran Reservoir, Tullaroop Reservoir and Laanecoorie Reservoir, all maintained and operated by Goulburn-Murray Water (GMW).

The Tullaroop Reservoir is situated on Tullaroop Creek, a tributary of the Loddon River. It has a capacity of approximately 73,000 ML and is used as a storage supply for irrigators and a water supply for Maryborough. The tributary joins the Loddon River downstream of the Cairn Curran Reservoir at the Laanecoorie Reservoir.

The Cairn Curran Reservoir is a significant water storage, with a capacity of 147,000 ML over almost 2,000 ha. It is situated on the Loddon River proper and is used as a supply for irrigators.

The Laanecoorie Reservoir is downstream of both Cairn Curran and Tullaroop reservoirs and has a capacity of 8,000 ML. Despite its relatively small size, the Laanecoorie Reservoir is of significance for the Bridgewater Flood Study. Laanecoorie Reservoir is the last storage on the system before the Loddon River flows out over the lower floodplain. As it is gauged and captures the majority of the upper catchment it offers the opportunity to act as a flood warning location for the lower Loddon River floodplain.

By undertaking a flood frequency analysis on the outflow from Laanecoorie Reservoir, the need to assess joint probability flows from all reservoirs (which can be complex and less accurate) is negated for determining design flows.

The Laanecoorie Reservoir has a full supply level of 160.2 m AHD[4]. The primary spillway is a series of automatic flood gates, which become fully open at a water level of 160.81 m AHD. A secondary bywash spillway exists on the north-west side of the reservoir, with a crest level of 160.53 m AHD. It joins the Loddon River downstream of the main embankment. These two spillways can be seen in Figure 2-13 and Figure 2-14. Four 915 mm diameter pipes allow the release of low operating flows down the Loddon River.

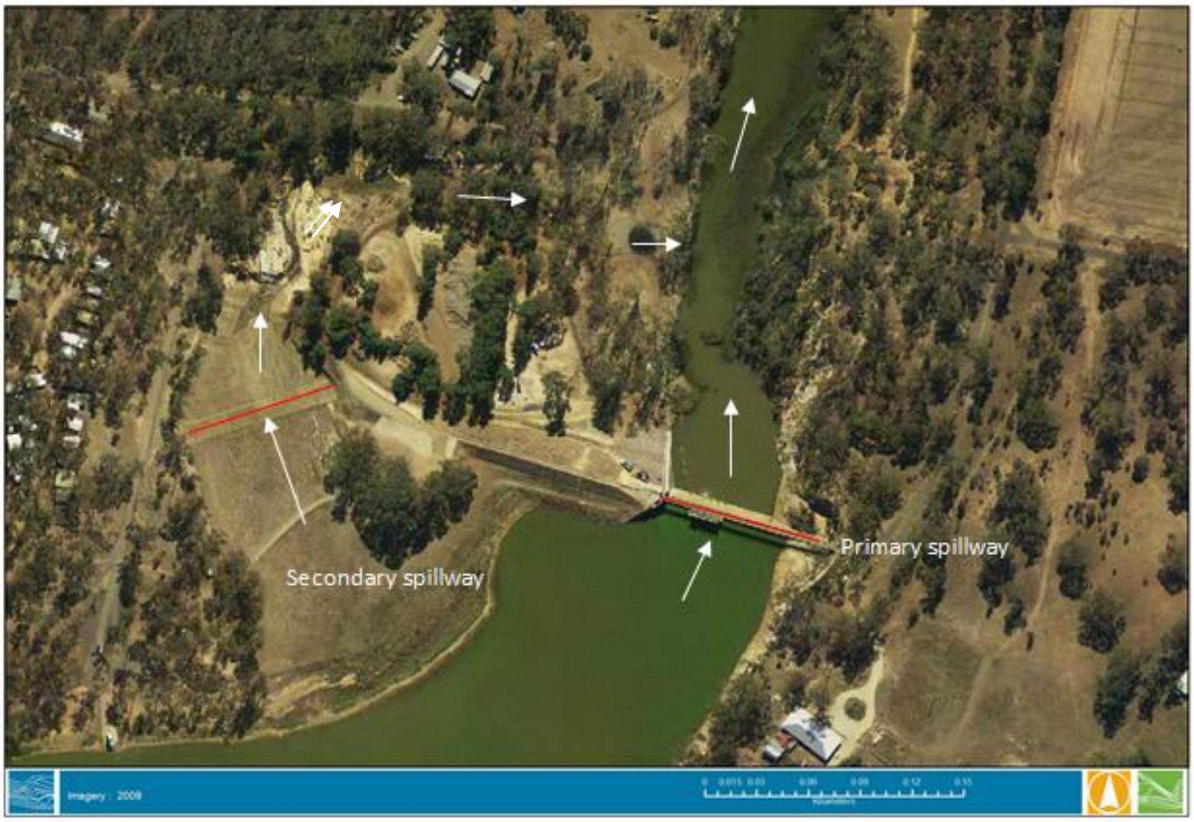


Figure 2-13 Laanecoorie Reservoir layout

[4] Sinclair Knight Merz (2012). *Laanecoorie Dam: Flood Hydrology Update and Construction Flood Risk.* Report for Goulburn-Murray Water.

Figure 2-14 Laanecoorie Reservoir during January 2011 flood (NCCMA)

2.3 Flood Records

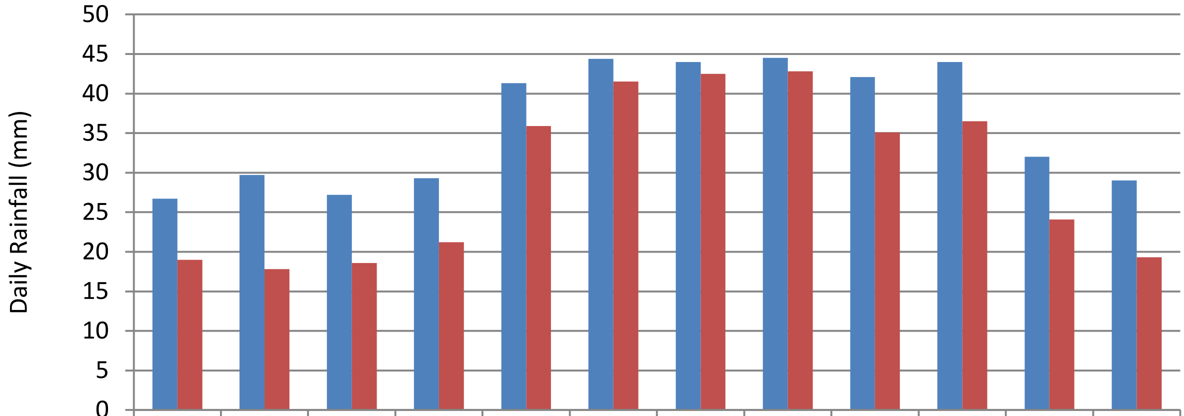
2.3.1 Historical Records

The township of Bridgewater has a long history of flooding and has been impacted by several large events. Historical records and anecdotal evidence indicates that major flood events occurred during the following months:

- August 1909 (the Laanecoorie reservoir was significantly damaged during a large storm event causing significant flooding throughout Bridgewater)
- September 1983
- September & December 2010
- January 2011 (considered the largest on record).

The recent January 2011 flood event is thought to be the largest flood event in living memory. Records indicate that flooding historically occurs over the spring/summer period, corresponding to periods of heavy rainfall as indicated by the Bureau of Meteorology (BoM) records.

Figure 2-15 shows the mean and median monthly rainfall totals for the entire length of record at the Bridgewater Post Office rainfall gauge. The wettest months are largely in winter with June, July and August recording the highest mean values.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	26.7	29.7	27.2	29.3	41.3	44.4	44	44.5	42.1	44	32	29
Median	19	17.8	18.6	21.2	35.9	41.5	42.5	42.8	35.1	36.5	24.1	19.3

Figure 2-15 BOM historical rainfall records for the Bridgewater Post Office rainfall gauge (BOM, 2014)

2.3.2 Recent Flood Events

Victoria was subject to a number of widespread heavy rainfall and flood events between late 2010 and early 2011. Bridgewater was impacted during this period with severe flooding in September and December 2010 and January 2011.

Figure 2-16 shows historic water levels in the Laanecoorie Reservoir, with large peaks identifying the September/December 2010 and January 2011 floods.

The flood in September 1983 has also been ear-marked as a potential flood to use for calibration, due to the availability of data. The Victorian Flood Database maintains records of observed flood heights for the 1983, 2010 and 2011 flood events, as seen in Figure 2-17.

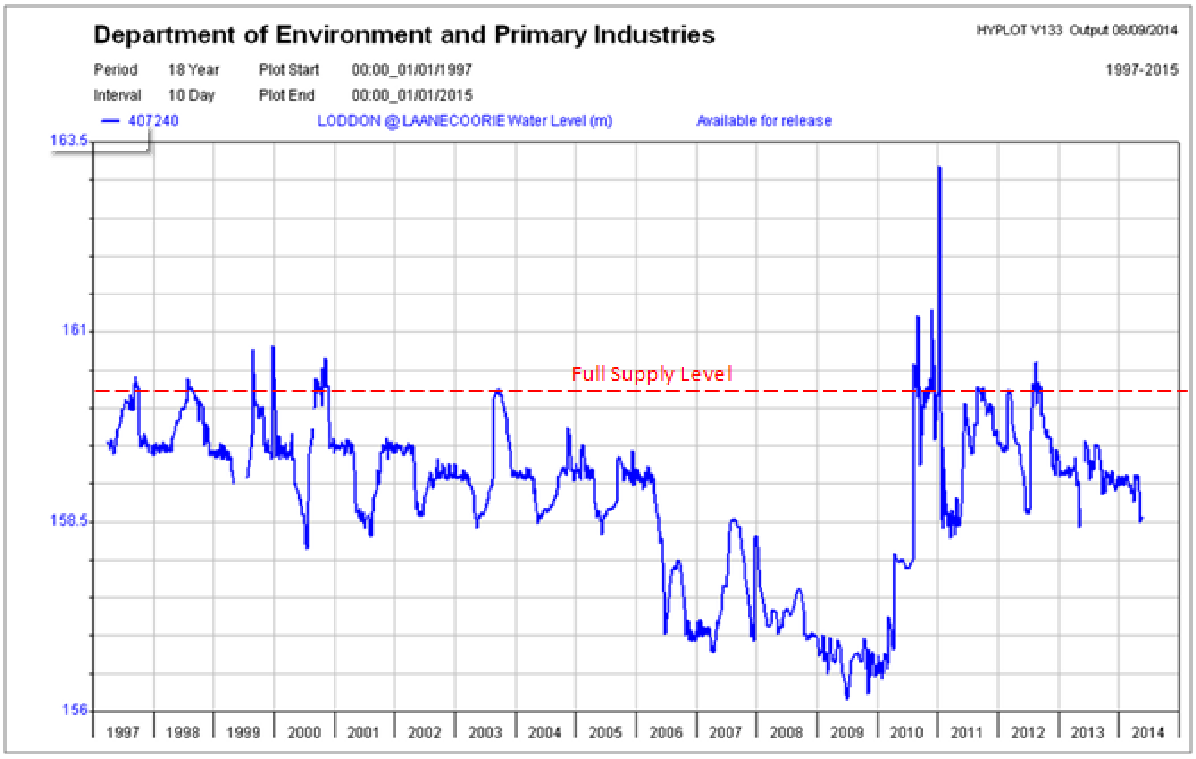


Figure 2-16 Laanecoorie Reservoir historic water levels (DEPI, 2014)

Figure 2-17 Historic Flood Heights from the Victorian Flood Database

September 1983

The September 1983 flood event was a result of heavy rainfall in the catchment falling over a 4 day period, during which Bridgewater received 49 mm, with a maximum daily rainfall total of over 20 mm. The upper catchment received significantly more rainfall, with totals greater than 100 mm recorded.

There is little anecdotal information regarding the flood; however gauge data is available at the Laanecoorie and Serpentine gauges. In addition, eight historic spot flood heights are available through the Victorian Flood Database.

September 2010

Flooding in September 2010 was a result of over 43 mm rainfall on the already wet catchment over a four day period, with the majority of rain (39 mm) falling on the 4th September. Discharge from the Laanecoorie Reservoir peaked at 700 ML/d on the 5th September after a rapid rise from zero flow the preceding day.

Eight flood heights within the township of Bridgewater were surveyed following the September 2010 floods.

Streamflow data for the event is available from the Laanecoorie Reservoir and Serpentine gauges.

January 2011

The January 2011 event is the largest flood event on record. Rainfall at Bridgewater exceeded the mean monthly average by approximately 700%, and equalled about 50% of the average annual rainfall[5].

The heavy rainfall, coupled with storages that were already full from flooding in late 2010 led to large flood flows in the river. Floodwaters overtopped the banks of the Loddon River within Bridgewater itself, and broke away upstream, proceeding to flow down the main street of the town, as seen in Figure 2-18.

Historical records and anecdotal evidence indicate the floodwaters peaked within the township at 4am on Saturday the 15th January.

The Laanecoorie gauge, downstream of the reservoir, was damaged during this flood event, and is therefore unusable for calibration to the January 2011 event. Goulburn Murray Water has provided calculated streamflow for this gauge, based on a theoretical rating curve developed by Thiess for the event. A peak discharge of 194,700 ML/d was estimated in the evening of Friday 14th January.

Five flood heights were surveyed within the township of Bridgewater. These, along with the considerable volume of anecdotal evidence and flood photos provided by the steering committee and community members, provides a good basis for understanding flooding in Bridgewater and calibration of the hydraulic model.

[5] Bureau of Meteorology (2014) < http://www.bom.gov.au/climate/data/index.shtml>

Figure 2-18 Bridgewater flooding 14 January 2011 (Bendigo Advertiser)

2.4 Physical Features

2.4.1 Topographic and Physical Survey

Three sources of topographic/survey data were obtained for this study:

- Vicmap Elevation DEM 20 m grid (a raster representation of Victoria's elevation at a 20 m grid resolution as provided by DELWP).
- Various LiDAR datasets (provided by the North Central CMA on the 11 February 2013).
- Field and bathymetric survey, commissioned by NCCMA.

Digital Elevation Model (DEM)

A 20 m grid digital elevation model (DEM) of the entire State was trimmed to the catchment boundary for this study. This dataset was provided by DELWP. This dataset was used as the basis for stream identification and catchment delineation in ArcGIS for the hydrological modelling.

Light Detection and Ranging (LiDAR)

LiDAR data for the region was made available from the North Central CMA and consisted of a number of datasets:

- North Central CMA Floodplains LiDAR at a 1 m grid resolution
  - NCCMA Floodplains, flown between 1st December 2009 and 22nd August 2011
  - Bendigo Floodplains, flown between 22nd April 2010 and 15th May 2010
  - NCCMA Stage 2 Floodplains, flown between 31st July and 23rd August 2011
- Index of Stream Condition (ISC) Rivers LiDAR at a 1 m grid resolution. Covering all major rivers and riparian zones within the NCCMA area, flown between 1st December 2009 and 9th October 2010.

Both the Floodplains and ISC Rivers dataset had a 1 m grid resolution with the Floodplains dataset extending further across the model area. The extent of the two datasets is shown in Figure 2-19. There was generally good agreement between the two datasets, and no adjustments were required. The two datasets were merged into a single Digital Elevation Model (DEM), taking the minimum value where the datasets overlapped, to give the best channel representation.

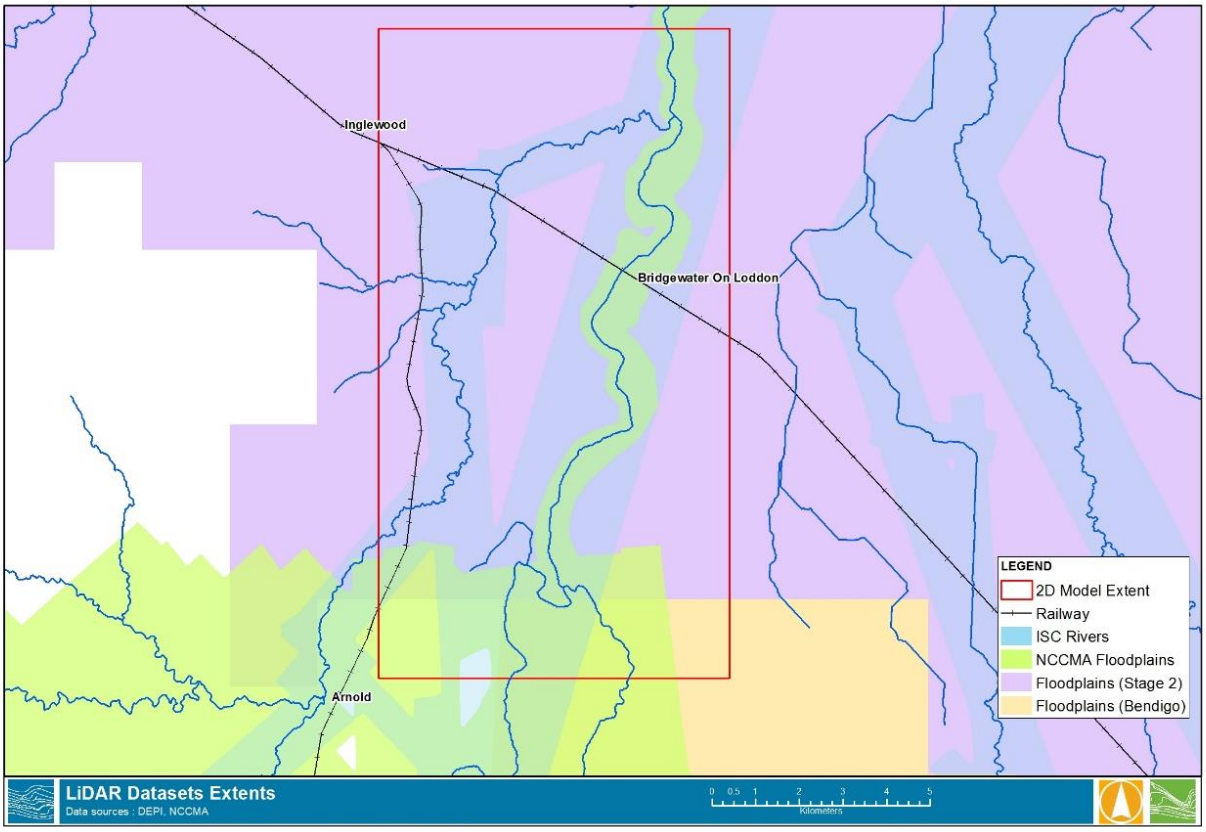


Figure 2-19 Extent of LiDAR sets used in the construction of DTM

A comparison between LiDAR elevations and surveyed elevations was made to determine the consistency of the data. Two 100 m transects, with points surveyed at 10 m intervals were taken along Lyndhurst Street and Brougham Street in Bridgewater.

As seen in Figure 2-20 and Figure 2-21, the LiDAR elevations were consistently lower than the surveyed elevations. The differences are summarised in Table 2-2. The differences are small and within the specified vertical accuracy of LiDAR (+/- 0.1 m), and therefore the LiDAR is considered to be sufficiently accurate. No corrections to the data set were required.

Table 2-2 Statistics for difference between LiDAR and surveyed elevations (m)

Statistic	Transect 1 (Lyndhurst St)	Transect 2 (Brougham St)
Minimum	-0.055	-0.065
Maximum	-0.015	-0.035
Mean	-0.035	-0.050
Standard Deviation	0.014	0.010

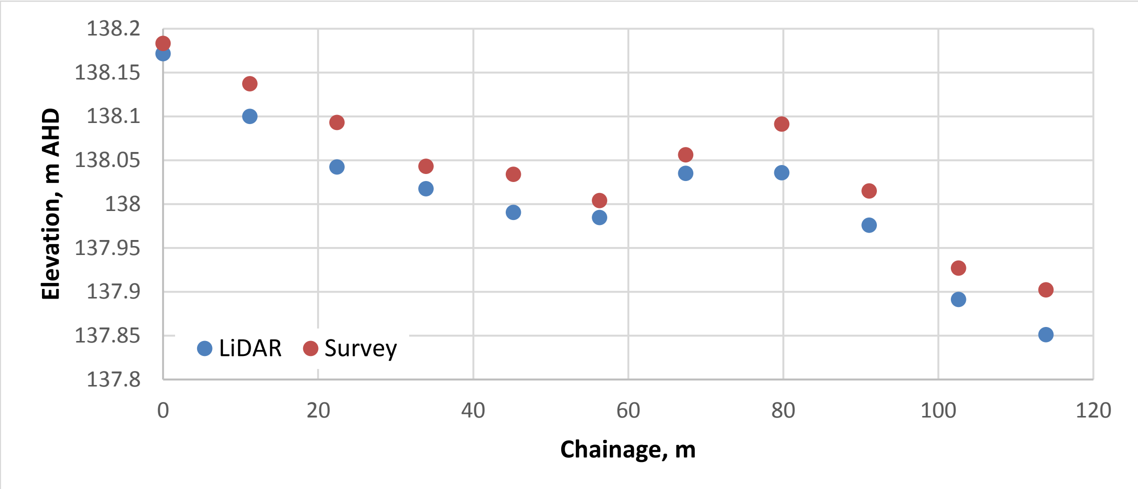


Figure 2-20 LiDAR and survey elevations along Lyndhurst Street

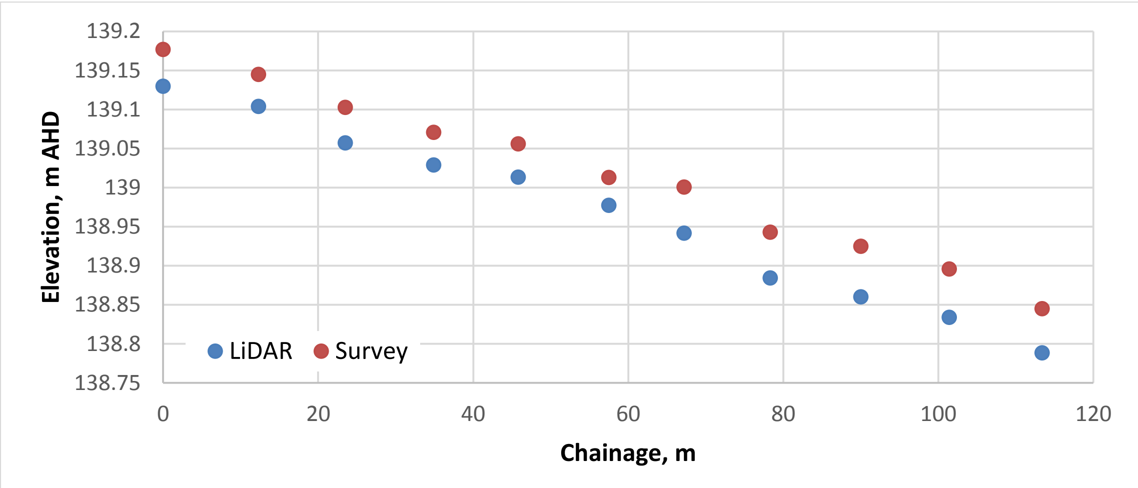


Figure 2-21 LiDAR and survey elevations along Brougham Street

Field and Bathymetric Survey

Throughout the main waterway (Loddon River), the LiDAR does not provide an adequate representation of the waterway capacity due to the inability of LiDAR to penetrate the water surface. Therefore using bathymetric survey, the DEM was manually adjusted to provide a better representation of the waterway.

Field survey, undertaken by Price Merrett for this study, included:

- 6 bathymetric cross sections of the Loddon River;
- Details of 6 key hydraulic structures within the catchment; and
- Two 100 m long transects, for LiDAR verification (as noted above).

The locations of these features are shown in Figure 2-22.

Floor level survey for all properties (commercial and residential) within an extrapolated extent based on flooding in January 2011 was captured by Think Spatial. This included 219 buildings.

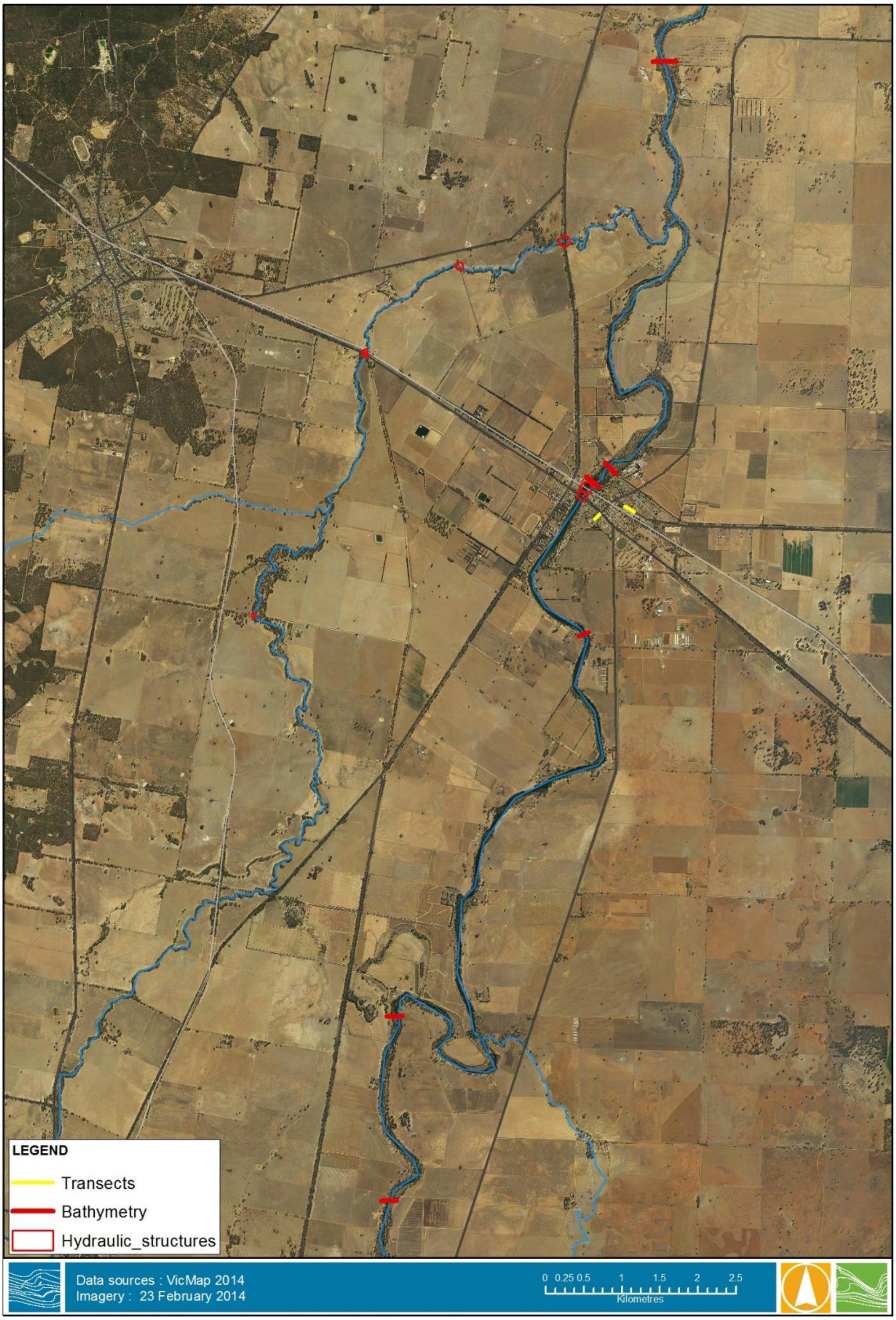


Figure 2-22 Locations of field survey taken

2.5 Site Visit

A site visit was undertaken by Water Technology on the 4th September 2014 of the township of Bridgewater, Inglewood, Newbridge and Laanecoorie and parts of the surrounding floodplain.

During the site visit a number of photos were taken of the Loddon River and its tributaries, drainage structures (including the Laanecoorie Reservoir) and floodplain features. A selection of these photos, showing key hydraulic features are presented in Appendix A. The study team visited Bridgewater many times for Steering Committee meetings and each time additional sites were visited to gain a better understanding of the site and to validate observations from the hydraulic modelling. On some of the site visits local landholders were approached to ask questions of the observed flood behaviour in their location. This uncovered invaluable local information that was used during the calibration of the hydraulic model, which lead to an improvement in the final flood mapping produced in this study.

2.6 Local Knowledge

A request for anecdotal evidence was provided to members of the steering committee through a short survey which specifically asked for details of the January 2011 flood event. Requests were made for any data available for the 1983, 2010 and 2011 flood events, including photography, timing of flood levels, peak water marks (with reference to a known location) etc. The responses received indicated the flood levels peaked in Bridgewater at 4 am on Saturday, 15th January. Furthermore, it was apparent that the community felt that there was insufficient warning and communication from authorities throughout the flood event.

A community consultation drop-in session was held on the 7th November 2014, providing an opportunity for interested members of the public to discuss their experiences of flooding in Bridgewater and comment on the development of the study. A number of residents were able to provide flood related information (in the form of photos, anecdotes and records). There was general agreement with the draft modelled flood extent for the January 2011 flood event which was presented at the drop-in session. It was again evident that flood warning and communication with flood response authorities is a general concern for the residents of Bridgewater.

Some anecdotal evidence was found in historic newspaper articles describing flooding in the area. This data was useful for model calibration and validation.

Local landholders between the Loddon River and Bullabul Creek were door knocked to seek further understanding of the flow directions during the January event, as some conflicting anecdotes were reported during the drop-in session. Both landholders independently reported the same information that water first flowed from Bullabul Creek, breaking out of the creek and onto the surrounding floodplain, flowing in a northerly direction before the Loddon River broke out of bank and flowed toward Bullabul Creek. The water over the floodplain from the Loddon River was very slow moving.

3. HYDROLOGY ANALYSIS

The dominant flood mechanism at Bridgewater is via flooding from the Loddon River. Upstream of Bridgewater the Loddon River catchment has significant storages at Cairn Curran, Tullaroop and Laanecoorie Reservoirs. The local catchment runoff also feeds a number of small creeks and tributaries to the Loddon River downstream of Laanecoorie Reservoir, including Bullabul Creek. These two flow components have been assessed using flood frequency analysis and runoff-routing modelling respectively.

Preliminary hydraulic modelling has been incorporated in the development and verification of the hydrology, to demonstrate breakouts of flow from the Loddon River across the wider floodplain, which occurs in large flood events and was observed in the January 2011 flood event.

3.1 Hydrology Approach

The hydrology of the Bridgewater catchment is complex as a result of significant breakouts from the Loddon River across the wider floodplain and the subsequent interaction between flows from the Loddon River and the Bullabul Creek. A combined approach to the hydrology has therefore been adopted for this study, incorporating RORB modelling, flood frequency analysis and hydraulic modelling to improve understanding of the river breakout flows.

The following steps detail the hydrological approach that was used:

1. Breakout flow locations and proportions from the Loddon River were determined through the development of a Graphical Processing Unit (GPU) TUFLOW hydraulic model of the Loddon River and floodplain from Laanecoorie to Waranga Channel (60-70 km reach of river). The model was run for a range of steady state flows.
2. Construction of a RORB model for the Bullabul Creek and local catchment, with flows from Laanecoorie Reservoir included as an inflow hydrograph, and flow splits represented by diversions.
3. Calibration of the RORB model to historic events of January 2011, September 2010 and September 1983.
4. Flood frequency analysis of both peak flows and flood volumes for the Loddon River at Laanecoorie.
5. Determination of design hydrographs for Loddon River at Laanecoorie based on representative historic flood hydrograph shape.
6. Determination of design hydrographs for catchment flows from RORB.
7. Assessment of the timing between start of rainfall, peak rainfall and peak Loddon flow at Laanecoorie to align design flood frequency hydrographs with RORB design catchment modelling.

3.2 Loddon River Breakouts

In some flood events the Loddon River breaks away from its usual course and spreads onto the wider floodplain. These breakout flows result in several of the gauges located on the Loddon River misrepresenting the actual flow of the floodplain, only measuring the small component of flow in the channel, and missing the majority of flow on the floodplain bypassing the gauges.

A hydraulic model of the Loddon River floodplain from Laanecoorie Reservoir to the Waranga Channel was developed to assess the location and magnitude of these breakouts over the 60-70 km stretch of river. This led to a far greater understanding of the broader floodplain and assisted in better scoping the detailed hydraulic model. This modelling confirmed the significant breakout from the Loddon River to the Bullabul Creek upstream of Bridgewater, resulting in the study team extending the hydraulic modelling area to upstream of the breakout so this could be included in detail.

3.2.1 Rapid Hydraulic Model Construction

A regional scale hydraulic model was constructed in TUFLOW and run on the computer's graphics processing unit (GPU). The GPU version of TUFLOW uses a fully conservative finite volume formulation which uses an adaptive timestep approach. This approach has undergone significant verification testing and benchmarking throughout the UK and is recommended for broad scale rapid flood modelling. Benchmarking and testing of the GPU version by Water Technology has generally found that the GPU model leads to slightly different water levels and requires some adjustments to Manning's roughness to reproduce results from the classic versions of MIKE FLOOD and TUFLOW. Modelling in this way, though potentially not as accurate as the central processing unit (CPU), allows for rapid simulations of extensive areas which would otherwise be time prohibitive. Due to the faster run times it can also allow higher resolution 2D grids to be modelled of large areas.

Model Version

The TUFLOW model was constructed using MapInfo V12.0 and text editing software. The single precision version of the latest TUFLOW release (as of November 2014) was used for all simulations (TUFLOW Version: 2013-12-AC-iSP-w64).

2D Grid Size and Topography

A single 2D domain was used with a grid size of 25 m, with elevations derived from DELWP's 20 m DEM data set. The extent of the hydraulic model can be seen in Figure 3-1. Polyline Z Shapes were used to represent the Calder Highway and The Western Waranga Main Channel within the topography, key hydraulic structures that would otherwise not have been captured at the 25 m grid resolution.

Roughness

A Manning's n roughness coefficient of 0.04 was applied across the model domain. This value is representative of farmland and open grassed areas/parks[6].

Boundary Conditions

A single inflow boundary was created at the location of the Laanecoorie gauge to represent flow in the Loddon River. No other inflows were incorporated into the model. This model was developed to represent breakout flows originating from the Loddon River and subsequent breakout floodplain flows, as such the outcomes of this modelling does not discriminate between tributary flows and Loddon River flows. Tributary inflows were therefore not included.

An outflow level-time (H-T) boundary extended along the entire northern edge of the model domain, approximately 1 km downstream of the Waranga Western Main Channel. The H-T relationship was based on the general topography at the downstream end of the model such that it did not impact on water levels within the key study area.

[6] Chow, 1959 *Open-Channel Hydraulics*. McGraw-Hill, New York.

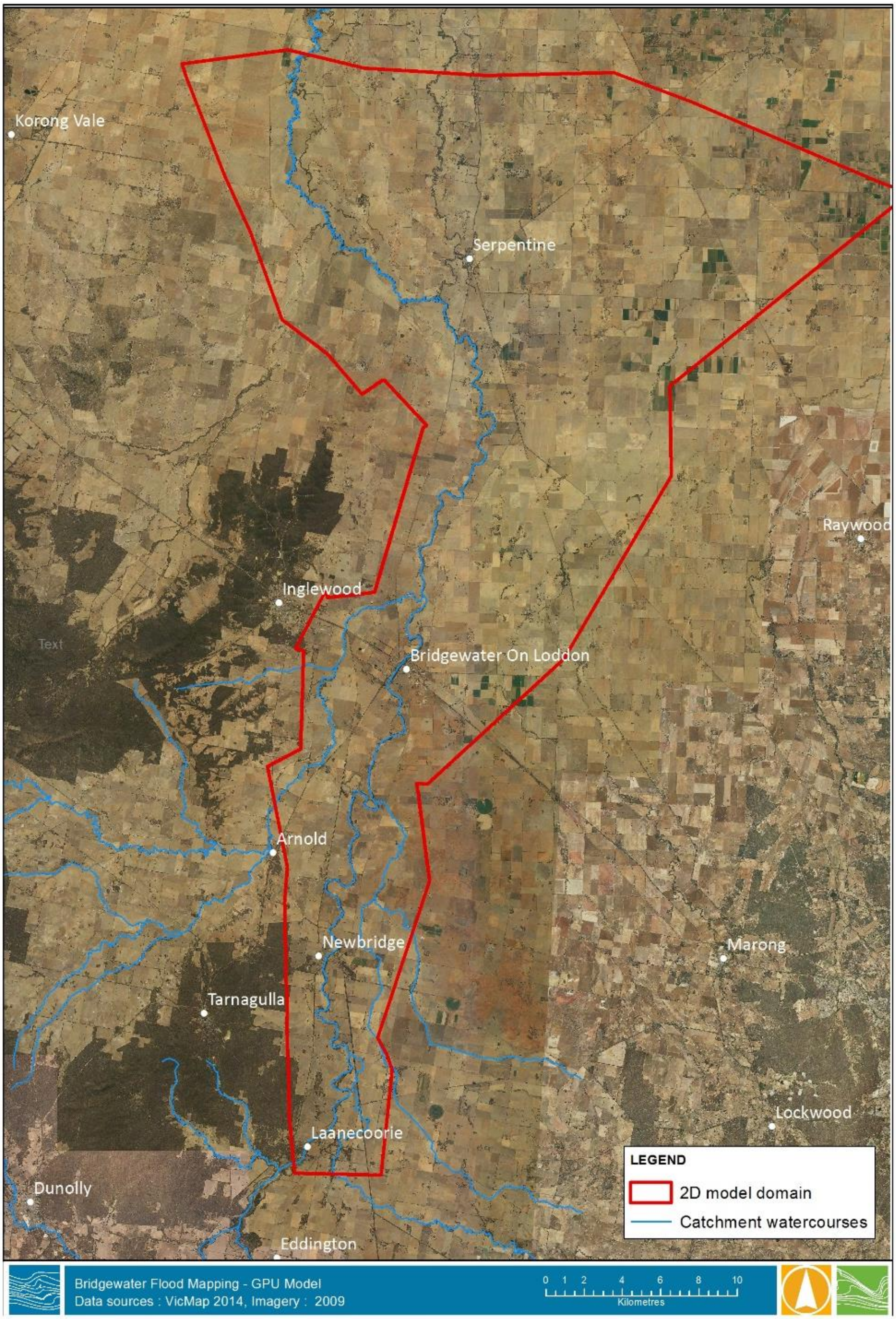


Figure 3-1 Catchment scale hydraulic model

3.2.2 Rapid Hydraulic Model Verification

The January 2011 flood event was used to verify the hydraulic model. Streamflow data developed by GMW based on a theoretical rating curve specific to the flood event was used as an inflow hydrograph to the model to represent flow in the Loddon River at Laanecoorie.

A constant water level boundary of 103.0 m AHD was set across the model domain approximately 1 km downstream of the Waranga Western Main Channel. Due to a lack of available data, this water level was chosen by trial and error, ensuring that the boundary conditions were not impacting on the model results by either producing a backwater effect or excessively pulling water from the model. The boundary is sufficiently downstream of the area of interest to have negligible impact on the extent upstream of Serpentine.

Figure 3-2 shows the breakout locations from the Loddon River for the January 2011 event verification run. There is significant breakout from the Loddon River midway between Newbridge and Bridgewater where aerial photography indicates evidence of a paleo-channel. Flood flows break out predominately to the north-west and join the Bullabul Creek, re-entering the Loddon River downstream of Bridgewater. It is understood that North Central CMA had heard of this breakout but had no information other than anecdotal evidence to support it. This behaviour has since been verified by numerous local community members. This behaviour is further supported by the fact that North Central CMA enlisted university students to do a preliminary hydraulic assessment of Bridgewater, and they found that in order to reproduce flood levels in Bridgewater the Loddon River flows had to be reduced by something in the order of 60% of that of the Laanecoorie flows.

Within the Bridgewater Township there is a breakout from the east bank of the Loddon River, slightly south of Peppercorn Lane, as seen in Figure 3-3. Water flows north-east across farm land on the western side of Bridgewater-Maldon Road, heading north west as it meets the Calder Highway and flowing through the centre of the town back to the Loddon River. This breakout location and the direction of flow is consistent with anecdotal evidence provided by the Steering Committee and local residents.

Floodwaters are largely contained within bank immediately downstream of the confluence of the Loddon River and Bullabul Creek for approximately 2.5 km before breaking out across the wider floodplain. At Serpentine, floodwaters from the Loddon River span a width of almost 20 km.

Modelled flood depths were compared to surveyed flood levels at five points in Bridgewater, as seen in Figure 3-4. The difference in water surface elevations, summarised in Table 3-1, indicate that the hydraulic model is, on average, underestimating depths by 0.24 m. This result is fit for purpose, given the purpose of this rapid modelling and the fact that the model does not include flow contributions from Bullabul Creek and the local catchment, and is only preliminary modelling assuming constant roughness, with no detailed representation of structures, etc. It confirms that the hydraulic model is behaving as expected, and within reasonable accuracy given the coarseness of the input data and the relatively short amount of time that was invested into the development of this coarse model.

Table 3-1 Surveyed and modelled flood levels for January 2011 flood event

Survey mark	Modelled level, m AHD	Surveyed level, m AHD	Difference, m
LODF208	135.29	136.42	-1.13
LODF209	136.35	136.92	-0.57
LODF211	138.17	138.17	0.00
LODF207	138.42	138.13	0.29
LODF210	138.98	138.77	0.21
		AVERAGE DIFFERENCE	**-0.24**

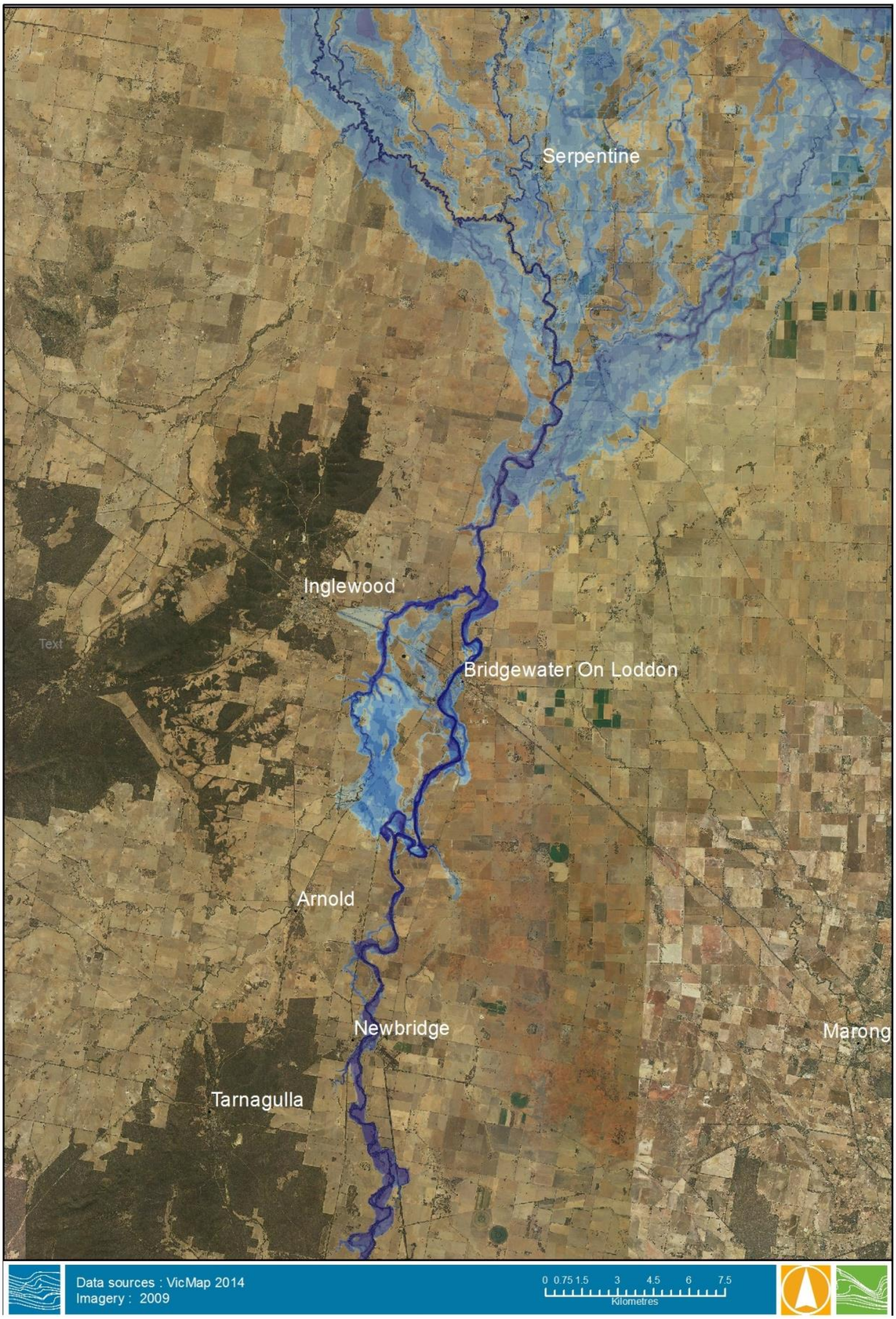


Figure 3-2 Modelled breakout flows from the Loddon River (whole model extent)

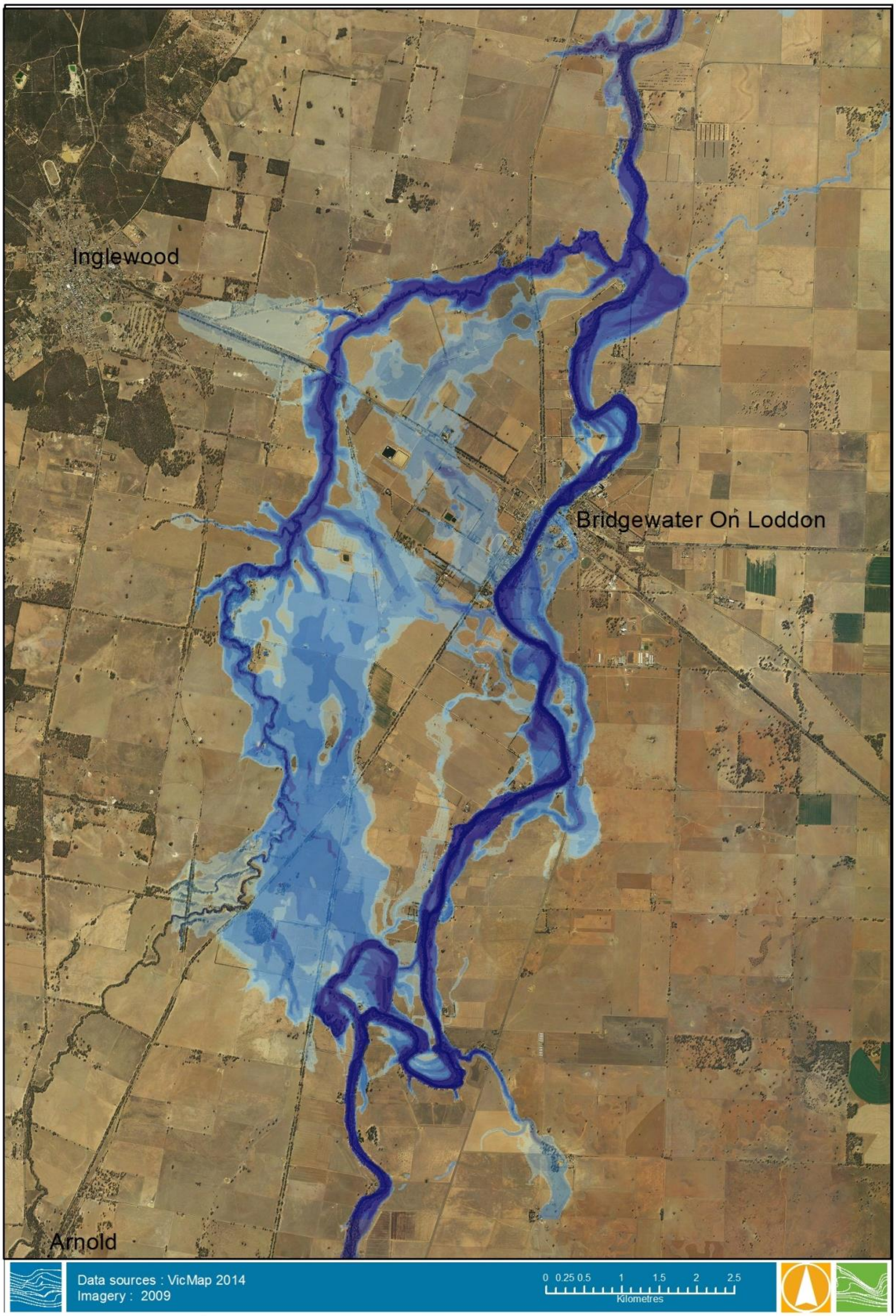


Figure 3-3 Modelled breakout flows from the Loddon River surrounding Bridgewater

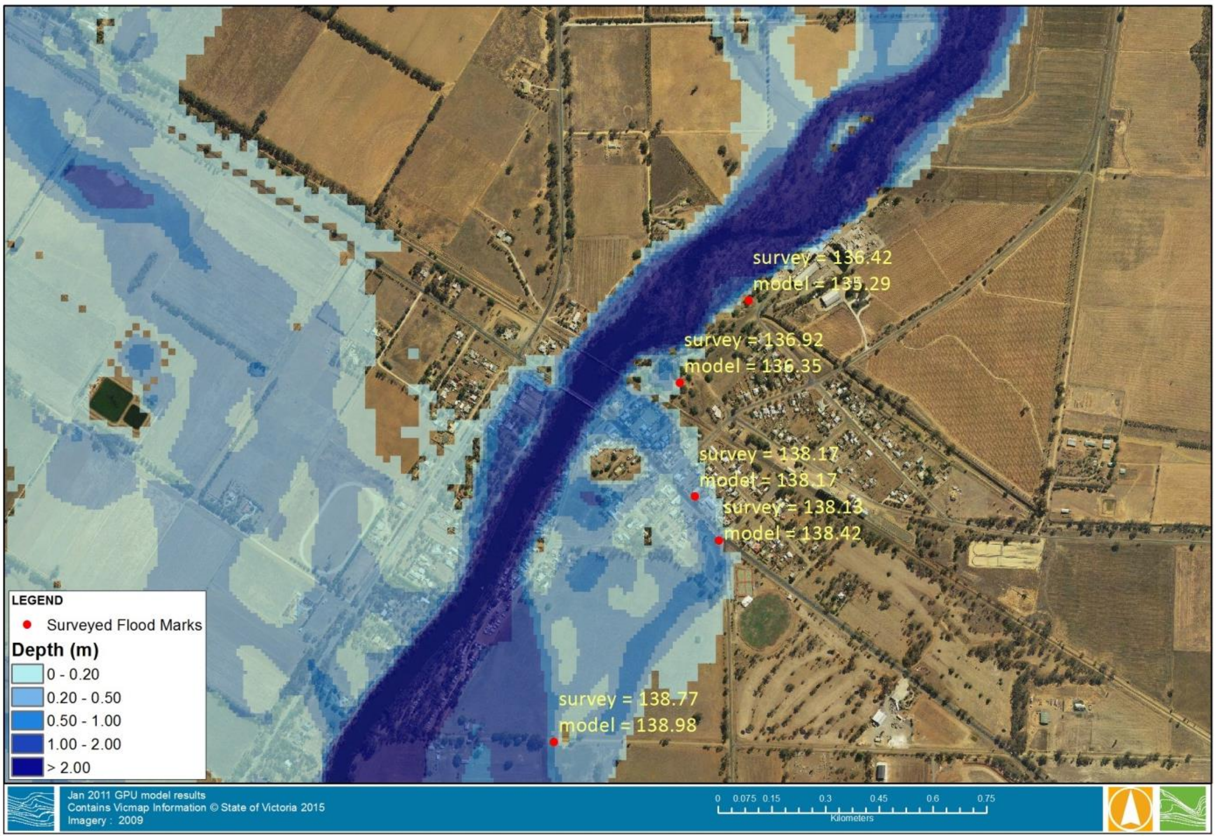


Figure 3-4 Surveyed and modelled flood heights for Jan 2011 flood event

3.2.3 Rapid Hydraulic Model Results

The model was run with steady state inflows for flows between 10,000 and 100,000 ML/d (in 10,000 ML/d increments). Each flow rate was run for 2 weeks of simulation time to ensure steady state conditions were reached.

