WATER TECHNOLOGY
WATER, COASTAL & ENVIRONMENTAL CONSULTANTS

Bendigo Urban Flood Study

Final Report

November 2013

NORTH CENTRAL Catchment Management Authority
Connecting Rivers, Landscapes, People

CITY OF GREATER BENDIGO

State Government Victoria

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PROJECT DETAILS

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Cover Photo: Bendigo Creek looking towards town centre

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EXECUTIVE SUMMARY

Overview

Water Technology was commissioned by the North Central Catchment Management Authority (NCCMA) in conjunction with the City of Greater Bendigo (CoGB) to undertake the Bendigo Urban Flood Study. This study involved detailed hydrological and hydraulic modelling for Bendigo's urban areas and its outskirts, including Bendigo Creek and its major tributaries and the overland flow paths. The flood mapping of the Bendigo Creek Catchment was one of the most technically comprehensive studies ever undertaken in Victoria. Water Technology believes that this study is a landmark study for flood mapping of large urban areas, it is the first of its kind, setting the benchmark for future work of this nature.

Modelling and Mapping

Mapping of the creek systems using traditional methods combined with the Rain on Grid mapping of the greater catchment provides NCCMA and CoGB an unprecedented amount of flood intelligence and data.

Three major models were built for this study, these included:

- A hydrological RORB model calibrated to known events and verified by an external, independent expert panel.
- A detailed 1D-2D flood model of all the major waterways within the study area (Spine model). This provides a high resolution flood map and associated data for future flood intelligence requirements.
- Comprehensive high resolution Rainfall on Grid (ROG) models providing exceptional flood intelligence at a very fine resolution. This mapping will provide Council with a highly valuable dataset on which to base future development decisions whilst the model itself will assist with infrastructure design and feasibility assessment.

Historic Event Calibration

The hydrologic RORB model was calibrated over a range of recent events with mixed success. The available calibration data was of low quality with gauge records not matching with anecdotal information and regional comparisons to nearby gauges. To compensate for this lack of confidence in the available gauge information a variety of checks were performed. Preliminary hydraulic model simulations on the estimated historic flows were run with feedback received from Council and CMA on the results. This feedback was used to refine the model development.

Design Event Modelling

The models were all run for the 5, 10, 20, 50, 100 and 200 year ARI design events with multiple durations. The RORB model was utilised with the following design assumptions:

- Design rainfall depths for Bendigo from BoM IFD values
- Zone 2 design temporal patterns
- Areal Reduction Factors for an area upstream of 203 km^2
- Uniform spatial rainfall pattern across the entire catchment
- kc of 14 for the upper catchment, 17 for the lower catchment.
- Design losses; an initial loss of 10 mm for the upper catchment, 20 mm for the lower catchment and a continuing loss of 2.5 mm/hour.

These design assumptions were thoroughly tested with sensitivity analysis and further verified using Flood Frequency Analysis, Rational Method calculations, Regional Method estimates and comparison to previous studies. The design hydrology results for the Spine model are presented below.

Table 1 RORB model design peak flows and critical storm durations at selected locations

ARI	Bendigo Creek at Bendigo		Bendigo Creek at Huntly		Furness St, Kangaroo Flat Inflow (IF2 - 2)		Back Creek (Huntly) Inflow (IF7 - 41)		Eaglehawk Creek Inflow (IF8 - 27)	
	Peak flow (m^3/s)	Duration (hrs)	Peak flow (m^3/s)	Duration (hrs)	Peak flow (m^3/s)	Duration (hrs)	Peak flow (m^3/s)	Duration (hrs)	Peak flow (m^3/s)	Duration (hrs)
5	63.3	12	75.8	6	8.8	12	3.6	72	4.0	6
10	79.5	3	104.6	6	11.5	3	5.3	72	5.4	12
20	101.6	3	148.0	6	15.0	3	7.6	72	7.6	12
50	132.7	3	209.9	6	20.4	3	11.3	48	10.0	3
100	156.9	3	260.7	6	24.9	3	14.4	48	12.4	3
200	182.3	3	315.0	6	29.6	3	17.3	6	14.9	3

The design flows indicate that the March 2010, September 2010 and February 2011 flood events were approximately <5, 5 and 50 year ARI events respectively in Bendigo Creek at Bendigo and Huntly.

The latest TUFLOW version was utilised following the Melbourne Water 2D Modelling Guidelines[1] during all stages of model development. The ROG modelling approach is quite different to traditional hydrology and hydraulics and was validated successfully against the Rational Method, with peak flows for the 100 year ARI event within 10% at all locations tested. An extensive number of hydraulic structures were included in the TUFLOW models, with more than 3,000 major pipes of 600 mm diameter or greater, and over 18,000 minor pipes of 300 mm to 525 mm diameter. Many bridges and culverts were also included.

Flood Mapping

As the ROG method generates flow on every grid cell a number of filtering algorithms must be applied. For the Bendigo study the following filtering parameters have been applied:

- All depths less than 0.05 m have been removed from the mapping
- Velocity x Depth areas less than 0.008 m^2/s have been removed from the mapping
- All puddles less than 100 m^2 have been removed from the mapping

These parameters are generally in line with other known studies throughout Victoria. Extensive checks and quality assurance was completed on the modelling results.

The processed results were converted into a number of mapping outputs. It should be remembered that the mapping depicts the maximum flood depth at any given location. The maximum flood depth is the deepest water recorded throughout any given ARI for all of the different duration events. This will tend to display maximum depths for short duration storms at the top of any given catchment, and maximum depths for the longer duration storms towards the bottom of any catchment. The flood maps include flood extents, flood depths, overland flow velocities, and flood hazard.

[1] Melbourne Water Corporations - Flood Mapping Projects: Guidelines and Technical Specifications, November 2012.

PDF flood mapping products and digital mapping deliverables were produced and supplied along with the study report, and should be viewed in conjunction to this report.

Flood Damages

The flood damages estimated during this study is very different to that estimated for other riverine flood studies across Victoria. Due to the nature of this study investigating not only riverine flooding, but flooding of urban overland flow paths, the total flood damages are much greater than traditional studies. The 1% AEP has an estimated 15,000 properties impacted at a total flood damage cost of $424.2 M. The Average Annual Damage was calculated at $68.0 M. This very large flood damage cost reflects the risk of flooding over the entire Greater Bendigo catchment, however the dollar value should not be used for financial risk planning as it is an overestimate due to the nature of the urban stormwater flood mapping methodology.

Mitigation Scenarios

A number of scenarios were modelled, testing various mitigation options. The first scenario considered levee breaches in the downstream section of Bendigo Creek around Epsom and Huntly, clearly demonstrating the large area protected by these levee systems, supporting the need to resolve the ownership and future maintenance requirements of this critical flood mitigation infrastructure. The second scenario considered numerous local flood mitigation measures, many of which were shown to have some merit, some would most likely not pass a benefit-cost test, but some are worth considering further. The third scenario looked at retardation basins and using the Crusoe reservoir to store flood flows. This was shown to have significant downstream benefits and should be considered further, although the benefit-cost ratio may prove low. The assessment of mitigation options for Bendigo was not extensive and covered a handpicked number of scenarios. It is recommended that a wider flood mitigation assessment be considered. This may provide significant benefits to Bendigo in terms of reducing the current legacy flood risk, but may also allow future development to be progressed in flood protected areas, facilitating future development in growth areas.

Additional Outcomes

Using the outcomes of the data review, modelling and flood mapping, a flood warning discussion paper was developed to allow both the CoGB and NCCMA to consider their options regarding flood warning. This is included as an appendix to this report and should be read in conjunction with both this report and the flood mapping outputs.

Appendices to the Municipal Flood Emergency Plan were also developed and should be reviewed by VICSES and uploaded into the Council's Municipal Flood Emergency Plan.

The flood mapping outputs should now be used to update the Greater Bendigo Planning Scheme. The new data will assist the assessment of development within both the major floodplain and other overland flow paths throughout Bendigo. Appropriate planning tools should be considered to identify the various flood depths and hazards that have been shown in the maps associated with this report. Stronger planning controls should be considered for the greater depths and hazardous areas, with lesser controls applied on more manageable flow paths and flood fringe areas – in accordance with the Department of Planning and Community Development Practice Notes. The provision of a fully functional flood model will enable the CMA and Council to undertake rigorous feasibility assessment on major developments within the floodplain or any proposed changes to local stormwater infrastructure prior to approval or construction. This will ensure that new development is designed appropriately, that the flood risk to existing development is not exacerbated, and that proposed changes to local stormwater infrastructure meet relevant industry standards or local community expectations.

Finally given the high level of rigour associated with this study it is hoped that a level of confidence can be shown to the community surrounding the understanding of flood behaviour within the limits of the study area, providing backing for Council decision making.

Acknowledgements

Water Technology would like to take this opportunity to thank North Central CMA, City of Greater Bendigo and all members of the steering committee for their assistance and contribution to the development of the deliverables of this study.

GLOSSARY

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 datum's.
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. The AEP is the ARI expressed as a percentage.
Cadastre, cadastral base	Information in map or digital form showing the extent and usage of land, including streets, lot boundaries, water courses etc.
Catchment	The area draining to a site. It always relates to a particular location and may include the catchments of tributary streams as well as the main stream.
Design flood	A significant 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).
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.