Figure 3-5 shows the resulting flood extents upstream of Bridgewater for four flow thresholds. Flow remains largely within the banks of the Loddon for flows up to 50,000 ML/d, with water only breaking out into the paleo-channel and across some farmland to the east.

At flows of 70,000 ML/d, the Loddon River begins to break out to the north-west towards Bullabul Creek. By 80,000 ML/d the Loddon has broken out to the west at three locations, with three distinct flow paths forming. It is at 80,000 ML/d that water begins to breakout near Peppercorn Lane, flowing towards the Calder Highway.

Based on the location of these breakout flows a revised extent was proposed for the detailed hydraulic model. This extent can be seen in Figure 3-5 along with the original study area. Expanding the hydraulic model extent has allowed modelling of the interactions between Loddon River breakout flows and Bullabul Creek flows. This allows the Loddon River flow from RORB to be entered as an inflow boundary upstream of the breakout, with the detailed hydraulic model controlling the flow split between river and floodplain.

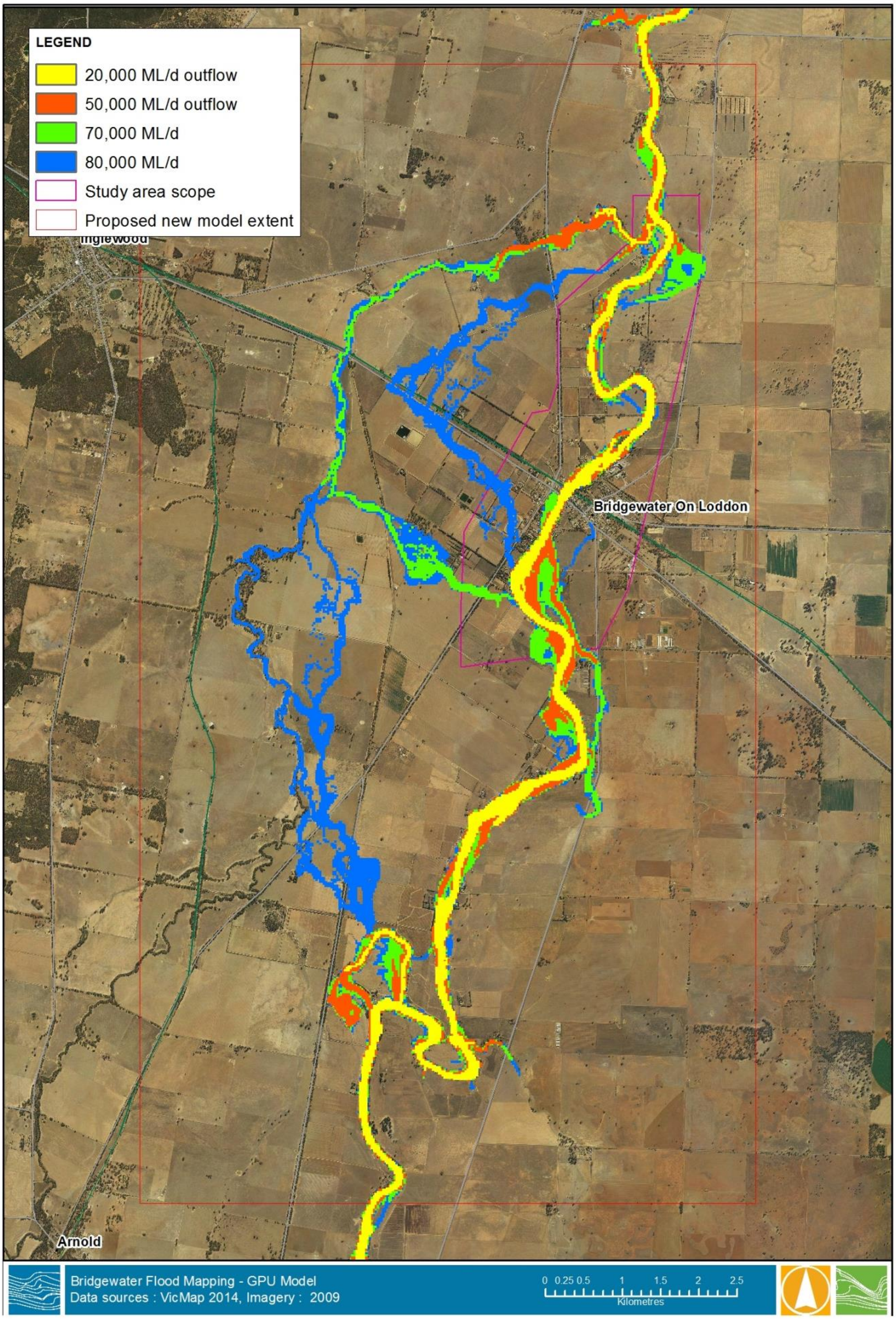


Figure 3-5 Flood extents for various Loddon River flows

The results from this hydraulic model have also allowed investigation into the proportion of flow splits across the catchment. Flow hydrographs were extracted at a number of locations within the model to determine the amount of break out flow from the Loddon River for each of the inflow rates.

While there was significant flooding across the wider floodplain at Serpentine, flows in the Loddon River at the Serpentine Weir gauge were within bank, resulting in a distinct flow path. This delineation allowed for the development of a flow-split relationship, with flow passing the Serpentine gauge as a function of total flow in the Loddon River at a point upstream of any breakouts. This flow-split relationship is summarised in Table 3-2. The results indicate the Loddon River has a capacity of approximately 21,000 ML/d at Serpentine, with the majority of the flow breaking away to the north through Serpentine Creek and other anabranches.

Table 3-2 Flow diversions from the Loddon River upstream of Serpentine

Total flow in Loddon (ML/d)	Flow passing Serpentine gauge (ML/d)	Flow diverted (breakouts) (ML/d)
10,000	10,000	0
20,000	20,000	0
30,000	21,000	9,000
40,000	21,000	19,000
50,000	21,000	29,000
60,000	21,000	39,000
70,000	21,000	49,000
80,000	21,000	59,000
90,000	21,000	69,000
100,000	21,000	79,000
140,000	21,000	119,000
190,000	21,000	169,000
260,000	30,000	230,000

3.3 RORB Model Construction

A hydrological model of the catchment was developed for the purpose of estimating historic flood flows for calibration and design flows from the local catchment. These flows were used in conjunction with design flows from Laanecoorie Reservoir, as determined by Flood Frequency Analysis (FFA), as boundary conditions in the hydraulic model. The rainfall-runoff program RORB (Version 6) was used for this study.

RORB is a non-linear rainfall runoff and streamflow routing model for calculation of flow hydrographs in drainage and stream networks. The model requires catchments to be divided into subareas which are connected by a series of conceptual storages and reaches. Design storm rainfall is input to the centroid of each subarea. Specific losses are then deducted, and the excess routed through the reach network.

A new RORB hydrological model was developed using MiRORB (MapInfo RORB tools). The following methodology was applied to construct the RORB model:

- Delineation of the Loddon River and Bullabul Creek catchment area between the Laanecoorie Reservoir outlet and upstream of the Serpentine Weir;
- Division of the catchment into subareas based on the site's topography and required hydrograph print (result) locations;
- Construction of the RORB model using appropriately selected parameters including reach types, fraction impervious values and rainfall information;
- Loddon River inflow hydrograph at the Laanecoorie Reservoir outlet adopted from the gauge record and FFA for design peak flow.
- Calibrate the model parameters to the selected historical flood events with respect to timing and peak flows.
- Develop design flow estimates using appropriate design parameters.
- Compare RORB design estimates to other alternative methods for verification.

3.3.1 Model Structure

Sub-areas

The RORB model was constructed using MiRORB (MapInfo RORB tools), RORB GUI and RORBWIN V6.15. A catchment boundary was delineated from the 20 m VicMap Elevation Digital Terrain Model (DTM) of the area. Sub-area boundaries were delineated using ARC Hydro and revised as necessary to allow flows to be extracted at the points of interest. The RORB model was delineated into 45 sub-areas. Figure 3-6 shows the RORB sub area delineation for the catchment. The RORB model did not include the catchment upstream of the Laanecoorie Reservoir as streamflow data was available at this point for input directly into RORB in the form of an input hydrograph.

The RORB model covered a catchment area of 1,067 km^2 and included the catchments of Bullabul Creek, Little Creek and Murphy Creek, as well as the local catchment of the Loddon River downstream of Laanecoorie reservoir.

Reach types

Reach types were set to be consistent with land use across that catchment. Five different reach types are available in RORB (1 = natural, 2 = excavated & unlined, 3 = lined channel or pipe, 4 = drowned reach, 5 = dummy reach). All reaches were set to natural, representative of the open grassed areas and natural waterways in the catchment.

Sub-area nodes

Nodes were placed at areas of interest (i.e. at the streamflow gauge at Laanecoorie Reservoir, confluence of Bullabul Creek and Loddon River) as well as the junction of any two reaches. Nodes were then connected by RORB reaches, each representing the length, slope and reach type.

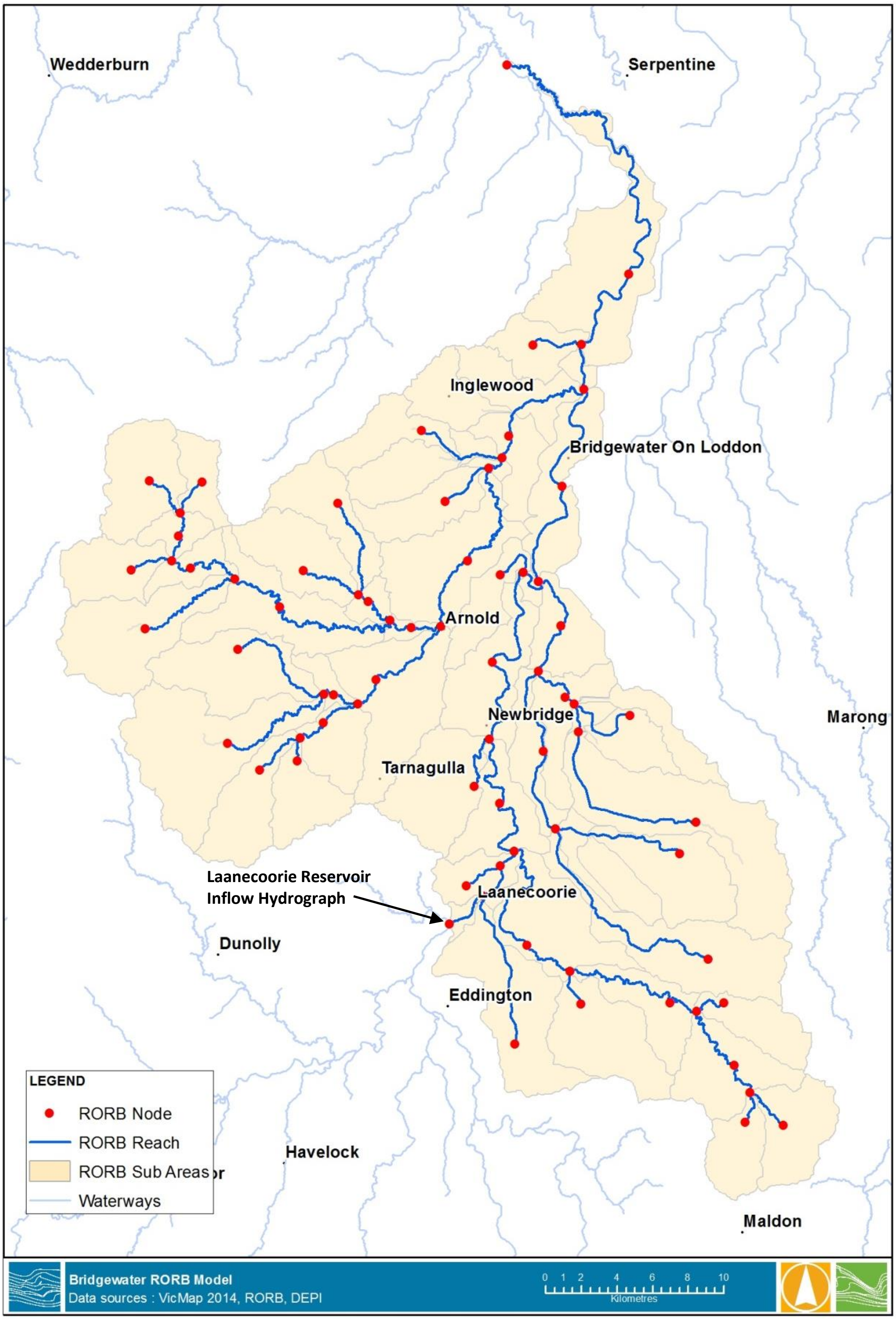


Figure 3-6 RORB Catchment Delineation

Inflows and Diversions

A hydrograph inflow location was incorporated into the RORB model to represent outflow from Laanecoorie Reservoir. The hydrograph for each calibration event was adopted from historical records at the Laanecoorie tail gauge.

An outflow/diversion structure was incorporated at a location upstream of the Serpentine weir to account for flow that breaks out from the Loddon River. The flow-diversion relationship was developed from the rapid hydraulic modelling results described in Table 3-2.

Model print locations

Flow hydrographs at the location of the Serpentine gauge were output for calibration. Hydrographs were also printed at locations where the flow rates could be used as inflow boundaries within the hydraulic model.

Fraction Impervious

Fraction impervious values were allocated to each of the RORB model subareas based on Land Use Zoning in the area (VicMap, 2015). The zones found within the catchment and the adopted fraction impervious values can be seen in Table 3-3. Each subarea was assigned an area-weighted average fraction impervious, to represent the catchment conditions. Much of the area within the RORB model is farming or public conservation area, generally with a low fraction impervious, as demonstrated in Figure 3-7.

Table 3-3 Land use zones and adopted fraction impervious[7]

Land Use Zone	Fraction Impervious
Business	0.9
Farming	0.1
Industrial	0.9
Low density residential & rural living	0.2
Medium density residential	0.45
High density residential	0.6
Mixed use	0.7
Public park and recreation	0.1
Public use – service and utility	0.05
Public use – education, health and community, transport, local government	0.7
Public use – cemetery, other	0.6
Major roads	0.7
Minor roads	0.6
Special use	0.6
Township	0.55

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

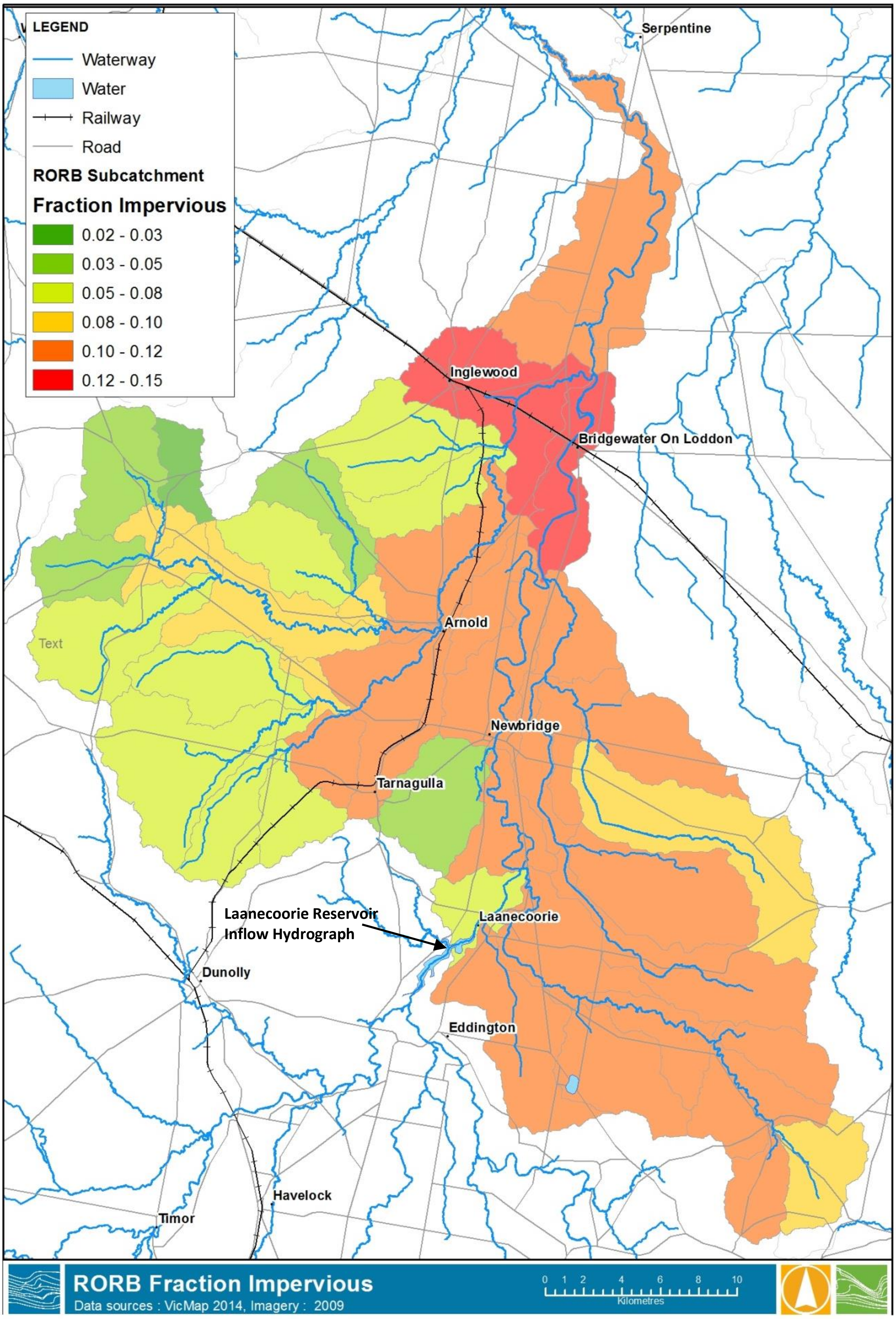


Figure 3-7 Area weighted fraction impervious across the RORB catchment

3.4 Model Calibration

The focus of the RORB model calibration was to determine the value of kc and loss values for the catchment, such that the model could suitably replicate output hydrographs at the Serpentine gauge and produce flood hydrographs that once run through the hydraulic model replicated observed flooding at Bridgewater.

The RORB model was calibrated to the recent large flood event of January 2011, as well as September 2010 and September 1983. These events were chosen due to the quality of information available for rainfall and streamflow, as well as the information pertinent to the hydraulic model calibration (i.e. surveyed flood marks). Furthermore, the January 2011 and September 2010 flood events were sufficiently recent to reflect the most up to date approximation of the current catchment conditions and behaviour.

3.4.1 Observed Rainfall

Both pluviograph and daily rainfall records are required for hydrological analysis. The daily rainfall gauges record the 24 hour rainfall total prior to 9am on any given day, whereas the pluviograph/tipping bucket rainfall gauges record rainfall on a continuous basis, measuring the rainfall intensity sub-daily.

Pluviograph data was used to define the temporal distribution of rainfall during an event while daily rainfall data provided the basis for the spatial distribution. Figure 3-8 shows the location of the daily rainfall and pluviograph stations in the region.

No pluviograph records were available within the RORB model catchment, however the Cairn Curran Reservoir, Bendigo Airport and Natte Yallock pluviograph stations are all within reasonable distance. Daily rainfall records were available for a number of stations spread out across the catchment.

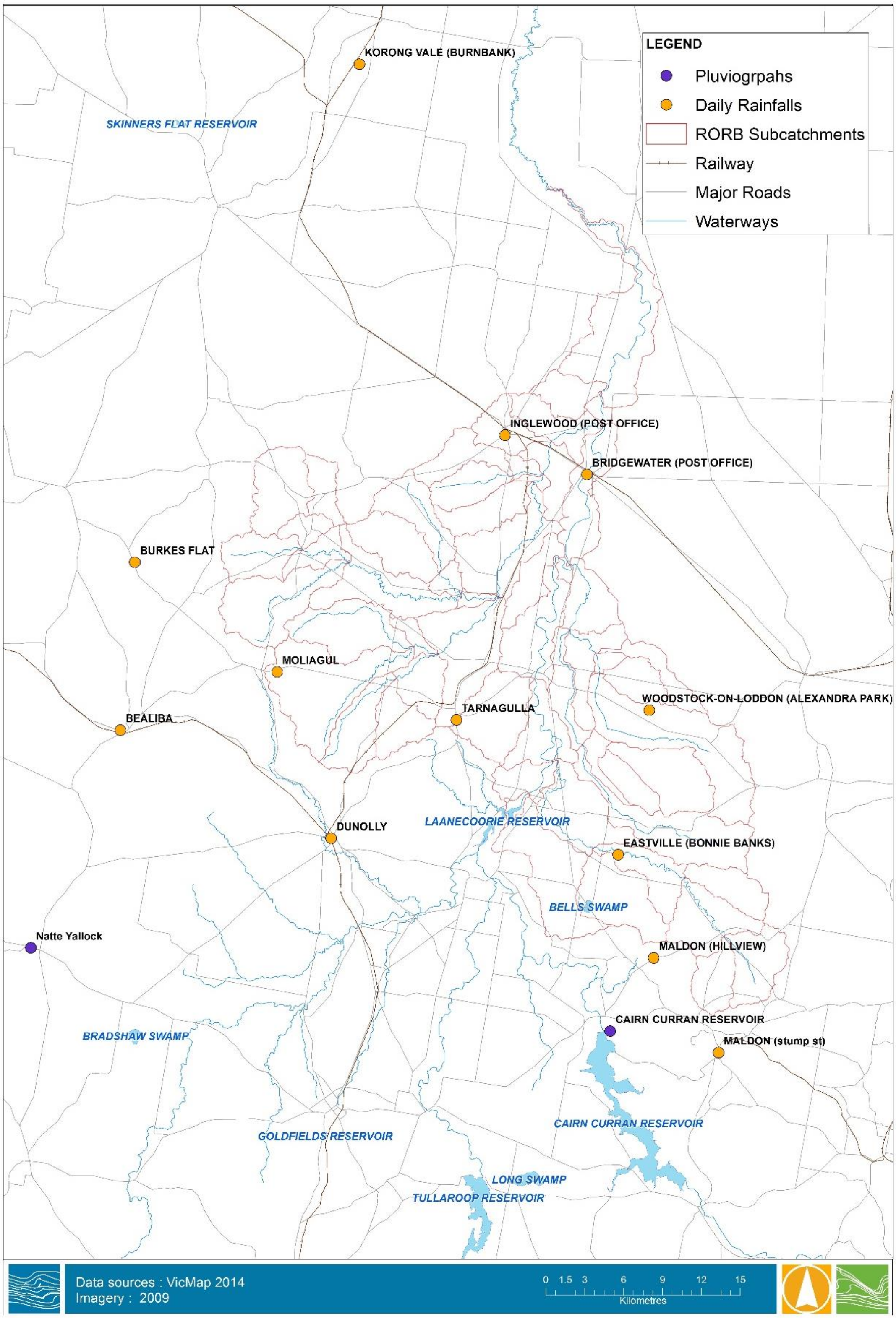


Figure 3-8 Rainfall Gauge Locations

Temporal patterns

Three pluviograph rainfall stations exist near the study area, including Cairn Curran Reservoir, Bendigo Airport and Natte Yallock, yet none within the delineated catchment. Of these, the Cairn Curran Reservoir pluviograph station is considered to be the most suitable data set for use in this study due to its proximity to the centre of the catchment.

January 2011

Rainfall data at each of the gauges was compared to test the variability of temporal patterns across the catchment. For the January 2011 event the three gauges followed a similar trend, with large bursts of rain occurring in the early morning of the 10th January, middle of the day on the 11th January and middle of the day on the 13th January. The temporal pattern at each of the pluviograph stations for the January 2011 storm event can be seen in Figure 3-9.

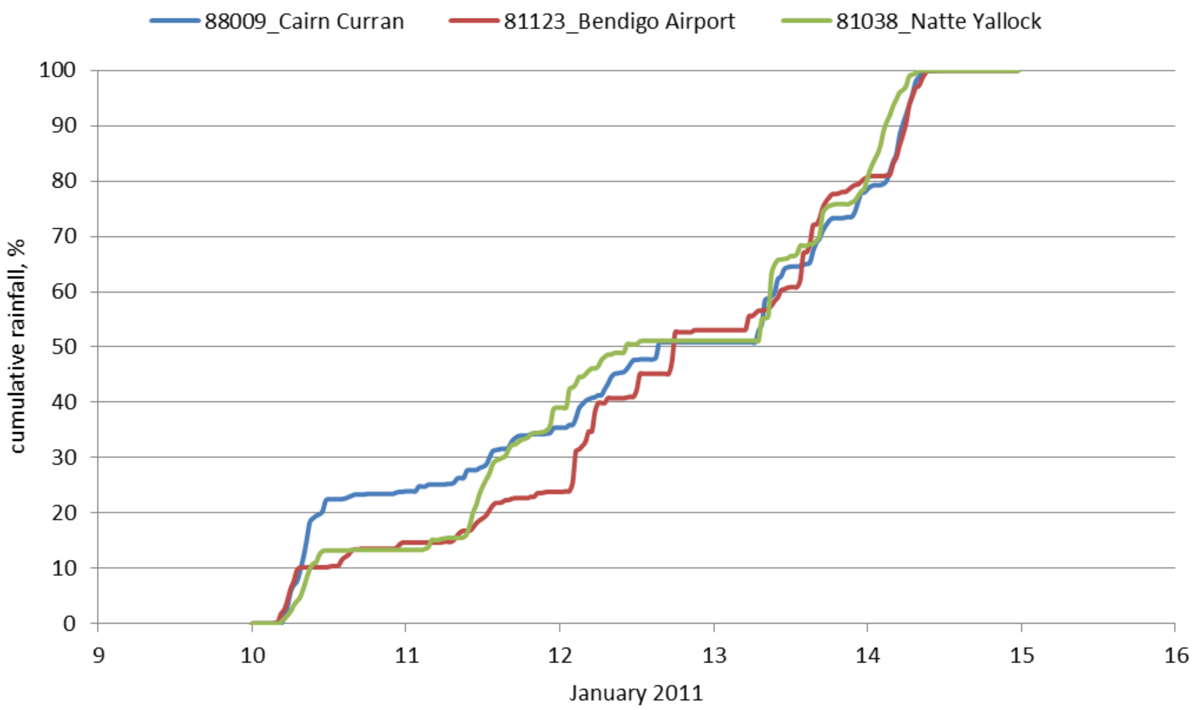


Figure 3-9 Cumulative rainfall at pluviograph stations near Bridgewater catchment for January 2011 storm event

The lack of significant variation in timing between stations suggests that adopting a single temporal pattern for the calibration process is appropriate. Hence, the Cairn Curran rainfall gauge has been adopted for calibration to the January 2011 flood event. The Cairn Curran rainfall gauge recorded a slightly larger percentage of rainfall in the first rainfall burst, but the remainder of the event showed a very similar temporal trend compared to the other two pluviography stations.

The January 2011 event is the largest flood event on record. Rainfall at Bridgewater exceeded the mean monthly average by approximately 700%, and equalled about 50% of the average annual rainfall[8].

A total of 167 mm fell over a five day period beginning on the 10th January. Rainfall over this period observed at the Cairn Curran gauge can be seen in Figure 3-10. Rainfall intensities peaked at 9 mm/hr.

[8] Bureau of Meteorology (2014) < http://www.bom.gov.au/climate/data/index.shtml>

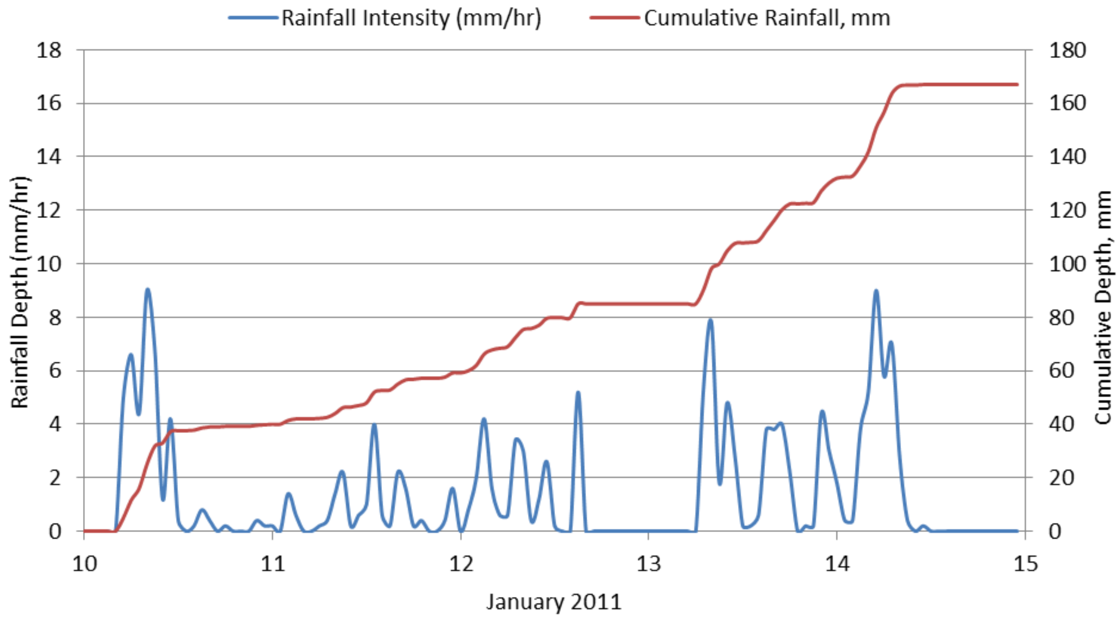


Figure 3-10 Temporal rainfall distribution at the Cairn Curran gauge for the January 2011 storm event

September 2010

Instantaneous rainfall data existed at only the Cairn Curran and Natte Yallock pluvio stations for the September 2010 flood event. The temporal pattern for these two gauges was very similar, and can be seen in Figure 3-11.

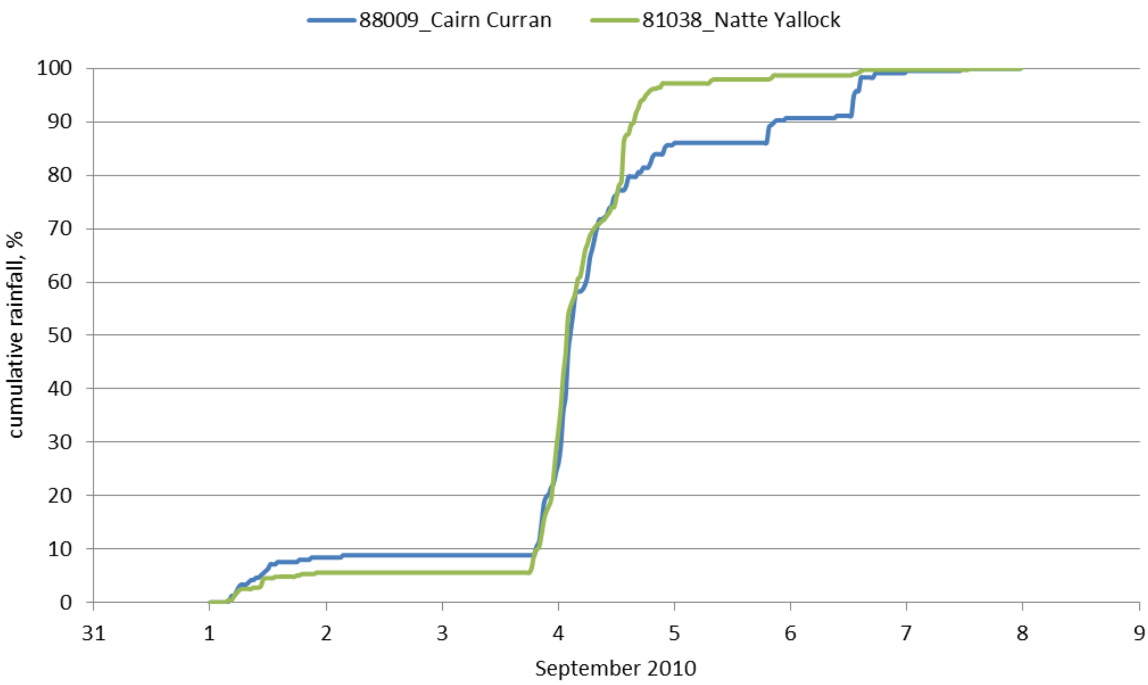


Figure 3-11 Cumulative rainfall at pluviograph stations near Bridgewater catchment for September 2010 storm event

Given the lack of significant variation in timing between the two stations a single temporal pattern for the calibration process was deemed appropriate. The Cairn Curran rainfall gauge was adopted for calibration to the September 2010 flood event.

Flooding in September 2010 was a result of over 43 mm rainfall on the already wet catchment over a four day period, with the majority of rain (39 mm) falling on the 4th September over a 13 hour period. The rainfall over this period observed at the Cairn Curran gauge can be seen in Figure 3-12. Rainfall intensities peaked at 3.8 mm/hr.

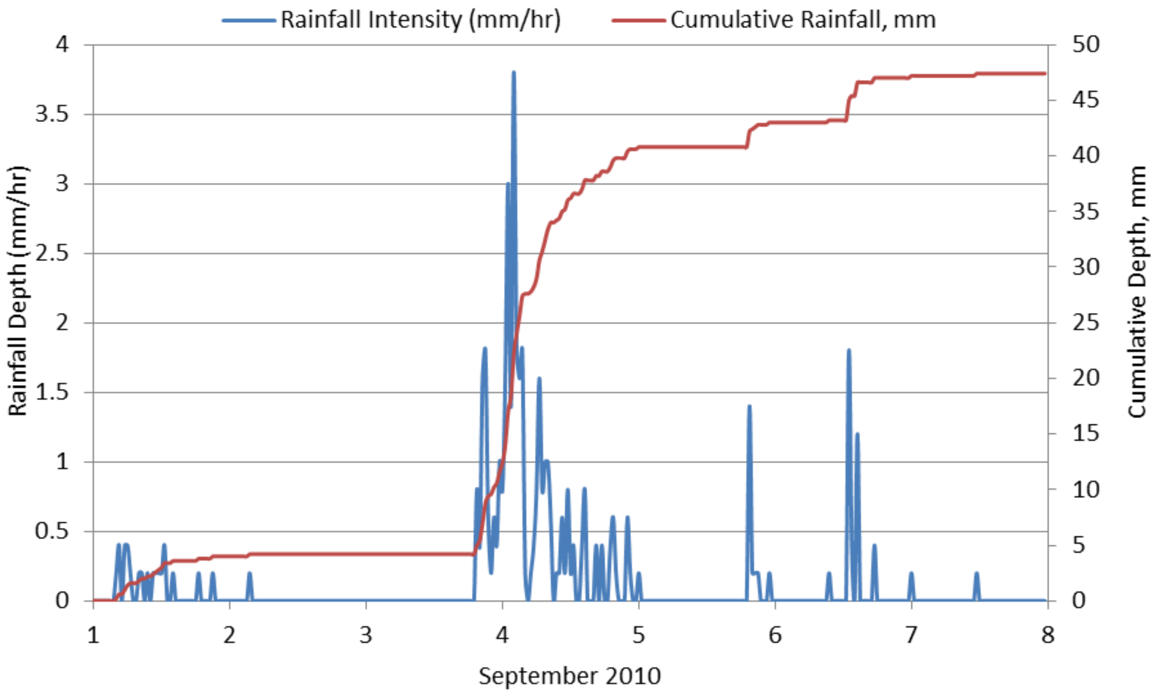


Figure 3-12 Temporal rainfall distribution at the Cairn Curran gauge for the September 2010 storm event

September 1983

Data for the September 1983 flood event was only available at the Natte Yallock pluvio station, and hence this was adopted as the representative temporal pattern for the event.

The September 1983 flood event was a result of heavy rainfall in the catchment falling over a 4 day period, during which Bridgewater received 49 mm, with a maximum daily rainfall total of over 20 mm.

Instantaneous rainfall data was not available at the Cairn Curran gauge for this storm event. Rainfall observed at Natte Yallock, the nearest pluvio station with available data, can be seen in Figure 3-13. A peak rainfall intensity of 6.9 mm/hr was recorded.

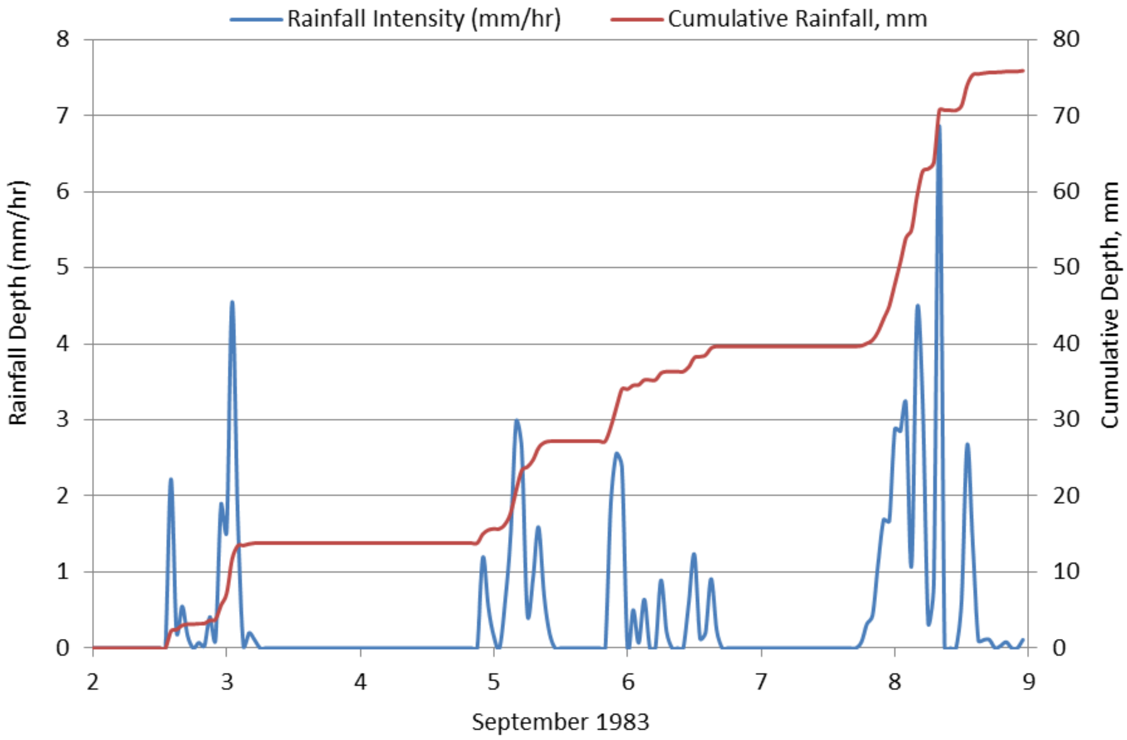


Figure 3-13 Temporal rainfall distribution at the Natte Yallock gauge for the September 1983 storm event

Spatial Patterns

To determine the spatial distribution of rainfall for the calibration events, the rainfall totals from each daily rainfall gauge across the catchment was used to create a Triangulated Irregular Network (TIN).

From the TIN of rainfall depths, a total depth for the event is determined for each RORB subarea (the average rainfall total across each area). This depth is then distributed over the duration of the event according to the assigned temporal distribution.

The triangulated rainfall values for the January 2011 flood event is shown below in Figure 3-14. The distribution shows that rainfall was heaviest on the western side of the catchment (i.e. the catchment of Bullabul Creek), with rainfall totals weakening to the east. A difference of 40 mm in the total rainfall for the five day storm event was observed across the catchment.

The September 2010 spatial distribution showed variability of up to 45 mm across the catchment, as seen in Figure 3-15, however proportionally this difference is larger due to the smaller rainfall event totals. Rainfall totals decrease towards the north-east of the catchment.

The spatial variability is greater again for the September 1983 event, with isolated high rainfalls occurring at Moliagul and Laanecoorie, as seen in Figure 3-13.

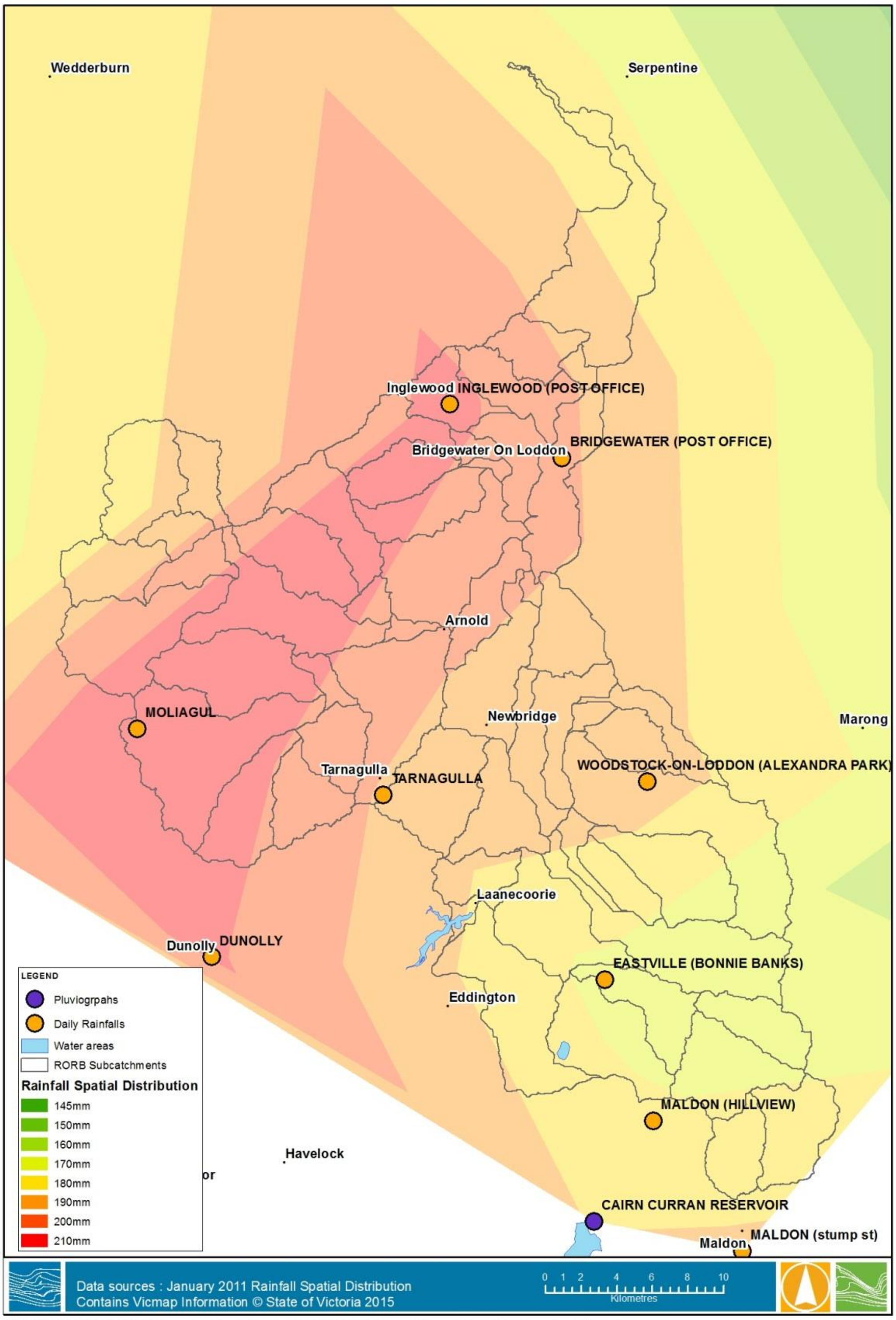


Figure 3-14 January 2011 rainfall spatial pattern

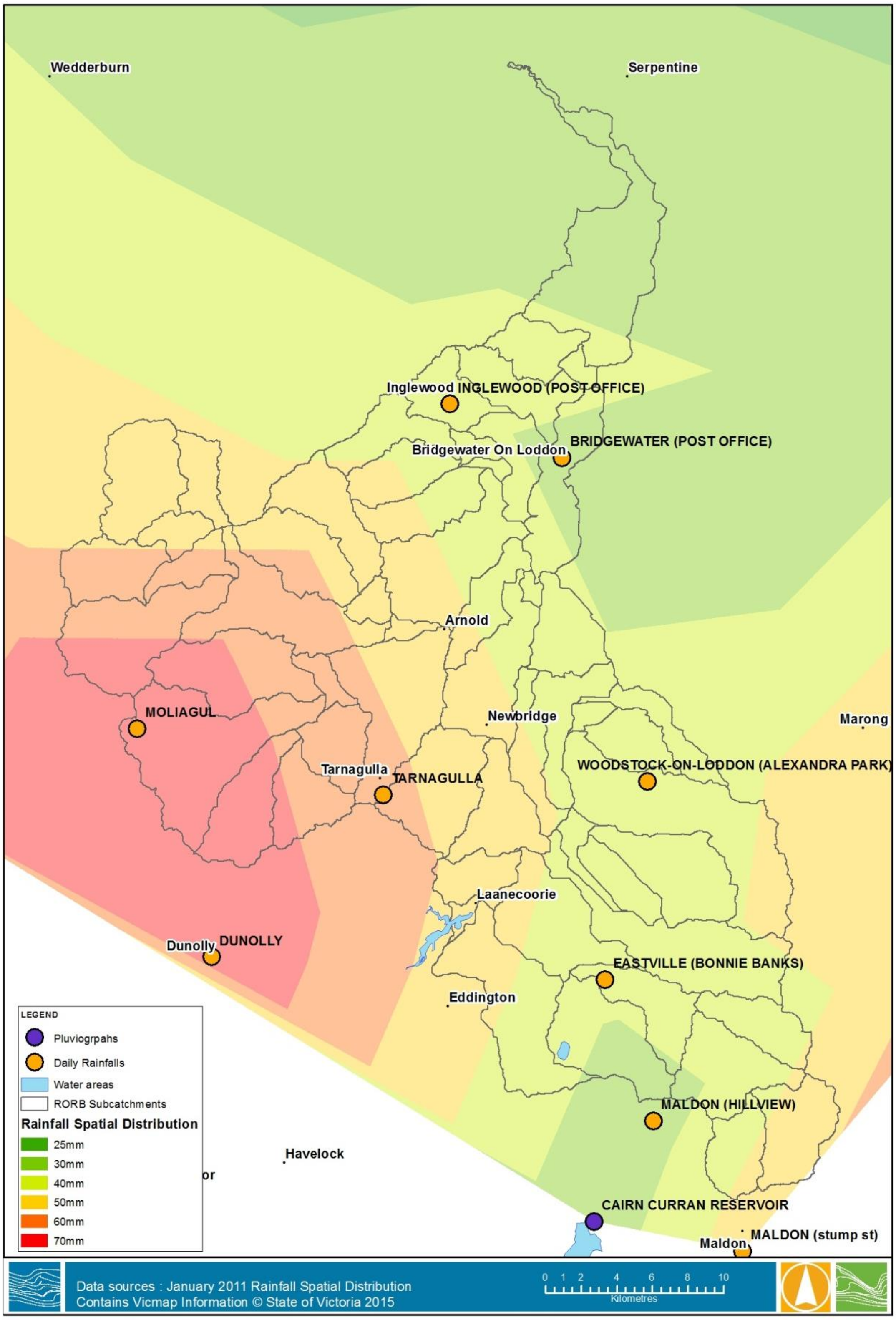


Figure 3-15 September 2010 rainfall spatial pattern

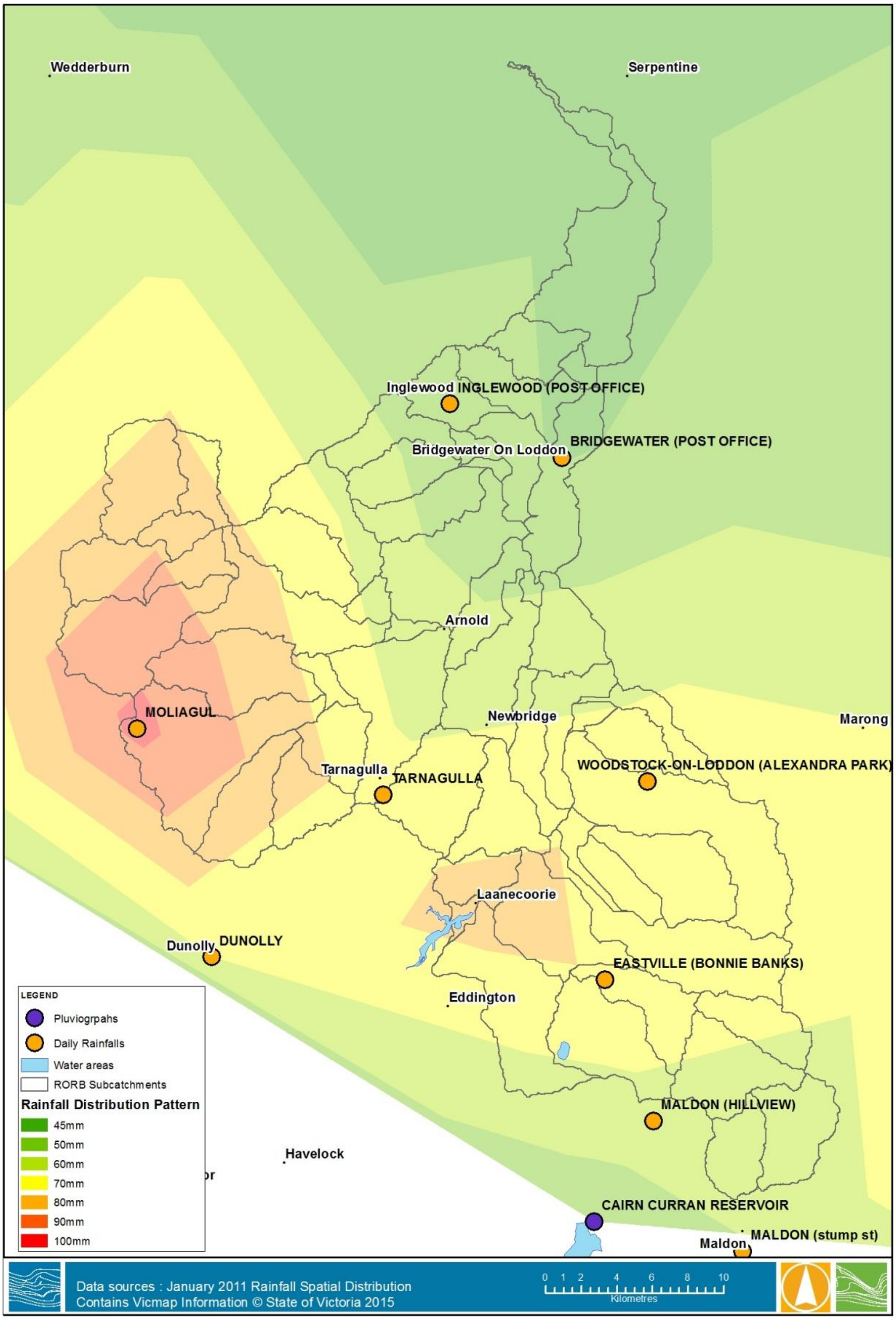


Figure 3-16 September 1983 rainfall spatial pattern

3.4.2 RORB Model Parameters

Kc value

The RORB model Kc value was initially estimated using the Australian wide Dyer (1994) method (Pearse et al 2002). This method assumes the Kc value to be a function of the average flow distance in the channel network of sub area inflows. The initial Kc value was used as a starting point for selecting the model parameters to optimise the fit between the resulting and actual hydrographs at Serpentine Weir for each of the calibration events. The known timing of the flood peak at Bridgewater from anecdotal local information was also used to inform the choice of Kc.

m

The RORB parameter m is a measure of the non-linearity of a catchment and is typically set at 0.80. This value remains unchanged and is an acceptable value based on Australian Rainfall and Runoff (1987).

Losses

The loss model chosen for the catchment was the initial and continuing loss model. This is thought to be a suitable representation of losses in the catchment, which is predominately rural and hence likely to have high rainfall infiltration at the beginning of an event when the ground is dry, reducing to a constant loss rate over the remainder of the event.

3.4.3 Calibration Results

For the three historical events, kc and loss parameters were adjusted iteratively until the model hydrograph at Serpentine Weir (407229) matched the peak flow and timing of observed data.

Given such large volumes of water bypassing the Serpentine gauge, calibration to *only* the gauge data is unreliable. Hence, anecdotal evidence was utilised, where available, to verify the timing of peak water levels within the Bridgewater township.

January 2011

For the January 2011 flood event, the modelled hydrograph at Serpentine Weir reproduced the peak flow and volume closely, though there was a slight difference in the rising limb of the hydrograph, as seen in Figure 3-17.

The modelled peak discharge was within 6% of the gauge readings at Serpentine, and the volume within 1.3%. There was only 3 hours difference in the time to the peak of the hydrograph.

Community feedback indicated that the peak flood level in the Bridgewater township was experienced at approximately 4-5am on the morning of the 15th January (Saturday). The modelled hydrograph at Bridgewater estimated that the peak flow in the Loddon River occurred at 8 am on the 15th January, approximately 3 hours after the observed peak.

A kc value of 85.40, initial loss of 10 mm and continuing loss of 2 mm/hr were adopted for the January 2011 calibration event. Without a good streamflow hydrograph to calibrate to, the appropriateness of the RORB calibration will be further justified in the hydraulic model calibration discussed later in the report.

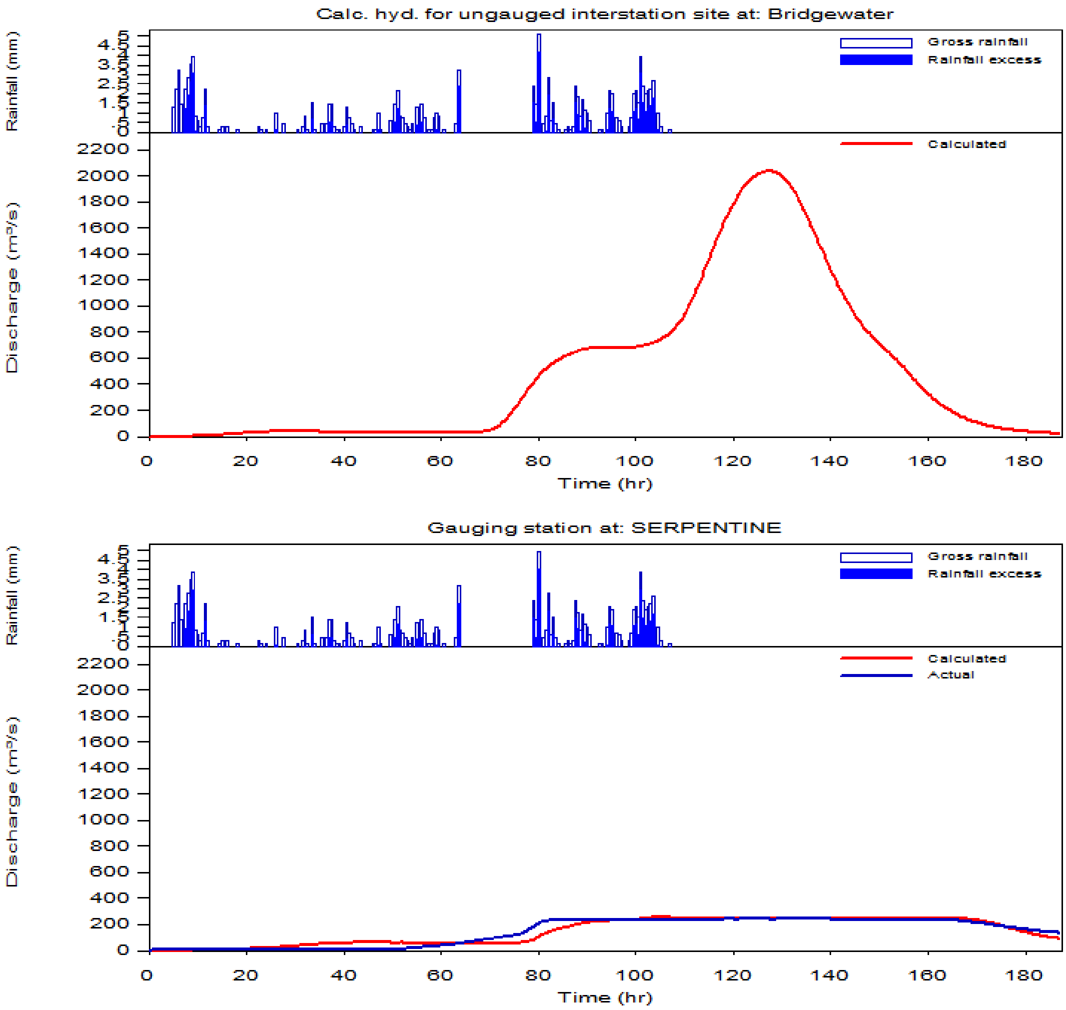


Figure 3-17 Calculated hydrograph in the Loddon River at Bridgewater and modelled and observed hydrograph at Serpentine Weir from 12am 10th January 2011

September 2010

The calculated and actual discharge at Serpentine Weir for the September 2010 flood event can be seen in Figure 3-18. The RORB model was able to accurately replicate the peak flow at Serpentine (a difference of less than 1.3% was observed), however the calculated hydrograph peak occurred 7.5 hours after the actual peak flow (a difference of 31%). Despite the differences in the rising limb of the hydrograph, the falling limb follows a similar shape/grade to actual.

At Bridgewater, the peak water level was calculated to occur after 21 hours, i.e. 4 pm on the 4th September 2010. This is consistent with some accounts which indicate peak levels occurred in the late afternoon of the 4th September, though the exact timing of the peak is not clear.

The adopted kc value for this flood event was low, at 40.0. The adopted initial loss was 5 mm, with a continuing loss of 2 mm/hr.

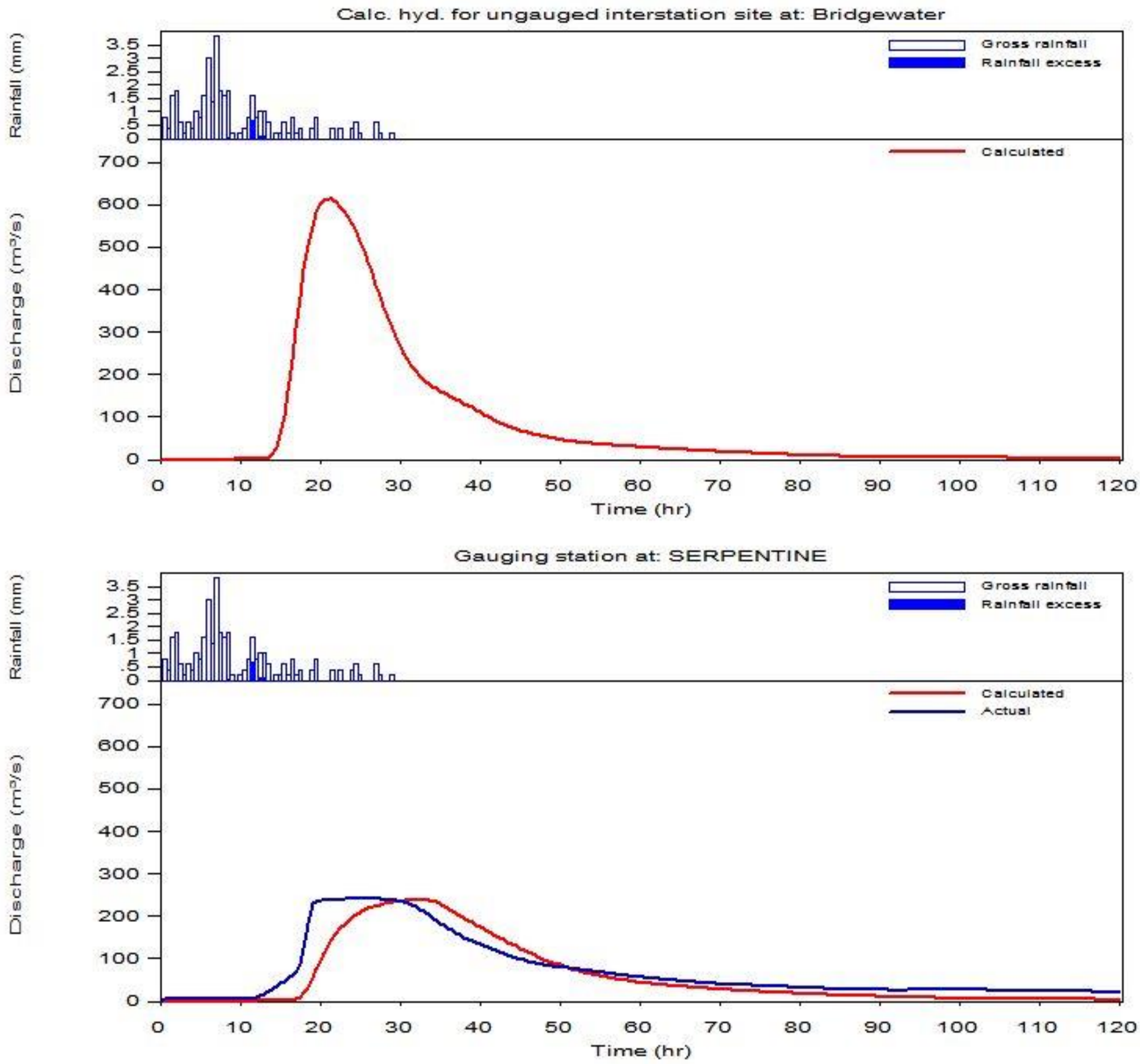


Figure 3-18 Calculated hydrograph in the Loddon River at Bridgewater and modelled and observed hydrograph at Serpentine Weir from 7pm 3rd September 2010

September 1983

The adopted parameters for the September 1983 event were more similar to those of the January 2011 event, with a kc value of 70.0, and initial and continuing losses of 5 mm and 2 mm/hr respectively.

The shape of the calculated and actual hydrographs at Serpentine, seen in Figure 3-19, indicates good agreement. The calculated peak discharge of 243 m^3/s was 12% less than the actual peak of 278 m^3/s. Similarly to the two other calibration events, there are some discrepancies in the rising limb of the hydrograph, however the falling limb seems to match well.

The calculated peak discharge at Bridgewater occurred at 6pm on the 9th September.

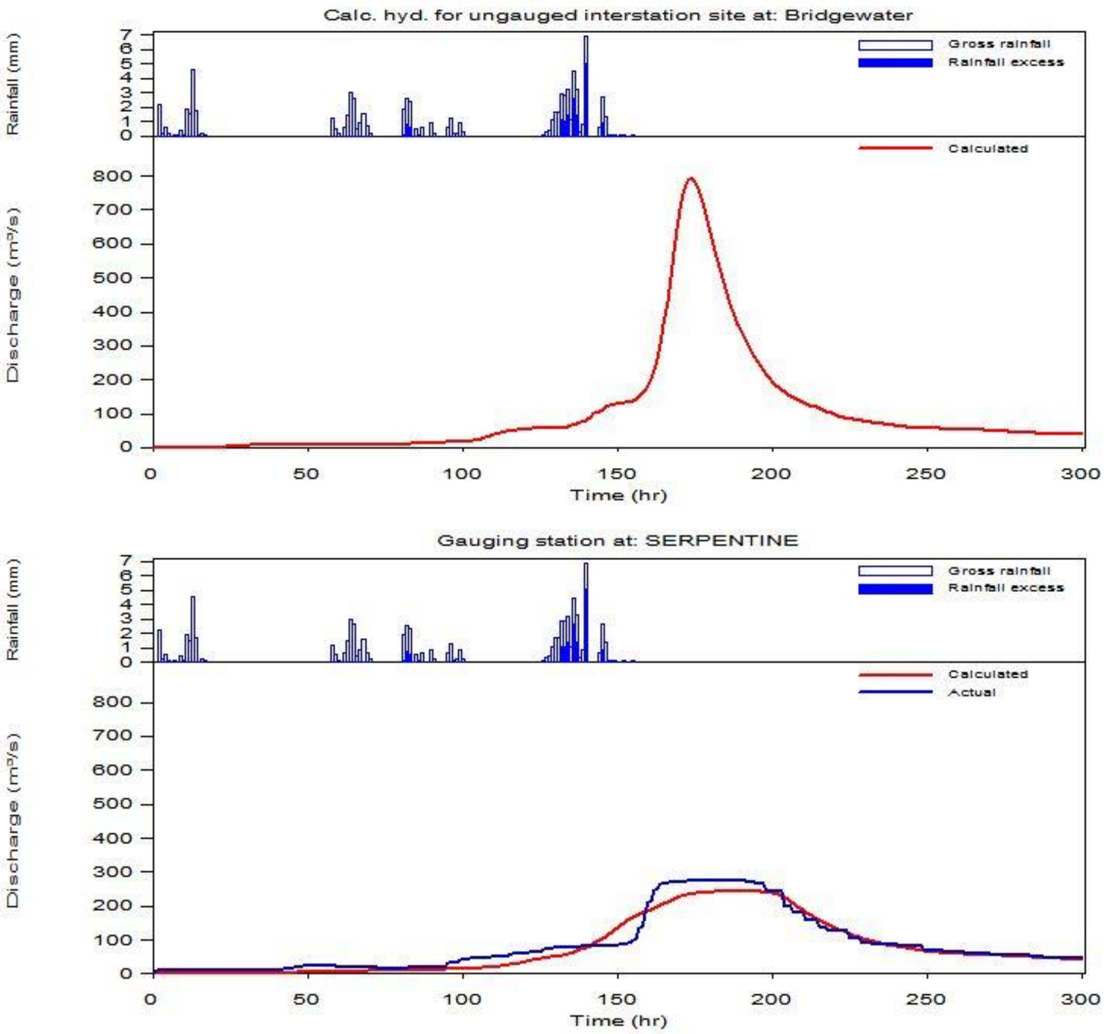


Figure 3-19 **Calculated hydrograph in the Loddon River at Bridgewater and modelled and observed hydrograph at Serpentine Weir from 12pm 2nd September 1983**

Summary and Discussion

The RORB model was able to replicate the peak discharge at Serpentine Weir within reasonable accuracy. While there were some discrepancies in the timing of the peak discharge, the volume of the hydrograph was able to be reasonably replicated for the three calibration events. The differences between calculated and actual hydrograph statistics can be seen in Table 3-4.

Despite being able to accurately replicate the hydrograph at Serpentine Weir, confidence in the calibration is limited as a result of significant flow volumes being diverted upstream of the gauge. Furthermore, flow at this point is dominated by Loddon River flows, and hence the characteristics for the Bullabul Creek catchment have little impact at this point.

In order to address the uncertainty regarding the RORB model calibration, the hydraulic model was developed in tandem and used to verify the RORB calibration. Details of the hydraulic analysis can be found in Section 4.

Table 3-4 Calibration statistics for calculated and gauged flows at Serpentine Weir

	Calculated	Gauged	Difference	Difference, %
JANUARY 2011				
Peak discharge	256.0 m^3/s	241.4 m^3/s	14.6 m^3/s	6.0%
Time to peak	104 hr	124 hr	-20 hr	
Volume	96700 ML	95500 ML	1230 ML	1.3%
SEPTEMBER 2010				
Peak discharge	238.1 m^3/s	241.1 m^3/s	-3.1 m^3/s	-1.3%
Time to peak	31.5 hr	24 hr	7.5 hr	
Volume	25400 ML	30900 ML	5460 ML	-17.7%
SEPTEMBER 1983				
Peak discharge	242.9 m^3/s	276.9 m^3/s	-34.0 m^3/s	-12.3%
Time to peak	193 hr	179 hr	14 hr	
Volume	84100 ML	94100 ML	10100 ML	-10.7%

The adopted RORB model parameters for each calibration event are summarised in Table 3-5.

Table 3-5 RORB model calibration parameters

Event	Kc	Initial Loss, mm	Continuing loss, mm/h
January 2011	85.4	10	2
September 2010	40	5	2
September 1983	70	5	2

3.5 Flood Frequency Analysis

A flood frequency analysis (FFA) allows the estimation of design flow peaks based on a statistical analysis on an annual series of peak flood flows. Similar analysis can be undertaken on flood volumes, which in some catchments can be an important characteristic of the flood hydrograph.

Flood frequency analysis is considered a better approach to estimating peak design flows than rainfall-runoff models given a reliable streamflow gauge with a long period of record is available. Furthermore, the use of flood frequency analysis negates the need to undertake complex joint probability analysis to include the effect of initial storage levels in the reservoirs upstream of Laanecoorie, as the flood frequency analysis incorporates this natural variability in starting storage level and reservoir inflows.

3.5.1 Peak Flow

An annual flood series was taken from the Laanecoorie Reservoir tail gauge (407203), for which there were flow records from 1891 to 2014 (124 years). It should be noted that this dataset was amended to include the January 2011 flow estimate missing from the DELWP streamflow dataset.

To prevent skewing of the data, low flows were censored using the Multiple Grubbs Beck Test, which resulted in the removal of the 53 lowest flows in the series. Censoring of low flows is especially significant for gauges in the Loddon River catchment due to the number of low flow years that are present in each gauge annual series. These peaks cannot be classified as “floods” and skew the analysis.

Flood frequency analysis was undertaken using a range of typical flood frequency distributions including Generalised Extreme Value (GEV), Log Normal and Log Pearson Type 3 (LPIII). A LPIII distribution was found to be the best match for all datasets. The distribution and associated confidence limits can be seen in Figure 3-20. The resulting peak flow rates, along with historical flood flows are summarised in Table 3-6.

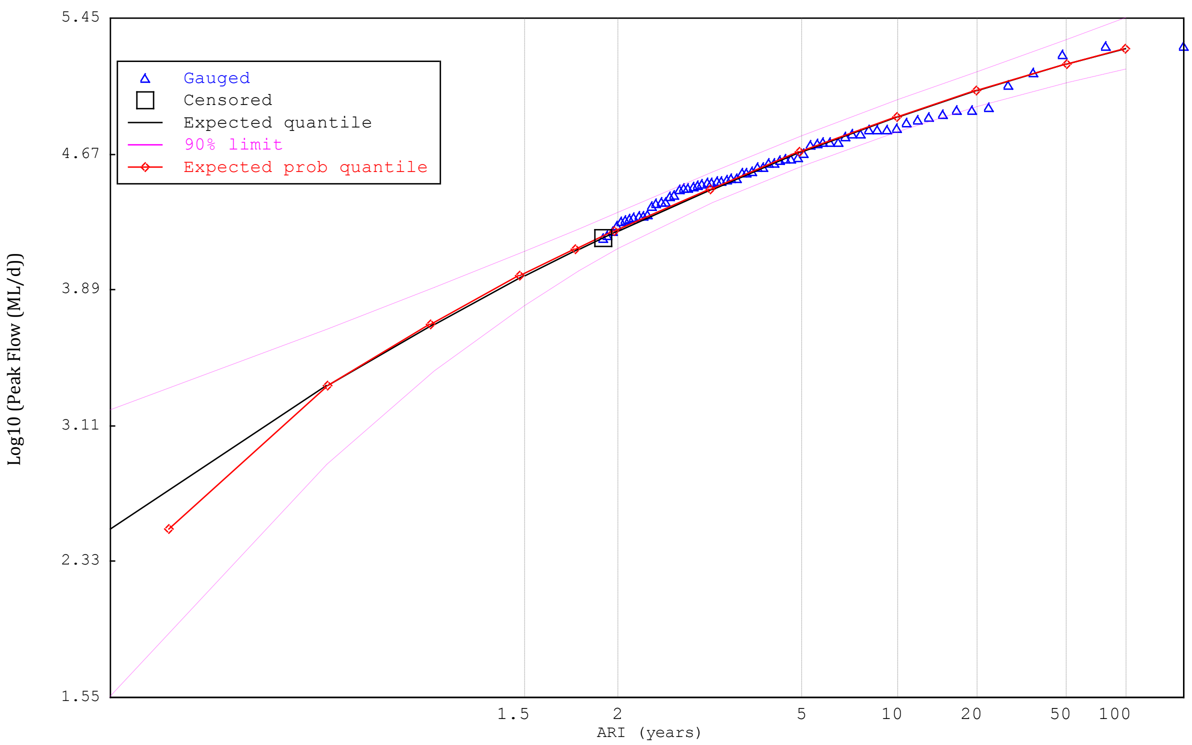


Figure 3-20 LPIII distribution with Grubbs Beck test censoring for Laanecoorie peak flow

Table 3-6 FFA design peak flood estimates (LPIII)

AEP %	Peak Flow (ML/d)
0.1	317,000
0.2	278,300
0.5	227,600
January 2011	194,700
1	190,000
2	153,500
5	108,000
10	76,300
September 1983	73,300
September 2010	65,200
20	48,000

With respect to peak flow, the fitted distribution suggests that the January 2011 flood event was slightly bigger than a 1% AEP flood. The September 1983 and 2010 flood events ranked between 20% and 10% AEP floods.

3.5.2 Flood Volume

In order to estimate the shape of the design flow hydrographs, a flood frequency analysis of flood volumes was also undertaken. A review of significant events in the flow record at Laanecoorie revealed that the average flood event duration was 3 days. At the Laanecoorie gauge the maximum 3 day flood volume was calculated for each year (over the 124 years of record), using mean daily flows to calculate volume.

Distributions were fitted to the Laanecoorie annual flood volume series in FLIKE. The Multiple Grubbs Beck test was once again used to filter low volumes which represented non-floods. A total of 53 flood volumes were censored.

The LPIII distribution was again found to have the best fit as shown in Figure 3-21. The resulting design flood volumes are given in Table 3-7, along with volumes of historic flood events.

The January 2011 flood volume ranked between a 0.5% and 0.2% AEP flood event, whereas the September 1983 and 2010 events ranked between 20% and 10% AEP floods.

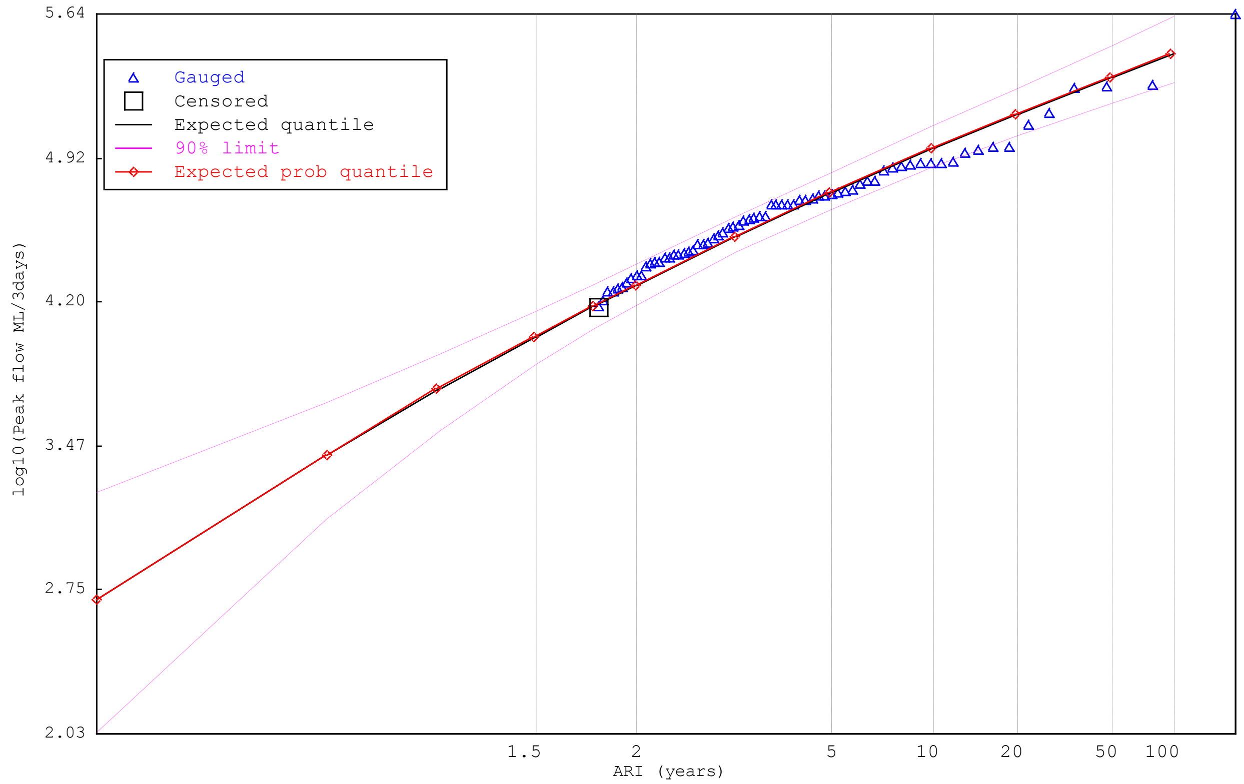


Figure 3-21 LPIII distribution with Grubbs Beck test censoring for Laanecoorie 3 day volume

Table 3-7 FFA design flood volume estimates (LPIII)

AEP, %	Flood Volume, ML/3 days
0.1	700,000
0.2	537,500
January 2011	435,800
0.5	374,400
1	280,600
2	206,600
5	132,000
10	89,000
September 1983	78,200
September 2010	60,800
20	55,200

3.5.3 Sensitivity

It is noted that the period of data for which the FFA has been conducted may not be homogenous because of the construction of dams upstream of Laanecoorie on the Loddon River and its tributaries (in particular, the Cairn Curran reservoir which was constructed in 1956).

To test the homogeneity of the data set, a sensitivity analysis was undertaken by comparing the resultant AEP design flows for the time periods of: 1891 – 2014 (full record); 1891 – 1955 (pre Cairn

Curran reservoir); and 1956-2014 (post Cairn Curran reservoir construction). The 1% AEP flows are included here in Table 3-8 for comparison.

Table 3-8 1% AEP peak flow FFA results for different data periods

Period of Record	No. Records	1% AEP peak, ML/d	Difference
1891 – 2014	66	188,736	-
1891 – 1955	42	239,709	+19%
1956 – 2014	28	201,082	+7%

The peak flow estimate for the period after Cairn Curran reservoir was constructed is only slightly larger than the peak flow for the full record. While the flow is greater, and therefore would be more conservative, the FFA is more susceptible to skew as a result of fewer data points. The FFA plot indicates a better fit is achieved over the full flow record.

Construction of the Laanecoorie Reservoir was completed in 1891 and therefore impacts only on the first year of available records at Laanecoorie (if at all). Given the minimal impact of the Cairn Curran Reservoir on the gauge record, the Laanecoorie Reservoir is likely to have no impact on flows given its considerably smaller size than the Cairn Curran reservoir.

3.6 Design Modelling

Design hydrographs for input to the hydraulic model were developed using a combination of the flood frequency analysis and RORB modelling methodologies as discussed above.

For this study the 20, 10, 5, 2, 1 and 0.5% AEP events were required. The inputs for design flood estimation are described throughout the following sections.

3.6.1 Loddon River Flow from Laanecoorie

Model hydrographs were selected from the gauge records at Laanecoorie and scaled by peak flow and volume to give the design flow hydrograph. The November 2010 flood hydrograph was chosen as the model design hydrograph shape as it had a similar ratio of flood volume to peak flow as the 1% flood frequency analysis ratio. Further, it was a relatively smooth hydrograph with only a single peak.

The November 2010 flood hydrograph can be seen in Figure 3-22 along with the adopted 1% AEP design hydrograph. The January 2011 flood hydrograph is also shown on the same plot, demonstrating the close fit of this historic event to the 1% AEP design flood hydrograph.

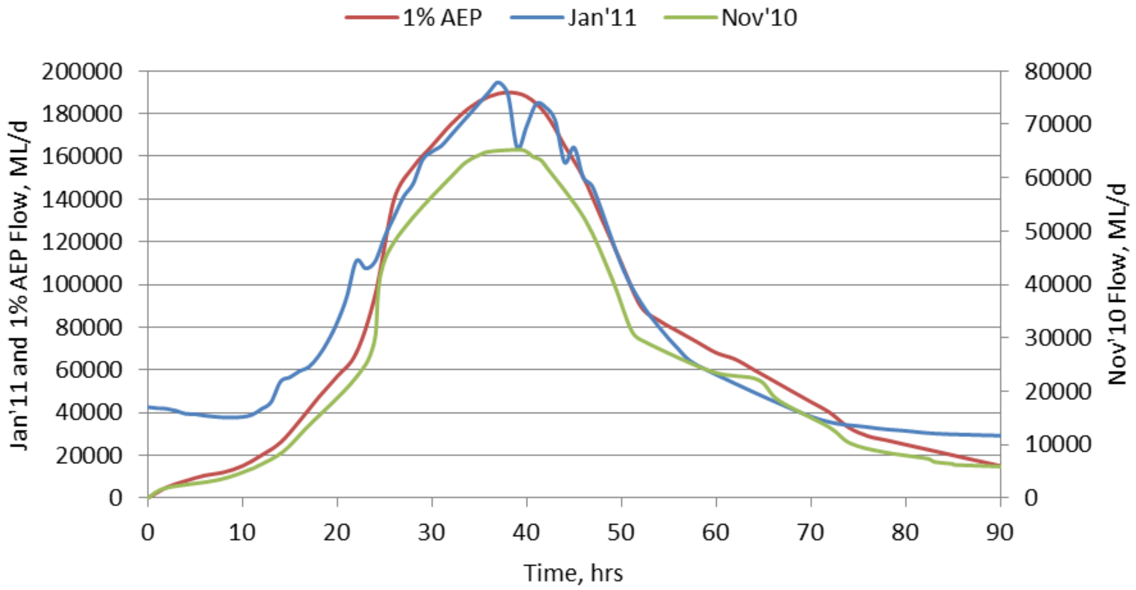


Figure 3-22 1% AEP design hydrograph with November 2010 and January 2011 flood hydrographs

All design hydrographs were developed by scaling the November 2010 hydrograph to match the peak flow with volume within 5% of the FFA results.

3.6.2 RORB Design Modelling

Following on from the successful RORB model calibration, a series of design events were modelled. This required the adoption of various design parameters to be included within RORB to generate design hydrographs for input to the hydraulic model.

This section presents the design parameter selection and subsequent flows generated within RORB and the hydraulic model results.

Rainfall Depths

Design rainfall depths were determined using the IFD methodology outlined in AR&R Volume 2, 1987. IFD parameters were generated from the Bureau of Meteorology's online IFD Tool[9]. The IFD parameters were generated for a location at the centroid of the Bridgewater catchment (-36.050 S, 143.950 E) and are shown in Table 3-9 below. The resulting IFD curves can be seen in Figure 3-23.

Table 3-9 Catchment IFD parameters for Bridgewater

$2I_1$ (mm/hr)	$2I_{12}$ (mm/hr)	$2I_{72}$ (mm/hr)	$50I_1$ (mm/hr)	$50I_{12}$ (mm/hr)	$50I_{72}$ (mm/hr)	G	F2	F50	Zone
17.66	2.98	0.77	39.4	6.79	1.68	0.05	4.36	15	2

[9] BoM Online IFD Tool - http://www.bom.gov.au/hydro/has/cdirswebx/cdirswebx.shtml Accessed: June 2013

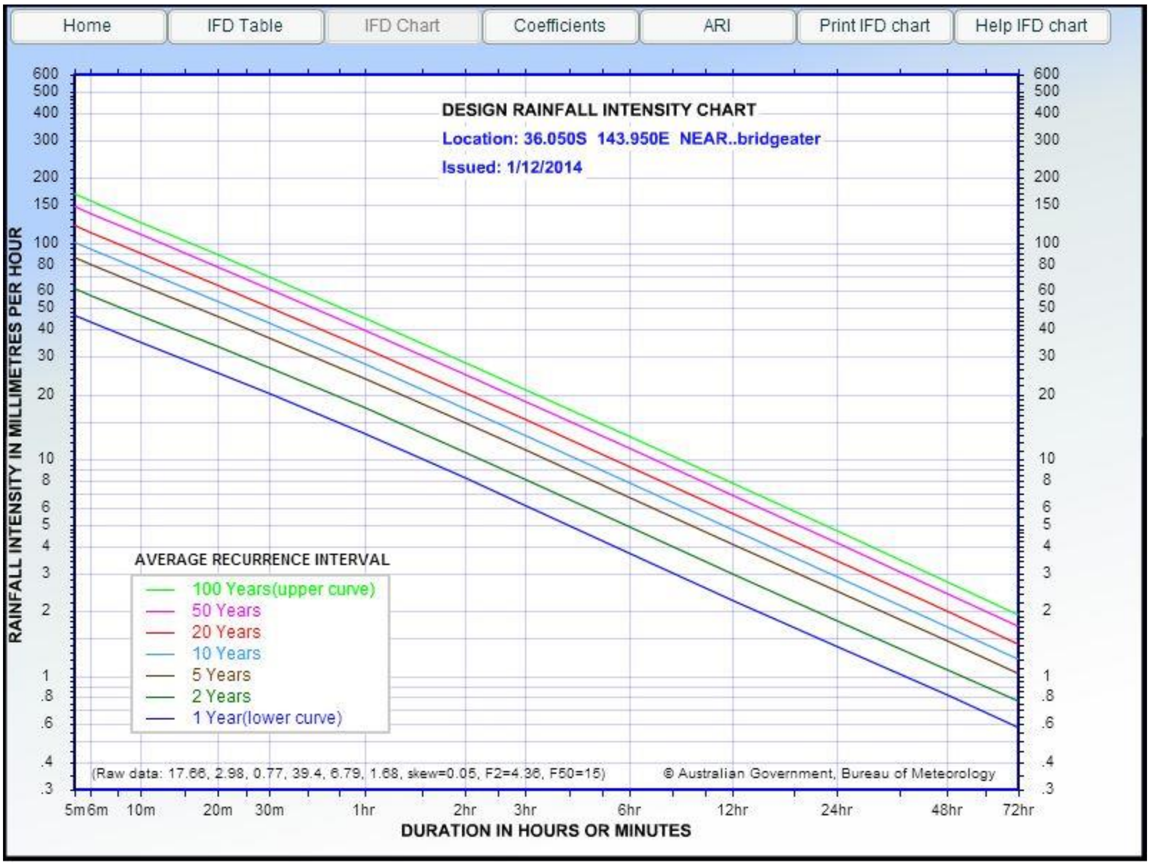


Figure 3-23 IFD curves extracted from the BoM online IFD tool[9] for Bridgewater catchment

RORB uses the IFD parameters to develop design rainfall depths for AEPs up to 0.5%. For the more extreme 0.1% AEP, the statistical package CRC-Forge[10] was used to develop a point rainfall estimate for the catchment.

Temporal Pattern

Design temporal patterns were taken from AR&R (1987) for design floods of up to 0.1% AEP. Temporal patterns for a range of storm durations are described in AR&R (1987) for various zones across Australia. The Bridgewater catchment is located within Zone 2. Inspection of the hydrographs at the inflow of Bullabul Creek to the hydraulic model (the largest inflow other than the Loddon River) for all durations for the 1% AEP event found the 30 hour duration storm to be the critical duration, as seen in Figure 3-24.

Updated temporal patterns are being produced as part of the revision of Australian Rainfall and Runoff, however these were not yet available for use at the time of completing the hydrology for this study. Alternative temporal patterns to Australian Rainfall and Runoff do exist, however it was deemed unnecessary to invest much time is exploring these options given that flooding in Bridgewater is dominated by the Loddon River flows from Laanecoorie (estimated by FFA), rather than local runoff (estimated by RORB).

The 30 hour duration storm event was adopted for all design AEP floods. Other smaller tributaries would most likely have a critical duration shorter than 30 hours. These smaller tributaries are of far

[10] CRC Forge – Extract Version 1.0, April 2000. Developed by Siriwardena (CRC for Catchment Hydrology, Monash University) and Nandakumar (Department of Land and Water Conservation, NSW).

lesser risk to the township of Bridgewater, with flood risk dominated by the Loddon River and to a lesser extent Bullabul Creek for a select number of rural properties.

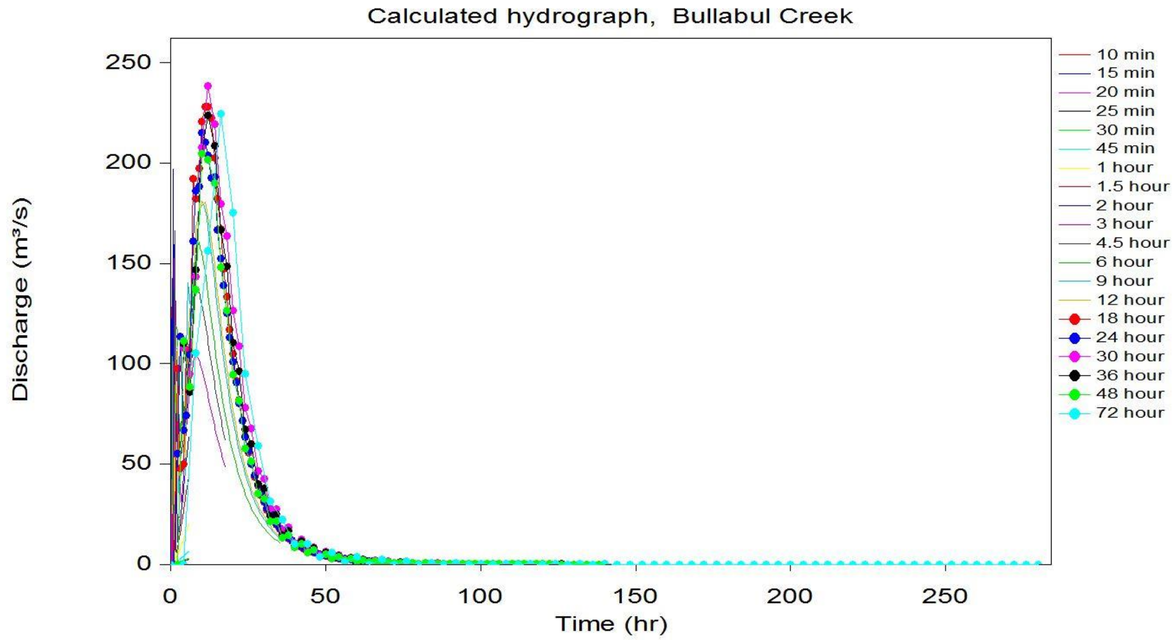


Figure 3-24 Calculated hydrographs at Bullubul Creek for 1% AEP design flood

Spatial Pattern

A uniform spatial rainfall pattern (i.e. the same rainfall depths applied to the entire catchment) was adopted for the generation of design flood hydrographs for all design storms. This is reasonable given the rainfall-runoff modelling is only used for the catchment downstream of Laanecoorie.

Aerial Reduction Factors

Areal reduction factors convert point rainfall to areal estimates and are used to account for the variation of rainfall intensities over a large catchment. Siriwardena and Weinmann (1996) reduction factors were applied to the catchment area of 1,067 km^2. It is understood that revised areal reduction factors are being released in the 2015 revision of ARR, a review of the draft revised chapter revealed that any changes in Victoria are likely to be quite minor.

Design Model Parameters

Routing Parameters

Calibration of the model resulted in the use of a unique kc value for each of the three calibration events, ranging between 40 and 85. Given the variability across events, various regional kc estimation equations were used to examine the range of plausible kc values, summarised in Table 3-10.

With the exception of the September 2010 flood event and Vic MAR < 800 mm estimate, all kc estimates were in the relatively narrow range of 65 – 85. The default RORB method was deemed a suitable estimate given it was in the middle of this range and generally accepted by the industry. A kc value of 71.9 was therefore adopted for design modelling in this study.

Table 3-10 RORB kc Estimates

Method	Estimated kc
Default RORB	71.9
Vic MAR < 800 mm	45.6
Vic data (Pearse et al, 2002)	85.5
Aust Wide Dyer	78.0
Aust Wide Yu	65.7
Sep-83 calibration	70.0
Sep-10 calibration	40.0
Jan-11 calibration	85.4
AVERAGE	**67.7**

Design Losses

An initial loss of 25 mm and a continuing loss of 2.5 mm/hr was adopted as the design loss parameters for this study. The loss parameters were applied across all AEP events and durations.

The loss parameters adopted were consistent with design loss parameters set out in AR&R 1987 and correlate well to those described by Hill et al (1998). The method proposed by Hill et al (1998) uses a baseflow index (35% for the Bridgewater catchment, based on regional maps) and mean annual potential evaporation to calculate the initial and continuing losses, as per Equation 3-1 below.

Equation 3-1 Loss Equations as described by Hill, Mein and Siriwardena (1998)

$$Initial\ Loss = (-25.8\ \times BFI) + 33.8$$

$$Continuing\ Loss = (7.97\ \times BFI) + (0.00659\ \times PET) - 6$$

Where: BFI is the baseflow index

PET is the mean annual potential evaporation (mm)

A summary of the initial and continuing losses predicted by each method (and comparison to nearby Dunolly catchment) can be seen in Table 3-11.

Table 3-11 Loss estimates

Method	Initial Loss (mm)	Continuing Loss (mm/hr)
Dunolly Flood Study	25	2.5
Hill et al (1998)	24.8	5
AR&R (1987)	15-35	2.5

It should be noted that design losses were not based on the losses adopted in the calibration events. Losses are highly dependent on antecedent catchment conditions and are not suitable for design flood estimation.

Sensitivity Testing

A sensitivity analysis was undertaken to determine the impact of variation in the RORB model parameters on the resulting hydrographs, and hydraulic model extents. It is thought that because flooding in Bridgewater is dominated by flow from the Loddon River, the selection of design parameters is not as critical in the hydrology development as it will only influence local catchment flows, which are comparatively small.

Parameters chosen for the sensitivity analysis were those that would produce the largest increase in design flow from within the range of considered estimates (see Table 3-10 and Table 3-11). These values are summarised in Table 3-12, and were used to compare output for the 1% AEP event.

Table 3-12 Adopted and comparative model parameters for sensitivity testing

Parameter	Adopted value	Comparative value
Kc	71.9	40
m	0.8	0.8
Initial loss	25	15
Continuing loss	2.5	2.5

The resulting output hydrographs for flow in Bullabul Creek, the Loddon River (including flow from Laanecoorie developed in the FFA) and Little Creek can be seen in Figure 3-25, Figure 3-26 and Figure 3-27 respectively. These hydrographs have been extracted at the points that are boundary locations to the hydraulic model. The results show that the comparative RORB parameters, used for the sensitivity analysis result in a much greater peak discharge occurring faster, with steeper rising and falling limbs for the Bullabul Creek and local catchment runoff. This difference is of course not as apparent on the Loddon River as the flow at Laanecoorie is input as an inflow hydrograph with no catchment area routing.

The different RORB model outputs have been input to the detailed hydraulic model to compare the resulting extent and peak water levels. The difference between the two hydraulic results can be seen in Figure 3-28. As expected, the Bullabul Creek catchment experiences slightly higher water surface elevations as a result of the increased peak runoff. Water levels along the reach of the Loddon River are slightly reduced, as a result of the change in the relative peak timings.

The differences, however, are largely within 2 cm. This indicates that there is little difference in hydraulic model output as a result of variation in RORB parameter selection, particularly given the 'true' representative parameters would be more similar to those adopted than the values chosen for comparative purposes. The more extreme values have been chosen to represent the maximum practical difference, however there is less justification for selecting these parameters.