Geographical information systems (GIS)	A system of software and procedures designed to support the management, manipulation, analysis and display of spatially referenced data.
Hydraulics	The term given to the study of water flow in a river, channel or pipe, in particular, the evaluation of flow parameters such as stage and velocity.
Hydrograph	A graph that shows how the discharge changes with time at any particular location.
Hydrology	The term given to the study of the rainfall and runoff process as it relates to the derivation of hydrographs for given floods.
Intensity frequency duration (IFD) analysis	Statistical analysis of rainfall, describing the rainfall intensity (mm/hr), frequency (probability measured by the AEP), duration (hrs). This analysis is used to generate design rainfall estimates.
LiDAR	Light Detection And Ranging is a survey technique used to capture high resolution survey data over a large area. A laser mounted on the underside of a fixed wing aircraft shoots pulses of light toward the ground and the time it takes for the light to reflect back to the plane is a measure of distance. This can be used to calculate the level of the ground surface. The raw elevation data is processed to remove buildings and trees to provide a bare earth digital terrain model. The LiDAR for Bendigo was captured in 2009.
Probability	A statistical measure of the expected frequency or occurrence of flooding. For a fuller explanation see Average Recurrence Interval.
Rainfall On Grid	A modelling technique used to distribute rainfall across a catchment and route flow hydraulically through the catchment
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.
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.
1D (one dimensional)	Refers to the hydraulic modelling where creeks and hydraulic structures are modelled using 1 dimensional methods. Using surveyed cross-sections to represent the path of water flow, the model calculates how high and how fast the water will flow for the specified flow path.
2D (two dimensional)	Refers to the hydraulic modelling where the floodplain is modelled using 2 dimensional methods. Using a grid of topography data the model will estimate not only how high and how fast water will flow but will also calculate the direction of flow across the 2D grid.

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1. INTRODUCTION

The regional center of Bendigo lies in one of Victoria's fastest growing municipalities, with a large population of around 110,000 people and expected to grow to 130,000 people in 10 years time[2]. The CBD and surrounding urban areas are intersected by Bendigo Creek and its tributaries, with many residential, commercial and industrial areas as well as rural floodplain on the outskirts of Bendigo at risk of flooding.

Bendigo Creek has been substantially modified by deepening, widening and lining, creating a constructed drain for much of its length through Bendigo. The creek flows north from Kangaroo Flat through the Bendigo CBD and on to Huntly, after which it merges with Myers Creek and Mount Hope Creek. Mount Hope Creek then flows on to Kow Swamp. Numerous tributaries flow into Bendigo Creek throughout the urban area of Bendigo.

Bendigo Creek and its tributaries have a long history of flooding, with the urban area typically impacted by intense thunderstorms. This is due to the relatively small catchment area upstream meaning that high intensity short duration storm events are critical.

Water Technology has been commissioned by the North Central Catchment Management Authority (NCCMA) in conjunction with City of Greater Bendigo (CoGB) to undertake the Bendigo Urban Flood Study. This study will involve detailed hydrological and hydraulic modelling for Bendigo's urban areas and its outskirts.

The hydrologic and hydraulic modelling was performed using a RORB runoff routing model and TUFLOW one and two dimensional hydraulic models. Due to the large extent of the study area and complexity of the drainage network including major creeks, pipes, bridges, culverts, dams and overland flow paths, the modelling was split into two components.

- Major creeks modelling (SPINE): Rainfall excess hydrographs calculated in a RORB model were used as input to the TUFLOW model as source inflows. The modelling results map the flood conditions along the main creeks through the township.
- Rainfall on Grid (ROG) modelling: An integrated hydrological and hydraulic modelling approach that directly applies rainfall on the catchment to generate excess runoff. This runoff is simultaneously routed downstream at the point of flow. The focus of this ROG modelling is to estimate flooding in areas that are not influenced by Bendigo Creek or are primarily constructed drainage systems.

This multipronged approach to the hydrological and hydraulic modelling of the study area is in response to the significantly different flood mechanisms of Bendigo Creek. In its lower reaches Bendigo Creek behaviours much like many other creeks in the region with some time delay between rainfall and the excess runoff generated in the creek. In the upper reaches including most of the urban area, the time between rainfall and runoff is very small, minutes to hours, depending on the location within the study area.

This report is structured into several major sections for easy reference, these sections are:

- Data Review
- Hydrologic analysis
- Hydraulic modelling of the creeks (Spine Model)
- Hydraulic modelling of the greater catchment (ROG model)
- Mitigation analysis
- Damages assessment

[2] http://www.bendigo.vic.gov.au/About_us/About_Greater_Bendigo/Population_and_Characteristics

- Conclusions and Recommendations

A number of appendices to this report were produced. These include additional items performed as part of this study including:

- Flood warning discussion paper
- Junortoun flood mapping
- Strathfieldsaye flood mapping
- Maiden Gully flood mapping

A full set of maps for the study were produced for the 100 year ARI including water surface elevations, depth, velocity, and hazard maps. The largest information source from the study was the actual digital model files and outputs. This is the largest single urban flood study performed in Victoria. All standard rainfall durations under 12 hours were run for the entire catchment at a very fine scale for all considered ARI events. Every pipe, culvert and bridge structure now has information around its critical flood duration, maximum flow, maximum pipe capacity and depth of ponding. Every flow path in the catchment has now been mapped for every event and a flow, depth, velocity and hazard are available.

This information gives both the NCCMA and the CoGB an enormous amount of data and intelligence to manage the catchment into the future. This report outlines the assumptions and decisions made by the technical reference group throughout the duration of the flood study.

1.1 Study Area

The Bendigo Creek Study area ranges from areas of moderate topographical relief at the top of the catchment to the relatively flat floodplains of Huntly towards the bottom of the study area. This covers an area of approximately 23,300 hectares, stretches from the top end of Bendigo Creek catchment in the South to the intersection of Old Murray Road and East Kamarooka Road covering Bendigo township, its outskirts and future urban growth areas. The study area and Bendigo creek modelling extents are shown in Figure 1-1 with the major waterways shown in Figure 1-2. The additional study areas (Junortoun, Strathfieldsaye and Maiden Gully) are discussed in the appendices to this report).

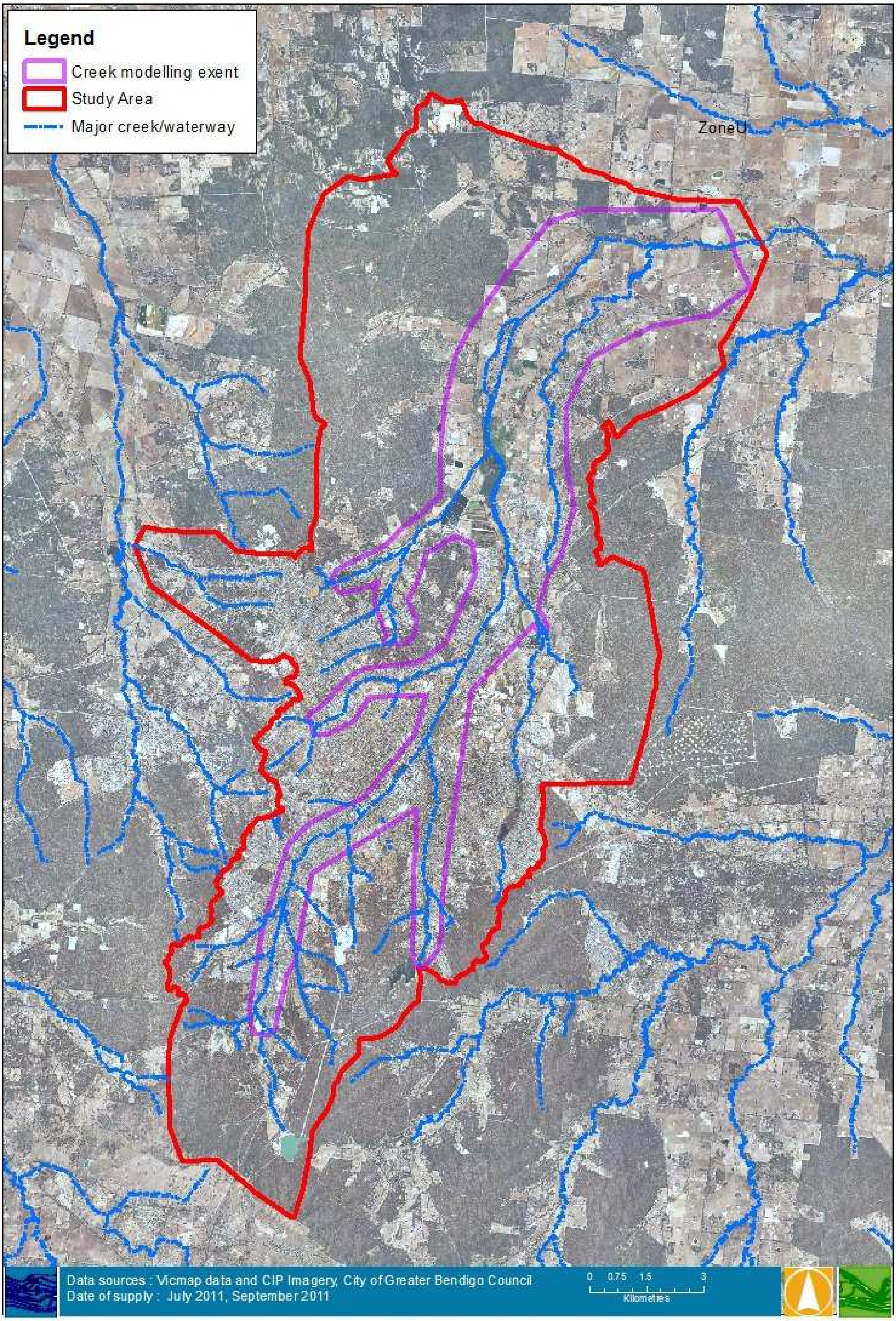


Figure 1-1 Study Area and Catchments

Figure 1-2 Major waterways surrounding Bendigo

1.2 Historical Flood Investigations

The Australian Government Geoscience Australia website provides a database of many existing Australian Flood Studies (http://www.ga.gov.au/flood-study-search/). It presents a list of all the flood studies including name, date, commissioning organisation, consultant and details of the study components per location.

The following historical flood studies were found for Bendigo;

- **Bendigo Flood Study Final Report Volume 1 & 2**, State Rivers and Water Supply Commission Victoria, 1984. It covered the Bendigo Creek, Back Creek, Racecourse Creek and Long Gully Creek.
- **Bendigo Flood Mitigation Scheme Levee Audit**, Findlay Irrigation Design Services for the Department of Conservation and Natural Resources, 1986. It covers Bendigo Creek and Spring Creek.
- **Bendigo Flood Study: 1% Probability Flood Levels**, State Rivers and Water Supply Commission, 1993. It covers Bendigo Creek only.
- **Splitters Creek Flood Study Final Report**, Ian Drummond and Associates for the North Central Catchment Management Authority, December 2000. It covers Splitters Creek only.
- **Bendigo Bank Flood Investigation**, Sinclair Knight Merz for Gallagher Jeffs, 2004. It covers Bendigo Creek only.
- **Back Creek Flood Study**, EarthTech for the City of Greater Bendigo, 2007. It covers Back Creek only.

Additional to these major studies a number of other smaller more specific studies have been undertaken and reviewed as part of this study, these include but are not limited to:

- **Marnie Road Catchment Report** prepared by GHD in September 2008
- **Chinese Gardens Report** prepared by Cardno in 2009

1.3 Historical Flood Records

A number of historical flood events were investigated during this study. This included photographs, videos and personal interviews and anecdotes collated by North Central CMA. A list of some of the historical events is listed below.

1.3.1 Historical Flooding

The following is a brief history of significant flood events in the Bendigo and Heathcote areas.

7 February, 1871.
Believed to be the heaviest flood ever experienced at the time. The 24 hour rainfall amounted to 3.22 inches which resulted in Charing Cross, High Street, Pall Mall, Bridge Street and the reserves being flooded. Many shops in the area were inundated.

23 February 1871.
A fall of 2.42 inches of rain resulted in flooding of the area as above.

June 1923.
Bendigo Creek caused serious flooding in the Bagshot area and caused road closures.

14 December 1923.
A severe storm over Bendigo in the early evening caused several businesses to be flooded.

23 December 1923.
A thunderstorm caused damage to stock in several businesses and the cancellation of sporting events.

19 February 1924.
A severe storm caused significant flooding in Bendigo with flooding of businesses in central Bendigo, flooding across roads in Long Gully and along Back Creek which resulted in poultry losses to farmers. Much land at Bagshot was again under water.

May 1930.
Torrential rain in the Bagshot area damaged roads in many places and caused a washaway on a section of the railway line to Rochester.

15 December 1930.
A severe thunderstorm caused stock to be spoilt in city business houses, damage to market gardens in the Sandy Creek, Huntly, Epsom and White Hills areas. The Axe Creek flooded so severely that bridges were washed away.

26 January 1933.
Bendigo received 180 points of rain in 2 storm bursts which caused flooding to houses and businesses in High Street between Short and Myrtle Streets.

30 November 1933.
One of the most severe floods in many years. Rising with characteristic suddenness, the Bendigo Creek overflowed its banks at both Kangaroo Flat and Golden Square, flooding some 100 houses in High Street and near the creek and a timber bridge in Alder Street was washed away. Much damage was done to furniture and fittings, fencing, vegetable gardens, roads and footpaths. At one point the Murray Road at Epsom was under 4 feet of water.

6 November 1949.
Following 3 inches of rain, the City experienced one of its worst floods in history. The Bendigo Creek overflowed and burst over the bridge at Charing Cross, inundating business houses. The water was four feet deep in one part of High Street, Golden Square. The water in the City Family Hotel reached a depth of 2 feet.

1951
Over two days, Bendigo received 318 points of rain which resulted in half a mile of railway line being washed away at Bagshot and large acreages of market gardens at Epsom and Huntly washed away. The Bendigo Creek broke its banks at Epsom and flooded Bendigo Pottery with water three to four feet deep over the Bendigo to Echuca Road. Creeks in surrounding districts were flooded with water up to waist deep at Kangaroo Flat and lapping the window sills of houses along Long Gully Creek.

18 February 1958.
A freak cloud burst which saw one and half inches of rain dropped in 30 minutes caused one of the worst floods in Huntly's history.

17 January 1962
More than an inch of rain fell in 15 minutes causing widespread flooding, the worst being the City shopping area.

February 1973
Bendigo received 389 points of rain in 24 hours which resulted in houses being flooded and long stretches of major roads under water. The worst hit area was California Gully with Eaglehawk Road under one foot of water.

1 January 1996
Heavy thunderstorms saw many shops and residences flooded in Kangaroo Flat.

1999 Onwards

Date	Area Affected	Rainfall		*Event*	Properties Affected
		Depth (mm)	Duration (hours)		
26 December 1999	Bendigo East to Epsom ~1 in 100 year ARI	75	45	Thunderstorm	Extensive flooding 10+ houses flooded.
27 December 1999	Strathdale, Bendigo East ~1 in 35 year ARI	21	15	Thunderstorm	Moderate property flooding. 1 property affected.
24 October 2000	Eaglehawk, Huntly, Kennington, Strathdale, Kangaroo Flat	-	-	Thunderstorm	5 properties affected
14 November 2000	Goornong, Huntly, Bagshot	-	-	Heavy rain.	1 house flooded, 3 properties affected.
December 2000	Long Gully, Maiden Gully, Bendigo East	-	-	Thunderstorm	1 house flooded, 6 properties affected.
1 February 2001	Strathdale 1 in 50 year ARI	19	9	Thunderstorm	1 property affected.
4 February 2001	Strathdale	25	9	Thunderstorm	3 properties affected.
18 May 2003.	Bendigo, Golden Square, Strathdale, Kennington, Maiden Gully, Strathfieldsaye	68	45	Tornado/ Thunderstorm	10 houses flooded, numerous properties affected.

1.3.2 Recent Flood Events

Three relatively recent flood events occurred over the last 5 years. These events are of particular relevance as a large amount of documented evidence for these events can be found. A number of pictures, personal experiences and videos of these events have been collected and in some cases used for verification in this study. These events included:

- March 2010 – Approximately 80 mm was recorded in 3 days with a maximum burst of around 40 mm in 2 hours. This event is recorded widely and has been used for calibration purposes
- September 2010 – Around 80 mm in 1 day with 40 mm over approximately 10 hours
- February 2011 – 100 mm recorded over 3 days with approximately 50 mm in a 5 hour burst

From this data some preliminary models were developed for calibration purposes. These were reviewed and comments provided, examples of the preliminary maps can be seen in Figure 1-3, with reviewed comments in Figure 1-4.