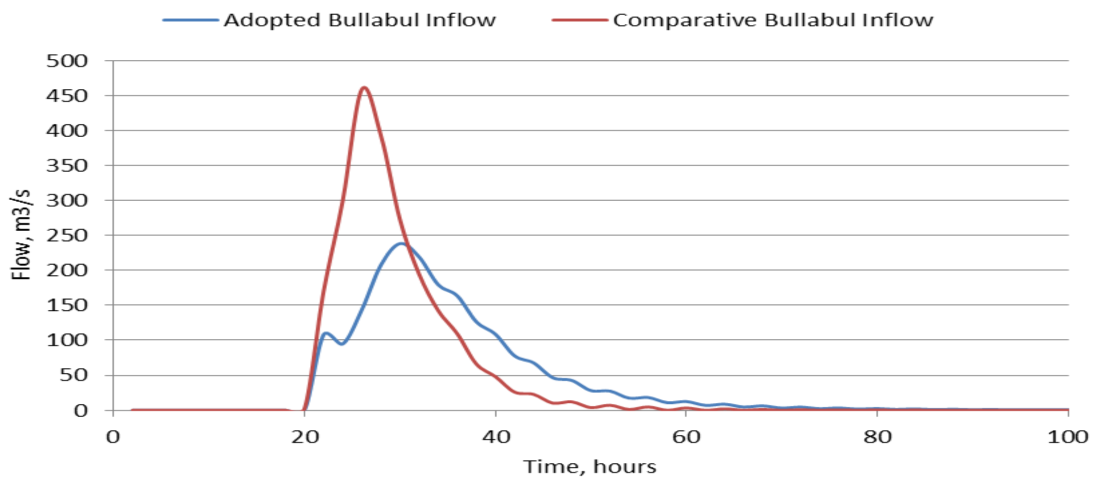


Figure 3-25 Bullabul Creek 1% AEP hydrograph

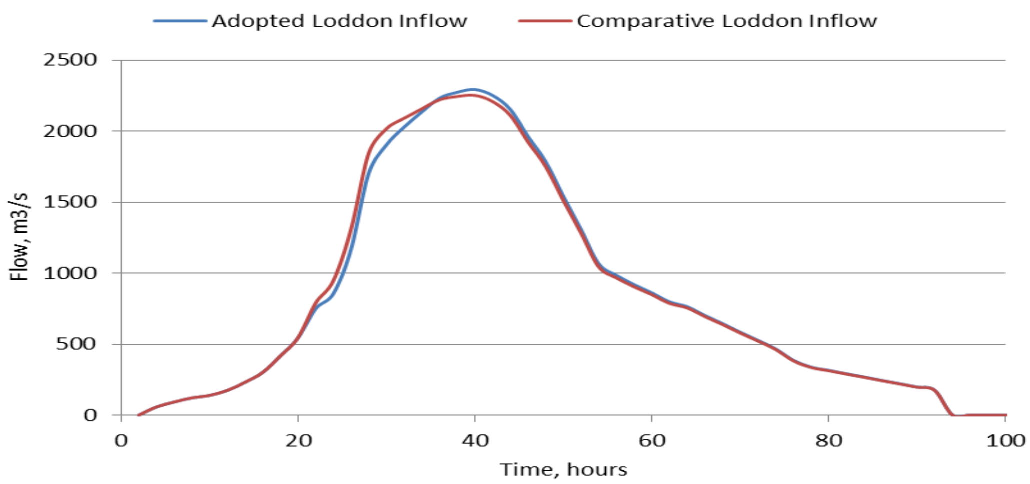


Figure 3-26 Loddon River 1% AEP hydrograph

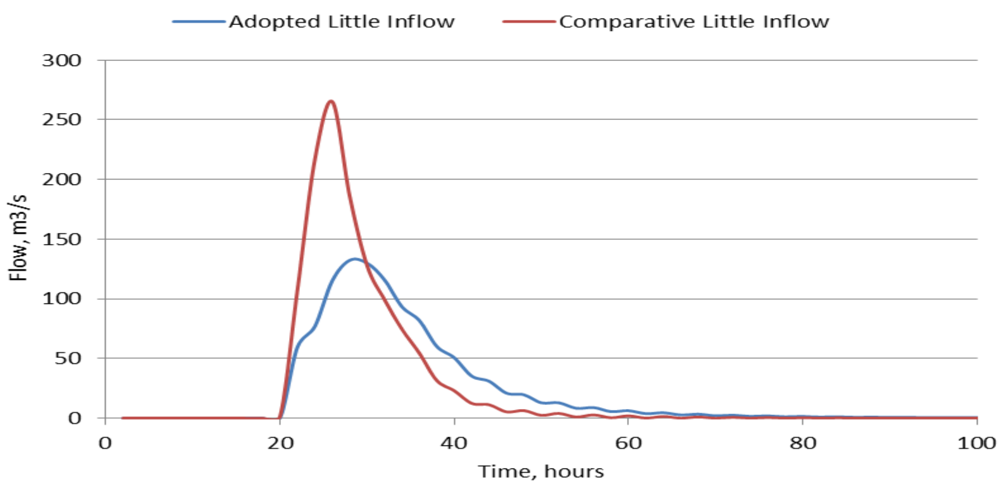


Figure 3-27 Little Creek 1% AEP hydrograph

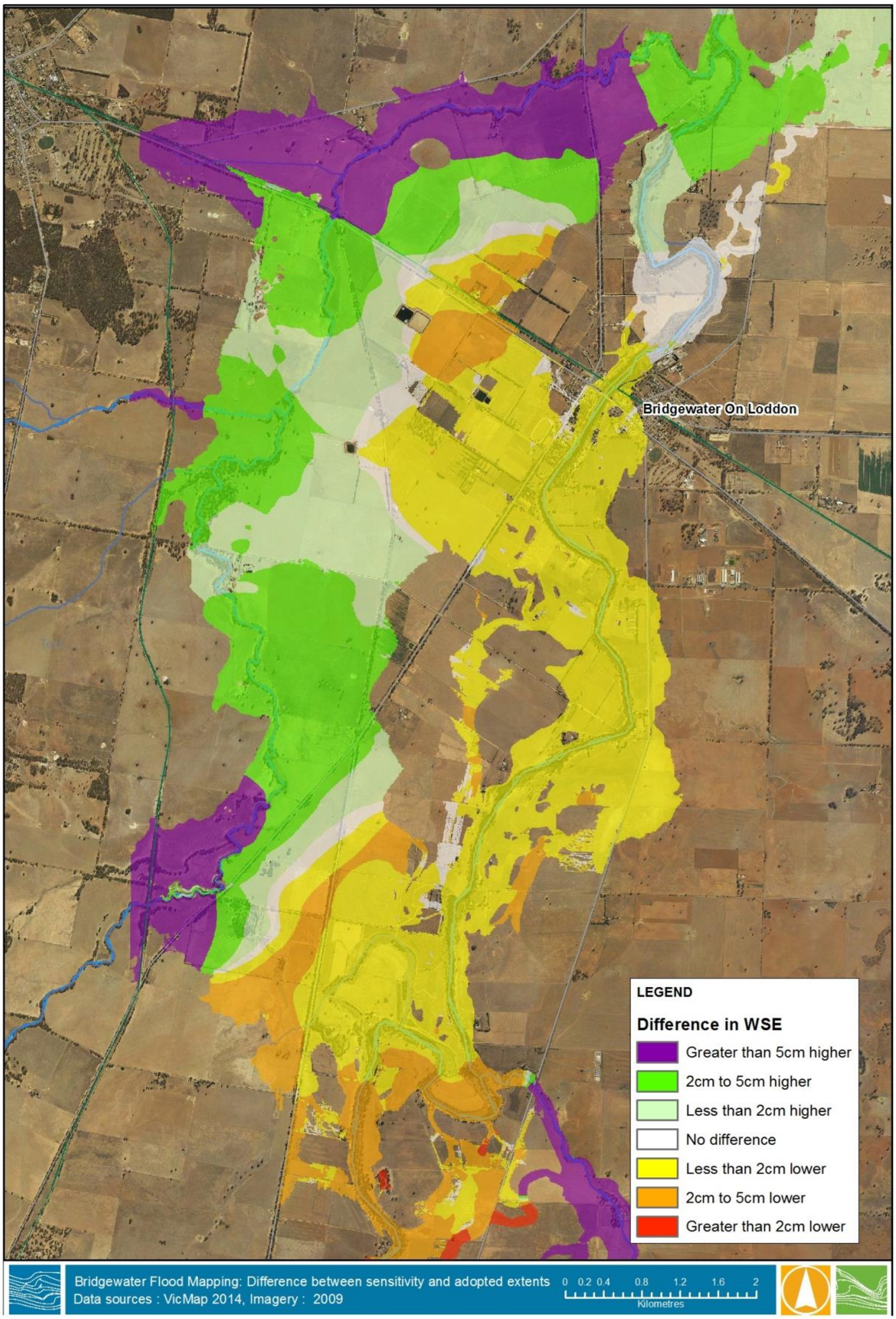


Figure 3-28 Difference in water surface elevation between extents produced using comparative and adopted RORB parameters for the 1% AEP extent

3.6.3 Outputs

Hydrographs from the RORB model (at various locations) and that developed for the Loddon River from the FFA have been used as input to the hydraulic model.. Inflow locations include: Loddon River, Bullabul Creek, Little Creek and 3 local catchments.

Historical floods were analysed to determine the relative timing of flows from the Loddon River and local catchment. It was found that on average, peak discharge at Laanecoorie occurred 18 hours after the peak rainfall. The design Loddon River hydrograph was therefore input to the RORB model to align with this timing, as indicated in Figure 3-29.

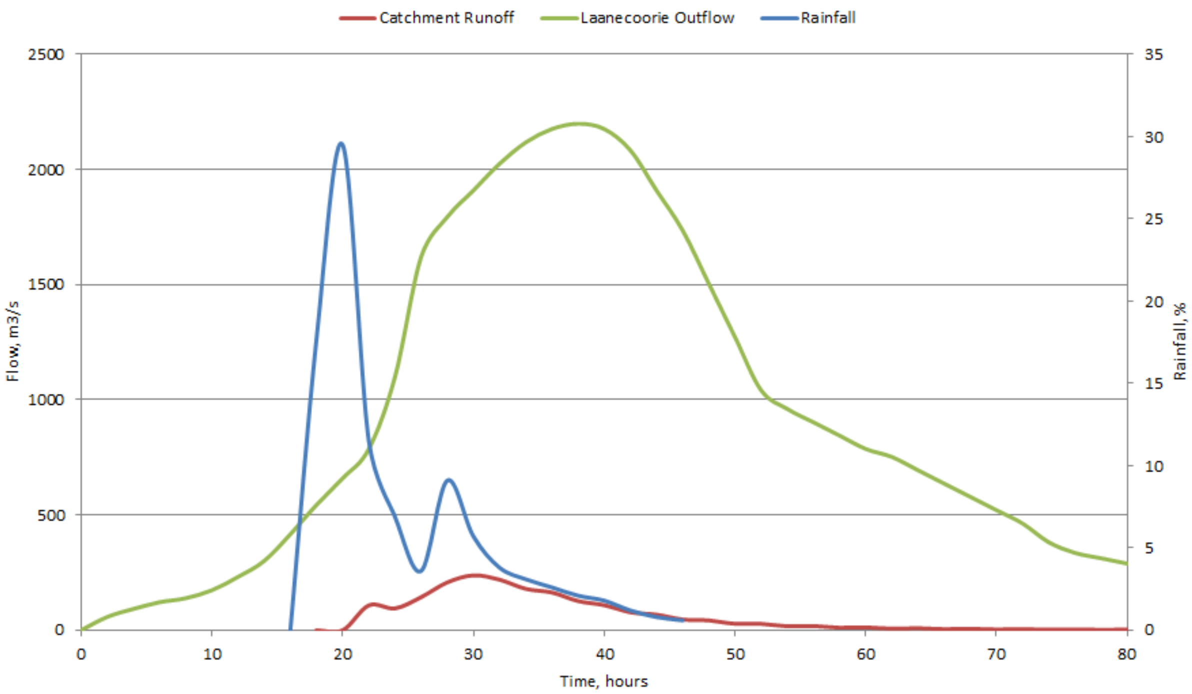


Figure 3-29 Relative timing of rainfall and runoff for the 1% AEP event

3.7 Hydrology Summary

A RORB hydrological model was used in combination with flood frequency analysis of Loddon River flows to generate design flows for the study. The RORB model developed for the catchment was calibrated to the January 2011 and September 2010 and 1983 flood events by comparing timing of peak flows at Bridgewater and gauge readings at Serpentine Weir. Gauge data available at Laanecoorie was used as input hydrographs to the RORB model.

The model was then used to generate design flows for the 20%, 10%, 5%, 2%, 1%, 0.5% and 0.1% AEP events. The choice of hydrological model parameters used to generate design flows was checked using sensitivity testing.

The design flows indicate that the January 2011 flood event was slightly greater than a 1% AEP event.

4. HYDRAULIC ANALYSIS

4.1 Model Development and Schematisation

A detailed 2D hydraulic modelling approach was adopted for this study using the TUFLOW software suite. TUFLOW is a widely used model for the analysis of overland flows in both urban and rural areas. The hydraulic model has three main inputs: topographic/structure geometry, hydraulic roughness description and boundary conditions. The floodplain was modelled as a two-dimensional topographic grid, with major hydraulic structures such as culverts and bridges incorporated in further detail.

4.1.1 Grid Extent and Resolution

Preliminary hydraulic modelling of the broader Loddon River floodplain was developed as part of the hydrology analysis to demonstrate breakouts of flow from the Loddon River. Based on the location of these breakout flows a revised model extent (from that provided in the tender documentation) was proposed for the detailed hydraulic model, as seen in Figure 4-1. Expanding the hydraulic model extent was required to allow modelling of the Loddon River breakouts to the Bullabul Creek system which can bypass the Bridgewater township in large flood events.

The model extends approximately 10 km upstream of Bridgewater to 5 km downstream of the town and incorporates inflow from the Loddon River, Bullabul Creek and local catchment runoff. The extent covers an area of approximately 96 km^2. A grid resolution of 5 m was adopted as it was sufficient to provide detail throughout the township and river channel whilst maintaining feasible run times.

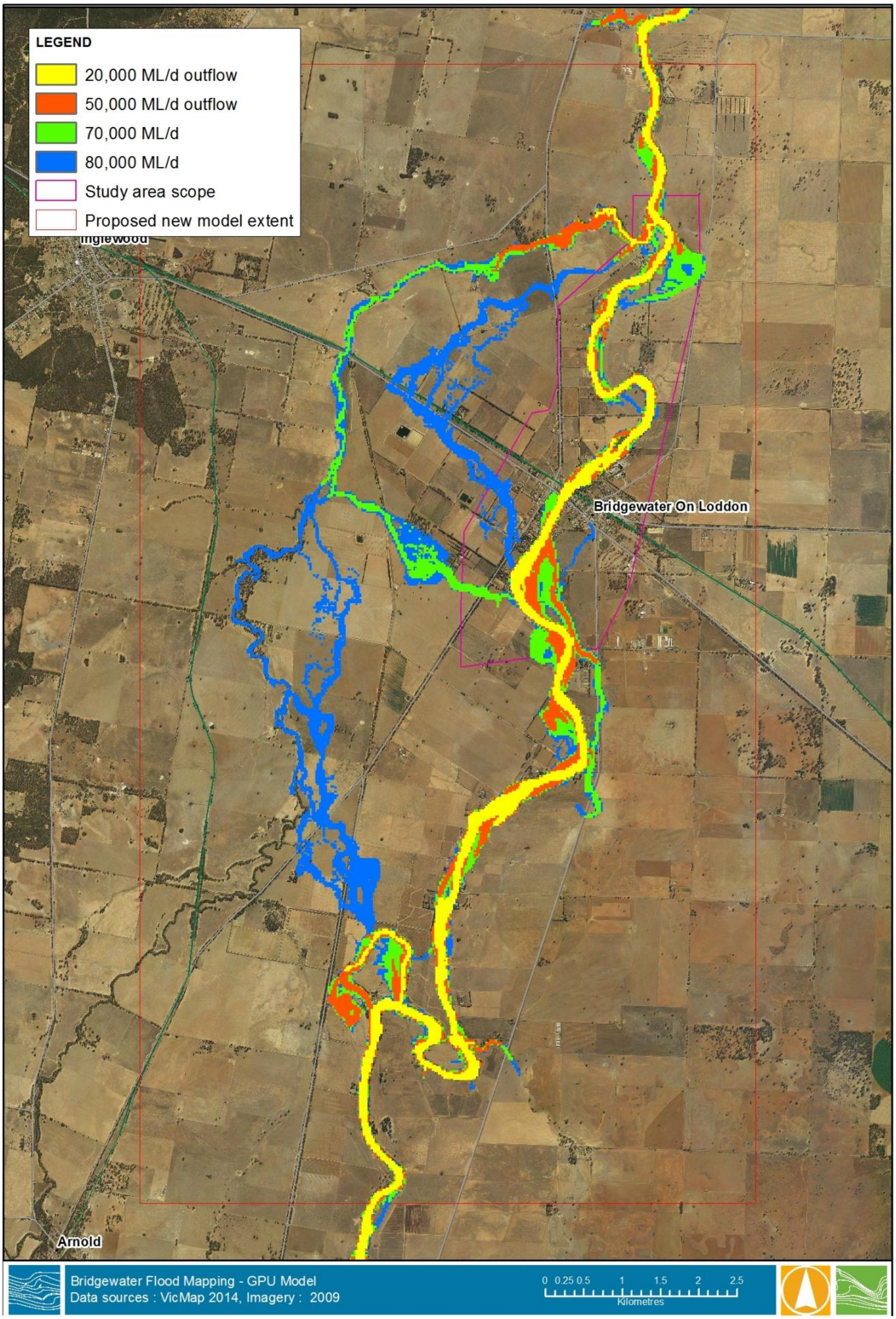


Figure 4-1 Flood extents for various Loddon River flows generated from preliminary rapid hydraulic modelling

4.1.2 Topography

A digital elevation model (DEM) was developed from a combination of LiDAR datasets which were verified by field survey (further details can be found in Section 2.4). Where datasets overlapped, preference was given to the lower dataset at that point, in order to provide the best channel representation. The resulting combined DEM was re-sampled to a 5 m grid.

As LiDAR is unable to penetrate water, none of the topographic data sets adequately represented the bathymetry of the Loddon River. Bathymetric survey was therefore used to develop a representation of the waterway capacity. The geometry of the channel between surveyed cross sections was modified to provide an estimate of the channel capacity. This is achieved in TUFLOW through the use of 'Z shapes'. Significant manual work went into defining this bathymetry, with upstream sections of the river near the Bullabul Creek breakout and sections downstream of the highway having islands and shallow benches etc. This achieved a far more accurate channel capacity than represented by the raw LiDAR.

4.1.3 Key Hydraulic Structures

Key hydraulic structures were simulated through the use of layered flow constrictions which enabled key features such as deck invert, obvert, pier blockage and losses to be accounted for.

Structures incorporated in this way included:

- The Calder Highway and adjacent railway bridge on the Loddon River;
- Sloans Road crossing on Bullabul Creek;
- Serpentine Road crossing on Bullabul Creek;
- The Calder Highway and adjacent railway crossing on Bullabul Creek;
- The Loddon Weir;
- The Calder Highway and railway crossing of Bullabul Creek

Details for these structures were developed from field survey and as-constructed drawings.

4.1.4 Boundary Conditions

Inflow boundaries were placed at eight locations in the model as 'SA Inflows' (i.e. flow across an area) to represent local catchment flows, Bullabul Creek flows and flow in the Loddon River. These hydrographs were obtained from the hydrology analysis and included rainfall-runoff modelling of Bullabul Creek and local catchment flows, Loddon River streamflow gauging and flood frequency analysis. The inflow boundaries can be seen in Figure 4-2, with external boundaries denoted as arrows, and local catchment contributions denoted as points.

The downstream end of the model utilised a "HQ" type boundary to allow the main flow out of the model which utilises the slope across the boundary and the model topography to estimate the rate at which water exits the model. The boundary location and level was initially developed from aerial photography showing the extent of water during the January 2011 flood event.

Several modifications of the downstream boundary were undertaken to maintain model stability, as a result of the relatively flat terrain and high volume of water spread across the model during large flood events. Several checks were undertaken to ensure these modifications did not impact on the results. As the downstream boundary is approximately 5 km downstream of the township, it was found that there were no impacts on water levels within or around the town.

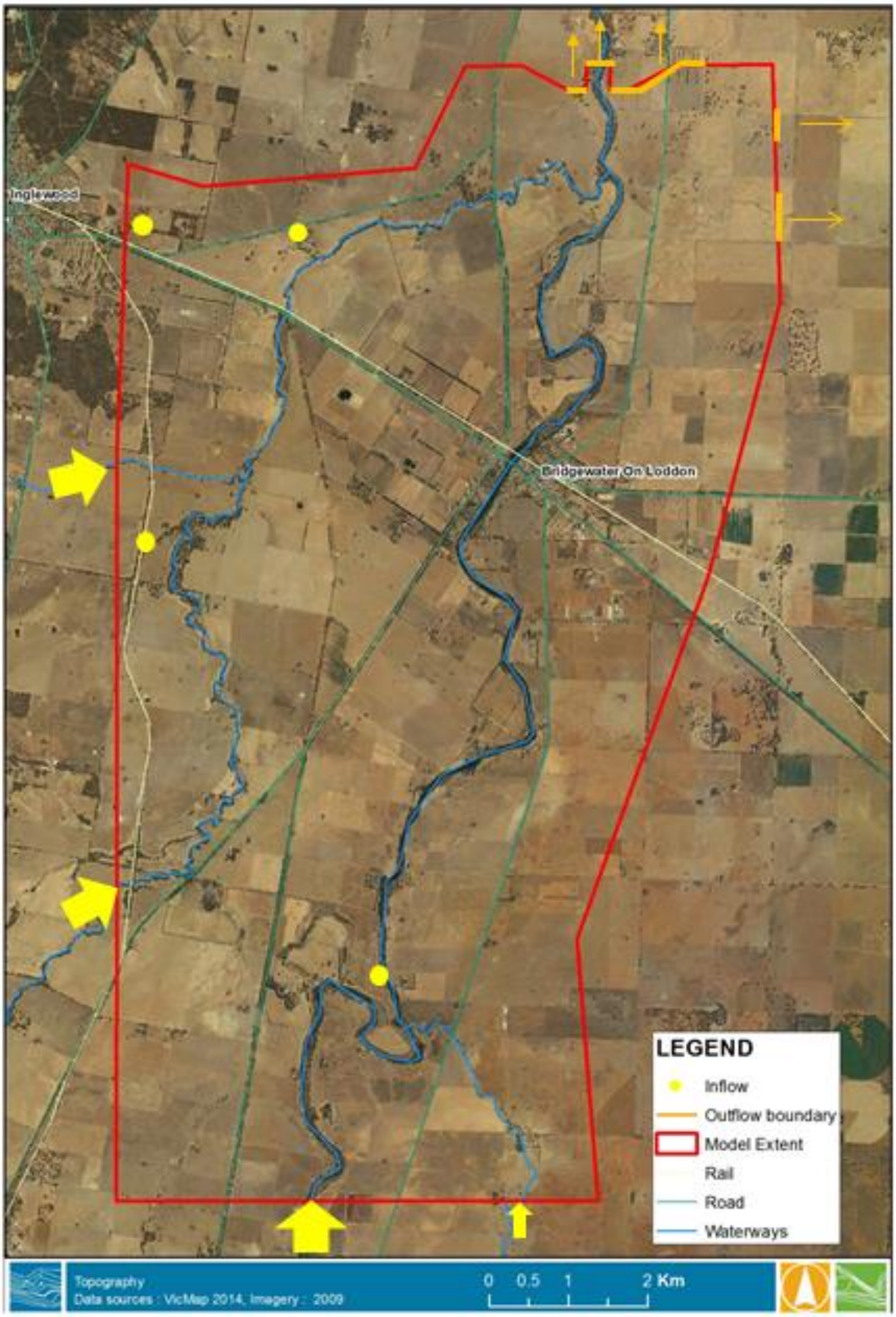


Figure 4-2 Inflow (yellow arrows/points) and downstream boundary (orange) locations of the hydraulic model

Hydraulic Roughness

Variations in the hydraulic roughness across the floodplain can be represented spatially as a 2D map. The hydraulic roughness (Manning's n) values for the floodplain were based on aerial photography, property parcel overlays and observations from the site inspection. Roughness categories used for the Bridgewater catchment are shown in Table 4-1 and Figure 4-3. These roughness values are well within the standard ranges expected for the relevant floodplain features. There are some areas of extremely densely vegetated waterway, particularly downstream of the weir which require a high roughness value. Residential areas have been assigned a high roughness value to model the combined effect of buildings and fences on slowing down the path of flood waters, but relatively speaking this roughness has less of an impact on overall flood levels as the velocity on the floodplain is slow. Roughness has a larger impact on water levels in areas of high velocity.

Table 4-1 2D hydraulic model roughness parameters consistent with standard values[11]

Land Use	Manning's n Roughness Coefficient
Commercial / Industrial buildings	0.350
Waterway (moderate vegetation)	0.055
Local and major roads	0.035
Railway Line	0.20
Waterway (dense vegetation)	0.20
Open waterways (no vegetation)	0.04
Farm/ grassed areas/ parks	0.05
Riparian fringe (dense vegetation)	0.08
Residential (Town Parcels)	0.30

Timestep

A time step of 2 seconds was adopted for this study. This means that during the model simulation the model will run the full suite of hydrodynamic calculations on every active wet cell, every 2 seconds of model time. In general, the smaller the grid cell size the smaller the timestep required for the model to run stable.

[11] Chow, 1959 – Open Channel Hydraulics

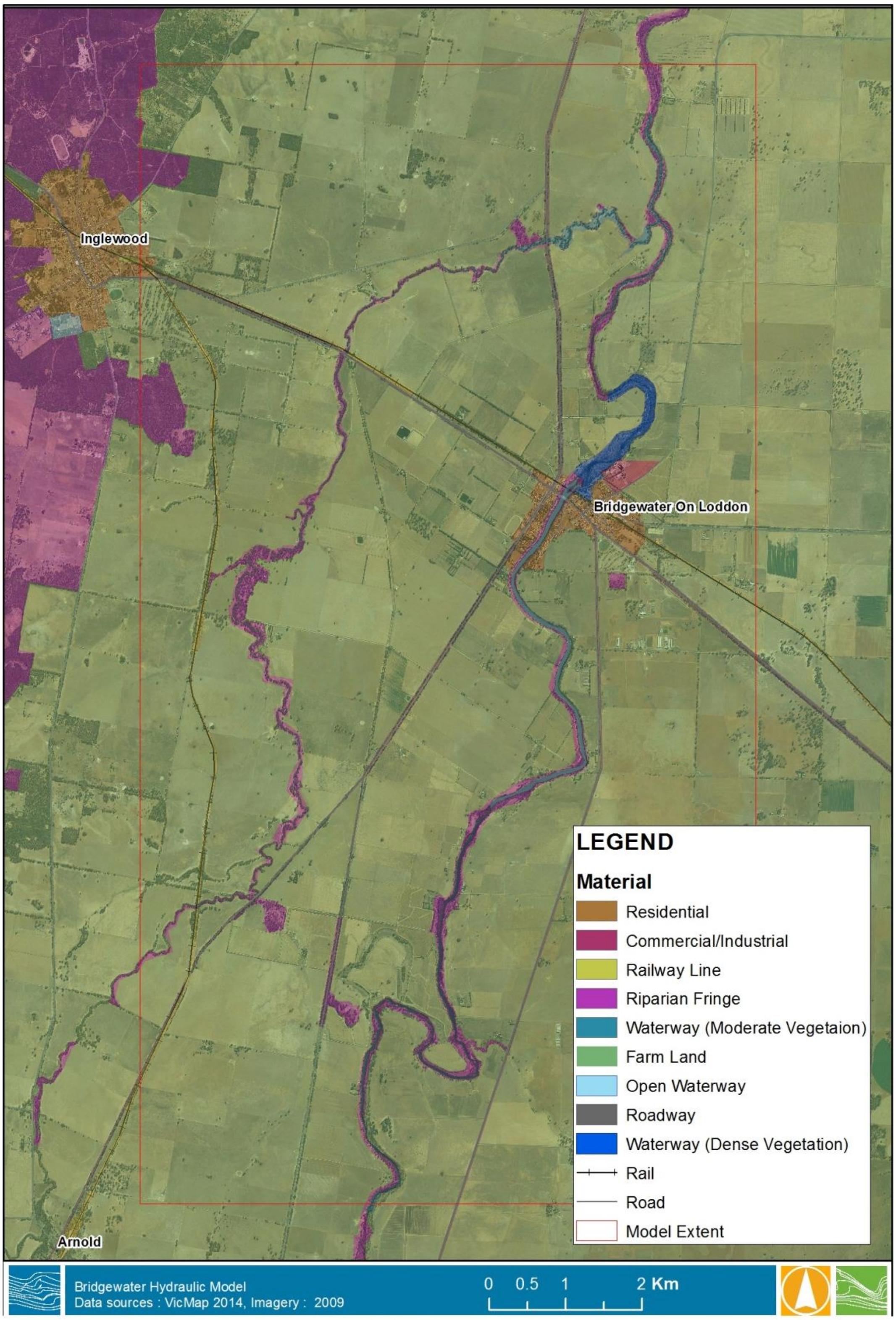


Figure 4-3 Manning's 'n' roughness coefficient values for the model extent

4.2 Hydraulic Model Calibration

This section details the calibration of the model to observed flood data. The model was calibrated to the recent flood event which occurred in January 2011, and the resulting model verified to the September 2010 and September 1983 events. Surveyed flood marks, general observations from local members of the steering committee and aerial flood imagery were used in the calibration.

The calibration of the model focused on the determination of Manning's n values for the river and floodplain, the representation of the bathymetry of the river and the incorporation of key hydraulic structures to achieve a reasonable agreement between observed and modelled flood levels.

4.2.1 January 2011 Event Calibration

A preliminary modelled flood extent for the January 2011 event was presented to the Steering Committee at a meeting held on 3 October 2014 and to local residents at a drop-in session on 7 November 2014. Feedback from these sessions, as well as responses to a flood intelligence questionnaire (provided to the Steering Committee), aerial photography, media articles and flood survey were used to refine the model.

Aerial photographs, such as those shown in Figure 4-4 and Figure 4-5 are invaluable to the calibration process. These photos are shown alongside the flood extent produced from modelling results and show a good calibration in regards to flood extent. It is rare to get such good coverage of observed flooding so close to the peak of the event, with these photos taken around 8-10 hours after the flood peak, however the flood extent is still visible in several locations. These photos (and many others) were used to validate the flood extent.

The preliminary model calibration aligned well with the anecdotal timing of the peak, with the model water level peaking in the Bridgewater Township at 4 am on the 15th January.

Feedback from the community drop-in session suggested the model was over estimating water levels in the Loddon River and under-estimating flow in Bullabul Creek. This variance was investigated further and the Loddon River bathymetry further refined in the area of the breakout. It was found that the first attempt at modifying the river bathymetry had removed a number of islands and was overestimating the rivers capacity, resulting in less water breaking out. Once this was rectified more water broke out of the Loddon River and flowed to Bullabul Creek.

The section of the Loddon River downstream of the weir was also further roughened to increase water levels at the downstream end (which were being under-estimated). Note that the hydraulic roughness, presented in Figure 4-3 above represents the final adopted roughness parameters.

There were originally some comments from residents suggesting the direction of flow within the floodplain between Bullabul Creek and the Loddon River was towards the Loddon River. This was in contrast to the model predictions, which indicated water was flowing from the Loddon River towards Bullabul Creek (albeit very slowly, with velocities of around 0.3 m/s). Given the importance of replicating flow behaviour (rather than just levels and timing), this was investigated further by approaching local residents within the area. A number of residents were able to confirm that the direction of flow was indeed from the Loddon River.

Anecdotal evidence received during community consultation as compared to model performance is provided in Table 4-2. The resulting calibrated flood extent can be seen in Figure 4-6. Five surveyed flood marks around Bridgewater were available for comparison to the model, as seen in Figure 4-7 and summarised in Table 4-3.

Table 4-2 Observed and modelled flood characteristics for January 2011 flood

Anecdotal Evidence	Model Comparison
Levels in the Loddon River overtopped the bank by around midday on Friday 14th Jan	Water overtops the eastern bank of the Loddon River between the highway and railway crossings at around 1pm on Friday 14th Jan
Water from the Loddon River reached the pub by early afternoon on Friday 14th Jan	Water levels in the Loddon River reached the pub by 3pm on Friday 14th Jan
At approximately 3am on Saturday 15th Jan water was flowing from the Maldon Road end of Bridgewater township across the highway and down the main street to join the river again at Lyndhurst St	The breakout from the Loddon River reaches the Highway (at the intersection with Bridgewater-Maldon Rd) at approximately 9pm on Friday 14th. The water then begins to flow down the main street around midnight Saturday 15th Jan.
Water levels peaked at the Lyndhurst St intersection around 12-1 am on Saturday 15th Jan	Water levels peak at Lyndhurst St intersection around 3 am on Saturday 15th Jan
Rising water levels slowed at around 4 am on Saturday 15th Jan	Water levels begin receding at 6 am on Saturday 15th Jan
Water levels in the caravan park peaked between 4 am and 5 am on Saturday 15th Jan	Water levels in the caravan park peak between 5 am and 6 am on Saturday 15th Jan
There was an estimated 300 mm head drop across the Calder Hwy bridge over the Loddon River	Modelled head drop across the Calder Hwy bridge was 400 mm

.

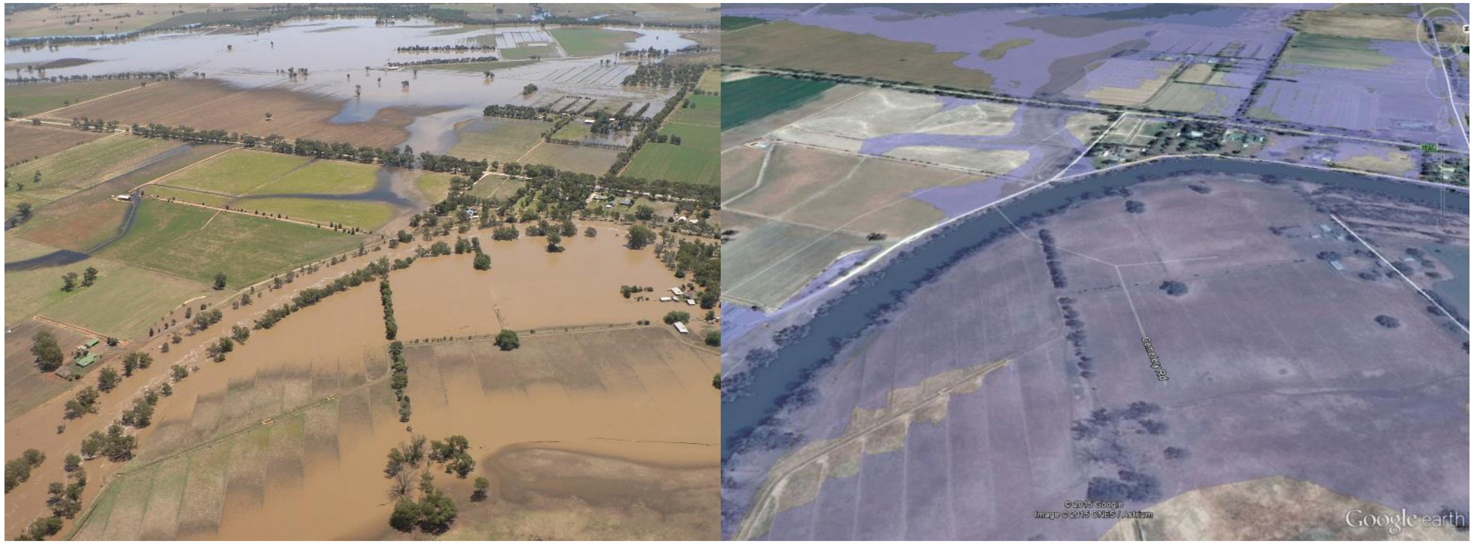


Figure 4-4 Bridgewater township on the 15th January 2011 looking north

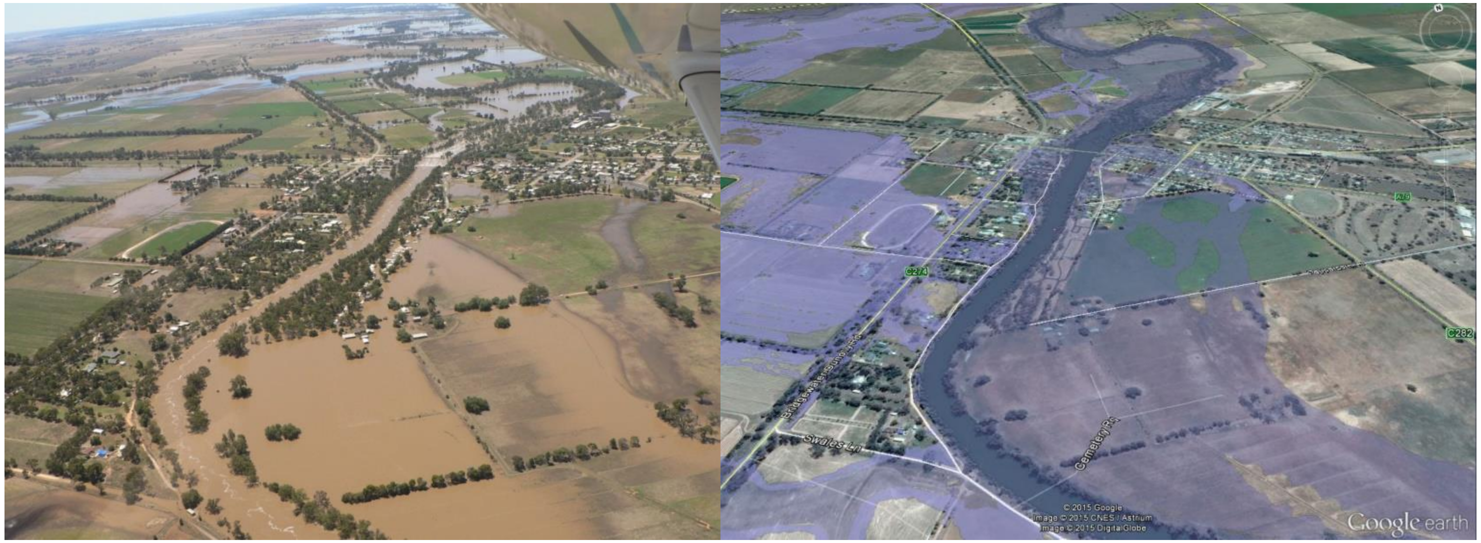


Figure 4-5 Bridgewater township on the 15th January 2011 looking North West

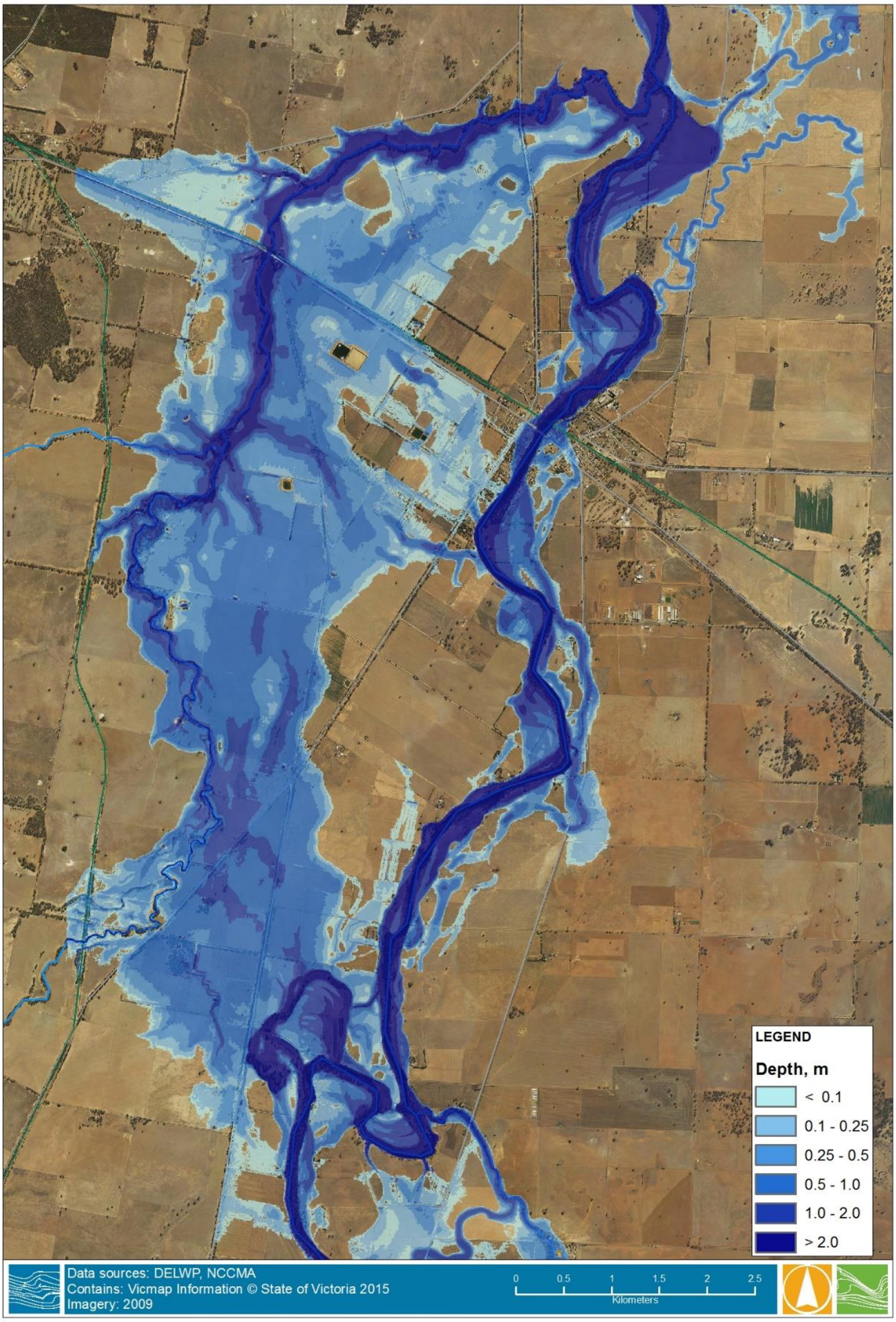


Figure 4-6 Calibrated January 2011 Flood Extent

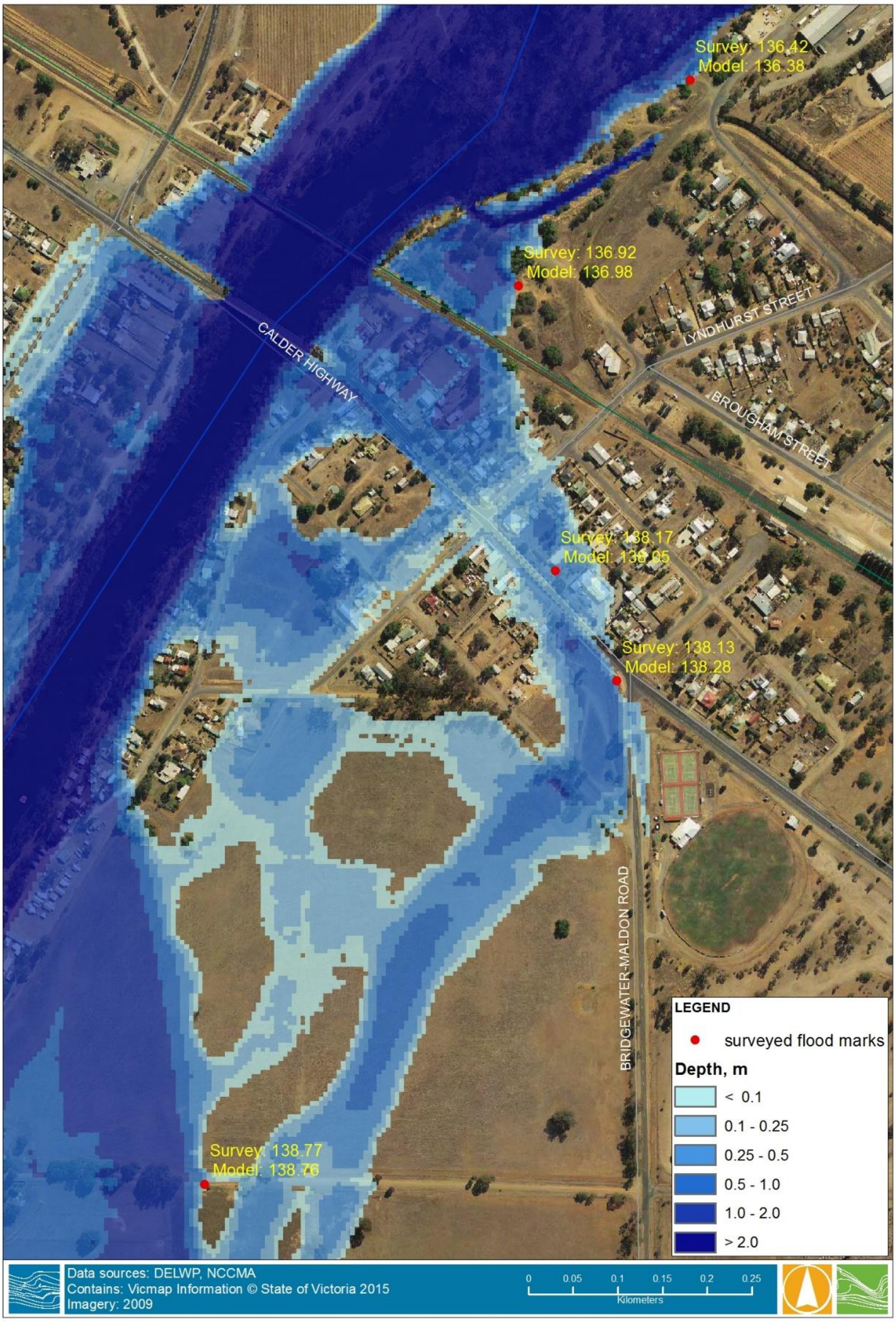


Figure 4-7 Surveyed and modelled flood levels for January 2011 flood event

Table 4-3 Modelled and surveyed flood levels for January 2011 flood event

Location	Modelled, m AHD	Surveyed, m AHD	Difference, m
Bridgewater-Maldon Rd cnr Calder Hwy	138.28	138.13	0.15
Lily St near flour mill	136.38	136.42	-0.04
Reserve behind Railway line (off Lyndhurst St)	136.98	136.92	0.06
Peppercorn Ln	138.76	138.77	-0.01
Bowling Club	138.05	138.17	-0.12

The modelled water levels are within 150 mm of the surveyed flood levels across all points. The survey point on the corner of the Bridgewater-Maldon Road and the Calder Highway is questionable, given the closest survey point downstream has a higher level. It's worth noting that the modelled water level at this point is above the surveyed and modelled level at the nearest downstream point.

Several other locations throughout the town had recorded anecdotal water levels, which were captured from personal photographs and the flood impact register undertaken by the Loddon Shire Council. These observed levels were able to provide further validation that the flood model was matching the January 2011 flood event well. At the Bridgewater Hotel, photographs show that water level appears 1-2 bricks above the floor level which was estimated at approximately 400 mm depth above ground level or 200-300mm above the floor level which was surveyed at 137.18 m AHD, giving an estimated flood level of 137.40-137.50m AHD. Model results show that around the hotel, flood levels were in the range of 137.38-137.42m AHD which matches well within the estimated flood level.

Figure 4-8 Bridgewater Hotel close to the peak of the January 2011 flood event

The Bridgewater bowls club also had observed flood levels from photographs just past the peak flood height. The photo shown in Figure 4-9 shows the peak flood level just under the level of the window sill. Using the surveyed floor level at the bowling club it was estimate that the flood level was approximately 750-900 mm above the ground level or 550-700 mm above floor level (136.94 m AHD) giving an approximate flood level of 137.50 – 137.65 m AHD. Modelling results showed that the peak water level at the bowling club was 137.47m AHD, close to the estimated flood level.

Figure 4-9 Bridgewater Bowling Club close to the peak of the January 2011 flood event

4.2.2 September 2010 Event Calibration

The resulting flood extent for the September 2010 event is shown in Figure 4-10. A number of surveyed flood marks were available, and have been compared to the modelled water surface elevations, as shown in Figure 4-11 and Table 4-4.