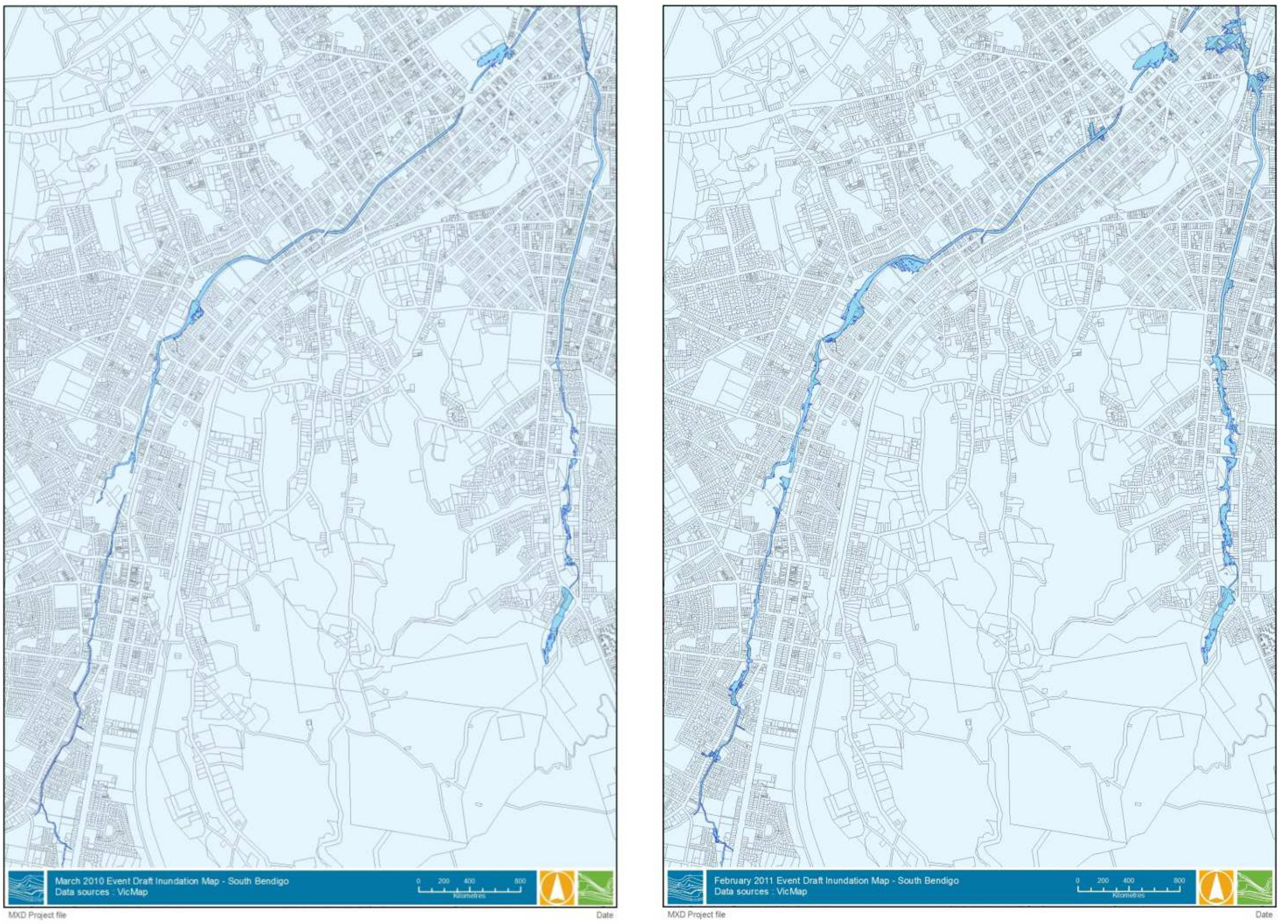
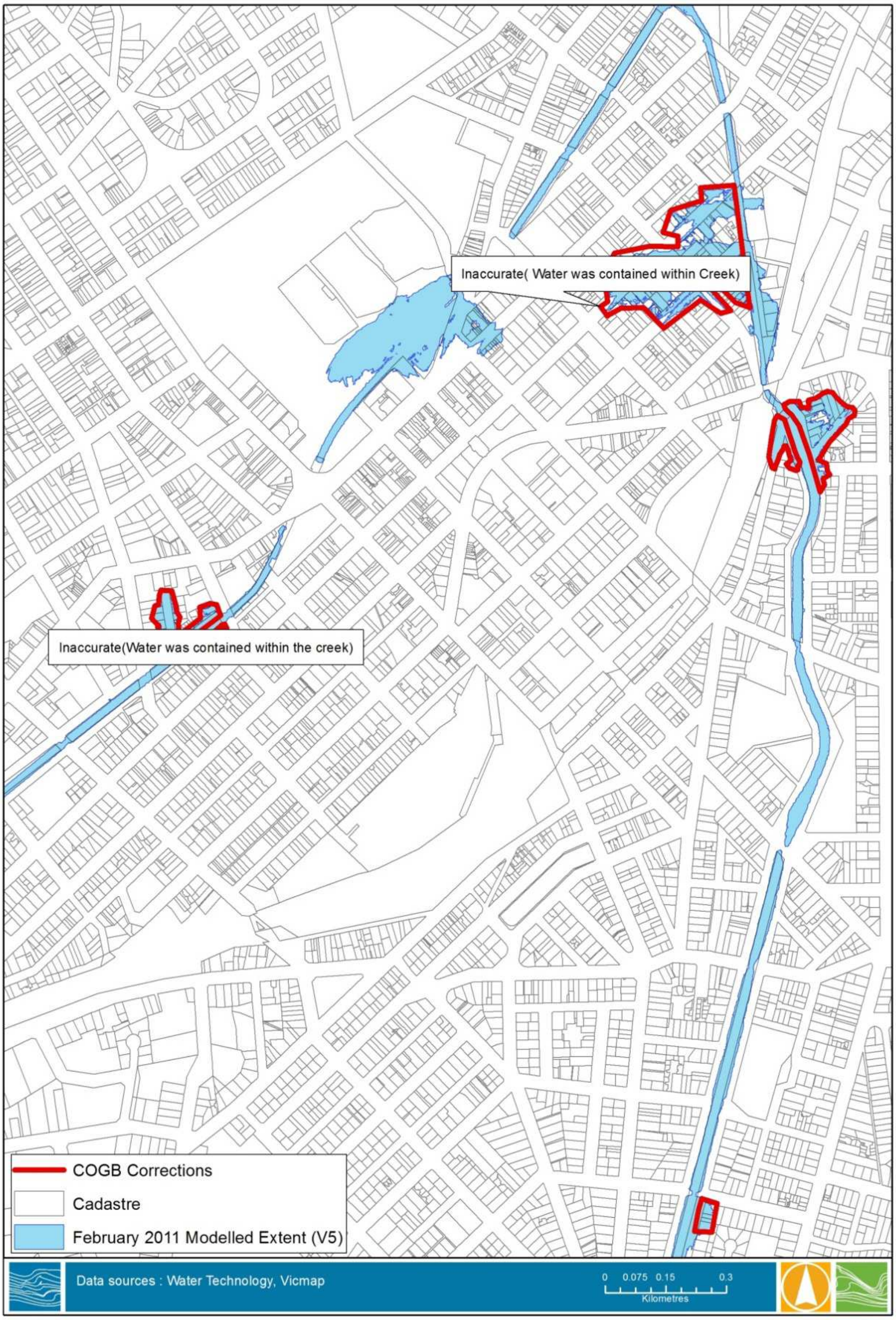


Figure 1-3 Calibration Events Preliminary Model (March 2010 left, February 2011 right)



MXD Project file

Figure 1-4 Rough flood extent prepared for the February 2011 event with review

1.4 Site Visits

A bicycle field trip was conducted on the 20th October 2011, with the aim to:

- Check the structures against existing survey and plans to ensure accuracy and appropriateness for use in hydraulic modelling;
- Review the structures which have no existing plans or survey and measure geometry where possible of these structures or flag for new survey if required;
- Assess the roughness values along Bendigo Creek and its major tributaries;
- Identify the location and characteristics of additional structures and levees which have not been previously flagged for inclusion in the model; and
- Record the locations and characteristics of all structures assessed during the field trip using a Trimble GPS unit.

Another site visit was conducted on the 1st of February, 2012 to measure some of the missing drainage infrastructure which had not been surveyed.

A selection of the photos taken during the inspections is presented below. It shows quite unique drainage infrastructure that requires the geometry and losses to be represented accordingly in the TUFLOW hydraulic model.












2. DATA REVIEW AND ASSESSMENT

2.1 Topographic and Physical Survey

2.1.1 LiDAR Data

Light Detection and Ranging (LiDAR) data for the region was made available from the NCCMA. LiDAR was available in 1 m and 10 m grid resolutions for the entire catchment. The LiDAR data was captured in 2009. This data was checked against known datum's and cross referenced against existing survey cross-sections.

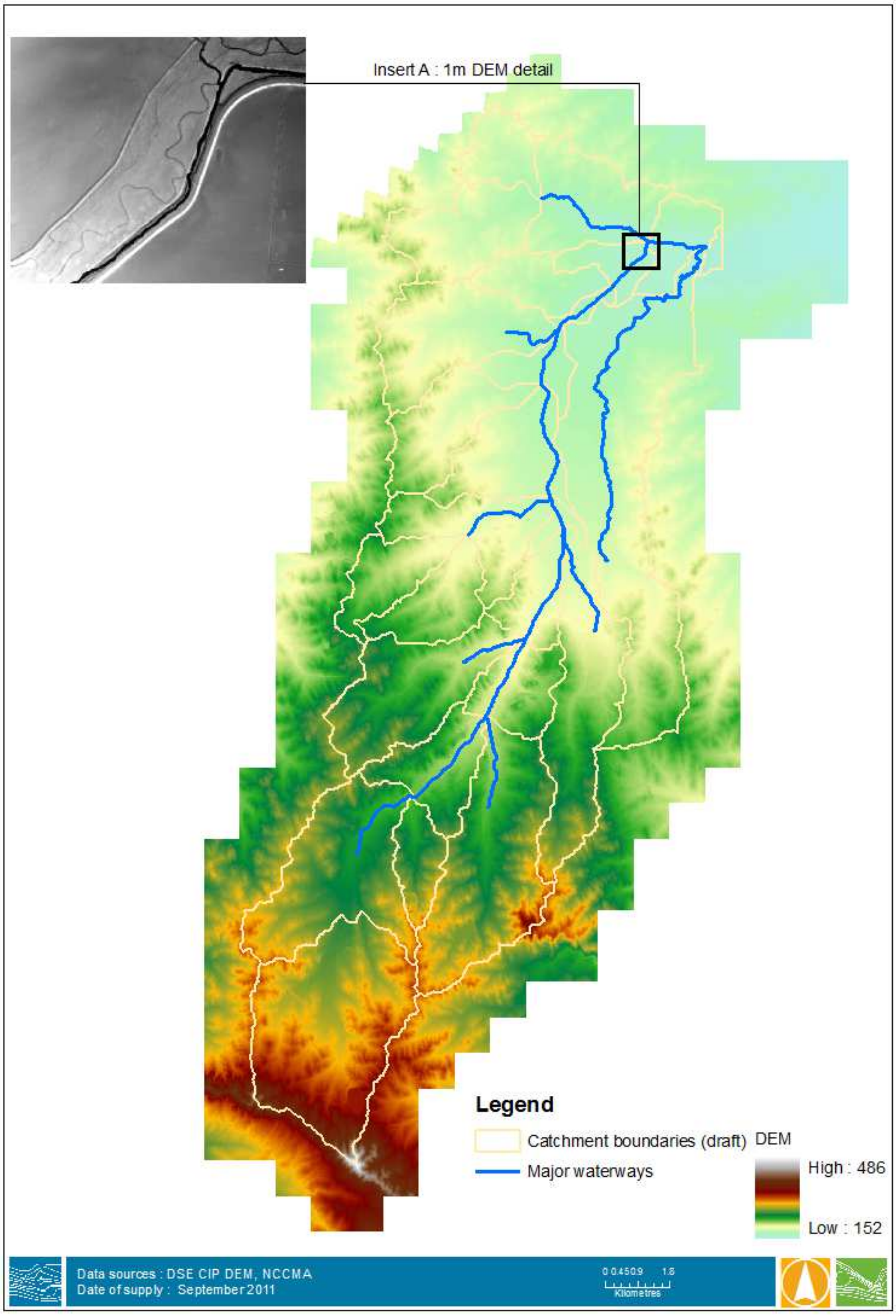


Figure 2-1 1 m resolution LiDAR coverage for Bendigo (source: DEPI)

2.1.2 Structure Survey

The Bendigo Creek catchment contains approximately 350 key hydraulic structures. Survey information of the key hydraulic structures was provided by CoGB and NCCMA. This data consisted of original structure plans as well as the results of a 1984 survey conducted as part of a flood study. Additional survey data was gathered from site visits. Where it was identified that the existing and gathered data was insufficient for modelling purposes new survey was requested. This occurred at 43 structures in the catchment.

These structures were input into a database with all the details required for later modelling. An extract from this database can be seen in Table 2-1.

2.1.3 Bendigo Drainage Network

The drainage network throughout Bendigo contains more than 18,000 pipes and culvert structures. Around 3,000 of these are of a greater diameter than 600 mm and were proposed for the modelling of the urban areas. As the project progressed it was decided to include all pipes that were feasibly recorded. This data collection provided a major phase of the project and took over 3 months to input into the model. All pipe systems were modified to ensure that the pipe network was without gaps and ran downhill. Pipe data was collected in 3 main phases, the initial Council held data was transferred and input into the TUFLOW model. A second round of data was provided once gaps were highlighted by the project team. A final round of additional data was provided after preliminary runs found flooding in areas of missing pipes.

Further detail on the pipe layouts and input can be found in section 5.3.7.

Table 2-1 Details of typical hydraulic structures in Bendigo

Flood Study ID	CoGB Bridge ID / Widen ID	CoB Ref	Model Ref	Plan CoGB	Plan 1984 Survey	Changes 1984 / Survey Required	Crossing Name	Asset Description	Suburb Name	Type Description	Date Constructed	Bridge Name	Location Description
1087	201683 202129	SN259	Spine		131804-3.tif		Back Creek	Hallam Street, Quarry Hill - Road Bridge (SN259) : Original Structure Dimensions	QUARRY HILL	Bridge Dimensions	2/02/1920	Hallam Street Bridge	0.14km from Carpenter Street
1088	522167 522168	SN454	Outside Model					Station Road, Bagshot - Crown Unit Culvert (SN454) : Original Structure Dimensions	BAGSHOT	Crown Unit Culvert Dimensions	1/01/2011	Station Road Bridge	0.11km North of Midland Highway
1089	201621 202239	SN276	Outside Model				Myers Creek	Myers Flat Road, Myers Flat - Road Bridge (SN276) : Original Structure Dimensions	MYERS FLAT	Bridge Dimensions	1/01/1942	Mars Bridge	0.45km from Loddon Valley Highway
1090	201624 202126	SN268	Spine	B0862		**Yes/no**	Long Gully Creek	Kinross Street, Long Gully - Pipe Culvert (SN268) : Original Structure Dimensions	LONG GULLY	Pipe Culvert Dimensions	1/01/1982	Kinross Street Bridge	0.26km E of Holdsworth Road
1091	201626 202178	SN278	Spine			No/Yes	Bendigo Creek (McGauchies Bridge)	Old Murray Road, Bagshot - Road Bridge (SN278) : Original Structure Dimensions	BAGSHOT	Bridge Dimensions	1/01/1974	Mcgauchies Bridge	4.21km from Bendigo - Tennyson Road
1092	201627 202044	SN235	Spine			No/Yes	Back Creek	Abbott Street, Bendigo - Road Bridge (SN235) : Original Structure Dimensions	BENDIGO	Bridge Dimensions	2/02/1910	Abbott Street Bridge	0.08km from McIvor Highway
1093	201628 202169	SN131	Direct ROG				Unnamed	Midland Highway at Stephensen Street, Huntly, Huntly - Foot Bridge (SN131) : Original Structure Dimensions	HUNTLY	Bridge Dimensions	2/02/1930	Midland Highway Bridge	Midland Highway at 11.98km from LHS

2.2 Streamflow Data

Streamflow data is required for the calibration of the hydrological model. The closest active streamflow gauges are 'Bendigo Creek in Bendigo' and 'Bendigo Creek in Huntly'. Instantaneous streamflow data for the March 2010, September 2010 and February 2011 flood events was sourced from the Department of Environment and Primary Industries (DEPI).

Table 2-2 Streamflow gauge details

Station Name	Station No.	Status	Data Type	Period of record
Bendigo Creek @ Bendigo	407254	Active	Instantaneous Flows, Instantaneous Water Levels	1977 - Present
Bendigo Creek @ Huntly	407255	Active	Instantaneous Flows, Instantaneous Water Levels	1977 - Present

A review of the gauge data quality codes at both sites identified that the while the event data was available, it was of poor quality and extrapolated beyond the minor flood level (approximately 60 m^3/s). Examination of the flood hydrographs for these events show fairly flattened peaks, not reaching a sharp peak that might be expected (particularly at the Bendigo gauge location where the hydrograph would respond quickly to urban runoff).

2.3 Rainfall Data

Both pluviograph and daily rainfall records are required for the calibration. Pluviograph rainfall data is used to understand the temporal distribution of rainfall during calibration events while daily rainfall data provides the spatial variation and rainfall depths for the specific calibration event.

Pluviograph records for the region were only available at the Bendigo Airport station (81123). Daily rainfall records were obtained from thirteen rainfall stations spread across and around the catchment. Notably, only the Bendigo Airport rainfall gauge lies within the Bendigo Creek catchment, with all other gauges outside the catchment boundary.

Table 2-3 Daily rainfall station details

Station Name	Station Number	Period of Record
Bendigo Airport	81123	1991 - Present
Sedgwick	81086	1954, 1957 - Present
Raywood	81041	1898 - Present
Bridgewater (Post Office)	81058	1894 - Present
Eppalock Reservoir	81083	1965 - Present
Eastville	81092	1969 - Present
Woodstock-on-Loddon	81100	1970 – Present
Knowsley	81118	1984 – Present
Maldon (Stump St)	88161	2005 - Present
Castlemaine Prison	88110	1966 - Present
Harcourt	88118	1968 – Present
Rochester	80049	1904 - Present
Kotta	80095	1967 - Present

2.4 Storage Data

There is several minor water storages located within the Bendigo Creek catchment:

- Crusoe Reservoir
- No. 7 Reservoir
- Spring Gully Reservoir
- Sandhurst Reservoir
- Gateway Park Lake

All of the storages were previously owned and operated by Coliban Water. A number of these have changed ownership to CoGB over the recent period. Water Technology liaised with Coliban Water in order to obtain any available information pertaining to the storages.

Coliban Water advised that other than Crusoe Reservoir, all of the reservoirs are considered offline and have catch drains to divert water from their upstream catchment around the reservoir and back into the stream/creek. Crusoe Reservoir was previously offline but in recent years a modification by CoGB has resulted in the reservoir now receiving an inflow from its catchment.

The stage-storage relationship for Crusoe Reservoir and the storage capacity are available, however it should be noted that this information predates modifications to the catch drains and was used when the reservoir was formerly a Coliban Water asset. No recorded water level data was available for any of the storages.

3. HYDROLOGIC ANALYSIS

3.1 Overview

A hydrologic model of the catchment was developed for the purpose of extracting flows to be used as boundary conditions in the 1D 'spine' hydraulic model. The rainfall-runoff program, RORB was utilised 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, connected by a series of conceptual reach storages. Observed or design storm rainfall is input to the centroid of each subarea. Specific losses are then deducted, and the excess routed through the reach network.