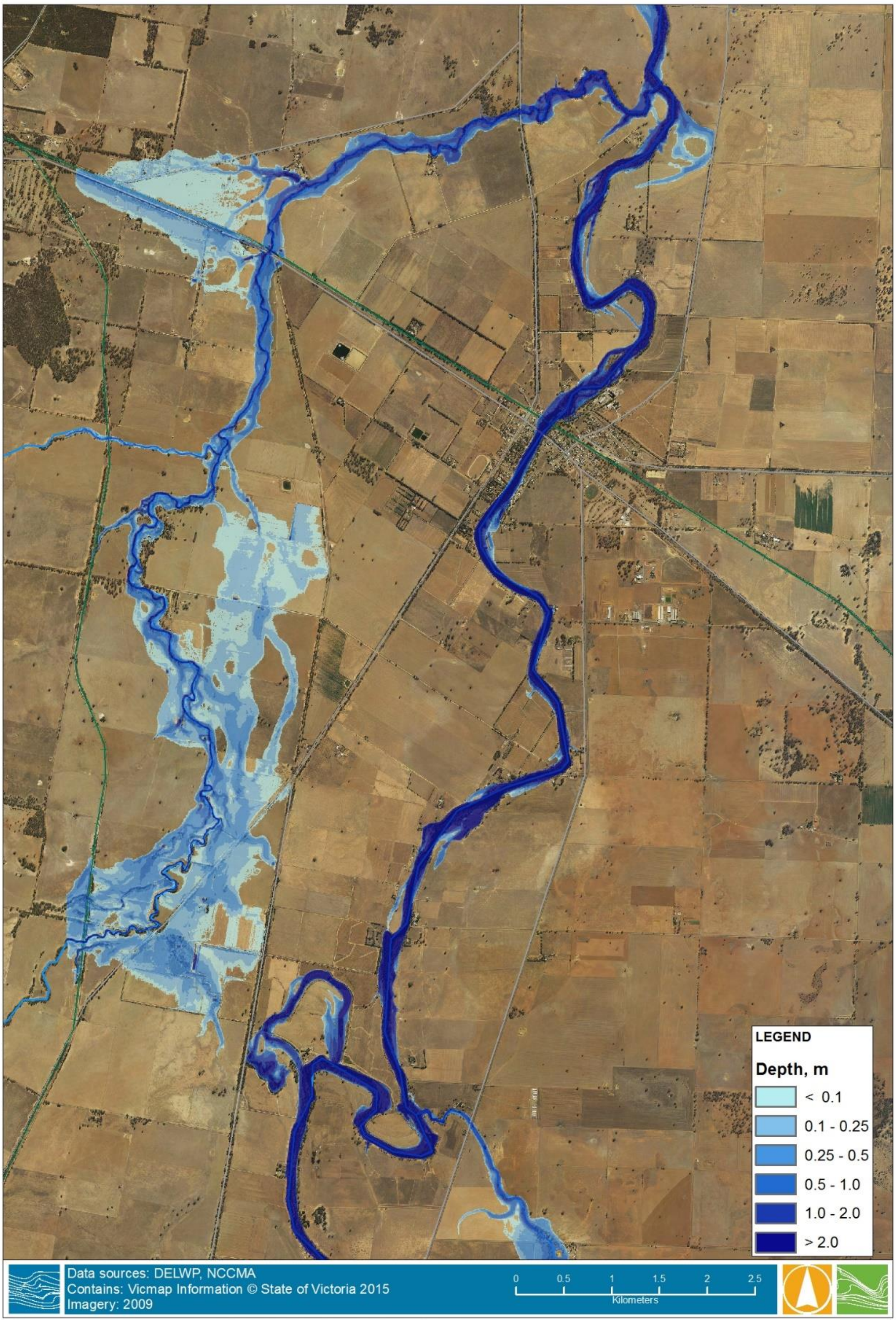


Figure 4-10 Calibrated September 2010 Flood Extent

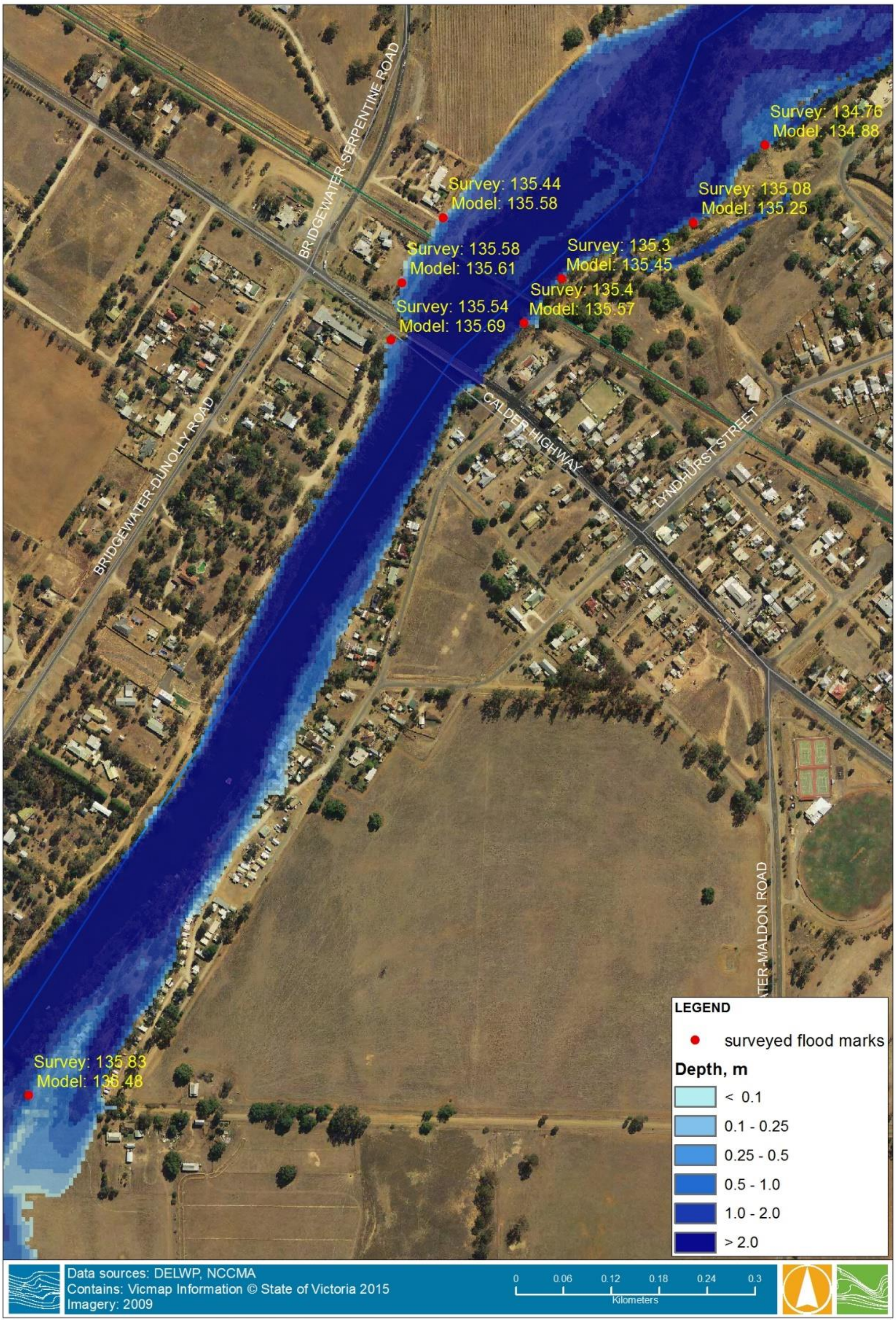


Figure 4-11 Surveyed and modelled flood levels for September 2010 flood event

Table 4-4 Modelled and surveyed flood levels for September 2010 flood event

Location	Modelled, m AHD	Surveyed, m AHD	Difference, m
Calder Hwy Bridge (west - upstream)	135.69	135.54	0.15
Calder Hwy Bridge (west – downstream)	135.61	135.58	0.03
Railway Bridge (west – downstream)	135.58	135.44	0.14
Caravan Park	136.48	135.83	0.65
Railway Bridge (east – upstream)	135.57	135.40	0.17
Railway Bridge (east – downstream)	135.45	135.30	0.15
Reserve downstream of weir (east)	135.25	135.08	0.17
Reserve near flour mill	134.88	134.76	0.12

The modelled water surface is within 200 mm of the surveyed levels in all locations except at the caravan park, though the reason for this localised discrepancy is unknown. The model appears to be slightly over-estimating flood levels for the September 2010 event, but given no bias appears in the calibration of the January 2011 event, this is not a large concern.

4.2.3 September 1983 Event Calibration

The resulting flood extent for the September 1983 event is shown in Figure 4-12. Four surveyed flood marks were available, and have been compared to the modelled water surface elevations, as shown in Figure 4-13 and Table 4-5.

Table 4-5 Modelled and surveyed flood levels for September 1983 flood event

Location	Modelled, m AHD	Surveyed, m AHD	Difference, m
Loddon River – upstream Bridgewater	141.75	139.63	2.12
Loddon weir – upstream	135.85	135.24	0.61
Calder Hwy – downstream bridge	135.97	135.75	0.22
Loddon River – downstream flour mill	134.19	135.24	-1.05

It is likely that there is a survey error in the point downstream of the flour mill, as the surveyed level indicates no grade in water surface from the Loddon Weir (approximately 1km upstream). LiDAR data indicates a normal difference in water level between these points of approximately 4 m. The difference in water surface elevation across these points for the calibrated January 2011 flood event is 1.9 m, hence the modelled grade in water surface for the September 1983 event (between a 2% and 5% AEP flood event) seems reasonable.

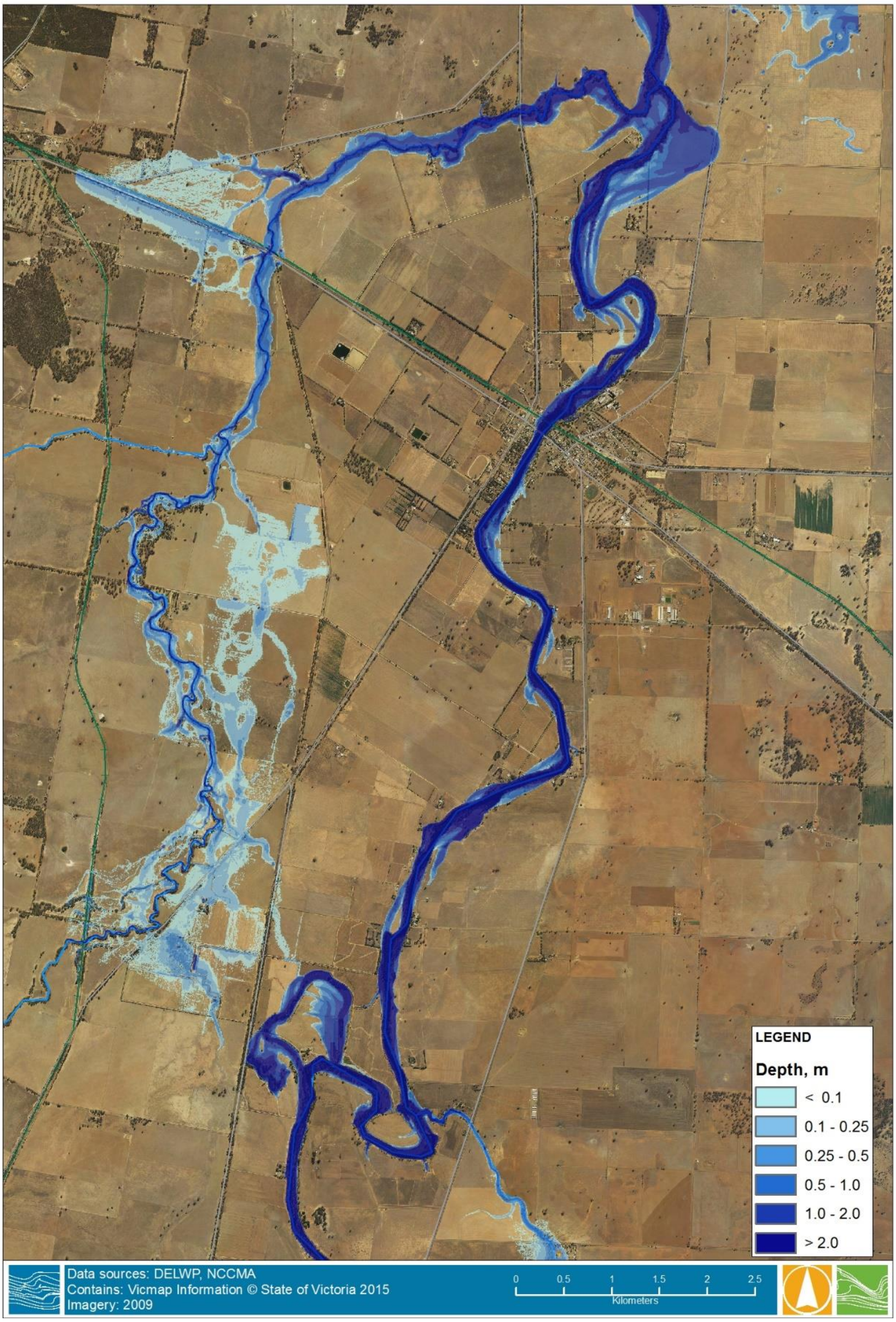


Figure 4-12 Calibrated September 1983 Flood Extent

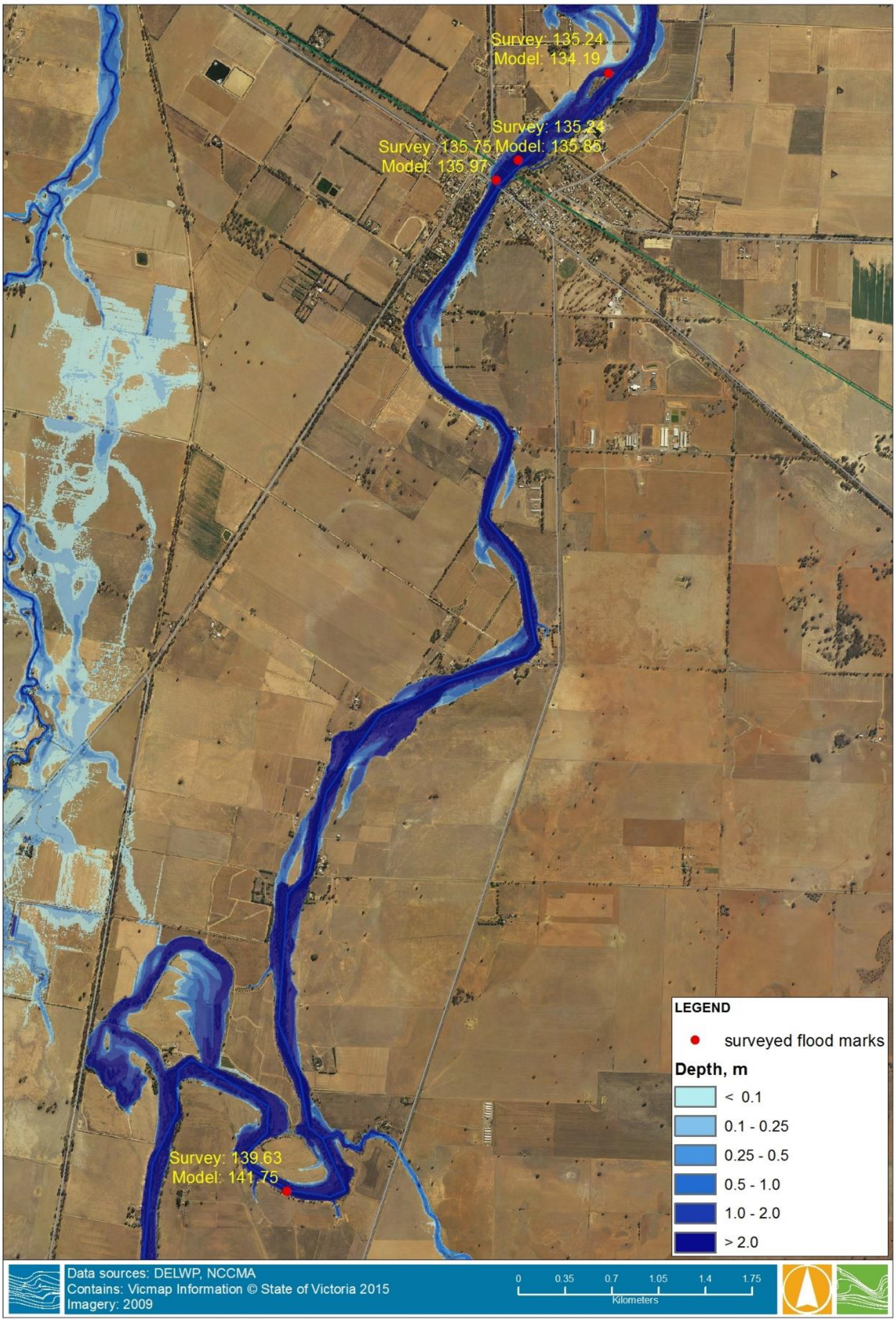


Figure 4-13 Surveyed and modelled flood levels for September 1983 flood event

4.3 Design Flood Modelling

Utilising input from the hydrology model, the design flood events were mapped for the 20%, 10%, 5%, 2%, 1%, 0.5% and 0.1% AEP flood events.

4.3.1 Design Flood Extents

A suite of flood maps showing the maximum depths, water surface elevations and flood extents have been produced, as shown in Appendix B. The overlayed design flood extents for the study area can be seen in Figure 4-14, and around Bridgewater in Figure 4-15.

Long-sections of the Loddon River and Bullabul Creek were developed to show the water level profile and the impact of structures on a range of AEP events. The length of the Loddon River was split into 2 (for enhanced visualisation), and can be seen in Figure 4-16 and Figure 4-17, while Bullabul Creek can be seen in Figure 4-18. The long sections were extracted along the centreline of the waterway. Horizontal lines on the graphs denote the level of the road/bridge deck at that location.

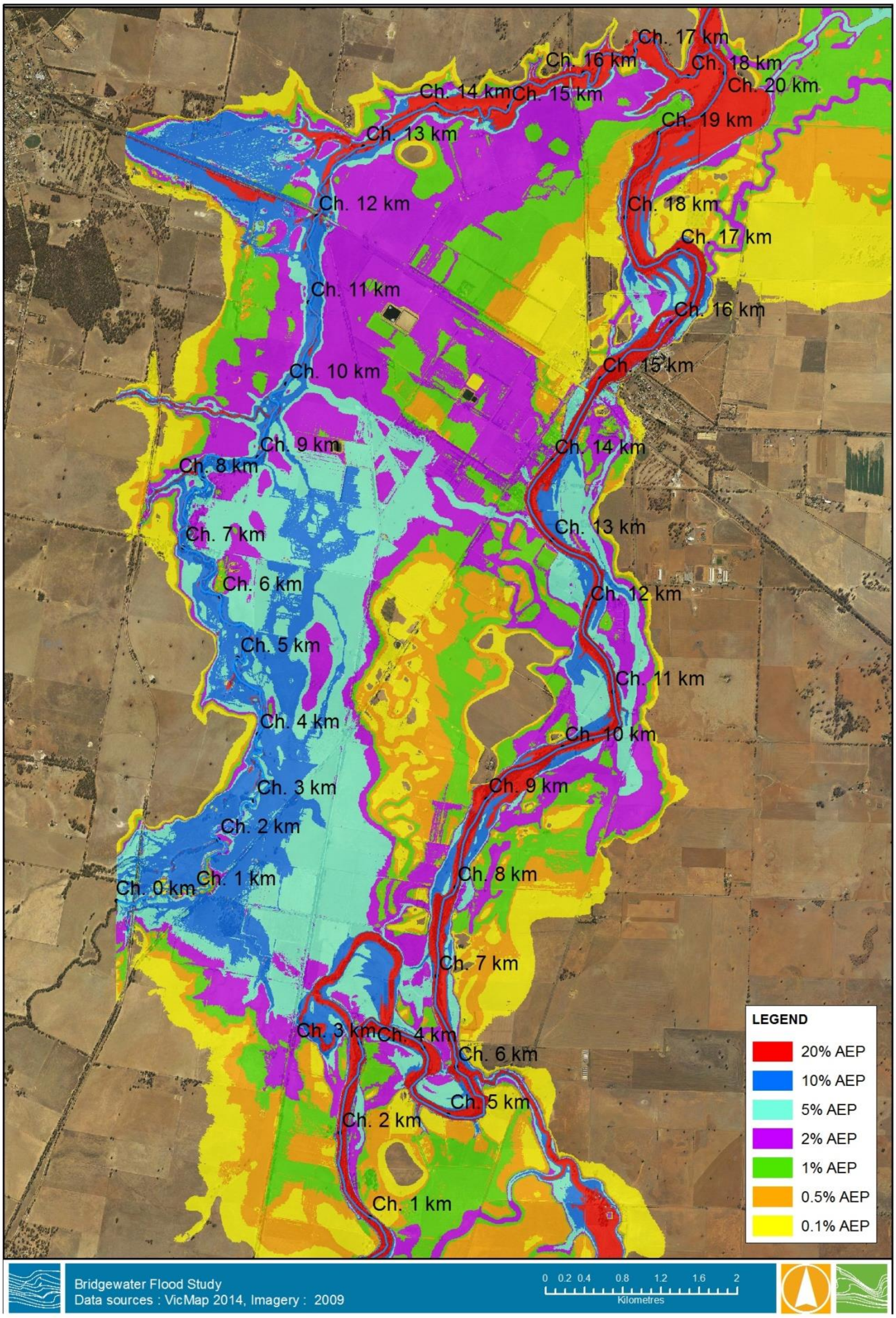


Figure 4-14 Design flood extents across the study area

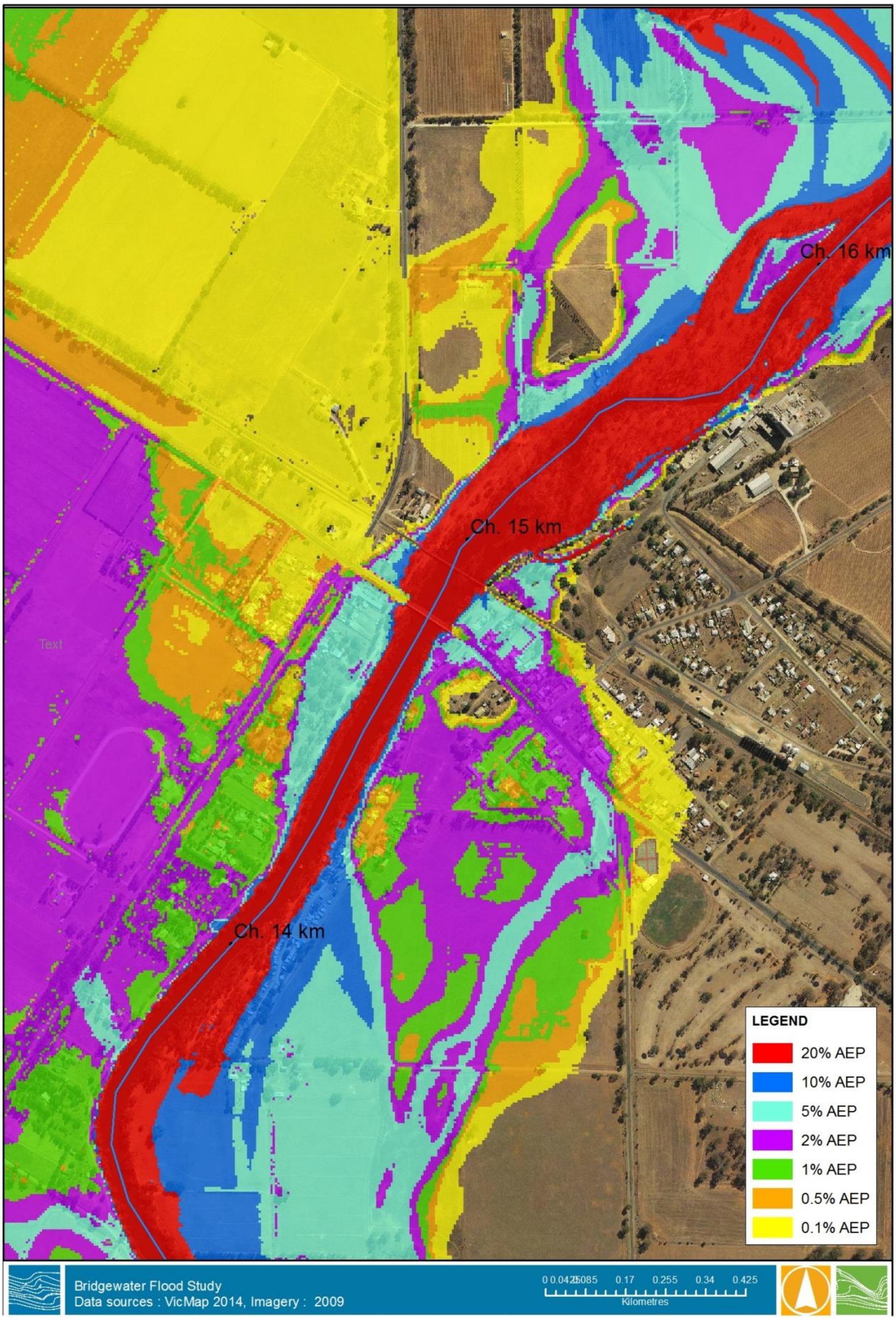


Figure 4-15 Design flood extents for the Bridgewater township

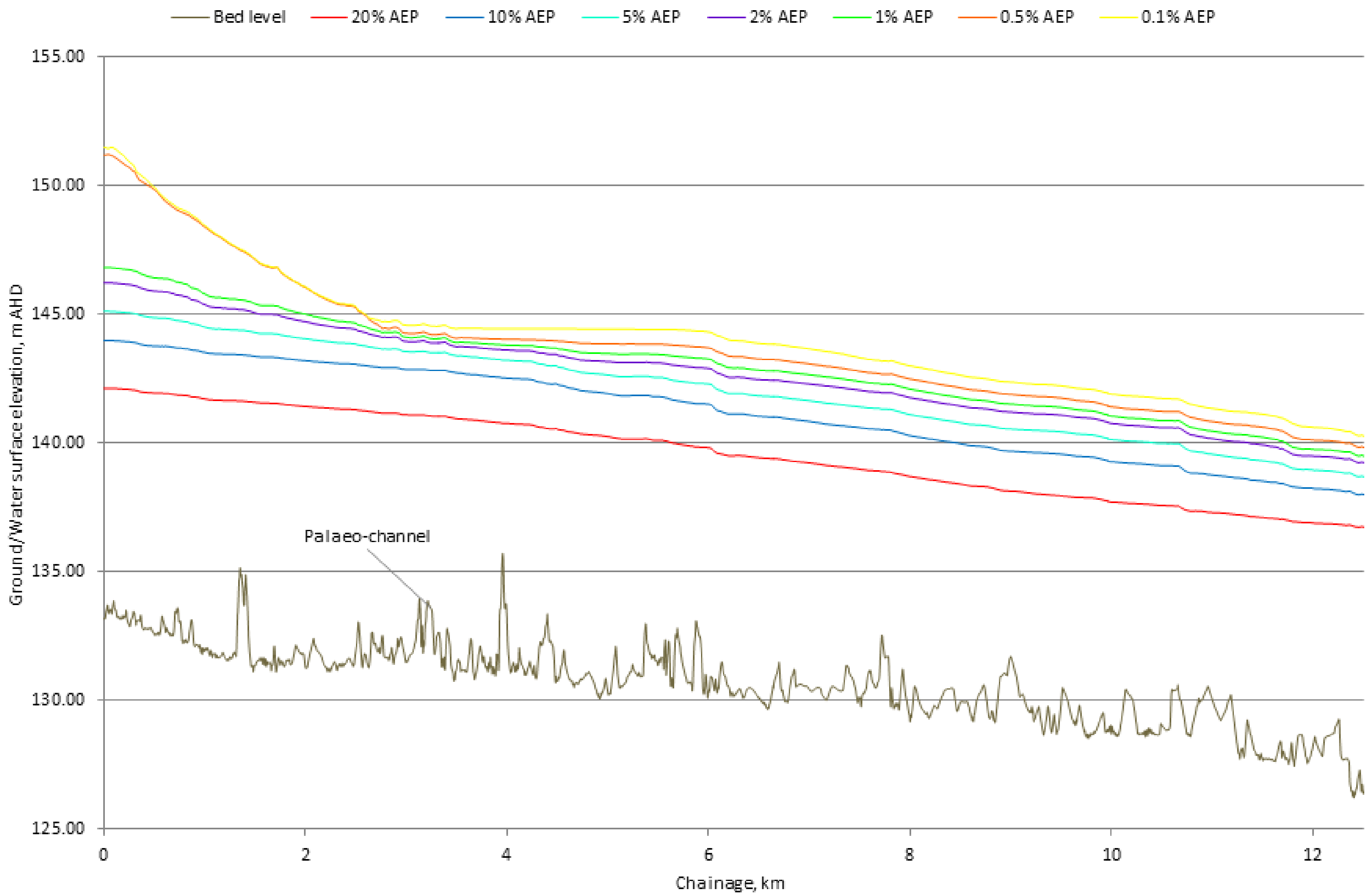


Figure 4-16 **Long section of the Loddon River showing modelled flood levels for a range of design flood events (1 of 2)**

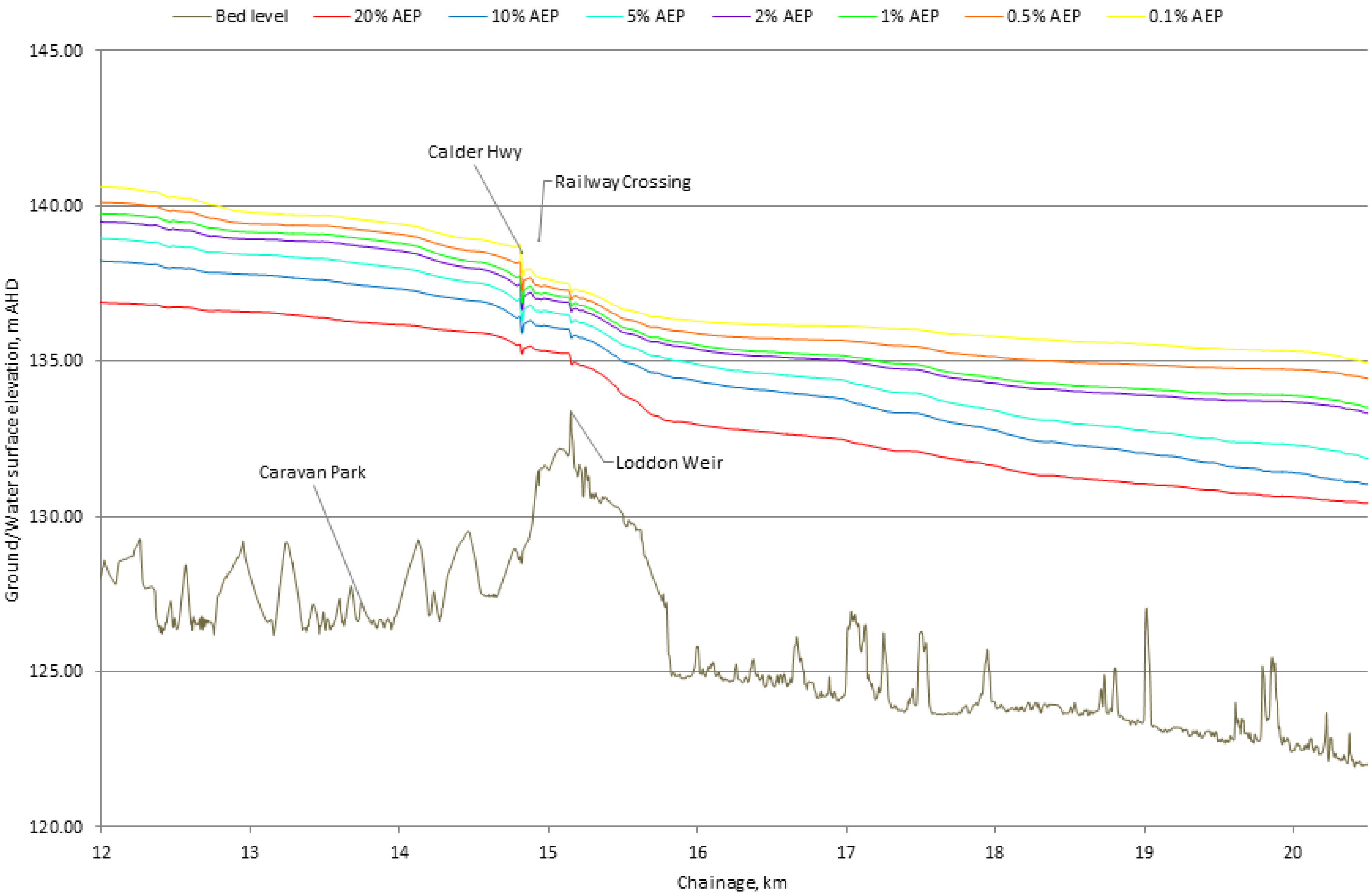


Figure 4-17 **Long section of the Loddon River showing modelled flood levels for a range of design flood events (2 of 2)**

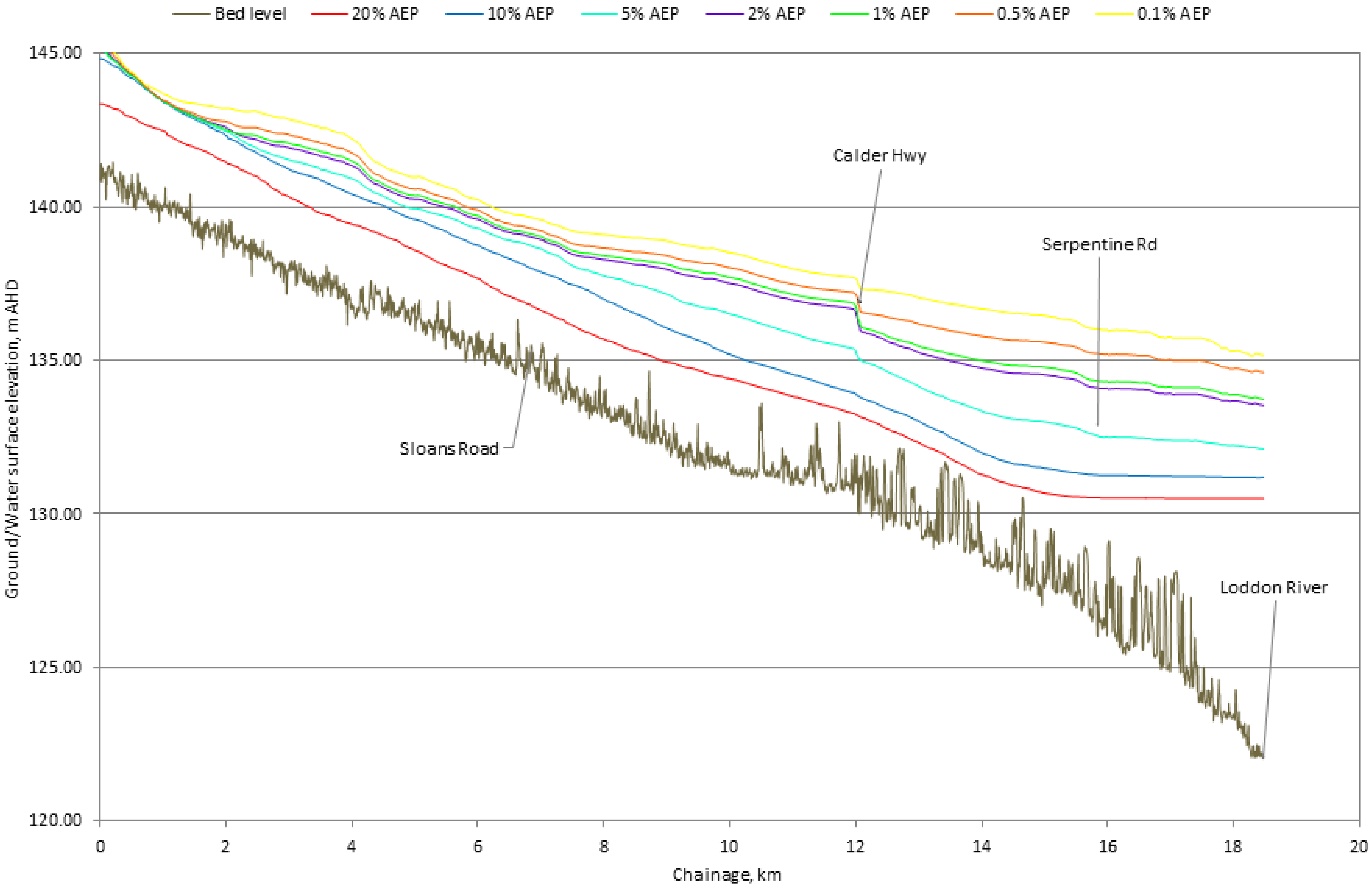


Figure 4-18 Long section of Bullabul Creek showing modelled flood levels for a range of design flood events

4.3.2 Design Flood Behaviour

The following comments describe the key flood characteristics within the study area for each design event. Note that this is taken further in the Municipal Flood Emergency Plan, consequence table and property table, which included details regarding which properties are impacted above and below flood level for different AEP design events as well as a detailed list of road closures, etc. The below description should be read in conjunction with the maps presented in Appendix B. The below description lists incremental changes from the lesser events to the larger magnitude events, so if the reader seeks to understand the impacts of a 2% AEP event they should read first the 20% AEP through to the 2% AEP event in order of increasing magnitude. The description of lesser events can also be used to identify the first impacts of a larger event.

20% AEP Event

- Water breaks out from Loddon River into the palaeo-channel, but does not spread out across the floodplain
- The south-western corner of the caravan park and approximately 70 m of the western end of Peppercorn Lane becomes inundated up to depths of 2.3 m
- Bullabul Creek breaks out onto the floodplain in low locations from the highway down to the confluence with the Loddon River, but is otherwise contained within bank

10% AEP Event

- Flow from the paleo-channel breaks out and shallowly flows across the floodplain to Bullabul Creek, inundating the Bridgewater-Newbridge Road and the Bridgewater-Dunolly Road to a maximum of 300 mm
- Bullabul Creek and Loddon River flows shallowly inundate farmland along the Bullabul Creek floodplain between the Bridgewater-Dunolly Road and the Calder Highway (approximately 150 mm deep)
- The caravan park is entirely inundated, with depths between 0.4 and 3.5 m
- House at the end of Peppercorn Lane becomes isolated by floodwaters
- Breakouts from the Loddon River to the west begin to inundate properties along the Bridgewater-Dunolly Road, for approximately 300 m upstream of the Calder Highway.

5% AEP Event

- Flood flows break from the Loddon River to the north-east approximately 4 km upstream of Bridgewater, flowing along Bridgewater-Maldon Road and then overland to the north-west, re-joining the Loddon near the caravan park
- Floodwaters inundate Peppercorn Lane and flow directly through the caravan park, to hazardous depths and velocities.
- The floodplain between Bullabul Creek and the Loddon River (near the palaeo-channel) is widely inundated with flows breaking out of the Loddon River, resulting in widespread flooding across both the Newbridge-Bridgewater road and Bridgewater-Dunolly Road (depths up to 0.6 m)
- Park Street is inundated from Camp Street to the highway with water spilling over the highway and through to the railway line, inundating the area from the Bridgewater Hotel to almost Lyndhurst Street
- Properties along Bridgewater-Dunolly Road to the west of the Loddon River are entirely inundated by floodwaters.

2% AEP Event

- Water from Bullabul Creek initially banks up behind the highway and railway and flows towards Bridgewater, with a breakout from the Loddon River to the north west at Pondage Road then pushing back toward Bullabul Creek
- Almost the entire floodplain between the Bridgewater-Dunolly Road and Bullabul Creek upstream of the highway is inundated
- Breakout from the Loddon River to the north-east isolates the poultry farm south of Bridgewater.
- Another breakout from the Loddon River to the north-east flows to the intersection of the Bridgewater-Maldon Road and the Calder Highway before flowing in a north westerly direction down the Calder Highway to Lyndhurst Street
- The Calder Highway is overtopped along an approximate 1.5 km length between the Loddon River and Bullabul Creek as well as between the Loddon River and the Bridgewater-Maldon Road
- Flood waters are level with the bridge deck at Sloans Road on Bullabul Creek
- The Serpentine Road crossing on Bullabul Creek is overtopped by 1.02 m
- Properties east of the Loddon River, between the railway and Calder highway (up to Erskine St) are inundated up to 0.5 m
- Park Street inundated from Sugar Gum Drive to the Calder Highway
- Large parts of the town is now isolated on both banks of the Loddon River

1% AEP Event

- Sloans Road on Bullabul Creek is overtopped by 0.1 m
- Serpentine Road on Bullabul Creek is overtopped by 1.43 m
- Similar flood behaviour as previous event only larger inundation area and deeper flooding
- Almost all properties on the Bridgewater-Dunolly Road are now inundated
- The majority of the township is inundated
- The current farm land with planning permit to subdivide between Peppercorn Lane and Sugar Gum Drive is inundated
- The Bridgewater-Maldon Road is overtopped with flooding around the tennis courts and the football oval

0.5% AEP Event

- Sloans Road on Bullabul Creek is overtopped by 0.28 m
- Serpentine Road on Bullabul Creek is overtopped by 1.46 m
- The majority of the township is inundated

0.1% AEP Event

- Sloans Road on Bullabul Creek is overtopped by 0.65 m
- Serpentine Road on Bullabul Creek is overtopped by 3.14 m
- The majority of the land south of the railway line from the football oval to Bullabul Creek is inundated

4.4 Hydraulic Analysis Summary

The calibration of the model to the January 2011 event demonstrated that the model is capable of accurately predicting the flood levels, extents and timing of flooding through the township and broader floodplain.

Validation to the September 2010 and September 1983 flood events further confirmed the capability of the model to replicate flood extents and levels.

The calibrated hydraulic model has been used to develop design flood extents for the 20%, 10%, 5%, 2%, 1%, 0.5% and 0.1% AEP flood events. The results indicate that the low lying areas including the caravan park begin to be inundated in events as frequent as the 20% AEP event. Flows begin to breakout of the Loddon River from the paleo-channel to Bullabul Creek in frequent events like a 10% AEP event, with another breakout from the Loddon River to the east entirely inundating the caravan park. Floodwaters break out on the eastern side of the Loddon across Park Street inundating parts of the town in floods greater than the 5% AEP event. In the 2% AEP event a breakout from the Loddon further upstream flows toward the Bridgewater-Maldon Road interacts with the Calder Highway and flows back through town returning to the Loddon River, inundating many properties along the way. The floodplain between the Loddon River and Bullabul Creek becomes entirely engaged in events larger than or equivalent to the 1% AEP flood event, similar in magnitude to the January 2011 event.

5. FLOOD MITIGATION

This section provides an overview of the mitigation options considered to reduce the flood risk and flood damages in Bridgewater. The options are divided into structural (i.e. physical works) and non-structural mitigation options (i.e. planning, warning and response actions). It should be noted that flood warning was not a major item in the scope and as such only a cursory discussion has been provided.

5.1 Structural Mitigation Options

The aim of structural mitigation works is to reduce the flood risk in Bridgewater and protect, where feasible, vulnerable buildings and infrastructure. Protection of a 1% AEP event is typical, and has been adopted for this study.

Possible mitigation options, detailed in Table 5-1 were derived from suggestions from community members during the drop-in session, discussion with the Steering Committee and inspection of the flood modelling results by Water Technology.

Table 5-1 Potential mitigation options initially considered

Option No.	Detail	Source
1a	Culverts/bridge on the railway line behind the bowling club *Purpose:* improve conveyance across the railway line to lessen the impact of breakout flow from Peppercorn Lane which travels down the highway through the township. It is thought that the railway embankment currently impedes flow and causes increased flood levels in the township	Steering Committee
1b	Culverts/bridge on railway line near the corner of Park Street and Eldon Street *Purpose: improve conveyance across the railway line to prevent water level build up in the floodplain between the highway and railway line*	Water Technology
2	Increase capacity of the Calder Highway bridge *Purpose:* improve conveyance under the Calder Highway and lessen upstream water levels	Steering Committee & community
3	Levee along northern side of Peppercorn Lane *Purpose:* prevent breakout flows from Loddon river travelling across farmland towards highway	Steering Committee
4	Levee on eastern bank of Loddon River in front of the caravan park *Purpose:* protect caravan park and residential properties on Park Street	Water Technology
5	Create a flow diversion from Loddon River to Bullabul Creek *Purpose:* reduce flow (and levels) in the Loddon River	Community

6	Managed aquifer recharge *Purpose:* reduce flood volume by storing floodwaters in underground aquifers	Steering Committee
7	Series of culverts under the highway and railway between Bullabul Creek and the Loddon River *Purpose:* improve conveyance across the floodplain and prevent water backing up behind the highway	Steering Committee

5.2 Structural Mitigation Option Prefeasibility Assessment

Each mitigation option was assessed against a number of criteria: potential reduction in flood damage, cost of construction, feasibility of construction, and environmental impact. The score for each criterion was based on a ranking system of 1 to 5, with 1 being the worst score and 5 the best. Each criteria score was then weighted according to the weighting shown in Table 5-2. The reduction in flood damage was the most heavily weighted criteria as this is really the main objective for all flood mitigation. Table 5-3 reviews and scores each mitigation option against the four criteria and calculates a total score for each option. The options with the higher scores indicate the more appropriate mitigation solutions for Bridgewater. While these options were reviewed and scored individually it is important to consider a combination of options when developing a flood mitigation scheme.

Using the prefeasibility assessment above, the 8 identified mitigation options are listed in order of total weighted score as seen in Table 5-4.

Table 5-2 Ranking score for mitigation criteria

Score	Reduction in Flood Damages	Cost ($)	Feasibility/ Constructability	Environmental Impact
Weighting	**2**	**1**	**0.5**	**0.5**
5	Major reduction in flood damage	Less than $ 50,000	Excellent (Ease of construction and/or highly feasible option)	None
4	Moderate reduction in flood damage	$ 50,000 – $ 100,000	Good	Minor
3	Minor reduction in flood damage	$ 100,000 – $ 500,000	Average	Some
2	No reduction in flood damage	$ 500,000 – $ 1,000,000	Below Average	Major
1	Increase in flood damage	Greater than $ 1,000,000	Poor (No access to site and/or highly unfeasible option)	Extreme

Table 5-3 Mitigation option prefeasibility list

No.	Works Location	Mitigation Option	Criteria					Score
			Damage Reduction	Cost	Feasibility/ Constructability	Environmental Impact	Comments	
1a	Railway behind bowling club	Culverts/bridge on the railway line behind the bowling club *Purpose:* improve conveyance across the railway line to lessen the impact of breakout flow from Peppercorn Lane which travels down the highway through the township.	2	2	4	4	• It was thought that the railway embankment currently impedes flow from the breakout at Peppercorn Lane, however modelling shows this isn't the case • The railway impedes flow closer to the Loddon River	10
1b	Railway line on eastern bank of Loddon River	Culverts/bridge on railway line near the corner of Park Street and Eldon Street *Purpose: improve conveyance across the railway line to prevent water level build up in the floodplain between the highway and railway line*	3	2	4	4	• Costs to undertake works on the railway are not as prohibitive as usual given the railway line is not currently in use	12
2	Calder Hwy bridge	Increase capacity of the Calder Highway bridge *Purpose:* improve conveyance under the Calder Highway and lessen upstream water levels	3	1	3	4	• Approximately 300 mm head drop across the Calder Hwy bridge indicates some potential for reduced flood levels • Very expensive to carry out works on a major road	10.5
3	Peppercorn Ln	Levee along northern side of Peppercorn Lane *Purpose:* prevent breakout flows from Loddon river travelling across farmland towards highway	4	3	3	4	• Would need to be quite long (650 m) and high in parts • Protect eastern side of the township	14.5
4	Caravan Park	Levee on eastern bank of Loddon River in front of the caravan park *Purpose:* protect caravan park and residential properties on Park Street	4	3	3	3	• Community may be opposed to changed amenity • Will potentially increase water levels on the western side of the river	14
5	From palaeo-channel to	Create a flow diversion from Loddon River to Bullabul Creek *Purpose:* reduce flow (and levels) in the Loddon River	4	2	2	3	• Would require land acquisition or agreement with land-holders	12.5

	Bullabul Creek						• May have undesirable impact on properties adjacent to Bullabul Creek	
6	n/a	Managed aquifer recharge *Purpose:* reduce flood volume by storing floodwaters in underground aquifers	2	1	1	2	• An un-realistic pumping rate would be required to reduce the flooding volume; and would need to be automated • There are strict guidelines about the quality of water that can be injected into aquifers	6.5
7	Calder Hwy & railway between Bullabul Ck and Loddon River	Series of culverts under the highway and railway between Bullabul Creek and the Loddon River *Purpose:* improve conveyance across the floodplain and prevent water backing up behind the highway	3	3	3	4	• Would require a long bank (200 m) of small culverts as there is limited cover	12.5

Table 5-4 Ranked mitigation options

Rank	Mitigation Option	Weighted Score
1	Peppercorn Lane levee	14.5
2	Caravan Park levee	14
3	Flow diversion from Loddon River to Bullabul Creek	12.5
4	Culverts along the Calder Hwy and Railway between Bullabul Creek and the Loddon river	12.5
5	Culverts under the railway line on the eastern bank of the Loddon River	12
6	Upgrade of the Calder Hwy bridge	10.5
7	Culverts under the railway behind the bowling club	10
8	Managed aquifer recharge	6.5

5.3 Structural Mitigation Options Modelled

Preliminary modelling was undertaken to analyse the potential for proposed mitigation options to have an impact on flood levels and extents. Three scenarios were modelled, to assess the impact of:

1. Increasing the conveyance across the Calder Highway and Eaglehawk-Inglewood Rail line;
2. Diverting flow from the Loddon River to Bullabul Creek via a diversion channel; and
3. Constructing a levee along Peppercorn Lane and along the front of the caravan park.

In modelling these options, the approach was to start with extreme changes to determine if the proposed option could achieve a positive outcome, and then to refine (and downscale) the option accordingly.

5.3.1 Package 1

Package 1 involved the removal of the entire length of the Calder Highway and Eaglehawk-Inglewood Rail line. This was to assess the impact of increasing conveyance through these crossings. While unrealistic, it provides an indication of the types of changes to flood levels and extents that could be achieved through, for example, increasing the flow area under the bridges and/or introducing additional crossings (either culverts or bridges).

Topographic features of the highway and rail corridors were removed from the model, and surface elevations interpolated from the adjacent floodplain.

Results

The removal of the two crossings had the impact of reducing flood levels upstream of the Calder highway by up to 5 cm locally, and 2 cm for up to 2 km upstream. The extent, however, remained largely unchanged, with flow still breaking out around to the east of the town.

The changes also had the impact of increasing water levels downstream of the railway by more than 5 cm in some locations.

The difference in water surface elevation between the mitigation package and existing conditions can be seen in Figure 5-1. Given that removing the entire two crossings had an impact of reducing levels generally by less than 2 cm, it was considered not feasible to pursue the option further.

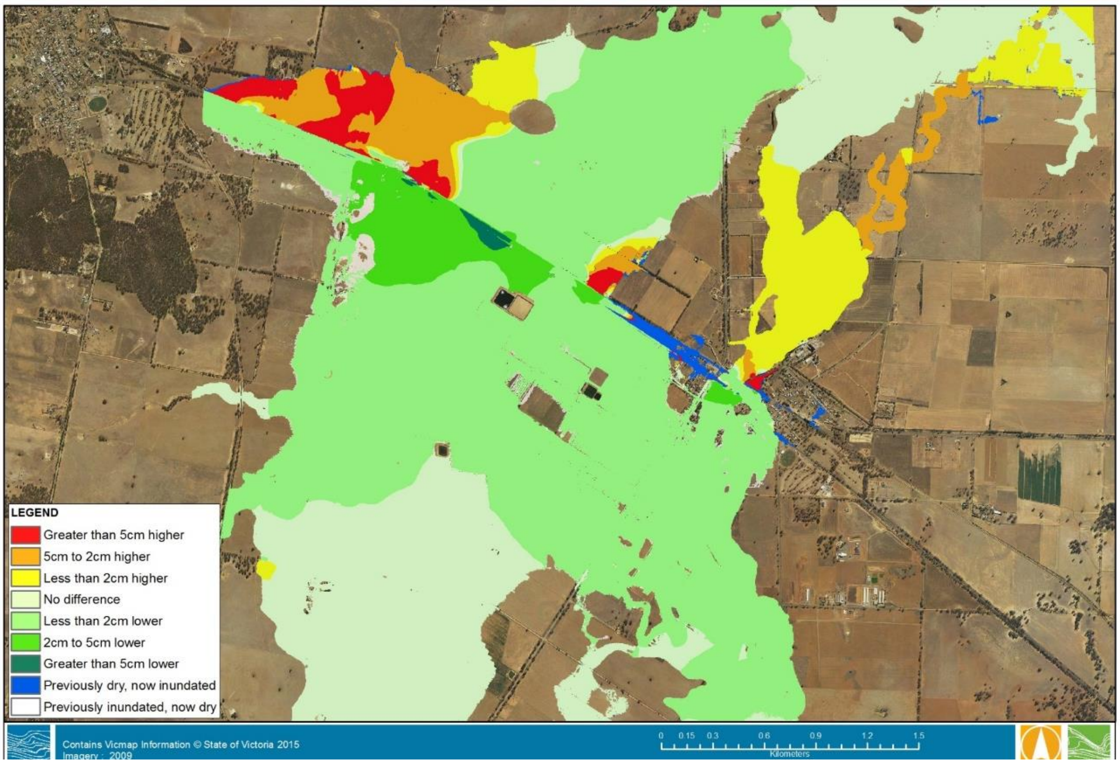


Figure 5-1 Difference in water surface elevation between package 1 mitigation option and existing conditions for the 1% AEP flood event

5.3.2 Package 2

The intent of package 2 was to determine if flood levels could be reduced by diverting water from the Loddon River to Bullabul Creek. It was thought that if the two waterways had different response timings, the peak flow in the Loddon could be reduced through the diversion, without worsening impacts elsewhere.

Similarly to package 1, an extreme change was initially trialled, to determine the potential impact of a diversion channel. Two diversion channels were created in the model, diverting water from the paleo-channel via natural flow paths to Bullabul Creek, as seen in Figure 5-2.

The two channels were given a moderate grade, with levels reduced from existing surface levels by 0.3 – 2.4 m.

Results

Modelling results showed the diversion channels to successfully lessen the flow in the Loddon River, and subsequently lower flood levels within the township by up to 2 cm. Flood levels along the Bullabul Creek, however, increased greater than 5 cm, and resulted in some areas previously not impacted by the 1% AEP flood being inundated.

The differences in water surface elevation between mitigation package 2 and existing conditions can be seen in Figure 5-3. It was decided by the Steering Committee that the option not be pursued further, due to the minimal benefit achieved for such major works. Furthermore, there were concerns around the potential level of community support, given that significant areas of land would need to be acquired, and the worsened impact to residents along Bullabul Creek.

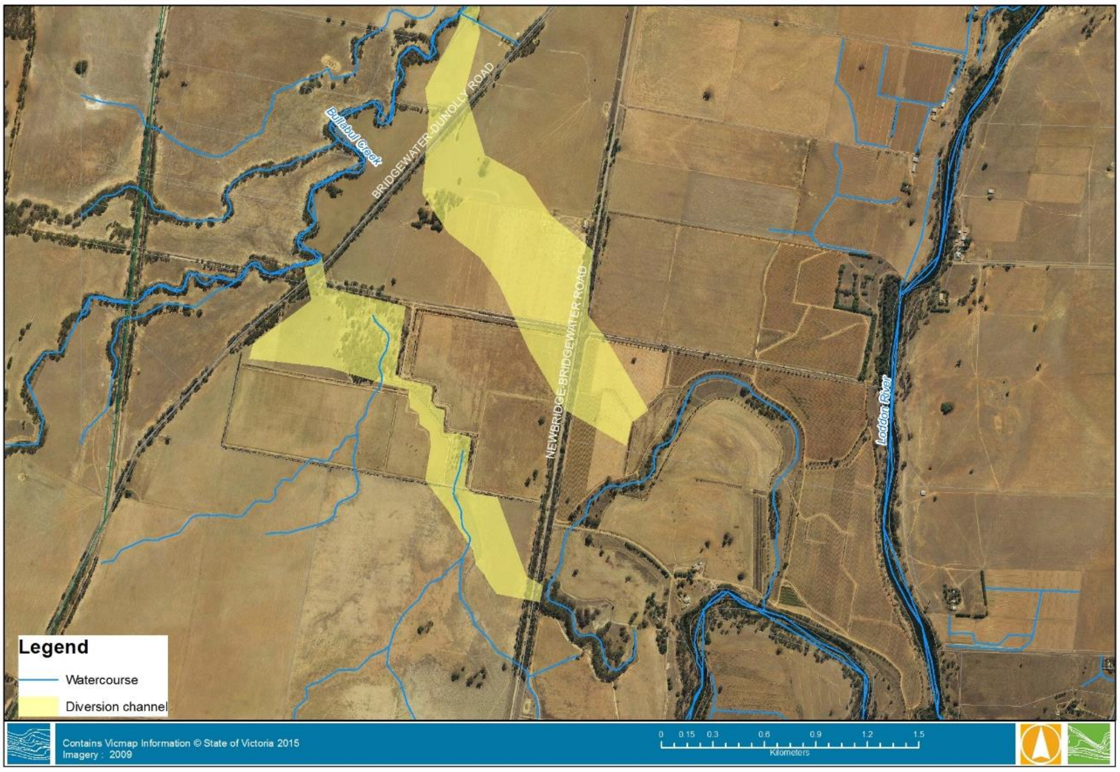


Figure 5-2 **Location of diversion channels**

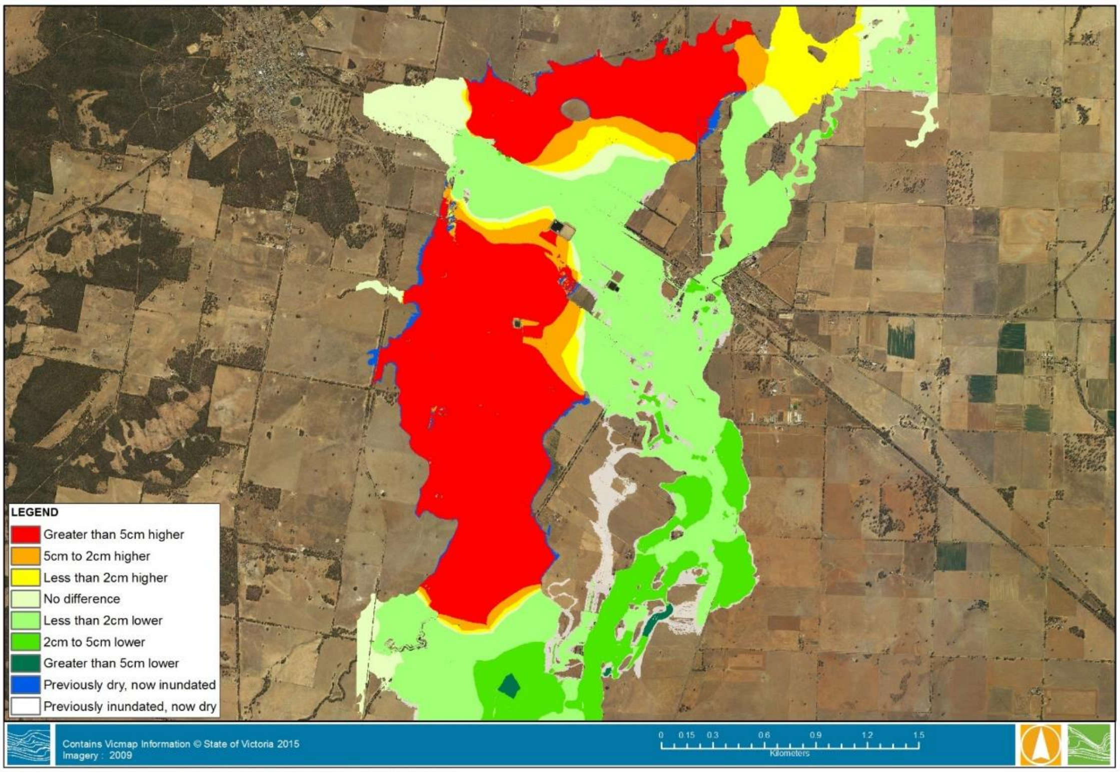


Figure 5-3 **Difference in water surface elevation between package 2 mitigation option and existing conditions for the 1% AEP flood event**

5.3.3 Package 3

The third package of mitigation options modelled was a system of levees to protect the township predominately from flow that breaks from the Loddon River to the north east at Peppercorn Lane. It was initially proposed that a single levee be tested, to impede the breakout, however this was found to increase levels within the Loddon River and re-distribute flow to the north-west, negatively impacting a number of properties.

The improved flood levels within the township, however, justified further investigation, and as such the configuration and alignment of the levees was iteratively refined until a feasible option was developed.

The final configuration of levees consists of:

- 1,350 m of levee along the eastern side of the Loddon River, between Peppercorn Lane and following Park Street through to the railway line in front of the Bridgewater Hotel (note that some sections of this levee will be temporary).
- 640 m of raised walkway along the western bank of the Loddon River.

Initial feedback from the Steering Committee was that there may be some resistance from the community for very high levees. This has been considered during the development of the mitigation package, and all effort has been made to find the alignment that best achieves flood protection with minimum changes to the existing surface, fitting in with existing infrastructure.

The resulting alignment of the levees in mitigation package 3 can be seen in Figure 5-4.

The levee on the eastern side of the Loddon River is intended to be an earthen levee from Peppercorn Lane to Park Street. The section along Park Street could either be comprised of a road side levee or possibly a raised road crest. A short section of temporary levee across the Calder Highway could be deployed when required. With the final piece of the levee, an earthen levee running through to the railway line in front of the Bridgewater Hotel.

Examples of earthen levees and temporary levees are given in Figure 5-5 and Figure 5-6 consecutively. There is a common misconception that levees dominant the aesthetics of a landscape, however earthen levees can (and have been) pleasingly integrated into the existing environment.

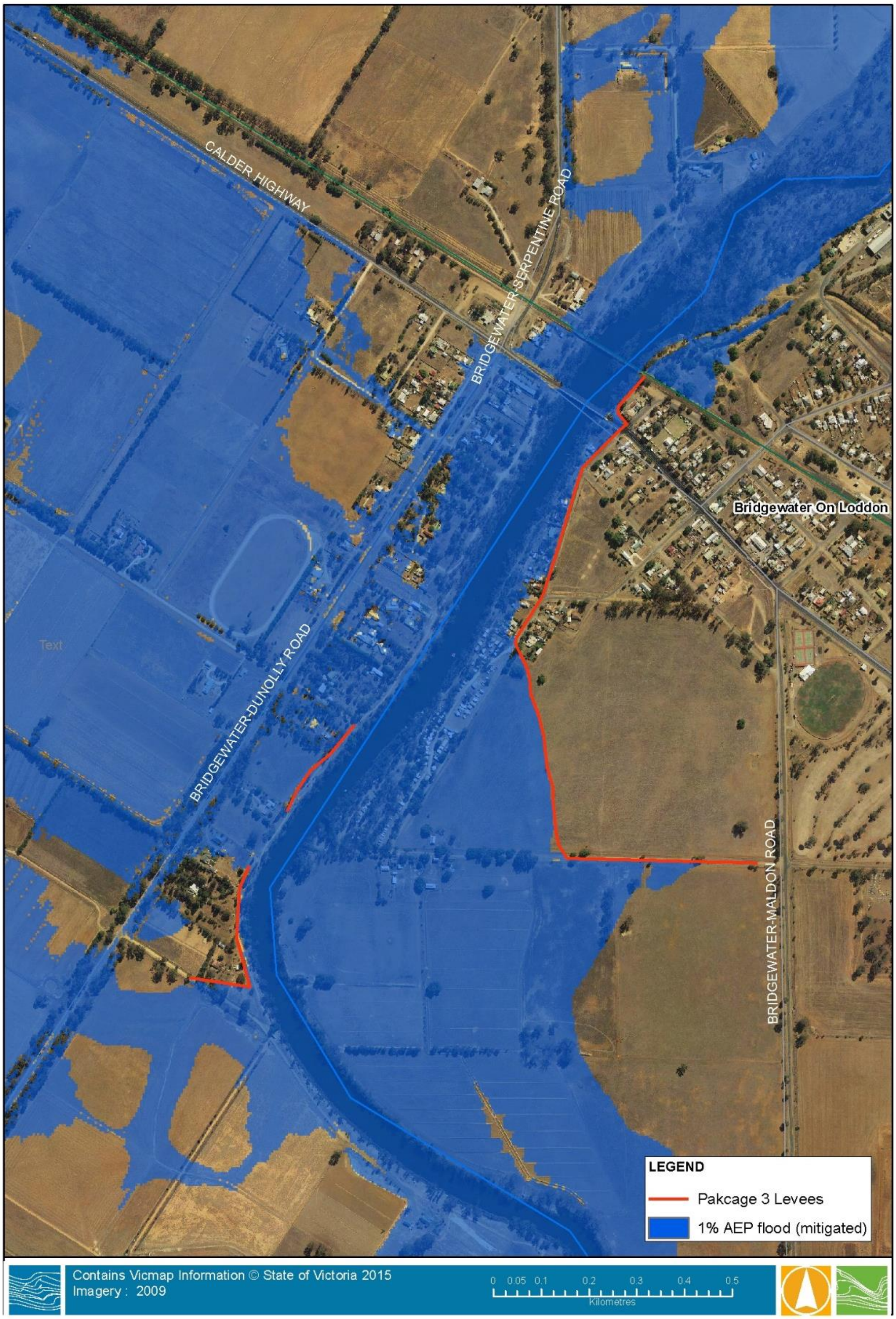


Figure 5-4 Mitigation package 3 preferred levee alignment and resulting 1% AEP flood extent

Figure 5-5 Examples of earthen levees

Figure 5-6 Examples of temporary levee systems

Results

The initial configuration of a single levee along Peppercorn Drive and in front of the caravan park was found to increase levels within the Loddon River and re-distribute flow to the north-west, negatively impacting a number of properties.

A number of alternative configurations were trialled. One option was for culverts across the Calder Highway and Railway to improve conveyance of increased flow towards the north-east, however this was found to have negligible impact. A levee along the western bank of the Loddon River was trialled, to prevent increased water levels to the north-west, however this resulted in large increases in water levels in the Loddon River, requiring very high levees along both the eastern and western banks, which likely would not have been supported by the community.

The final iteration found raising the walking trail on the western side slightly, so as to allow *some* water to be re-distributed to the north-west, to be able to sufficiently reduce flood levels in the township without an excessively high eastern levee.

This final configuration provides a compromise between the various options. The eastern levee provides the majority of protection, lessening the impact of flooding on the township. The levee on the western bank and raised walking track reduce the impact of increased water levels (as a result of the eastern levee) on properties, while still allowing the passage of shallow flood waters, and thereby preventing increased water levels at the Calder Highway bridge.

The resulting difference in water surface elevation between the final iteration of mitigation package 3 and existing conditions can be seen in Figure 5-7 and Figure 5-8. This is the preferred mitigation option for Bridgewater.

A freeboard of 0.3 m above the 1% AEP flood has been adopted for this option, providing protection to the 0.5% AEP flood (with no freeboard). Profiles of the eastern levee and western walking track can be seen in Figure 5-9 and Figure 5-10. The full suite of flood depth and hazard maps are provided in Appendix C.

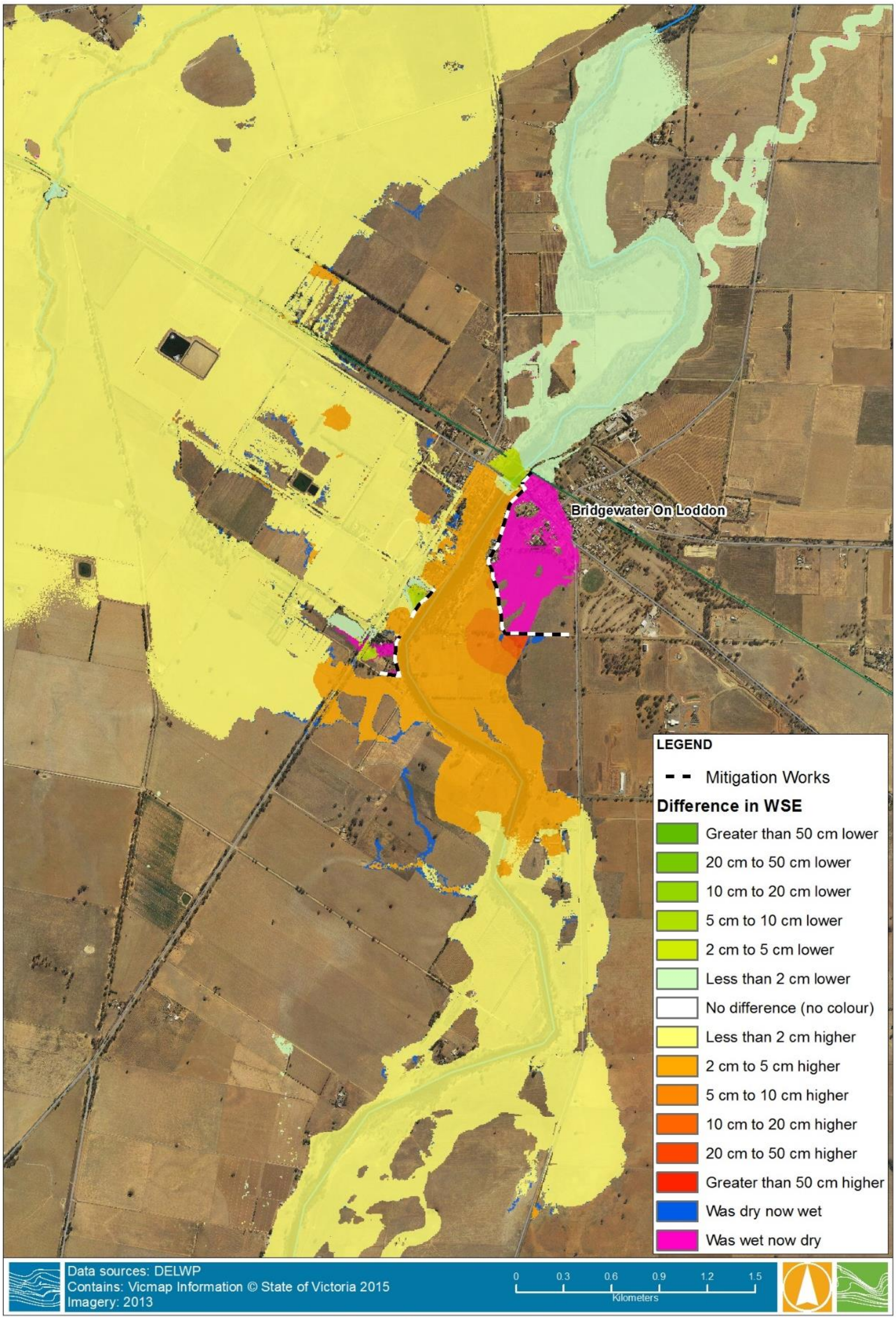


Figure 5-7 Difference in water surface elevation between package 3 mitigation option and existing conditions for the 1% AEP flood event

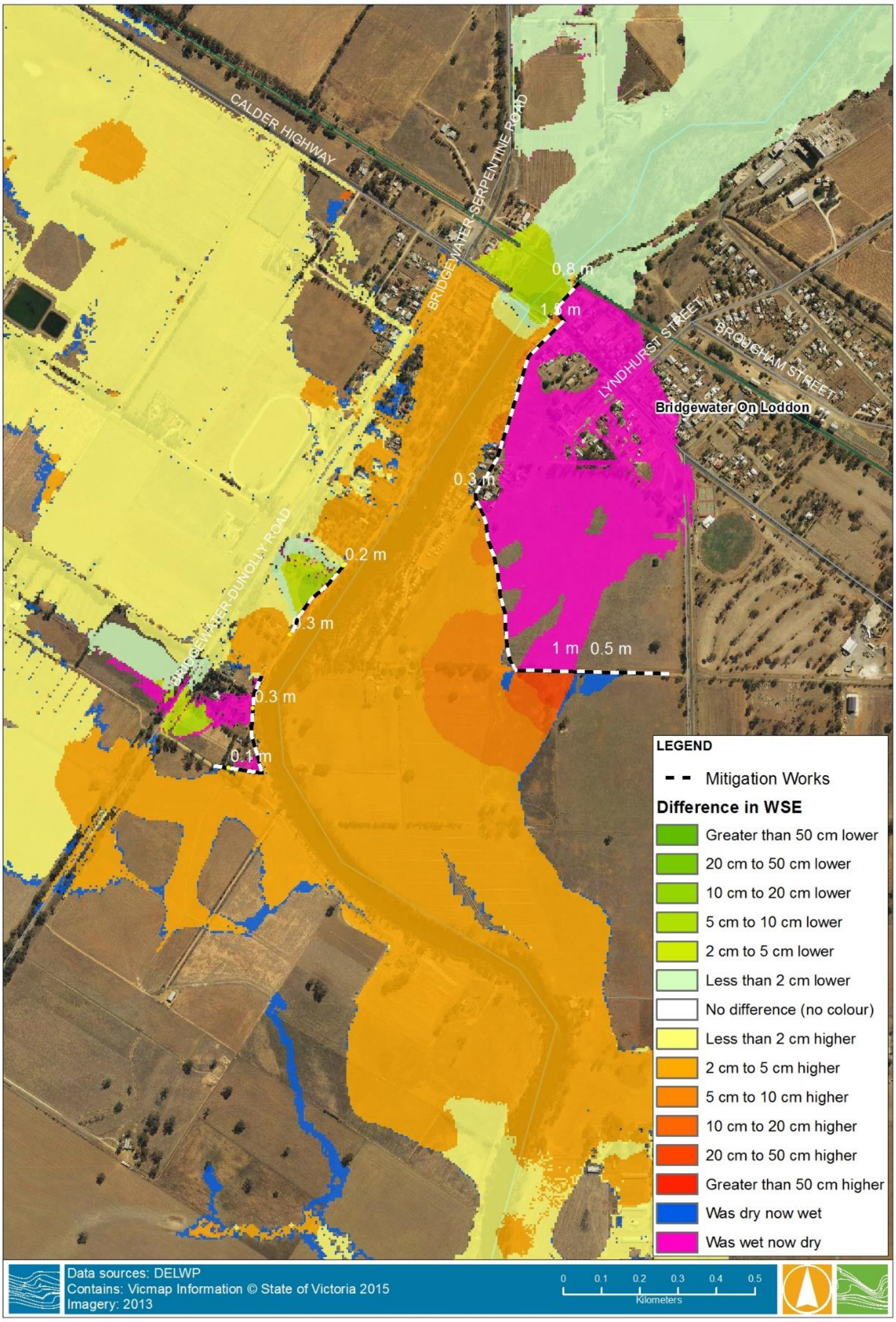


Figure 5-8 Difference in water surface elevation between package 3 mitigation option and existing conditions for the 1% AEP flood event (zoomed)

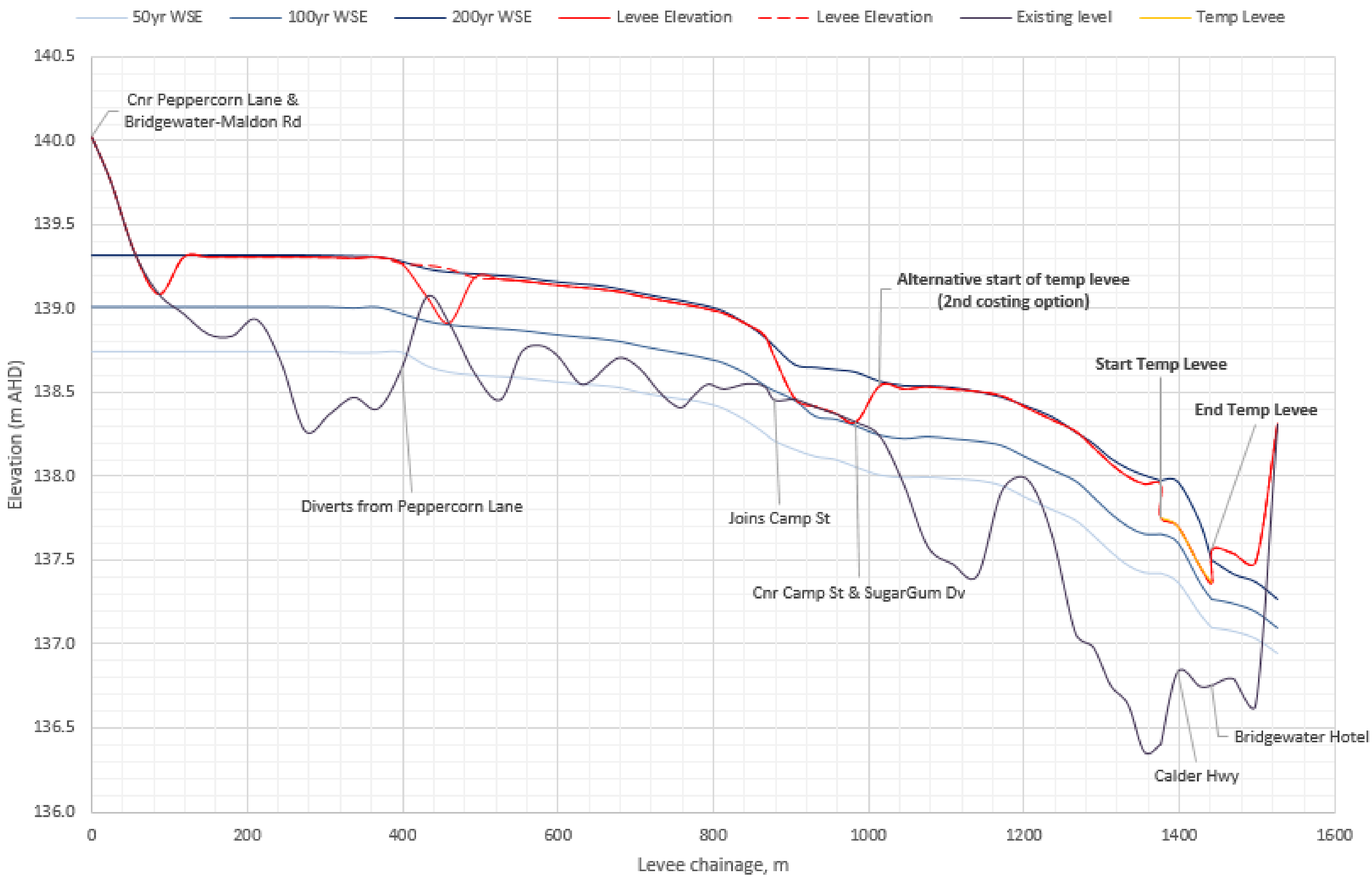


Figure 5-9 Eastern Levee Profile

Figure 5-10 **Western walking trail profile**

5.4 Non Structural Mitigation Options

There are a range of non-structural mitigation options that can be implemented including land use planning, flood warning, flood response and flood awareness.

5.4.1 Land Use Planning

The Victoria Planning Provisions (VPPs) contain a number of controls that can be employed to provide guidance for the use and development of land that is affected by inundation from floodwaters. These controls include the Floodway Overlay (FO), the Land Subject to Inundation Overlay (LSIO), the Special Building Overlay (SBO), the Urban Floodway Zone (UFZ) and the Environmental Significance Overlay (ESO).

Section 6(e) of the Planning and Environment Act 1987 enables planning schemes to 'regulate or prohibit any use or development in hazardous areas, or likely to be hazardous'. As a result, planning schemes contain State planning policy for floodplain management requiring, among other things, that flood risk be considered in the preparation of planning schemes and in land use decisions.

Guidance for applying flood controls to Planning Schemes is available from the Department of Planning and Community Development's (DPCD) Practice Note on Applying Flood Controls in Planning Schemes.

Planning Schemes can be viewed online at http://services.land.vic.gov.au/maps/pmo.jsp. It is recommended that the planning scheme for Bridgewater be amended to reflect the flood risk identified by this project.

Two alternative methods have been used to delineate the proposed FO. The first considers the flood hazard delineation, based on the 'Advisory Notes for Delineating Floodways' (NRE, 1998), as seen in Figure 5-11. The criteria for delineation are as follows:

- Depth > 0.5 m
- Velocity > 1.5 m/s
- Depth x velocity > 0.3 m^2/s.

The second method is broadly based on the new Australian Rainfall and Runoff Project 10 'Appropriate Safety Criteria for People'. Criterion for delineating the flood overlay considers both vehicle and people safety, and are as follows, based on the 1% AEP flood:

- Depth > 0.3 m
- Velocity > 1.5 m/s
- Depth x velocity > 0.3 m^2/s.

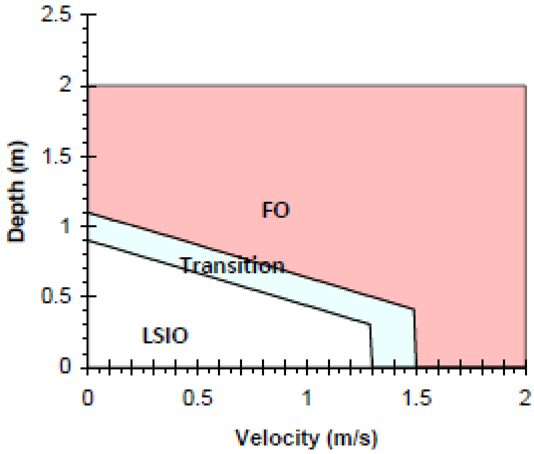


Figure 5-11 Flood Hazard Delineation of FO

With respect to flooding in Bridgewater, the dominant criteria for delineating the flood overlay is the depth. Further, only the depth differs between these two methods.

The Land Subject to Inundation extent has been taken as the full 1% AEP flood extent.

Figure 5-12 and Figure 5-13 show the proposed FO and LSIO maps for the two alternative delineation methods. Based on the extents shown, it is recommended that the FO adopting depth criteria of greater than 0.5 m.

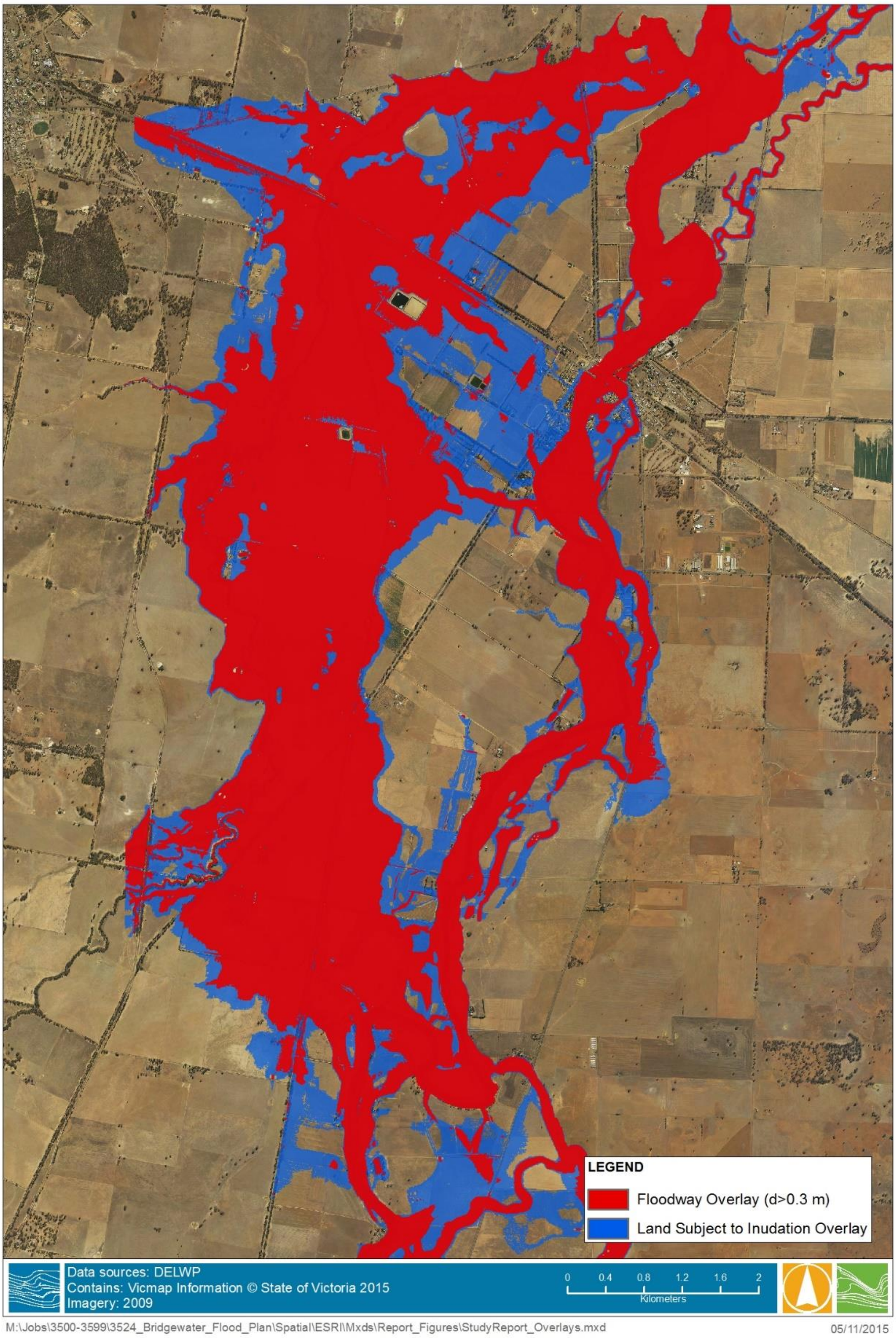


Figure 5-12 Draft LSIO and FO Map for Existing Conditions (FO based on d>0.3m)

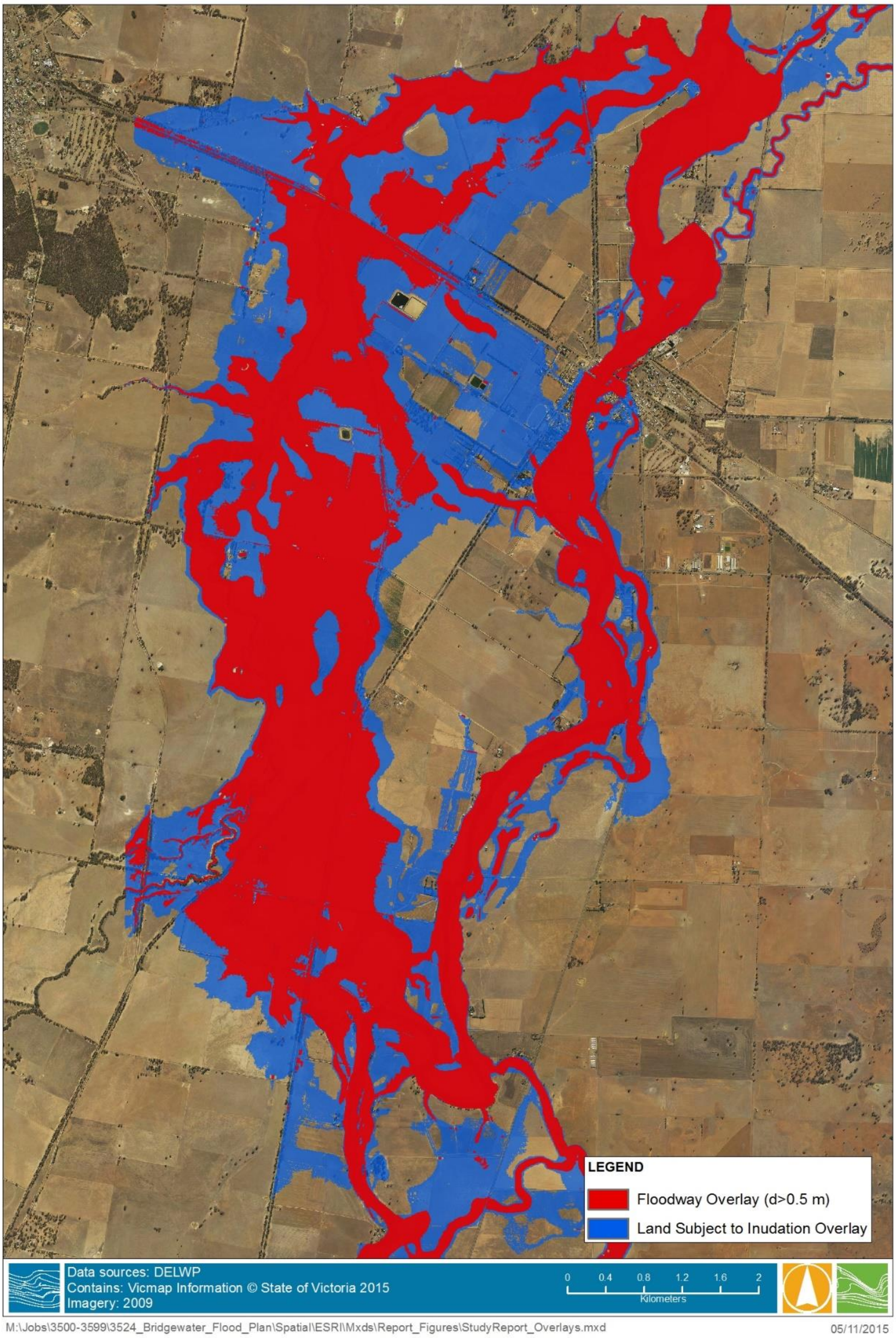


Figure 5-13 Draft LSIO and FO Map for Existing Conditions (FO based on d>0.5m)

5.4.2 Flood Warning, Response and Awareness

The aim of a Total Flood Warning System (TFWS) is to gather information about impending floods, communicating that information to those who need it (those at risk) and facilitating an effective and timely response. Thus, a TFWS aims to enable and persuade people and organisations to take action to increase personal safety and reduce the damage caused by flooding.

It is essential that flood warning systems consider not only the production of accurate and timely forecasts/alerts, but also the efficient dissemination of those forecasts/alerts to response agencies and threatened communities in a manner that elicits appropriate responses based on well-developed mechanisms that maintain flood awareness. Thus, equally important to the development of flood warning mechanisms is the need for quality, robust flood awareness (education) programs to ensure communities are capable of response.

Current Arrangements

The Bureau of Meteorology has an established flood warning service for a number of locations throughout Australia. Under this service, the Loddon River @ Laanecoorie streamflow gauge (#407203) is a designated forecast location, meaning that flood watches (notifications of expected flooding) are provided for the site, with reference to either the flood class or flood class and predicted level. The flood classes for the Laanecoorie gauge are given in Table 5-5. Note that Goulburn-Murray Water, as the storage operator of Laanecoorie Reservoir are responsible for providing the forecast for Laanecoorie to the Bureau of Meteorology.

Table 5-5 Flood class levels for the Laanecoorie gauge (#407203)

Flood Classification	Interpretation[12]	Level (m)
Minor	Causes inconvenience. Low-lying areas next to water courses are inundated. Minor roads may be closed and low-level bridges submerged. In urban areas inundation may affect some backyards and buildings below the floor level as well as bicycle and pedestrian paths. In rural areas removal of stock and equipment may be required.	1.5
Moderate	In addition to the above, the area of inundation is more substantial. Main traffic routes may be affected. Some buildings may be affected above the floor level. Evacuation of flood affected areas may be required. In rural areas removal of stock is required.	3.0
Major	In addition to the above, extensive rural areas and/or urban areas are inundated. Many buildings may be affected above the floor level. Properties and towns are likely to be isolated and major rail and traffic routes closed. Evacuation of flood affected areas may be required. Utility services may be impacted.	5.5

Flood watches are designed to inform both emergency services and the general public by providing early advice of riverine flooding (typically a few days warning). Flood Watches are issued when the combination of forecast rainfall and catchment (or other hydrological) conditions indicate that there is a significant risk of potential flooding.

[12] Bureau of Meteorology (2015) *Flood Warning Services* <http://www.bom.gov.au/water/floods/floodWarningServices.shtml> accessed 28 October 2015

The Bureau of Meteorology also provides a Flood Warning service for the Loddon River at Laanecoorie gauge location. A flood warning provides advice on impeding flooding, based on actual conditions (i.e. it is based on actual rainfall, rather than forecast rainfall).

Both Flood Watches and Flood Warnings are available through the Bureau of Meteorology website (www.bom.gov.au/australia/warnings) and through their telephone weather warning service, and may be made available through local response organisations (such as VicSES).

Flood information for individual properties can be accessed through the North Central CMA's online mapping tool, Flood Eye. The online tool enables flood reports to be developed for individual properties, citing the 1% AEP flood level, ground level and floor level where available (at no charge). The Flood Eye application has been updated to incorporate the information generated from Bridgewater Flood Management Plan, and provides residents with an indication of an approximate level at which flooding would occur on their property.

The Municipal Flood Emergency Plan (MFEP) for the Loddon Shire, which has been populated with flood intelligence for Bridgewater as part of this study, contains information and tools which relate river levels at Laanecoorie to expected inundation extents within Bridgewater and potential consequences of flooding. This includes areas that are likely to be impacted by floods of various magnitudes, the timing and behaviour of flooding through town, areas most at risk, identifying vulnerable communities, access and egress issues, buildings inundated above and below floor, areas that need to be evacuated as a priority, etc. This provides an action plan of sorts to enable emergency services to formulate a response.

Instrumentation

The Loddon River at Laanecoorie streamflow gauge (#407203) is sufficient for providing flood warning to the township of Bridgewater. The rating curve for this gauge has been reviewed as part of this study, and found to provide reasonable estimates of flow at Laanecoorie, resulting in a close match to observed flood levels in Bridgewater. The flood mapping developed as part of this study has been linked to water levels and flows at the Laanecoorie streamflow gauge, so a direct correlation can be made.

GMW, as the storage operator, provide streamflow forecasts at this gauge to the Bureau of Meteorology (as discussed above). Given the travel times between Laanecoorie and Bridgewater, there is reasonable time to convey warnings to residents of Bridgewater. Table 5-6 below, which is an extract from the Municipal Flood Emergency Plan, outlines the travel times based on the January 2011 flood event and 1% AEP design event modelling. For an accurately forecast flood event, at least two days warning should be able to be given to residents of Bridgewater prior to the first properties impacted, based on the timing from the start of rise at Laanecoorie Reservoir.

Table 5-6 Typical flood travel times

Location From	Location To	Typical Travel Time	Comments
Cairn Curran	Laanecoorie Reservoir	16 hours	GMW estimate of flood travel time
Laanecoorie Reservoir (start of rise)	Loddon River, 14 km upstream Bridgwater* (out of bank)	~ 5 hours	
	Calder Hwy Bridgwater (out of bank)	~ 16 hours	
	First properties impacted in Bridgwater	~ 32 hours	
Laanecoorie Reservoir (peak)	Loddon River, 14 km upstream Bridgwater* (peak)	~ 6.5 hours	
	Calder Hwy Bridgwater (peak)	~ 11 hours	~ 6 hours from Arnold to Bridgewater

* Upstream boundary of the hydraulic model (14 km upstream of Bridgewater, and 9 km downstream of Newbridge

The deployment of an additional gauge in the township of Bridgewater itself has been discussed with the Steering Committee, however it would not provide any advantage in terms of improving flood warning times. The intent of the gauge would be to facilitate a more flood aware community. This could equally be achieved through the construction of historic markers and manually read gauge boards

Issues

A key concern of the Steering Committee is the dissemination of information to those who need it. There was discussion from members of the committee regarding the appropriate lines of communication, based on experience from the January 2011 flood event. Members of the Steering Committee discussed delays observed in passing information between GMW, the Bureau of Meteorology and VicSES, and further delays with that information making its way to those on the ground. Some residents noted that they were receiving information from friends/relatives outside the region, who themselves were accessing the information from the news. There are opportunities to improve this chain of communication and message dissemination significantly, which would ultimately benefit the Bridgewater community and others residing along the Loddon river.

Consideration needs to be given as to how the information is to be conveyed in future, and how to minimise the time between forecasts of flow at Laanecoorie Reservoir by GMW, warnings produced by the Bureau of Meteorology and alerts provided to the community by VicSES. Consideration also needs to be given as to the format of communication as many residents were left without electricity (and hence access to landline telephones, radios and internet). It is also understood that areas in the vicinity of Bridgewater do not have strong mobile phone coverage.

A further concern of the Steering Committee is the community's awareness of flooding. There are many misconceptions commonly held regarding flooding that may prevent a person from preparing to and then evacuating prior to the arrival of a flood. A strong community awareness campaign will reduce these misconceptions, it will never eliminate them entirely, but it will ensure that a greater percentage of the community is aware and ready to act when a flood is imminent.

Flood awareness can be improved by making this study available to the public, as well as more condensed brochure style documents that clearly explain the risk and what is being done about it by the relevant agencies, but more importantly what individuals can do to best prepare themselves. Establishing an active community group that promotes flood related issues in the community, this can be run in conjunction with a more formal program such as VICSES' FloodSafe program. Installing flood markers of historic or potential design floods in suitable locations. Individual property flood intelligence cards have been prepared for some communities in Victoria. These generally link a flood level at a gauge to the commencement of flooding on the specific property, and the level at which above floor flooding is likely to occur, they also provide basic flood information including contact details and at what level on the gauge they should consider evacuating. More recently, online resources have become common, providing access to flood information, both pre-prepared maps, near real time information and useful information to assist communities to respond to and recover after a flood event.

Recommendations for Improvement

The development of a Total Flood Warning System (TFWS) for Bridgewater, and a corresponding regular flood awareness campaign has the potential to reduce flooding impacts within the township.

It is understood that the North Central CMA are soon to begin a revision of their Regional Flood Strategy and will be considering flood warning needs across the entire region. It is recommended that development of a TFWS for Bridgewater be a focus of this strategy, particularly given the lack of support for any structural mitigation options.

6. FLOOD DAMAGE ASSESSMENT

6.1 Overview

A flood damages assessment was undertaken for the study area under existing conditions. The flood assessment determined the monetary flood damages for design floods (20%, 10%, 5%, 2%, 1% and 0.5% AEP events). The flood damage assessment was also undertaken for the final mitigation package.

Water Technology has developed an industry best practice damage assessment methodology that has been utilised for a number of studies in Victoria, combining aspects of the Rapid Appraisal Method, ANUFLOOD, more recent damage curves from the NSW Office of Environment and Heritage and other relevant flood damage literature. The model results for all mapped flood events were processed to calculate the numbers and locations of properties affected. This included properties with buildings inundated above floor, properties with buildings inundated below floor and properties where the building was not impacted but the grounds of the property were. In addition to the flood affected properties, lengths of flood affected roads for each event were also calculated. Note, that rural agricultural damages have not been included in this study as the focus for mitigation is on the township. Details of the flood damage assessment methodology are provided in Appendix D.

6.2 Existing Conditions

The 1% AEP flood damage estimate for existing conditions was calculated to be $3,748,000. A total of 130 properties are flooded in a 1% AEP event, with 52 of those properties flooded above floor level. The Average Annual Damages (AAD) was determined as part of the flood damage assessment. The AAD is a measure of the flood damage per year averaged over an extended period. The AAD for existing conditions for the study is estimated at approximately **$163,000**. This is effectively a measure of the amount of money that must be put aside each year in readiness for the event that a flood may happen in the future.

Table 6-1 Flood damage assessment for existing conditions

ARI (years) AEP	200yr 0.50%	100yr 1%	50yr 2%	20yr 5%	10yr 10%	5yr 20%
Residential Buildings Flooded Above Floor	51	24	13	3	1	0
Commercial Buildings Flooded Above Floor	30	28	26	14	0	0
Properties Flooded Below Floor	75	78	65	47	27	6
Total Properties Flooded	**156**	**130**	**104**	**64**	**28**	**6**
Direct Potential External Damage Cost	$536,000	$444,000	$377,000	$248,000	$68,000	$13,000
Direct Potential Residential Damage Cost	$3,403,000	$1,541,000	$825,000	$183,000	$48,000	$0
Direct Potential Commercial Damage Cost	$1,720,000	$1,082,000	$716,000	$185,000	$0	$0
Total Direct Potential Damage Cost	**$5,659,000**	**$3,067,000**	**$1,917,000**	**$616,000**	**$116,000**	**$13,000**
Total Actual Damage Cost *(0.8*Potential)*	**$4,527,000**	**$2,454,000**	**$1,534,000**	**$493,000**	**$93,000**	**$10,000**
Infrastructure Damage Cost	**$1,892,000**	**$1,294,000**	**$1,021,000**	**$479,000**	**$276,000**	**$23,000**
Total Cost	**$6,419,000**	**$3,748,000**	**$2,555,000**	**$972,000**	**$369,000**	**$33,000**
Average Annual Damage (AAD)	$163,000					

6.3 Preferred Mitigation Option

The AAD for the preferred mitigation option (Package 3) was calculated to be approximately **$136,000**. During a 1% AEP event, the preferred option reduces the total number of properties inundated above floor level from 52 properties to 31 properties. Over a long period of time with a range of flood events, the AAD may be reduced by approximately **$27,000** per year by implementing mitigation package 3.