The following methodology was applied for the RORB modelling:

- ArcHydro software was used to provide an initial delineation of the RORB model area (the Bendigo Creek catchment area upstream of the Bendigo Creek at Huntly streamflow gauge).
- The resultant delineated catchment was then inspected and manually adjusted based on the site's topography and required hydrograph print (result) locations;
- The RORB model was constructed, selecting reach types, slopes and subarea fraction impervious values;
- Storm files for the March 2010, September 2010 and February 2011 events were constructed using pluviograph information and daily rainfall totals for the events;
- The RORB model parameter Kc was calibrated to the observed 'Bendigo Creek @ Bendigo' and 'Bendigo Creek @ Huntly' streamflow hydrograph for the March 2010, September 2010 and February 2011 events, selecting appropriate losses;
- Flood frequency analysis was carried out at the 'Bendigo Creek @ Bendigo' and 'Bendigo Creek @ Huntly' streamflow gauges, consistent with the approach outlined in Australian Rainfall and Runoff (1987);
- The RORB model was run in design mode to determine flood peaks for the 5, 10, 20 and 50 year ARI events. These were compared to flood frequency analysis at the two streamflow gauges to determine design loss parameters;
- Flood peaks, model parameters and losses were compared to regional estimates;
- Design flood events for the 5, 10, 20, 50, 100 and 200 year ARI events were run for multiple durations; and
- Hydrographs were extracted from RORB for use as inflow boundaries to the hydraulic model;

Design hydrographs were extracted at the following locations:

- Furness Street, Kangaroo Flat – (Bendigo Creek)
- Crusoe Road, Kangaroo Flat – (Dead Bullock Gully Inflow)
- Spring Gully Reservoir, Spring Gully (Spring Creek/Back Creek)
- Eaglehawk Road, Long Gully (Long Gully Creek)
- Prouses Road, California Gully (California Gully Creek)
- Averys Road, Eaglehawk (Eaglehawk Creek)
- Racecourse Road, Ascot (Racecourse Creek)
- Taylor Street, Epsom (Back Creek)

3.2 RORB Model Construction

3.2.1 Subarea Delineation and Reach Types

The downstream outlet of the RORB model was located at the 'Bendigo Creek @ Huntly' gauge, and covers the entire upstream catchment. The study area's catchment boundary covers an area of approximately 203 km^2, with approximately 62 km^2 upstream of central Bendigo.

The RORB model was constructed using MiRORB (MapInfo RORB tools), RORB GUI and RORBWIN V6.0. Initially a catchment boundary was delineated from the available 10 m contours of the area. Sub-area boundaries were then delineated using ArcHydro GIS software and revised as necessary to allow flows to be extracted at the points of interest. There are 75 sub-areas within the RORB model. Figure 3-1 below shows the RORB sub-area delineation for the study area.

Nodes were placed at areas of interest (including the Bendigo Creek @ Huntly and Bendigo Creek @ Bendigo streamflow gauges) and the junction of any two reaches. Nodes were then connected by RORB reaches, each representing the length, slope and reach type. Reach slopes were calculated using a digital elevation model (DEM) created from the 10 m contours.

Reach types in the model were set to be consistent with the land use across the 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). Drowned reaches were used within the storages. Reach types were determined from site visits and aerial photography. The reaches were predominantly set to natural with reaches around central Bendigo consisting of excavated and lined channels.

An interstation node was inserted into the RORB model so model parameters could be varied between the upper and lower parts of the catchment. There are significant differences in topography between the upper and lower parts of the Bendigo Creek catchment resulting in different runoff behaviour. The interstation node was placed at the Bendigo Creek at Bendigo gauge. This difference in behaviour is characterised within the RORB model by different Kc and loss values between the interstation areas.

3.2.2 Fraction Impervious Data

The RORB model requires an input of fraction impervious values for the subareas. Fraction Impervious values were calculated using MiRORB. Default sub-area fraction impervious values were calculated based on the current planning scheme zones and then reviewed and modified as necessary based on recent aerial photos (from GoogleMaps and other aerial imagery). The total imperviousness of the catchment was calculated to be 0.22 reflecting the predominantly rural nature of the catchment. The spatial distribution of the fraction impervious data is shown in Figure 3-2, showing the Bendigo township having a higher fraction impervious than the broader catchment.