Table 6-2 Flood damage assessment for mitigation package 3

ARI (years) AEP	200yr 0.50%	100yr 1%	50yr 2%	20yr 5%	10yr 10%	5yr 20%
Residential Buildings Flooded Above Floor	34	17	9	4	0	0
Commercial Buildings Flooded Above Floor	14	14	14	13	0	0
Properties Flooded Below Floor	50	66	42	31	28	6
Total Properties Flooded	**98**	**97**	**65**	**48**	**28**	**6**
Direct Potential External Damage Cost	$377,000	$530,000	$261,000	$196,000	$71,000	$13,000
Direct Potential Residential Damage Cost	$2,180,000	$1,086,000	$629,000	$213,000	$0	$0
Direct Potential Commercial Damage Cost	$654,000	$548,000	$437,000	$176,000	$0	$0
Total Direct Potential Damage Cost	**$3,212,000**	**$2,164,000**	**$1,327,000**	**$584,000**	**$71,000**	**$13,000**
Total Actual Damage Cost *(0.8*Potential)*	**$2,570,000**	**$1,732,000**	**$1,061,000**	**$467,000**	**$57,000**	**$10,000**
Total Cost	**$4,340,000**	**$2,950,000**	**$2,030,000**	**$924,000**	**$319,000**	**$34,000**
Average Annual Damage (AAD)	$136,000					

It should be noted that this mitigation option also provides protection to the proposed development between Sugar Gum Drive and Peppercorn Lane. If the development were included in the damages assessment, we would likely see a much greater difference between the average annual damages for existing and mitigated conditions. Protection of this area provides development opportunities for the Bridgewater township.

6.4 Non-Economic Flood Damages

The previous discussion relating to flood damages has concentrated on monetary damages, that is, damages that are easily quantified. In addition to those damages, it is widely recognised that individuals and communities also suffer significant non-monetary damage, i.e. emotional distress, health issues, etc. There has been extensive research undertaken and documented in the scientific literature relating to the individuals and communities response to natural disasters. A recent publication entitled *"Understanding floods: Questions and Answers"* by the Queensland Floods Science Engineering and Technology Panel, when discussing the large social consequences floods have on individuals and communities states:

Floods can also traumatise victims and their families for long periods of time. The loss of loved ones has deep impacts, especially on children. Displacement from one's home, loss of property and disruption to business and social affairs can cause continuing stress. For some people the psychological impacts can be long lasting.

The *"Disaster Loss Assessment Guidelines"* (EMA, 2002) make the following key points:

- *Intangibles are often found to be more important than tangible losses.*
- *Most research shows that people value the intangible losses from a flooded home—principally loss of memorabilia, stress and resultant ill-health—as at least as great as their tangible dollar losses.*
- *There are no agreed methods for valuing these losses.*

There is no doubt that the intangible non-monetary flood related damage in Bridgewater is high. The benefit-cost analysis presented later in this report has not considered this cost. Any decisions made that are based on the benefit-cost ratios need to understand that the true cost of floods in Bridgewater is far higher than the economic damages alone. This would have the effect of increasing the benefit cost ratio, improving the argument for approving a mitigation scheme at Bridgewater.

7. BENEFIT COST ANALYSIS

7.1 Overview

A benefit cost analysis was undertaken to assess the economic viability of the preferred mitigation option. Indicative benefit-cost ratios were based on the construction cost estimates and average annual damages. For the analysis, a net present value model was used, applying a 6% discount rate over a 30 year project life.

7.2 Mitigation Option Costs

The mitigation works were costed based on a number of key references:

- Melbourne Water's standard rates for earthworks and pipe/headwall construction costs.
- Rawlinsons Australian Construction Handbook Rates
- Comparison to cost estimates for similar mitigation works for other flood studies

Detailed costing was only carried out for mitigation package 3, as options in package 1 and 2 were found to be infeasible based on their increased flooding impacts at some properties. Three costing options have been presented, however, for the preferred mitigation option.

The first costing option presented is for a short section of temporary levee across the Calder Highway (limited to approximately 65 m), with earthen levee embankments along the remainder of the alignment. The second costing option is for the section of earthen levee along Park Street to be replaced by a raised roadway. This is likely to improve the functionality of the levee and its integration into the existing built environment. The third costing option is for a longer section of temporary levee, across the Calder Highway and along Park Street (approximately 550 m) to replace some proposed sections of earthen levee that may not get support from the community due to amenity reasons.

All three costing options are for the same alignment and require the same height of levee. The only difference is that the configuration of the levees along Park Street (i.e. earthen embankment, raised road or temporary levee).

The principal cost estimates for mitigation package 3 are the earthworks associated with constructing an earthen levee on the eastern side of the Loddon River; raising of the walking trail on the western side of the river; and purchase (and instalment of footing) of a suitable temporary levee.

A 30% contingency cost has been added along with engineering and administration costs. An annual maintenance cost of 3% of the works was also factored in for the levee works.

A summary of the costing can be seen in Table 7-1.

7.3 Benefit-Cost Ratio

A benefit-cost analysis was undertaken for the preferred mitigation option (package 3). The ratio is based on a 6% discount rate over a 30 year period, and existing conditions average annual damage cost of $163,500. The resulting ratio is high for cost options 1 and 3, strongly justifying construction of the levees. Further consideration into the configuration of the levees (i.e. earthen embankments, raising sections of the road and/or temporary levees) may be warranted after further community consultation.

Table 7-1 Package 3 Mitigation Option Cost Breakdown

	Cost Option 1: Short Temp Levee		Cost Option 2: Raised Road		Cost Option 3: Long Temp Levee	
Option	**Capital Cost**	**Maintenance**	**Capital Cost**	**Maintenance**	**Capital Cost**	**Maintenance**
Eastern levee (earthen)	$ 97,300	$ 1,800	$ 50,700	$ 1,000	$ 50,700	$ 1000
Eastern levee (raised road)	-	-	$ 426,000	$ 7,900	-	-
Eastern levee (temporary)	$ 42,100	$ 300	$42,100	$ 300	$ 136,300	$ 600
Western levee	$ 7,500	$ 150	$ 7,500	$ 150	$ 7,500	$ 150
TOTAL	**$ 146,900**	**$ 2,300**	**$ 526,300**	**$ 9,400**	**$ 194,500**	**$ 1,700**

Table 7-2 Benefit Cost Analysis

	Option 1: short temp levee	Option 2: raised road	Option 3: long temp levee
Average Annual Damage	$136,100	$136,100	$136,100
Annual Maintenance Cost	$2,250	$9,300	$1,700
Annual Cost Saving	$25,100	$18,000	$25,700
Net Present Value (6%)	$352,900	$253,500	$360,700
Capital Cost of Mitigation	$146,400	$526,300	$194,400
Benefit – Cost Ratio	2.4	0.5	1.9

8. PROJECT CONSULTATION

8.1 Overview

A key element in the development of the Bridgewater Flood Study was the active engagement of community members. This engagement was developed over the course of the study through community consultation sessions, public notices (in the Loddon Times, Bridgewater-on-Loddon Primary School Newsletter and Bridgewater Bulletin), meetings with a Steering Committee containing community representatives and mailouts. The community consultation sessions were jointly managed between the North Central CMA and Water Technology. The aims of the community consultation were as follows:

- To raise awareness of the study and to identify key community concerns; and
- To provide information to the community and seek their feedback/input regarding the study outcomes including the existing flood behaviour and proposed mitigation options for the township.

8.2 Steering Committee

The study was led by a Steering Committee consisting of representatives from North Central CMA, Loddon Shire Council, Department of Environment Land Water and Planning (DELWP), Goulburn Murray Water (GMW), Bridgewater-on-Loddon Development Committee, State Emergency Service (SES), Water Technology and the Bridgewater community. Members of the Steering Committee and their respective organisations were as follows:

- Cr Geoff Curnow (Loddon Shire Council)
- Cr Colleen Condliffe (Loddon Shire Council)
- Ian McLauchlan (Loddon Shire Council)
- Lynne Habner (Loddon Shire Council)
- Ken Coates (North Central CMA) – Steering Committee Chair
- Leila Macadam (North Central CMA)
- Shaun Morgan (North Central CMA)
- Dale Farnsworth (Goulburn Murray Water)
- Simone Wilkinson (Department for Environment, Land Water and Planning)
- Shane O'Loughlin (North Central CMA and community representative)
- Graham Morse (Bridgewater on Loddon Development Committee)
- Tim Ferguson (community representative)
- Prue Addlem (North Central CMA and community representative)
- Dave Edwards (community representative)
- Frank Coghlan (community representative)
- Jim Lawson (community representative)
- Mal Ross (VicSES)
- Matt Bunney (VicTrack)
- Peter Bradley (VicRoads)

The Steering Committee met on 5 occasions at key points throughout the study, to manage the development of the plan.

8.3 Community Consultation

Two formal information sessions were held throughout the course of the study. A drop in session was held on the 7th November 2014 providing an opportunity for interested members of the public to discuss their experiences of flooding in Bridgewater and comment on the development of the study.

Community members were largely in agreement with the modelled January 2011 flood extent, though presented useful information regarding improvements. Several residents were also able to provide flood related information (in the form of photos, anecdotes and records) which were instrumental in the validation of modelled flood extents.

The second round of community consultation was held by the North Central CMA on the 16th February 2016. Residents of Bridgewater were notified of the meeting through an information brochure outlining the progress of the study and potential mitigation options. A total of 19 one on one meetings were held, and 13 feedback forms were submitted (note that 6 feedback forms were from those who also attended a one on one meeting). The North Central CMA ensured that all residents who would be adversely impacted by the preferred mitigation option were consulted.

Approximately 70% of respondents indicated that they did not support any form of levee configuration presented, as seen in Table 8-1. It is interesting to note that of those who did not support any form of levee, 89% of those would have benefited from it. A common comment from residents was that the levee would be divisive and cause conflict between community members.

Table 8-1 Community feedback regarding level of support for preferred mitigation option

Level of Support	1: Raised Road	2: Earthen embankment	3: Temporary levee
Support	4	0	1
Don't Support	18	18	17
No response	4	8	7

As a result of this feedback, a decision was made by the Steering Committee not to recommend the levee mitigation option. The details developed for this study will be available to the North Central CMA and Loddon Shire Council if there is any interest to pursue structural mitigation options at a later stage.

The option for developing a Total Flood Warning System for Bridgwater is largely supported by the community, with over 30% of respondents explicitly supporting the implementation of a warning system and the remainder not providing any comment. No community member did not support the development of a warning system.

9. CONCLUSIONS AND RECOMMENDATIONS

The Bridgewater Flood Management Plan has successfully provided an improved understanding of flood behaviour at Bridgewater. It has allowed the development of detailed flood mapping and flood intelligence information that will greatly improve future flood response.

The identification of a cost-effective and feasible structural flood mitigation option, if supported by the community and funded by government, will lead to reduced flood risk for Bridgewater and allow for future development close to the town centre. The community has clearly expressed concerns with the levee option investigated during this study, and if this was to be revisited in the future would need to address these concerns.

The study involved the development of a hydrologic model of the Loddon River and Bullabul Creek catchments and hydraulic models of the township / study area. The models were successfully verified to the January 2011 flood event, and a number of design flood events were simulated along with the design of potential flood mitigation options.

Throughout the study, a range of community consultation activities were undertaken, including community drop-in sessions, media releases and questionnaires to ensure that community issues were heard and the ideas of the community were considered in the development of potential flood mitigation options. It must be noted that the community participation was very helpful, with photos of flooding, flood observations, local information and feedback on the study greatly improving the outcomes for the study.

An initial prefeasibility assessment of 8 structural mitigation options was undertaken. From this assessment, three options were selected for further analysis using the developed hydraulic model. These included improved conveyance across the Calder Highway and railway crossing; flow diversions from the Loddon River to Bullabul Creek; and levees to protect the township.

Both the increased conveyance and diversion channel were found to be infeasible (due to costs, community concerns and potential impact on flood extents) and were not pursued.

The option to incorporate levees was considered and refined a number of times until an optimal configuration was achieved. The final, refined option is for a levee along the eastern bank of the Loddon River, extending from Peppercorn Lane along Park Street to the Calder Highway and in front of the Bridgewater Hotel to the Railway line. A raised section of walking trail on the western side of the Loddon River attempts to ensure that flood waters are not redistributed to the detriment of others on the western side of the Loddon River. This option returned a high benefit to cost ratio of between 1.9 and 2.4. This ratio may be further reduced close to 1 if a more expensive option to raise Park Street instead of a roadside levee is adopted.

Regardless of the benefit cost ratio, no option is likely to be considered unless it has the strong support of the community, as was the case for Bridgewater. There was strong opposition to the preferred mitigation option, with residents commenting that it would divide the community. Approximately 70% of community members who provided feedback did not support any configuration of the levee. There was, however, strong support for the development of a total flood warning system.

Following significant consultation with the Bridgewater Community, the Bridgewater Flood Management Plan Steering Committee recommends the following actions:

- Amendment of the planning scheme for Bridgewater to reflect the flood risk identified by this project;
- Adopt the design flood levels for existing conditions for use in future planning related decisions;
- The adoption of the Municipal Flood Emergency Plan to improve the emergency response;

- Regular education/information sessions regarding the management of reservoirs to address community concerns regarding reservoir management;
  Investigation and development of a total flood warning system, with particular emphasis on the dissemination of information.

REFERENCES

Bureau of Meteorology, 2014. Climate Data Online. [ONLINE] Available at: http://www.bom.gov.au/climate/data/index.shtml [Accessed October 2014].

Bureau of Meteorology, 2015. Welcome to the IFD Program. [ONLINE] Available at: http://www.bom.gov.au/hydro/has/cdirswebx/cdirswebx.shtml [Accessed June 2013]

Chow, V.T., 1959. Open-Channel Hydraulics. New York, McGraw-Hill.

Department of Natural Resources and Environment, 1996. The Estimation of the 1% Flood Profile of the Loddon River from Laanecoorie to Bridgewater Township and the Declaration of 1% Flood Levels in Bridgewater Township. [ONLINE] Available at: http://www.ga.gov.au/flood-study-web/download/resource/269

Department of Environment, Land Water & Planning, 2015. Water Measurement Information System. [ONLINE] Available at: http://data.water.vic.gov.au/monitoring.htm [Accessed October 2014]

Emergency Management Australia, 2002. Disaster Loss Assessment Guidelines. [ONLINE] Available at: https://www.ag.gov.au/EmergencyManagement/Tools-and-resources/Publications/Documents/Manual-series/manual-27-disaster-loss-assessment-guidelines.pdf

Hill, P., Mein, R., Siriwardena, L. 1998. How Much Rainfall Becomes Runoff? Lodd Modelling For Flood Estimation. CRC for Catchment Hydrology. Report 98/5.

Melbourne Water, 2010. Music Guidelines, Recommended input parameters and modelling approaches for MUSIC users.

Pearse, M., Jordan, P., Collins, Y. 2002. A Simple Method for Estimating RORB Model Parameters for Ungauged Rural Catchments.

Pilgrim, DH, (ed)., 1987. Australian Rainfall & Runoff – A Guide to Flood Estimation, Institution of Engineers, Australia, Barton, ACT.

Planning and Environment Act 1987 (Vic).

Rural Water Commission of Victoria, 1990. Victorian Surface Water Information to 1987, Volume 5.

Sinclair Knight Merz, 2012. Laanecoorie Dam: Flood Hydrology Update and Construction Flood Risk. Report for Goulburn-Murray Water.

Siriwardena, L. & Weinmann, P.E. 1996. Aerial Reduction Factors. Section 3.1 in “Hydrologyical Recipes – Estimation Techniques in Australian Hydrology” (Grayson, Argen, Nathan, McMahon, Mein eds). CRC for Catchment Hydrology.

Thiess Services, 2012. Rating Table Extrapolations for the Upper Loddon Catchments. Report 307 for Department of Sustainability and Environment.

APPENDIX A: PHOTOS

Laanecoorie Reservoir

Laanecoorie Reservoir Spillway

Loddon River Floodplain (downstream of Newbridge)

Bullabul Creek Crossing on Black Bridge Road

Robinvale Line Rail Crossing over tributary to Bullabul Creek

Stock and domestic supply channel

Loddon Weir

Loddon Weir offtake to Mill

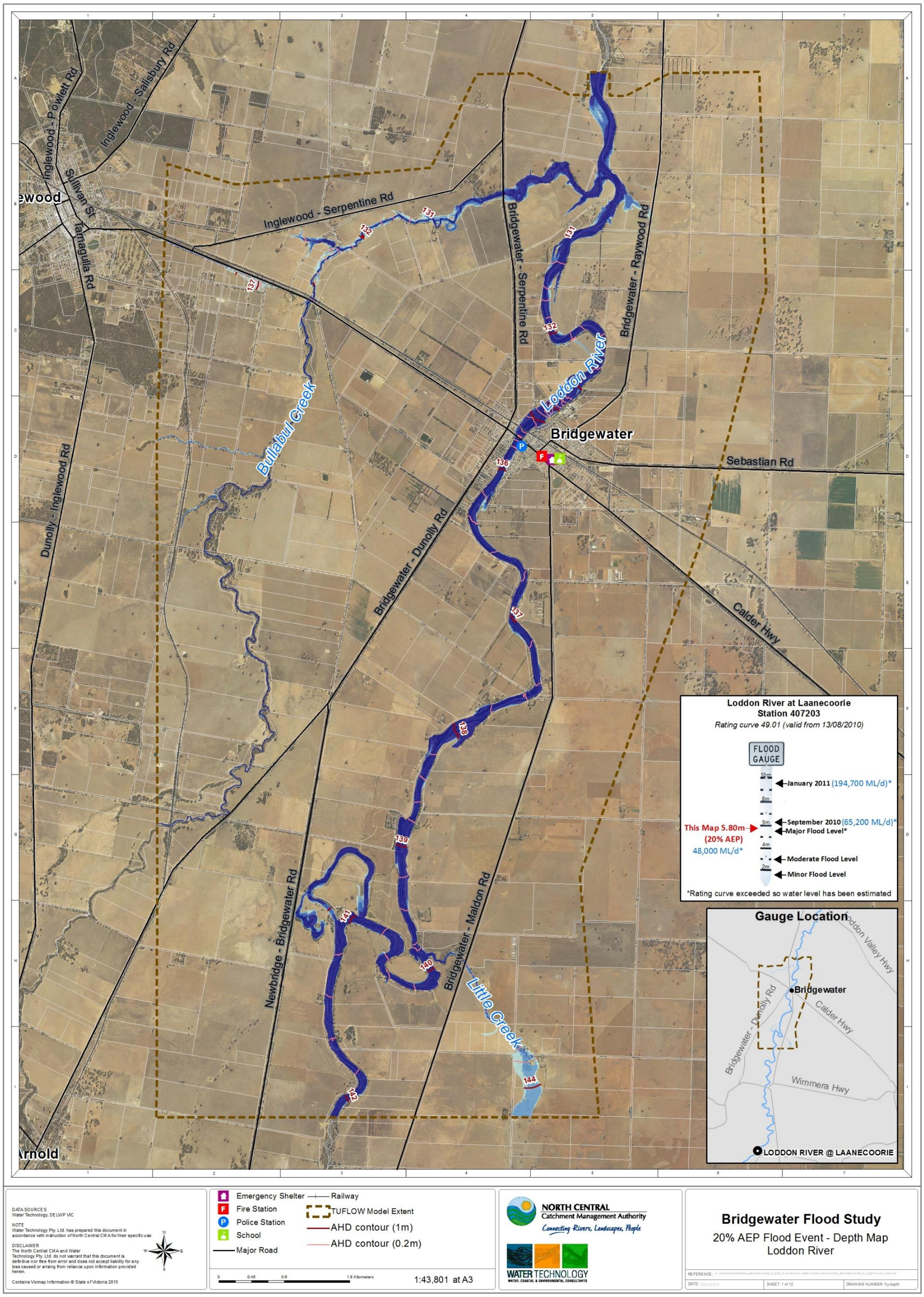
Calder Highway and Eaglehawk-Inglewood railway crossing Bullabul Creek

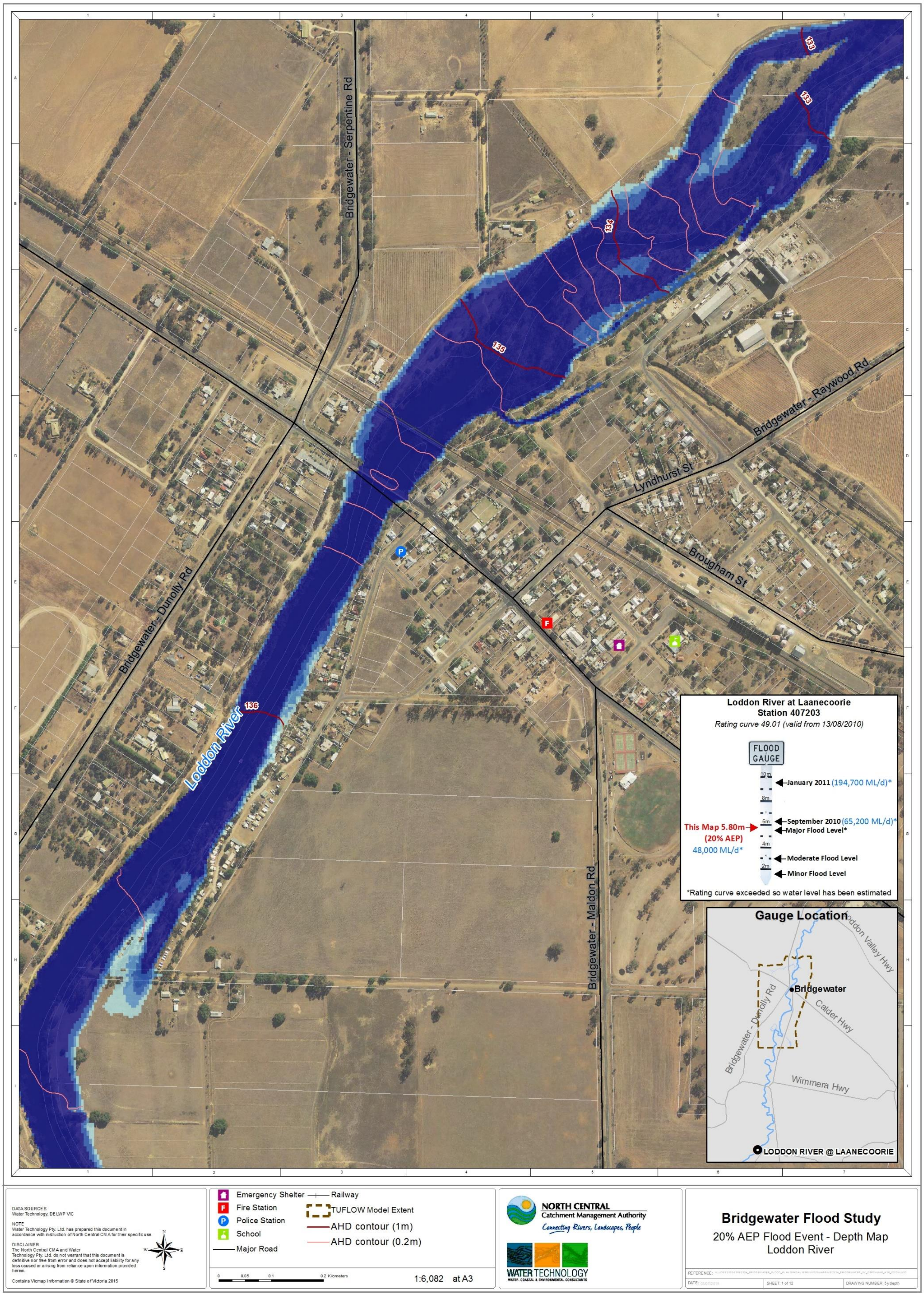
Eaglehawk-Inglewood Line crossing Loddon River

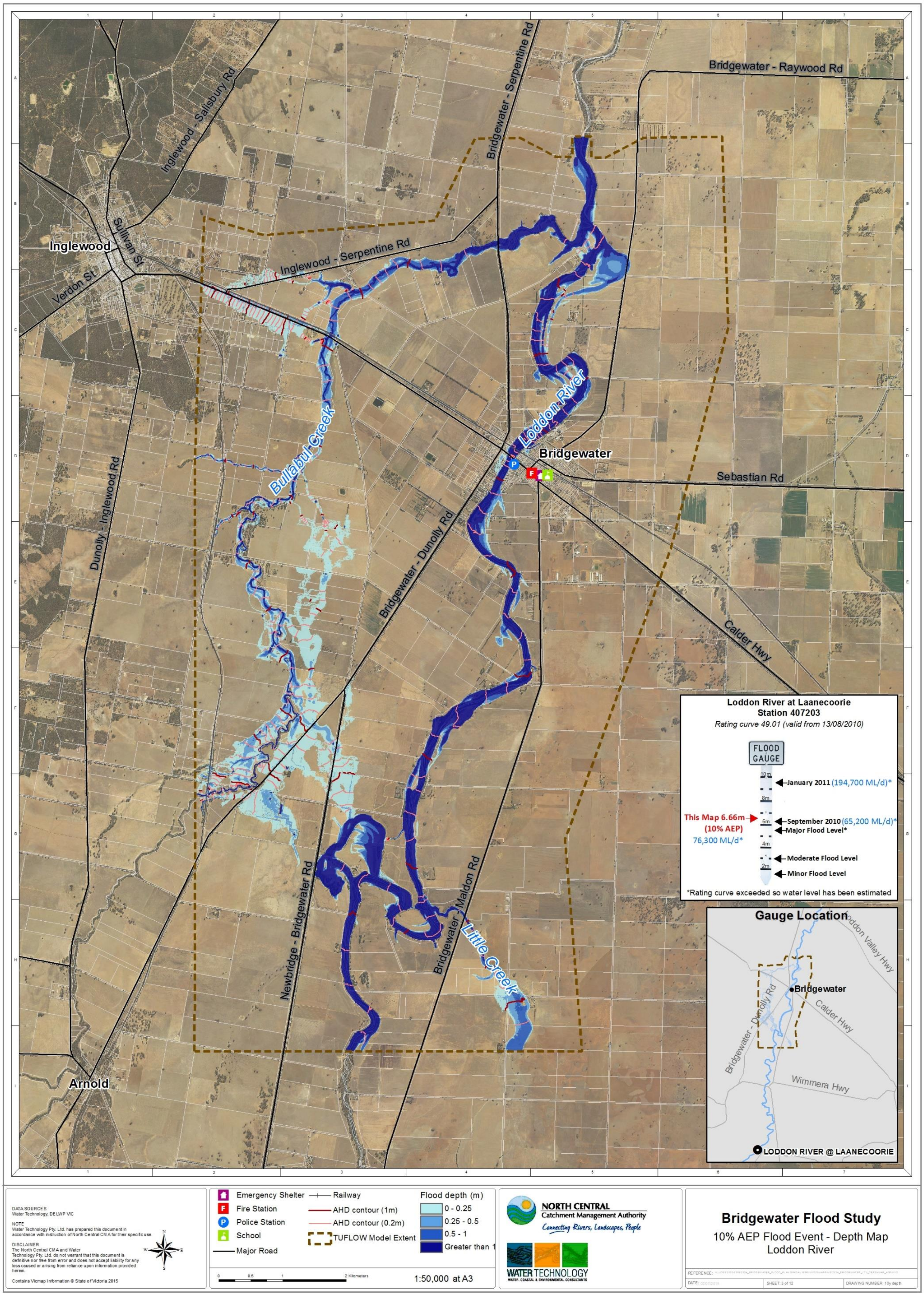
Peppercorn Lane depression

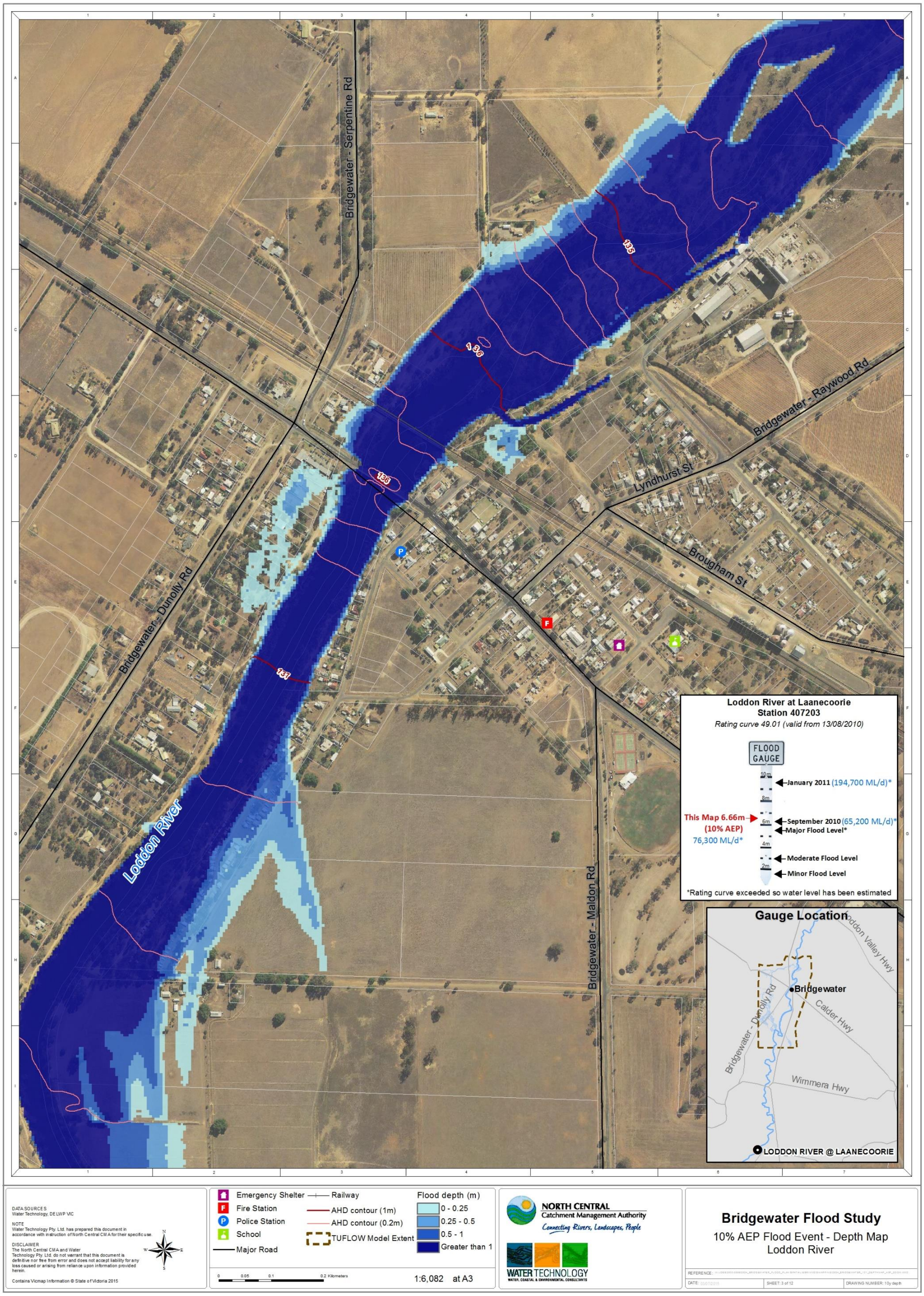
Loddon River @ Laanecoorie gauge location

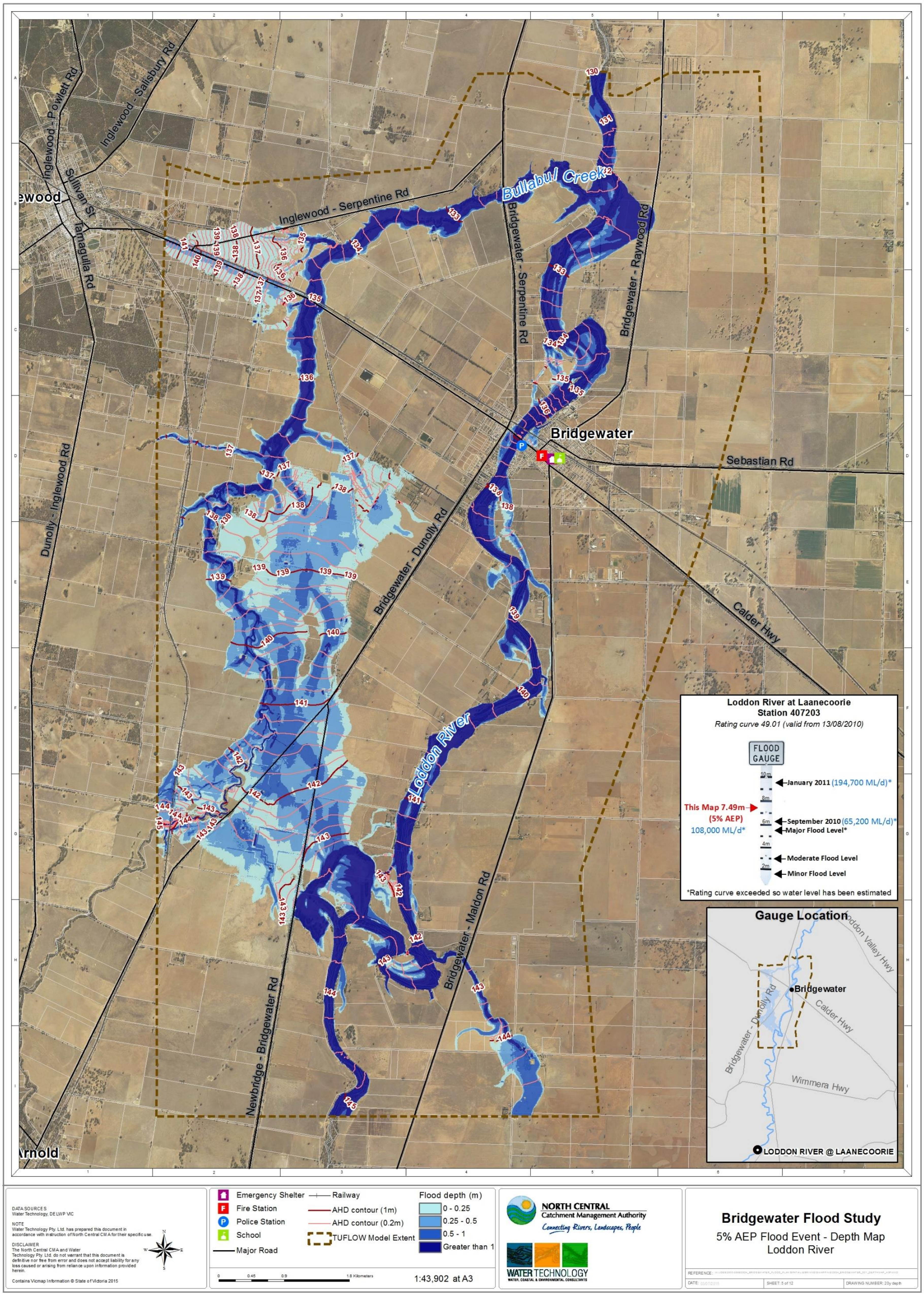
APPENDIX B: DESIGN FLOOD DEPTH MAPS

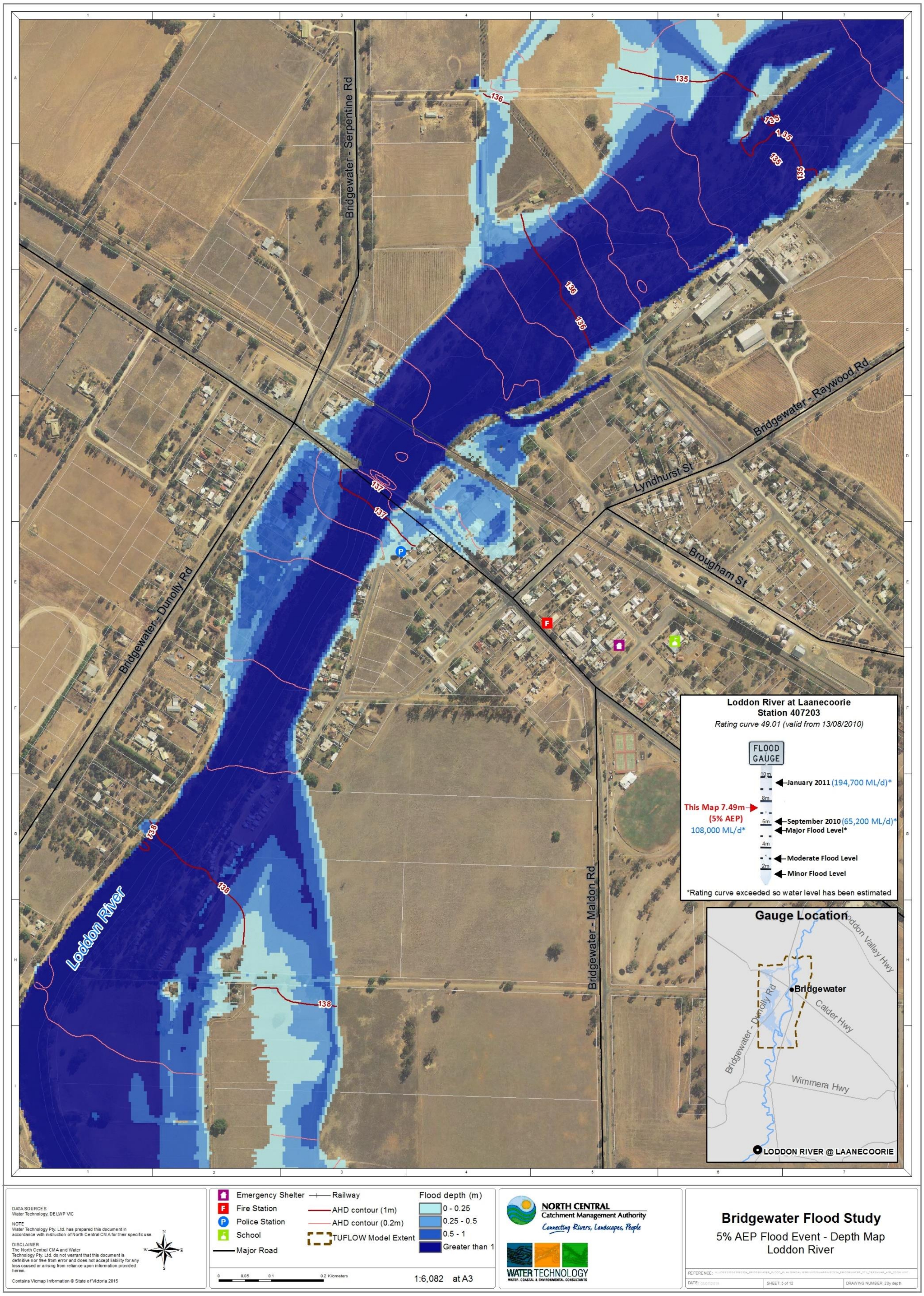

Loddon River
Bullabul Creek
Little Creek
Bridgewater
Inglewood - Serpentine Rd
Bridgewater - Serpentine Rd
Bridgewater - Raywood Rd
Bridgewater - Dunolly Rd
Newbridge - Bridgewater Rd
Bridgewater - Maldon Rd
Dunolly - Inglewood Rd
Inglewood - Powlett Rd
Inglewood - Salisbury Rd
Sullivan St
Tamagulla Rd
Sebastian Rd
Calder Hwy
Arnold
Loddon River at Laanecoorie
Station 407203
Rating curve 49.01 (valid from 13/08/2010)
FLOOD GAUGE
January 2011 (194,700 ML/d)*
September 2010 (65,200 ML/d)*
Major Flood Level*
This Map 5.80m
(20% AEP)
48,000 ML/d*
Moderate Flood Level
Minor Flood Level
*Rating curve exceeded so water level has been estimated
Gauge Location
Loddon Valley Hwy
Bridgewater
Calder Hwy
Bridgewater - Dunolly Rd
Wimmera Hwy
LODDON RIVER @ LAANECOORIE
Emergency Shelter
Fire Station
Police Station
School
Major Road
Railway
TUFLOW Model Extent
AHD contour (1m)
AHD contour (0.2m)
1:43,801 at A3
NORTH CENTRAL
Catchment Management Authority
Connecting Rivers, Landscapes, People
WATER TECHNOLOGY
Bridgewater Flood Study
20% AEP Flood Event - Depth Map
Loddon River

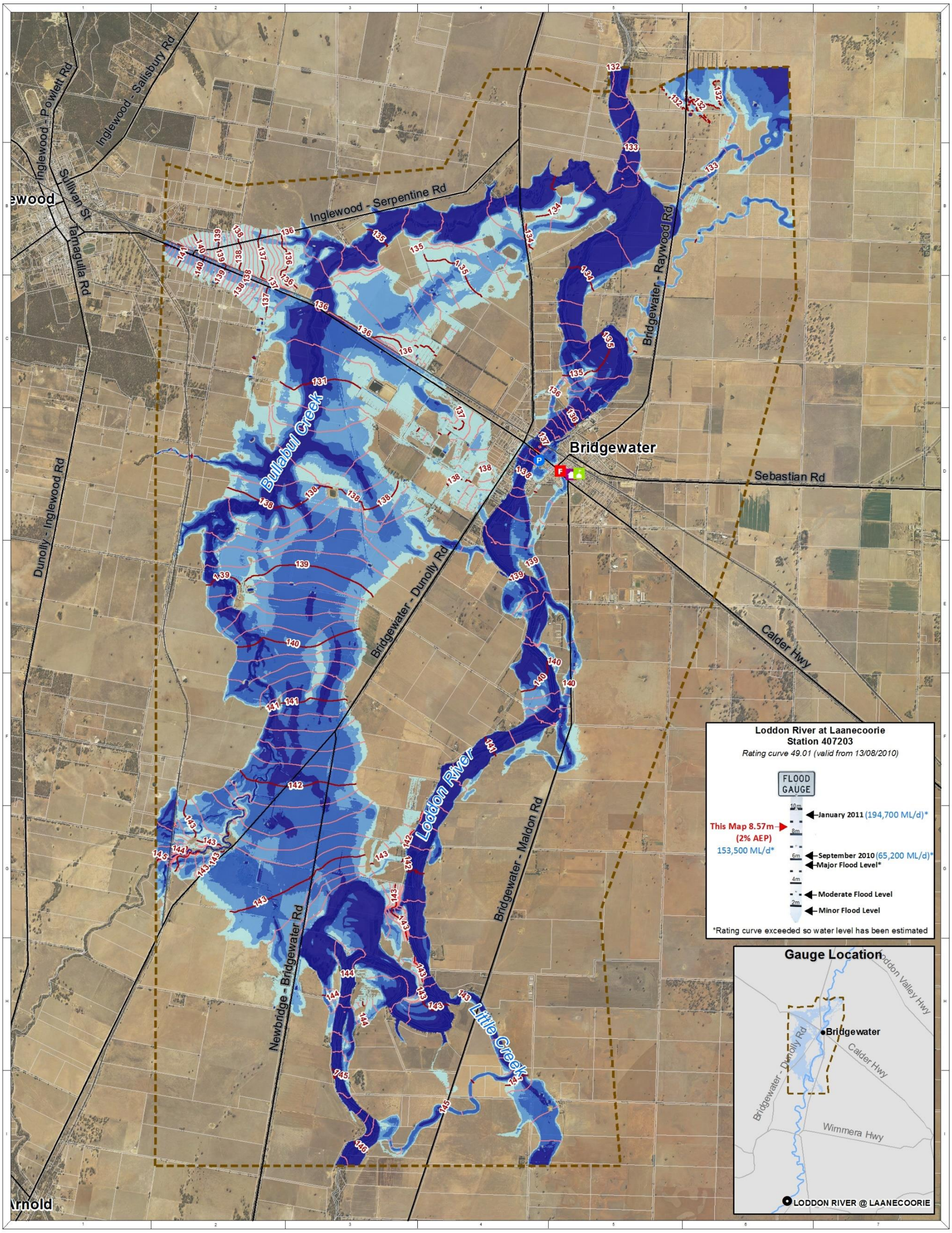

Bridgewater - Serpentine Rd
Bridgewater - Raywood Rd
Lyndhurst St
Brougham St
Bridgewater - Dunolly Rd
Bridgewater - Maldon Rd
Loddon River
133
134
135
136
Loddon River at Laanecoorie
Station 407203
Rating curve 49.01 (valid from 13/08/2010)
FLOOD GAUGE
January 2011 (194,700 ML/d)*
September 2010 (65,200 ML/d)*
Major Flood Level*
This Map 5.80m (20% AEP) 48,000 ML/d*
Moderate Flood Level
Minor Flood Level
*Rating curve exceeded so water level has been estimated
Gauge Location
Loddon Valley Hwy
Bridgewater
Calder Hwy
Bridgewater - Dunolly Rd
Wimmera Hwy
LODDON RIVER @ LAANECOORIE
Emergency Shelter
Railway
Fire Station
TUFLOW Model Extent
Police Station
AHD contour (1m)
School
AHD contour (0.2m)
Major Road
1:6,082 at A3
NORTH CENTRAL Catchment Management Authority
Connecting Rivers, Landscapes, People
WATER TECHNOLOGY
Bridgewater Flood Study
20% AEP Flood Event - Depth Map
Loddon River


Bridgewater - Raywood Rd
Inglewood - Salisbury Rd
Bridgewater - Serpentine Rd
Inglewood
Sullivan St
Verdon St
Inglewood - Serpentine Rd
Loddon River
Bridgewater
Bullabul Creek
Sebastian Rd
Dunolly - Inglewood Rd
Bridgewater - Dunolly Rd
Calder Hwy
Newbridge - Bridgewater Rd
Bridgewater - Maldon Rd
Little Creek
Arnold
Loddon River at Laanecoorie
Station 407203
Rating curve 49.01 (valid from 13/08/2010)
FLOOD GAUGE
10m
8m
6m
4m
2m
January 2011 (194,700 ML/d)*
This Map 6.66m
(10% AEP)
76,300 ML/d*
September 2010 (65,200 ML/d)*
Major Flood Level*
Moderate Flood Level
Minor Flood Level
*Rating curve exceeded so water level has been estimated
Gauge Location
Loddon Valley Hwy
Bridgewater
Calder Hwy
Bridgewater - Dunolly Rd
Wimmera Hwy
LODDON RIVER @ LAANECOORIE
DATA SOURCES
Water Technology, DELWP VIC
NOTE
Water Technology Pty. Ltd. has prepared this document in accordance with instruction of North Central CMA for their specific use.
DISCLAIMER
The North Central CMA and Water Technology Pty. Ltd. do not warrant that this document is definitive nor free from error and does not accept liability for any loss caused or arising from reliance upon information provided herein.
Contains Vicmap Information © State of Victoria 2015
Emergency Shelter
Fire Station
Police Station
School
Major Road
Railway
AHD contour (1m)
AHD contour (0.2m)
TUFLOW Model Extent
Flood depth (m)
0 - 0.25
0.25 - 0.5
0.5 - 1
Greater than 1
0
0.5
1
2 Kilometers
1:50,000 at A3
NORTH CENTRAL
Catchment Management Authority
Connecting Rivers, Landscapes, People
WATER TECHNOLOGY
Bridgewater Flood Study
10% AEP Flood Event - Depth Map
Loddon River


Bridgewater - Serpentine Rd
Bridgewater - Dunolly Rd
Bridgewater - Raywood Rd
Bridgewater - Maldon Rd
Lyndhurst St
Brougham St
Loddon River
135
136
136
137
Loddon River at Laanecoorie
Station 407203
Rating curve 49.01 (valid from 13/08/2010)
FLOOD GAUGE
January 2011 (194,700 ML/d)*
This Map 6.66m
(10% AEP)
76,300 ML/d*
September 2010 (65,200 ML/d)*
Major Flood Level*
Moderate Flood Level
Minor Flood Level
*Rating curve exceeded so water level has been estimated
Gauge Location
Loddon Valley Hwy
Bridgewater
Calder Hwy
Bridgewater - Dunolly Rd
Wimmera Hwy
LODDON RIVER @ LAANECOORIE
DATA SOURCES
Water Technology, DELWP VIC
NOTE
Water Technology Pty. Ltd. has prepared this document in accordance with instruction of North Central CMA for their specific use.
DISCLAIMER
The North Central CMA and Water Technology Pty. Ltd. do not warrant that this document is definitive nor free from error and does not accept liability for any loss caused or arising from reliance upon information provided herein.
Contains Vicmap Information © State of Victoria 2015
Emergency Shelter
Fire Station
Police Station
School
Major Road
Railway
AHD contour (1m)
AHD contour (0.2m)
TUFLOW Model Extent
Flood depth (m)
0 - 0.25
0.25 - 0.5
0.5 - 1
Greater than 1
0 0.05 0.1 0.2 Kilometers
1:6,082 at A3
NORTH CENTRAL Catchment Management Authority
Connecting Rivers, Landscapes, People
WATER TECHNOLOGY
Bridgewater Flood Study
10% AEP Flood Event - Depth Map
Loddon River


Bullabul Creek
Inglewood - Serpentine Rd
Bridgewater - Serpentine Rd
Bridgewater - Raywood Rd
Bridgewater
Sebastian Rd
Calder Hwy
Bridgewater - Dunolly Rd
Dunolly - Inglewood Rd
Loddon River
Bridgewater - Maldon Rd
Newbridge - Bridgewater Rd
Inglewood - Salisbury Rd
Inglewood - Powlett Rd
Sullivan St
Tamagulla Rd
Loddon River at Laanecoorie
Station 407203
Rating curve 49.01 (valid from 13/08/2010)
FLOOD GAUGE
January 2011 (194,700 ML/d)*
This Map 7.49m
(5% AEP)
108,000 ML/d*
September 2010 (65,200 ML/d)*
Major Flood Level*
Moderate Flood Level
Minor Flood Level
*Rating curve exceeded so water level has been estimated
Gauge Location
Bridgewater
Loddon Valley Hwy
Calder Hwy
Bridgewater - Dunolly Rd
Wimmera Hwy
LODDON RIVER @ LAANECOORIE
Emergency Shelter
Fire Station
Police Station
School
Major Road
Railway
AHD contour (1m)
AHD contour (0.2m)
TUFLOW Model Extent
Flood depth (m)
0 - 0.25
0.25 - 0.5
0.5 - 1
Greater than 1
1:43,902 at A3
NORTH CENTRAL
Catchment Management Authority
Connecting Rivers, Landscapes, People
WATER TECHNOLOGY
Bridgewater Flood Study
5% AEP Flood Event - Depth Map
Loddon River


Bridgewater - Serpentine Rd
Bridgewater - Dunolly Rd
Bridgewater - Maldon Rd
Bridgewater - Raywood Rd
Lyndhurst St
Brougham St
Loddon River
135
136
137
138
Loddon River at Laanecoorie
Station 407203
Rating curve 49.01 (valid from 13/08/2010)
FLOOD GAUGE
This Map 7.49m
(5% AEP)
108,000 ML/d*
January 2011 (194,700 ML/d)*
September 2010 (65,200 ML/d)*
Major Flood Level*
Moderate Flood Level
Minor Flood Level
*Rating curve exceeded so water level has been estimated
Gauge Location
Loddon Valley Hwy
Bridgewater
Calder Hwy
Bridgewater - Dunolly Rd
Wimmera Hwy
LODDON RIVER @ LAANECOORIE
DATA SOURCES
Water Technology, DELWP VIC
NOTE
Water Technology Pty. Ltd. has prepared this document in accordance with instruction of North Central CMA for their specific use.
DISCLAIMER
The North Central CMA and Water Technology Pty. Ltd. do not warrant that this document is definitive nor free from error and does not accept liability for any loss caused or arising from reliance upon information provided herein.
Contains Vicmap Information © State of Victoria 2015
Emergency Shelter
Fire Station
Police Station
School
Major Road
Railway
AHD contour (1m)
AHD contour (0.2m)
TUFLOW Model Extent
Flood depth (m)
0 - 0.25
0.25 - 0.5
0.5 - 1
Greater than 1
0.2 Kilometers
1:6,082 at A3
NORTH CENTRAL
Catchment Management Authority
Connecting Rivers, Landscapes, People
Bridgewater Flood Study
5% AEP Flood Event - Depth Map
Loddon River



DATA SOURCES
Water Technology, DELWP VIC

NOTE
Water Technology Pty. Ltd. has prepared this document in accordance with instruction of North Central CMA for their specific use.