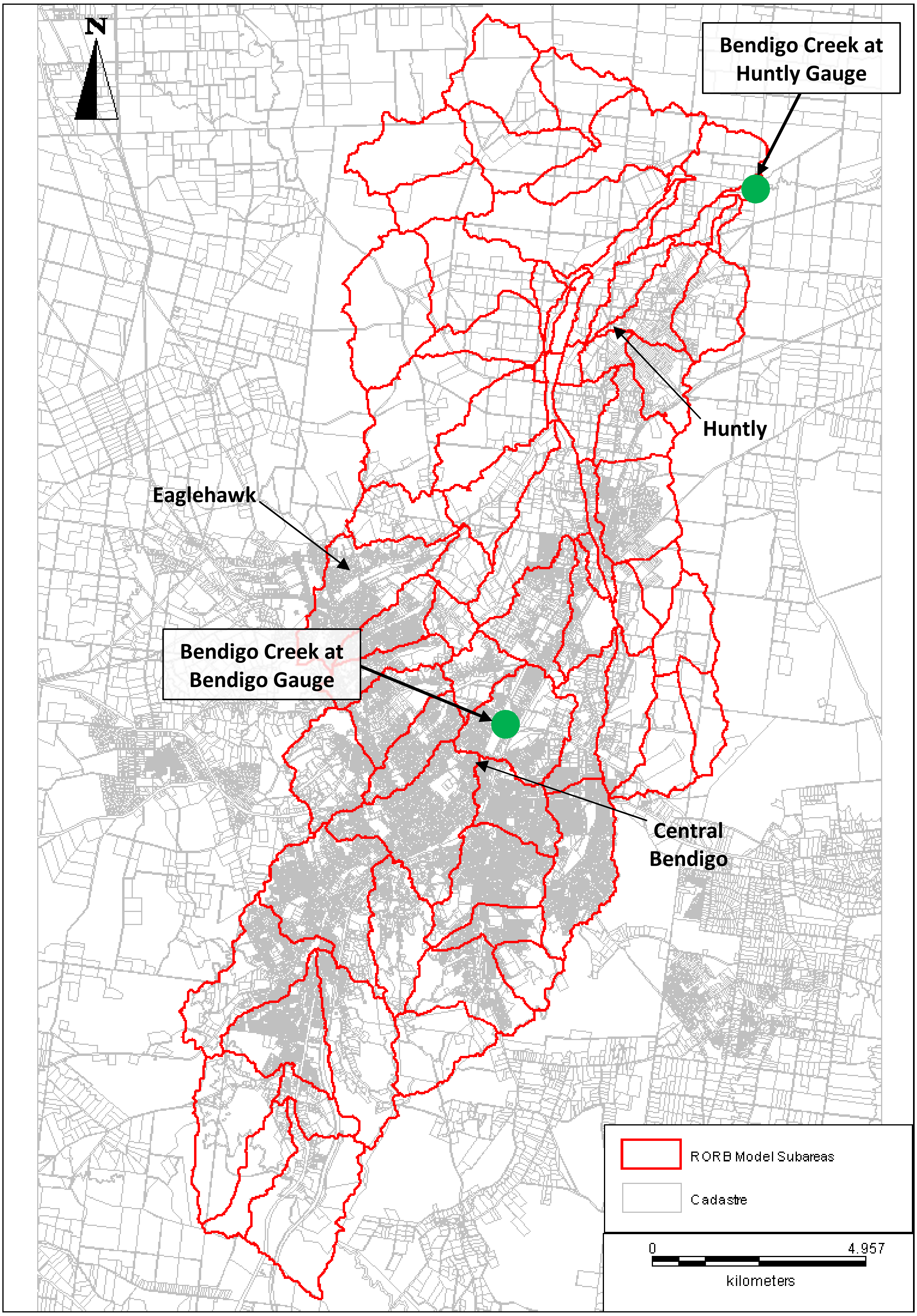


Figure 3-1 RORB Model Subcatchment Breakup and Stream Gauge Location

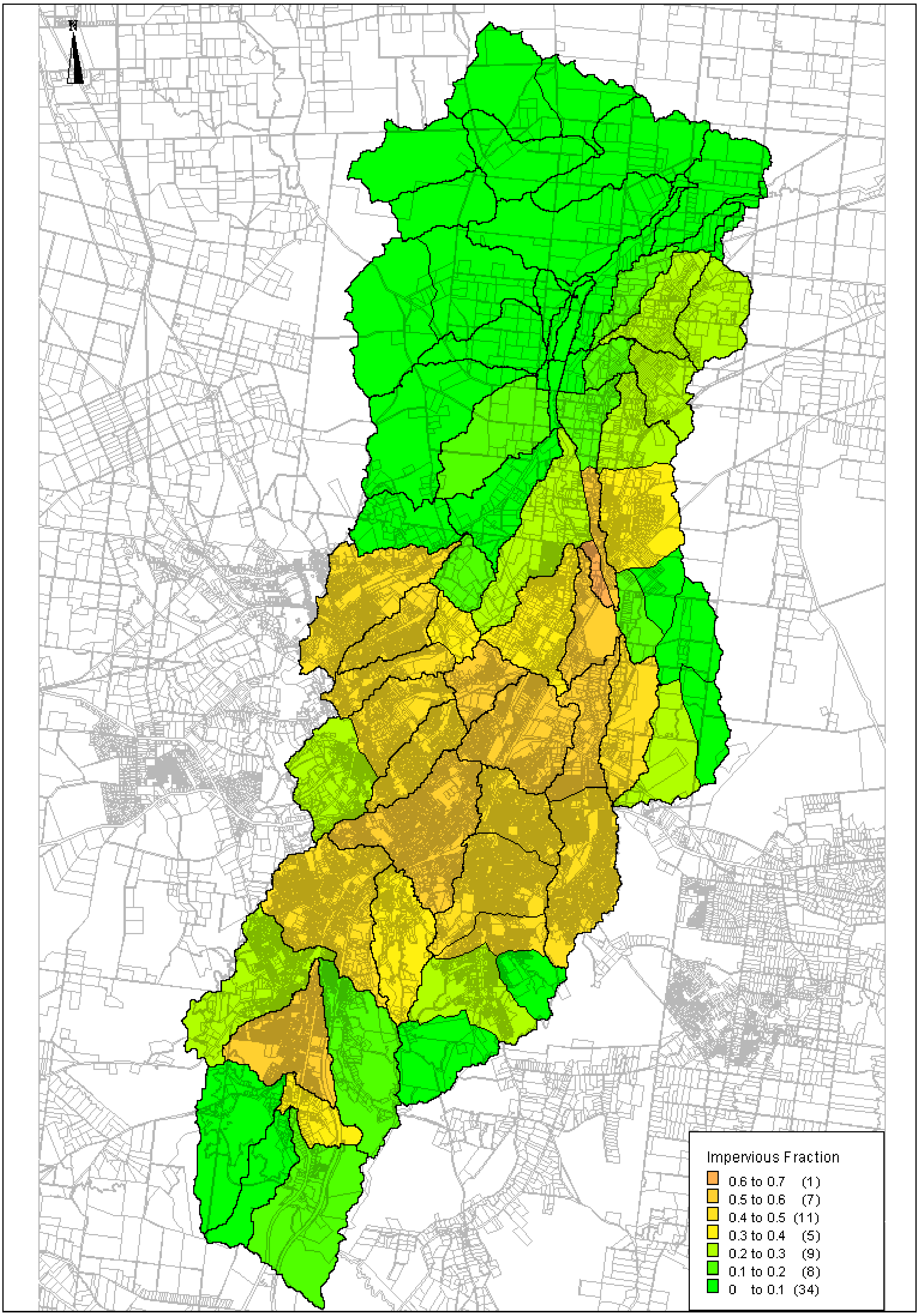


Figure 3-2 RORB Model Fraction Impervious Values

3.2.3 Storage Basins

It is important to incorporate online storages within the hydrological model as they may attenuate flows and can have a significant impact on downstream hydrographs. Crusoe Reservoir is the only large storage basin within the Bendigo Creek catchment which is considered 'online'. It has a capacity of 890 ML and a relatively small catchment area of 320 Ha.

To understand the sensitivity of flows to the attenuation provided by Crusoe Reservoir the RORB model was run with initial storage conditions set to full and empty. A sensitivity analysis comparing these conditions showed that the difference in peak flows at points of interest downstream was minimal and in the order of 2-3% depending on the event. Following this analysis and based on the available information, for the purposes of calibration and design, it is assumed that each of the storages is full at the commencement of rainfall events and provides no attenuation to flows.

3.3 RORB Model Calibration

3.3.1 Overview

Calibration of the RORB model required comparison of modelled flood hydrographs from the RORB model with the observed flood hydrographs at the 'Bendigo Creek @ Bendigo' and 'Bendigo Creek @ Huntly' streamflow gauges. The RORB model was calibrated to the March 2010, September 2010 and February 2011 flood events. These events were selected for calibration due to the large size of the events and that they represent recent experiences of flooding.

The focus of the RORB model calibration was the determination of Kc values for the entire catchment.

3.3.2 RORB Model calibration event data

Observed Stream Flow Data

Instantaneous streamflow data for the March 2010, September 2010 and February 2011 flood events was sourced from DEPI. These streamflow gauges are summarised in Table 2-2. The following points were observed:

- A review of the streamflow gauge data quality codes at both sites identified that both the flow and level data was of poor quality and extrapolated when flows were greater than approximately minor flood level. Examination of the flood hydrographs for these events show fairly flattened peaks, not reaching a sharp peak that might be expected.

  Following review of the data, it was understood that in fitting the calculated hydrograph from RORB to the observed hydrograph from the streamflow data, it was unlikely that the *peak flow* would be replicated. Given that the data is available, we have carried out a calibration of the RORB model in order to use for comparison. Also, calibration of the calculated rising and falling limbs of the hydrographs to the observed hydrographs for the three events will still be important in determining appropriate routing parameters.

- It was also noted that the Bendigo Creek at Bendigo Gauge barely recorded a rise in water level for the February 2011 event despite photos, videos and anecdotal evidence indicating a significant flood event through central Bendigo.

  It was therefore concluded that the gauge was not functioning properly during the event and it was understood that it would be difficult to achieve a reasonable fit of calculated to observed data. For this reason, the addition of a third event to the calibration was made. The large event observed in September 2010 was therefore selected.

Comparisons with regional information

Due to the poor quality of observed data to be used for calibration, the relative size of the events at nearby gauges was checked. Streamflow data was available at nearby Axe Creek and at a gauge further downstream on Bendigo Creek at Minto. Table 3-1 shows the peak flow estimates for these events and demonstrates inconsistences in the flow measurements. In particular the peak flow of 0.53 m^3/s recorded in Bendigo for the March 2010 event is at least an order of magnitude smaller than flows recorded downstream and in adjacent catchments. This again suggests the gauge was not functioning correctly.

Table 3-1 Comparison of peak flows for Calibration events

Location	March 2010 peak flow (m3/s)	September 2010 peak flow (m3/s)	Feb 2011 peak flow (m3/s)
Bendigo Creek at Bendigo	0.53	44.5	82.4
Bendigo Creek at Huntly	15.35	72.9	97.4
Bendigo Ck at Minto (DS of Bendigo)	8.67	66.86	144.7
Axe Creek (adjacent catchment)	5.42	99.2	98.0

Observed Rainfall Data

RORB has the option to distribute the rainfall data across separate rainfall bursts throughout an event. The purpose of using separate bursts is to allow the loss parameters to vary across each burst. For all three rainfall events, a multi burst approach was adopted as:

- The rainfall events ran over multiple days, resulting in daily variation of rainfall totals (from daily rainfall stations) across subareas;
- The pluviographs (Figure 3-5) show separate rainfall bursts during the February 2011 flood event. The events were separated by a 16 hour period of no rainfall; and
- The hydrographs recorded at both gauging stations also show multiple peaks. Multi-peaked hydrographs can be calibrated better if the event is treated as a multi burst event.

The rainfall depth for each subarea was estimated using storm event rainfall isohyets. Nine sets of rainfall isohyets were created, one for each of the three bursts for each event.

The temporal rainfall distribution was determined using the rainfall pattern from the Bendigo Airport pluviograph. Figure 3-3, Figure 3-4 and Figure 3-5 display the pluviographs for the three events. The Bendigo Airport gauge is located within the catchment and is the only gauge in the region to provide instantaneous rainfall data.