DISCLAIMER
The North Central CMA and Water Technology Pty. Ltd. do not warrant that this document is definitive nor free from error and does not accept liability for any loss caused or arising from reliance upon information provided herein.

Emergency Shelter
Fire Station
Police Station
School
Major Road
Railway
AHD contour (1m)
AHD contour (0.2m)
TUFLOW Model Extent

Flood depth (m)
0 - 0.25
0.25 - 0.5
0.5 - 1
Greater than 1

0 0.45 0.9 1.8 Kilometers

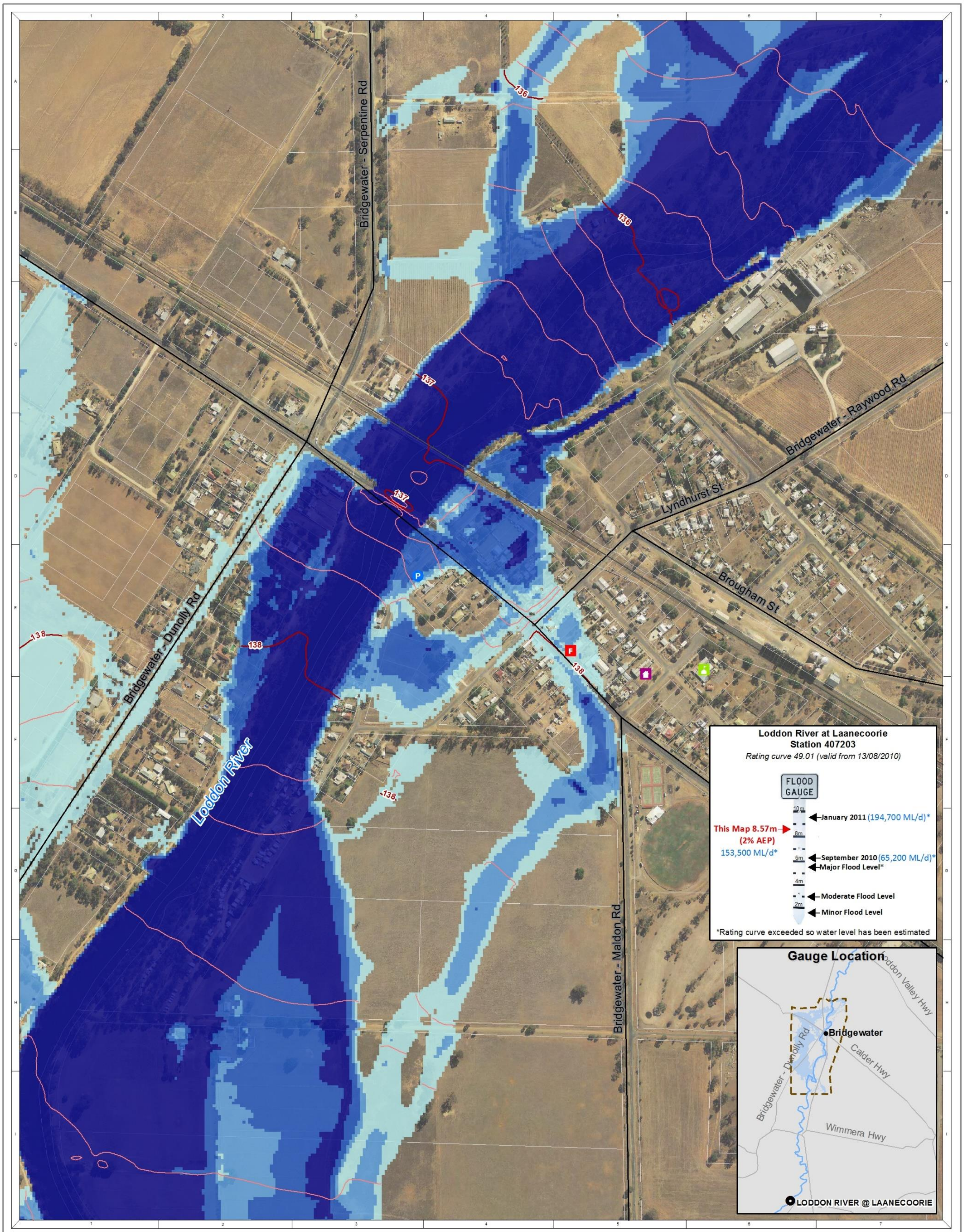
1:43,772 at A3

NORTH CENTRAL Catchment Management Authority
Connecting Rivers, Landscapes, People

WATER TECHNOLOGY

Bridgewater Flood Study

2% AEP Flood Event - Depth Map
Loddon River



DATA SOURCES
Water Technology, DELWP VIC

NOTE
Water Technology Pty. Ltd. has prepared this document in accordance with instruction of North Central CMA for their specific use.

DISCLAIMER
The North Central CMA and Water Technology Pty. Ltd. do not warrant that this document is definitive nor free from error and does not accept liability for any loss caused or arising from reliance upon information provided herein.

- Emergency Shelter
- Fire Station
- Police Station
- School
- Major Road
- Railway
- AHD contour (1m)
- AHD contour (0.2m)
- TUFLOW Model Extent

Flood depth (m)
- 0 - 0.25
- 0.25 - 0.5
- 0.5 - 1
- Greater than 1

0 0.05 0.1 0.2 Kilometers

1:6,082 at A3

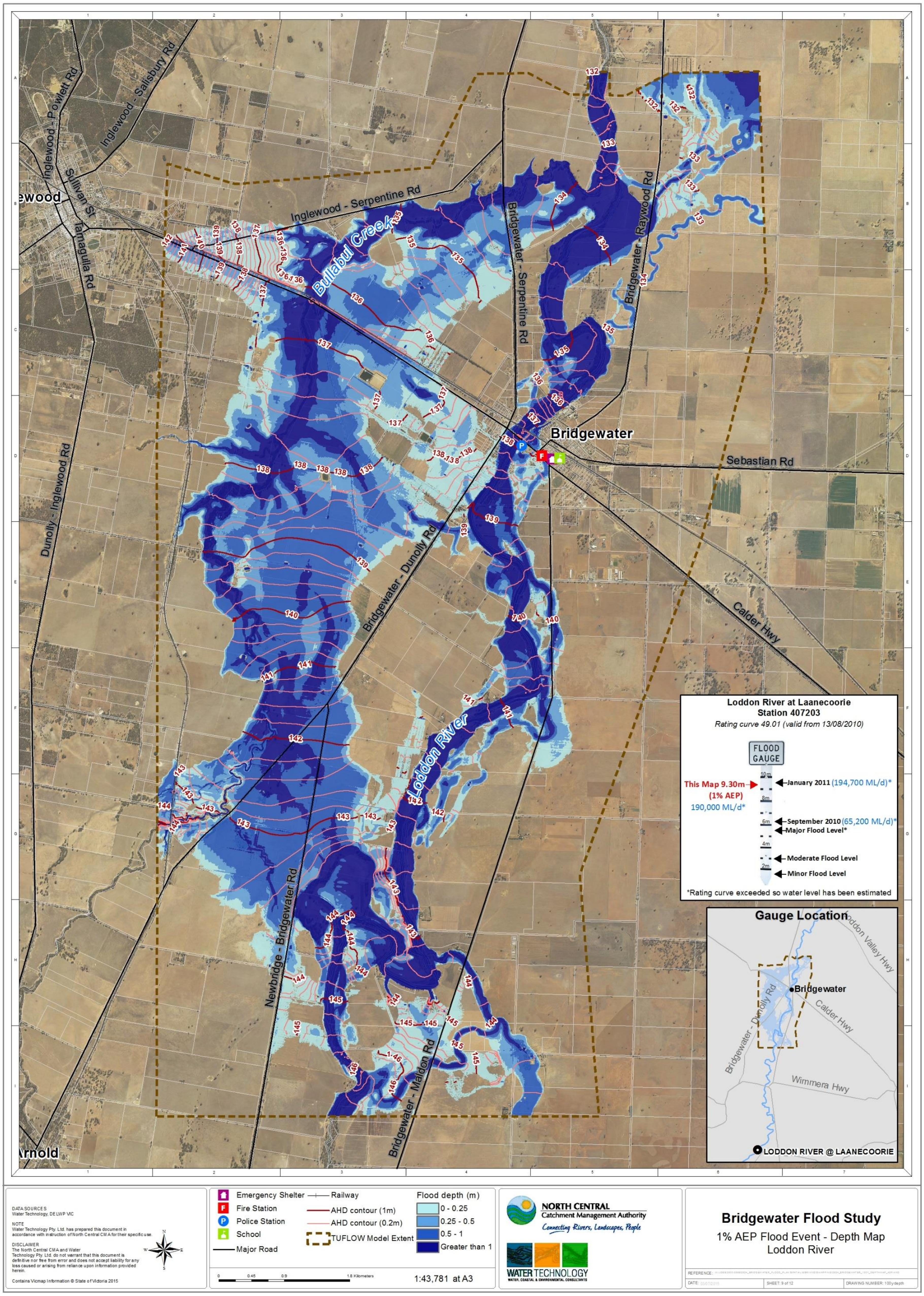
NORTH CENTRAL Catchment Management Authority
Connecting Rivers, Landscapes, People

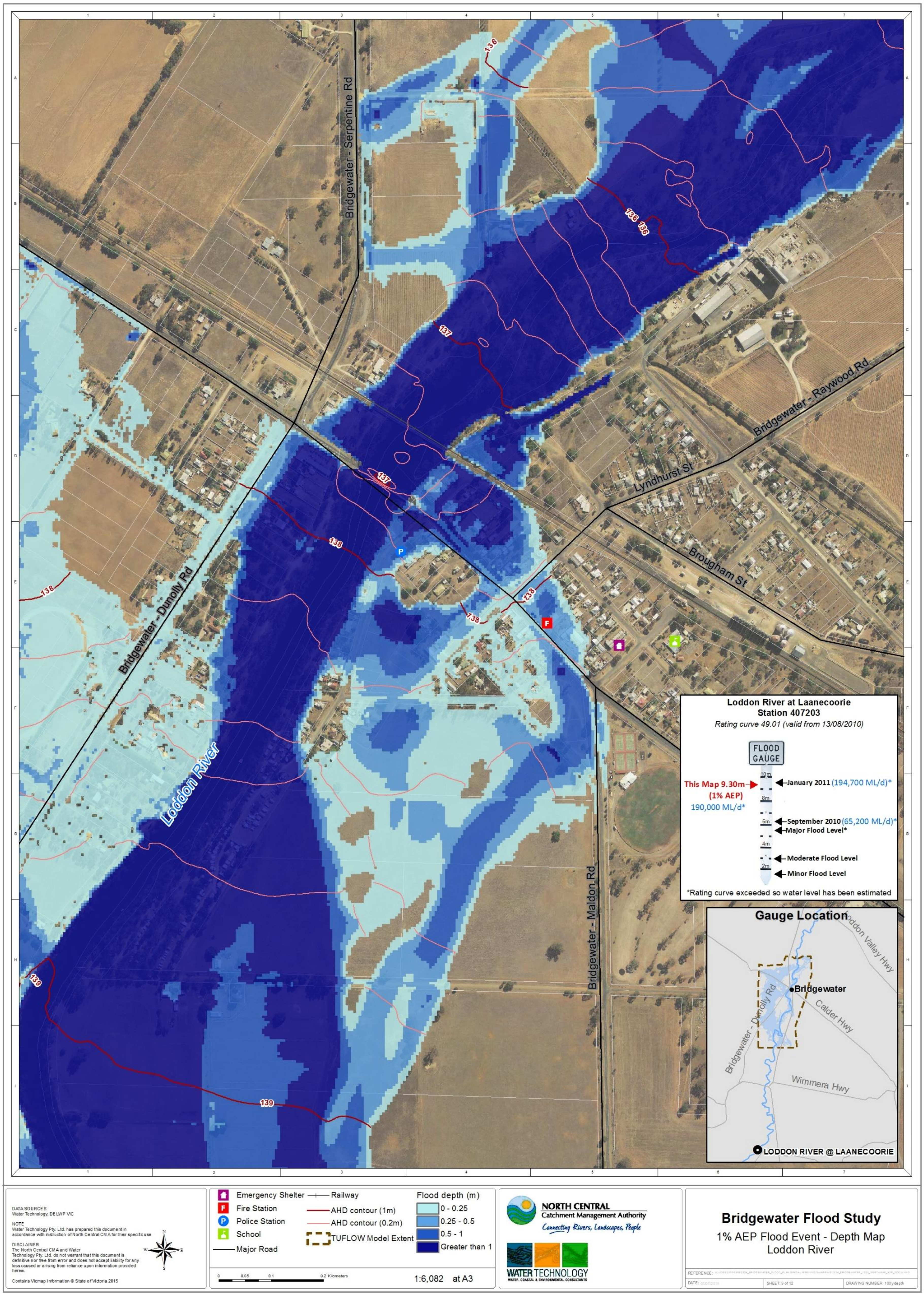
WATER TECHNOLOGY
WATER, COASTAL & ENVIRONMENTAL CONSULTANTS

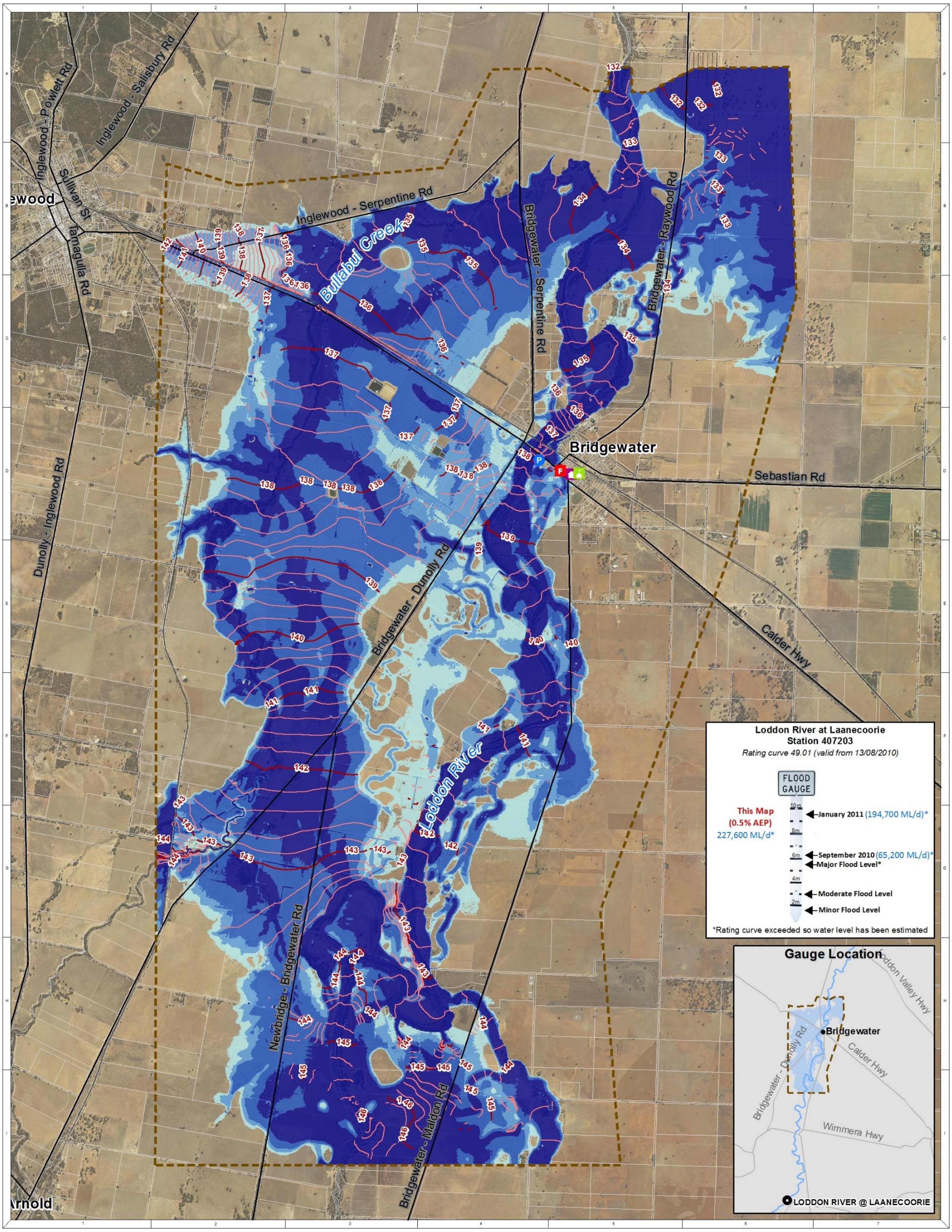
Bridgewater Flood Study

2% AEP Flood Event - Depth Map
Loddon River

REFERENCE:
DATE: 03/07/2015 | SHEET: 7 of 12 | DRAWING NUMBER: 50y depth


Bridgewater
Inglewood - Serpentine Rd
Bullabul Creek
Bridgewater - Serpentine Rd
Bridgewater - Raywood Rd
Sebastian Rd
Calder Hwy
Bridgewater - Dunolly Rd
Dunolly - Inglewood Rd
Newbridge - Bridgewater Rd
Bridgewater - Maldon Rd
Loddon River
Inglewood - Powlett Rd
Inglewood - Salisbury Rd
Sullivan St
Tamagulla Rd
Arnold
Loddon River at Laanecoorie
Station 407203
Rating curve 49.01 (valid from 13/08/2010)
FLOOD GAUGE
This Map 9.30m (1% AEP) 190,000 ML/d*
January 2011 (194,700 ML/d)*
September 2010 (65,200 ML/d)*
Major Flood Level*
Moderate Flood Level
Minor Flood Level
*Rating curve exceeded so water level has been estimated
Gauge Location
Bridgewater
Loddon Valley Hwy
Calder Hwy
Bridgewater - Dunolly Rd
Wimmera Hwy
LODDON RIVER @ LAANECOORIE
DATA SOURCES
Water Technology, DELWP VIC
Emergency Shelter
Fire Station
Police Station
School
Major Road
Railway
AHD contour (1m)
AHD contour (0.2m)
TUFLOW Model Extent
Flood depth (m)
0 - 0.25
0.25 - 0.5
0.5 - 1
Greater than 1
1:43,781 at A3
NORTH CENTRAL Catchment Management Authority
Connecting Rivers, Landscapes, People
WATER TECHNOLOGY
Bridgewater Flood Study
1% AEP Flood Event - Depth Map
Loddon River


Bridgewater - Serpentine Rd
Bridgewater - Raywood Rd
Lyndhurst St
Brougham St
Bridgewater - Dunolly Rd
Loddon River
Bridgewater - Maldon Rd
136
137
138
139
Loddon River at Laanecoorie
Station 407203
Rating curve 49.01 (valid from 13/08/2010)
FLOOD GAUGE
This Map 9.30m
(1% AEP)
190,000 ML/d*
January 2011 (194,700 ML/d)*
September 2010 (65,200 ML/d)*
Major Flood Level*
Moderate Flood Level
Minor Flood Level
*Rating curve exceeded so water level has been estimated
Gauge Location
Loddon Valley Hwy
Bridgewater
Calder Hwy
Bridgewater - Dunolly Rd
Wimmera Hwy
LODDON RIVER @ LAANECOORIE
DATA SOURCES
Water Technology, DELWP VIC
NOTE
Water Technology Pty. Ltd. has prepared this document in accordance with instruction of North Central CMA for their specific use.
DISCLAIMER
The North Central CMA and Water Technology Pty. Ltd. do not warrant that this document is definitive nor free from error and does not accept liability for any loss caused or arising from reliance upon information provided herein.
Contains Vicmap Information © State of Victoria 2015
Emergency Shelter
Fire Station
Police Station
School
Major Road
Railway
AHD contour (1m)
AHD contour (0.2m)
TUFLOW Model Extent
Flood depth (m)
0 - 0.25
0.25 - 0.5
0.5 - 1
Greater than 1
0.2 Kilometers
1:6,082 at A3
NORTH CENTRAL Catchment Management Authority
Connecting Rivers, Landscapes, People
WATER TECHNOLOGY
Bridgewater Flood Study
1% AEP Flood Event - Depth Map
Loddon River



DATA SOURCES:
Water Technology, DELWP VIC

NOTE
Water Technology Pty. Ltd. has prepared this document in accordance with instruction of North Central CMA for their specific use.

DISCLAIMER
The North Central CMA and Water Technology Pty. Ltd. do not warrant that this document is definitive nor free from error and does not accept liability for any loss caused or arising from reliance upon information provided herein.

Legend		Flood depth (m)
Emergency Shelter	Railway	0 - 0.25
Fire Station	AHD contour (1m)	0.25 - 0.5
Police Station	AHD contour (0.2m)	0.5 - 1
School	TUFLOW Model Extent	Greater than 1
Major Road		

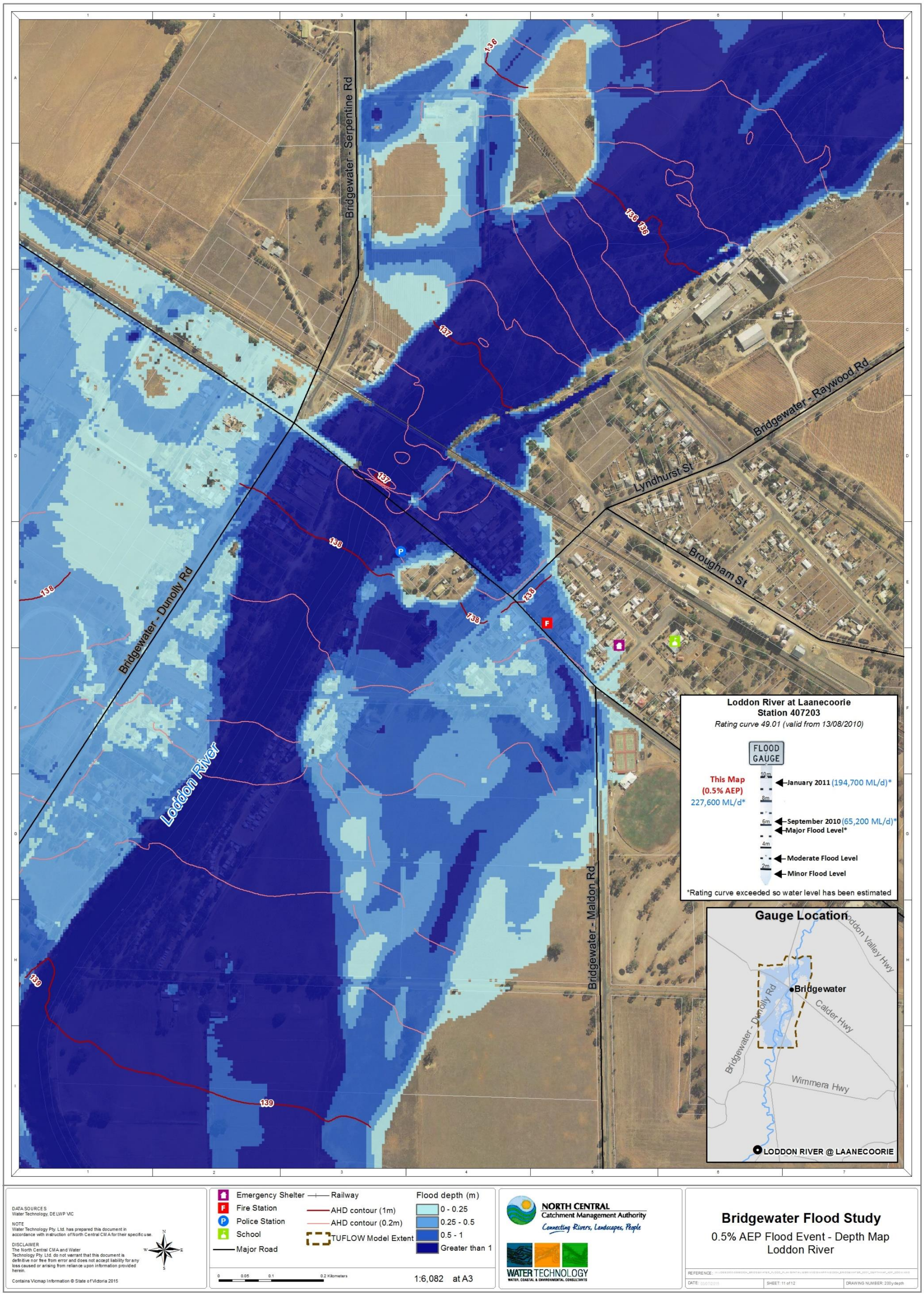
0 0.45 0.9 1.8 Kilometers
1:43,752 at A3

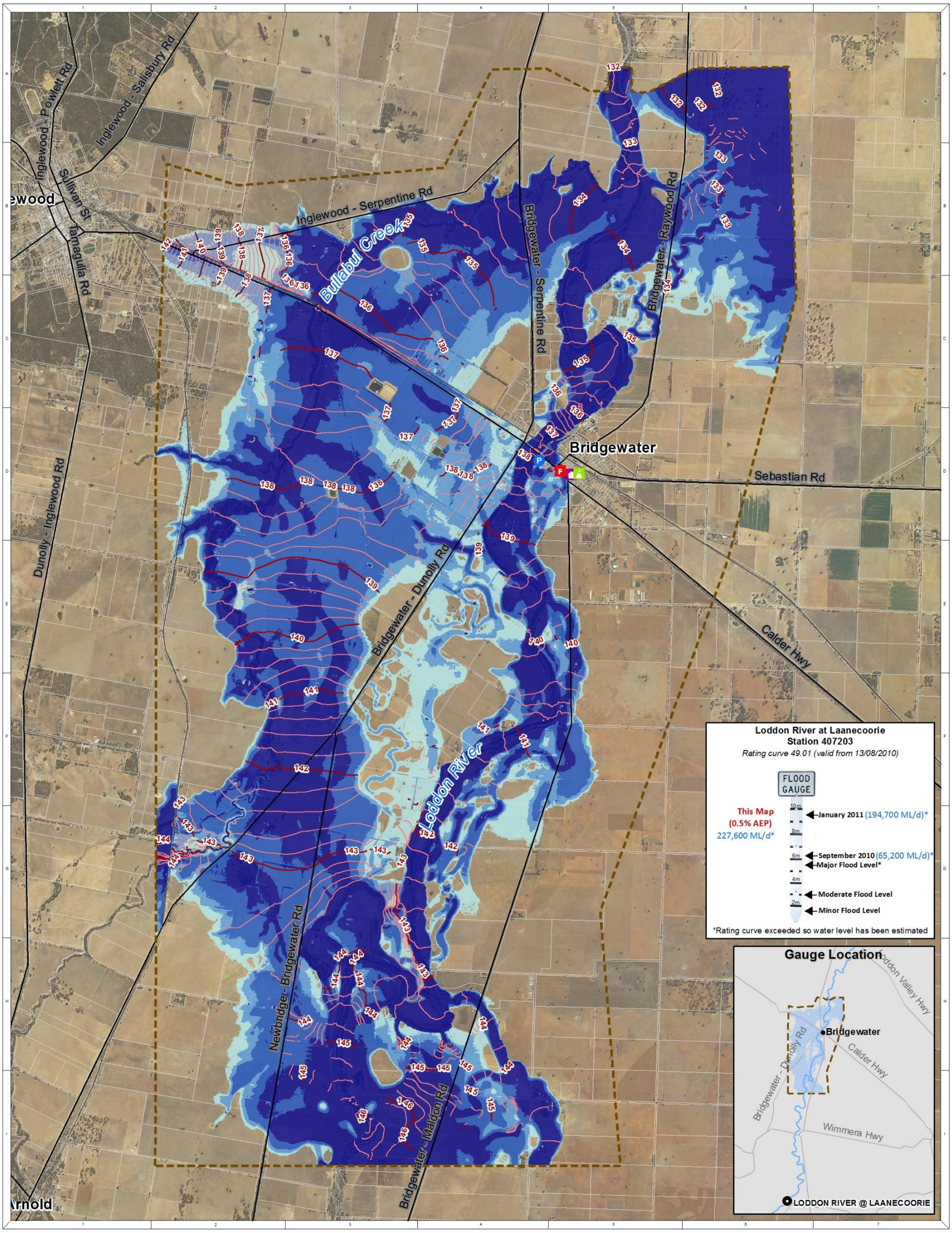
NORTH CENTRAL Catchment Management Authority
Connecting Rivers, Landscapes, People

WATER TECHNOLOGY

Bridgewater Flood Study
0.5% AEP Flood Event - Depth Map
Loddon River

SHEET: 11 of 12


Bridgewater - Serpentine Rd
Bridgewater - Dunolly Rd
Bridgewater - Maldon Rd
Bridgewater - Raywood Rd
Lyndhurst St
Brougham St
Loddon River
136
137
138
139
Loddon River at Laanecoorie
Station 407203
Rating curve 49.01 (valid from 13/08/2010)
FLOOD GAUGE
This Map
(0.5% AEP)
227,600 ML/d*
January 2011 (194,700 ML/d)*
September 2010 (65,200 ML/d)*
Major Flood Level*
Moderate Flood Level
Minor Flood Level
*Rating curve exceeded so water level has been estimated
Gauge Location
Loddon Valley Hwy
Bridgewater
Calder Hwy
Wimmera Hwy
Bridgewater - Dunolly Rd
LODDON RIVER @ LAANECOORIE
DATA SOURCES
Water Technology, DELWP VIC
Emergency Shelter
Fire Station
Police Station
School
Major Road
Railway
AHD contour (1m)
AHD contour (0.2m)
TUFLOW Model Extent
Flood depth (m)
0 - 0.25
0.25 - 0.5
0.5 - 1
Greater than 1
1:6,082 at A3
Contains Vicmap Information © State of Victoria 2015
Bridgewater Flood Study
0.5% AEP Flood Event - Depth Map
Loddon River



DATA SOURCES
Water Technology, DELWP VIC

NOTE
Water Technology Pty. Ltd. has prepared this document in accordance with instruction of North Central CMA for their specific use.

DISCLAIMER
The North Central CMA and Water Technology Pty. Ltd. do not warrant that this document is definitive nor free from error and does not accept liability for any loss caused or arising from reliance upon information provided herein.

Emergency Shelter
Fire Station
Police Station
School
Major Road
Railway
AHD contour (1m)
AHD contour (0.2m)
TUFLOW Model Extent

Flood depth (m)
0 - 0.25
0.25 - 0.5
0.5 - 1
Greater than 1

0 0.45 0.9 1.8 Kilometers
1:43,929 at A3

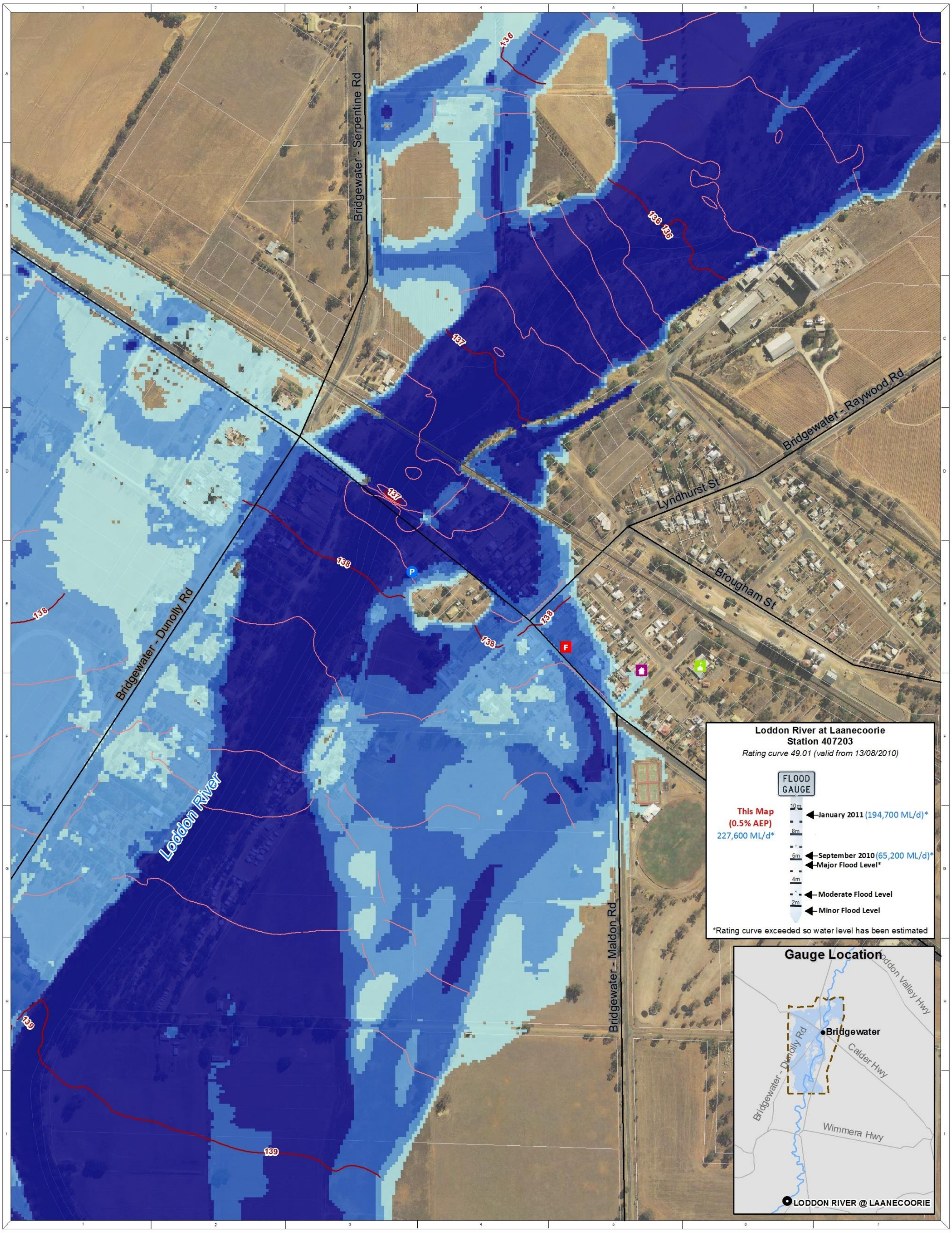
NORTH CENTRAL
Catchment Management Authority
Connecting Rivers, Landscapes, People

WATER TECHNOLOGY
WATER, COASTAL & ENVIRONMENTAL CONSULTANTS

Bridgewater Flood Study

0.5% AEP Flood Event - Depth Map
Loddon River

REFERENCE:
DATE: 03/07/2015
SHEET: 11 of 12
DRAWING NUMBER: 200ydepth



DATA SOURCES
Water Technology, DELWP VIC

NOTE
Water Technology Pty. Ltd. has prepared this document in accordance with instruction of North Central CMA for their specific use.

DISCLAIMER
The North Central CMA and Water Technology Pty. Ltd. do not warrant that this document is definitive nor free from error and does not accept liability for any loss caused or arising from reliance upon information provided herein.

Legend		Flood depth (m)
Emergency Shelter	Railway	0 - 0.25
Fire Station	AHD contour (1m)	0.25 - 0.5
Police Station	AHD contour (0.2m)	0.5 - 1
School	TUFLOW Model Extent	Greater than 1
Major Road		

0 0.05 0.1 0.2 Kilometers

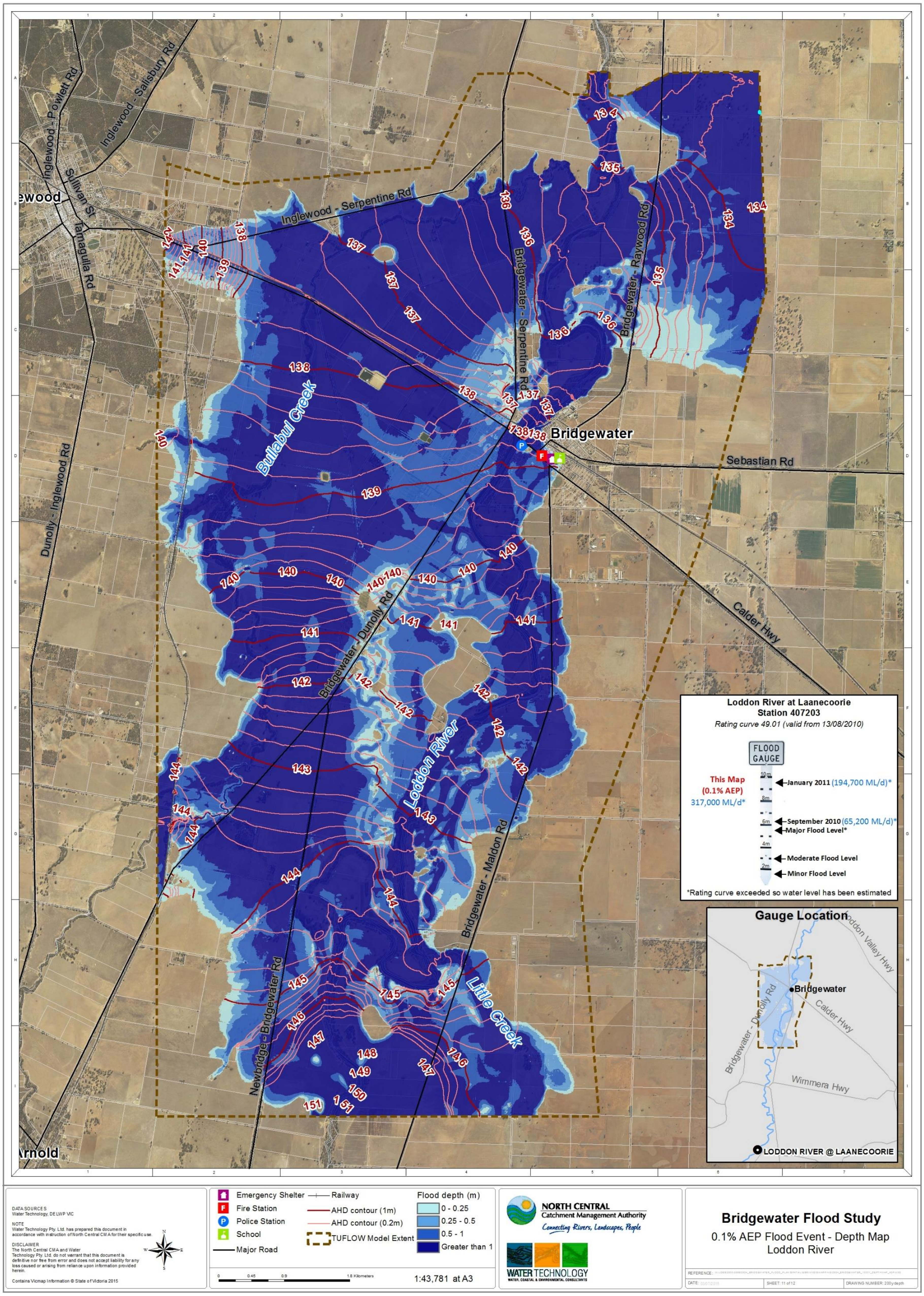
1:6,082 at A3

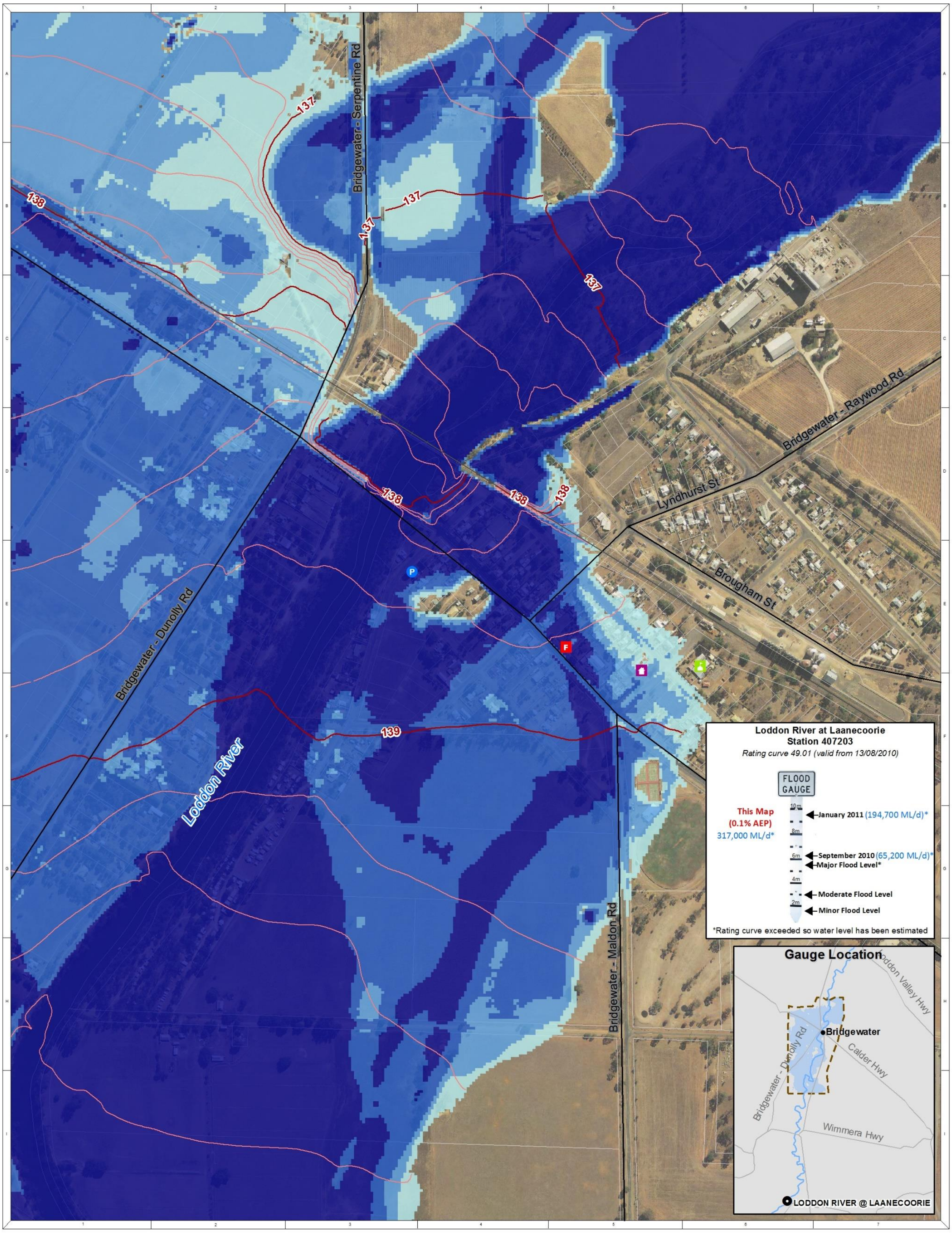
NORTH CENTRAL Catchment Management Authority
Connecting Rivers, Landscapes, People

WATER TECHNOLOGY

Bridgewater Flood Study

0.5% AEP Flood Event - Depth Map
Loddon River


Inglewood - Powlett Rd
Inglewood - Salisbury Rd
Sullivan St
Tarnagulla Rd
Inglewood - Serpentine Rd
Bridgewater - Serpentine Rd
Bridgewater - Raywood Rd
Bridgewater
Sebastian Rd
Calder Hwy
Bullabul Creek
Dunolly - Inglewood Rd
Bridgewater - Dunolly Rd
Loddon River
Bridgewater - Maldon Rd
Newbridge - Bridgewater Rd
Little Creek
Arnold
Loddon River at Laanecoorie
Station 407203
Rating curve 49.01 (valid from 13/08/2010)
FLOOD GAUGE
This Map (0.1% AEP) 317,000 ML/d*
January 2011 (194,700 ML/d)*
September 2010 (65,200 ML/d)*
Major Flood Level*
Moderate Flood Level
Minor Flood Level
*Rating curve exceeded so water level has been estimated
Gauge Location
Loddon Valley Hwy
Bridgewater
Calder Hwy
Bridgewater - Dunolly Rd
Wimmera Hwy
LODDON RIVER @ LAANECOORIE
DATA SOURCES
Water Technology, DELWP VIC
NOTE
Water Technology Pty. Ltd. has prepared this document in accordance with instruction of North Central CMA for their specific use.
DISCLAIMER
The North Central CMA and Water Technology Pty. Ltd. do not warrant that this document is definitive nor free from error and does not accept liability for any loss caused or arising from reliance upon information provided herein.
Contains Vicmap Information © State of Victoria 2015
Emergency Shelter
Fire Station
Police Station
School
Major Road
Railway
AHD contour (1m)
AHD contour (0.2m)
TUFLOW Model Extent
Flood depth (m)
0 - 0.25
0.25 - 0.5
0.5 - 1
Greater than 1
0 0.45 0.9 1.8 Kilometers
1:43,781 at A3
NORTH CENTRAL Catchment Management Authority
Connecting Rivers, Landscapes, People
WATER TECHNOLOGY
Bridgewater Flood Study
0.1% AEP Flood Event - Depth Map
Loddon River
SHEET: 11 of 12
DRAWING NUMBER: 200y depth



DATA SOURCES
Water Technology, DELWP VIC

NOTE
Water Technology Pty. Ltd. has prepared this document in accordance with instruction of North Central CMA for their specific use.

DISCLAIMER
The North Central CMA and Water Technology Pty. Ltd. do not warrant that this document is definitive nor free from error and does not accept liability for any loss caused or arising from reliance upon information provided herein.

Emergency Shelter
Fire Station
Police Station
School
Major Road
Railway
AHD contour (1m)
AHD contour (0.2m)
TUFLOW Model Extent

Flood depth (m)
0 - 0.25
0.25 - 0.5
0.5 - 1
Greater than 1

0 0.05 0.1 0.2 Kilometers
1:6,082 at A3

NORTH CENTRAL Catchment Management Authority
Connecting Rivers, Landscapes, People

Bridgewater Flood Study
0.1% AEP Flood Event - Depth Map
Loddon River

APPENDIX C: MITIGATION FLOOD DEPTH MAPS

INSERT MAPS HERE