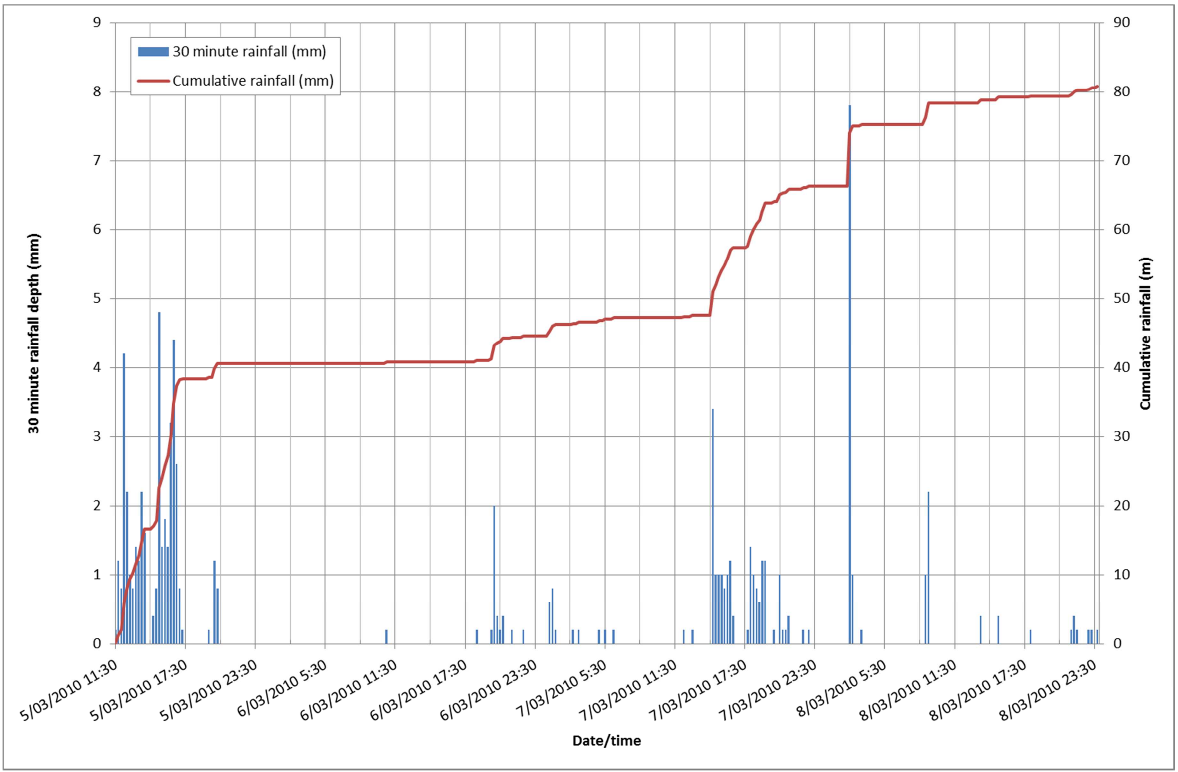


Figure 3-3 Pluviograph records (15 minute rainfall) - March 2010 Event

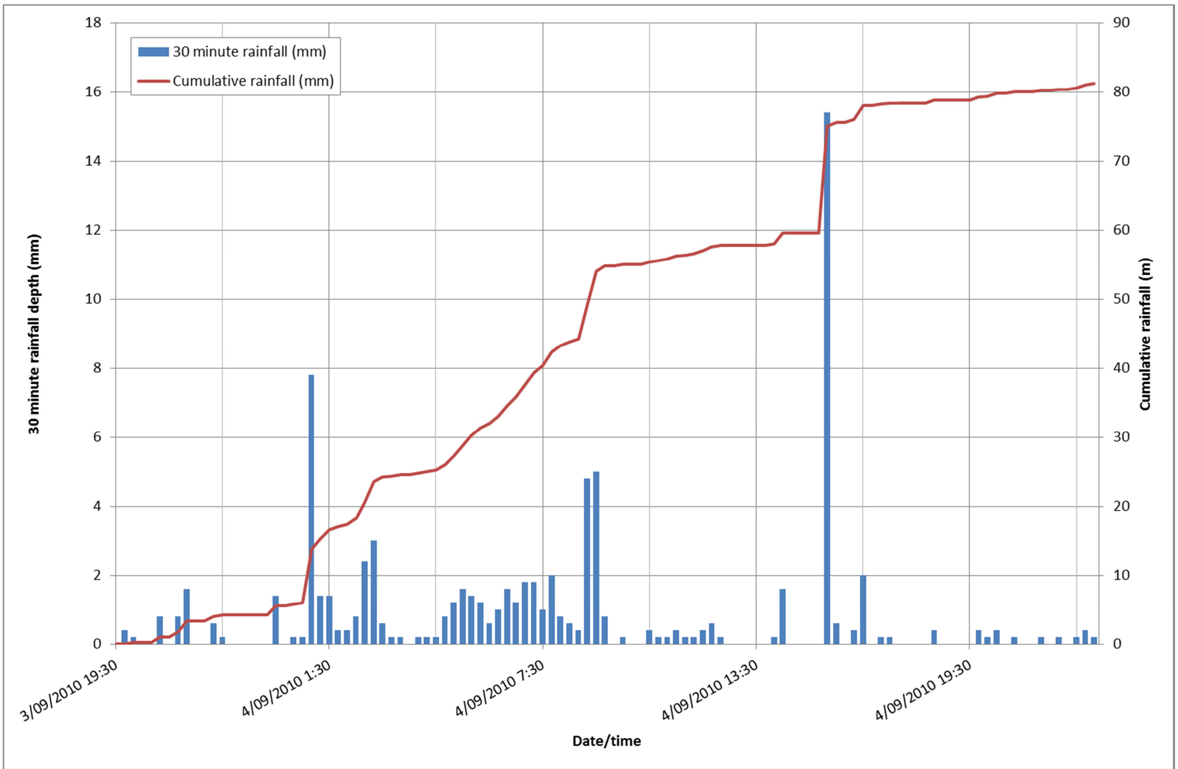


Figure 3-4 Pluviograph records (15 minute rainfall) - September 2010 Event

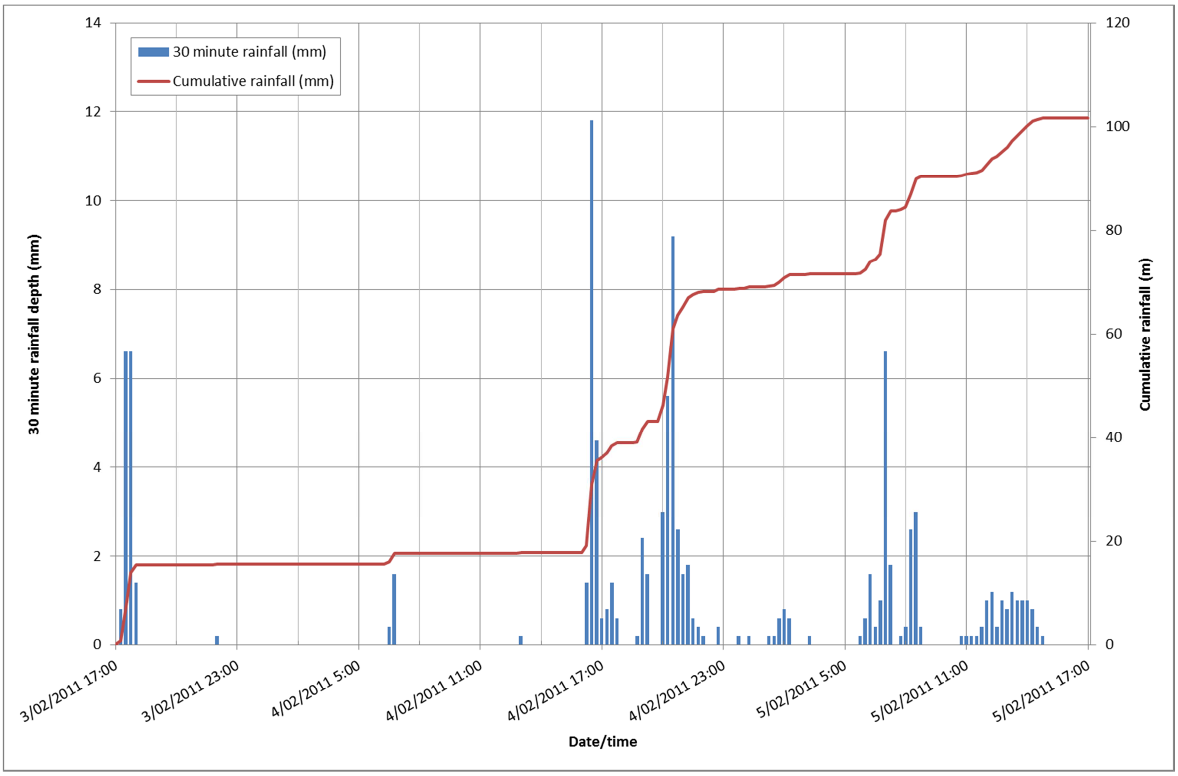


Figure 3-5 Pluviograph records (15 minute rainfall) - February 2011 Event

3.3.3 RORB Model Calibration Parameters

Within RORB, the model parameter Kc and losses are used to fit the calculated to observed hydrograph. An initial loss/continuing loss model was found to provide a better fit of observed and modelled flood hydrographs and was therefore adopted for this study.

The calibration approach adopted for this study was as follows:

- Set m = 0.80. This value is an acceptable value for the degree of non-linearity of catchment response (Australian Rainfall and Runoff, 1987).
- The initial loss parameter (IL) was determined by finding a reasonable match between the modelled and observed rising limbs of the flood hydrograph.
- A continuing loss (CL) was selected to achieve a reasonable fit between the modelled and observed hydrograph volumes.
- The RORB Kc parameter was initially calculated within RORB using a catchment area relationship (equation 2-5 in version 5 of RORB User Manual). This Kc value was then varied to achieve a reasonable fit of the peak flow and general hydrograph shape. Different Kc values were used for the upper and lower catchments, representing the different catchment characteristics.

Details of the selected calibration events are provided in Table 3-2 below.

Table 3-2 RORB Model Calibration Events

Event	Event Start & Finish Date	Average Catchment Rainfall (mm)	Recorded Peak Flow at Bendigo Gauge (m3/s)	Recorded Peak Flow at Huntly Gauge (m3/s)
March 2010	05/03/2010 11:00am to 10/03/2010 2:30am	89 mm (over a 3 day period)	0.53	15.35
September 2010	03/09/2010 7:45pm to 06/09/2010 12:00am	83.5 mm (over a 28 hour period)	44.5	174.6
February 2011	3/02/2011 5:00am to 8/02/2011 9:00am	99 mm (over a 48 hour period)	82.4	222.4

3.3.4 March 2010 Flood Event Calibration

Based on examination of daily rainfall, pluviograph and streamflow data, the March 2010 event was modelled from 11:30am on 5th March 2010 to 11:45 pm on 8th March 2010, with the first burst considered to be from 11:30am on 5th March to 7:45pm on 6th March, the second burst from 7:45pm on 6th March to 2:45pm on 7th March and the third burst from 2:45pm on 7th March to 11:45pm on 8th March. Observed and calculated hydrographs at Bendigo Creek at Bendigo (407254) and Bendigo Creek at Huntly (407255) are compared in Figure 3-6. The Kc and loss values adopted are summarised in Table 3-3.

The RORB model calibration for the March 2010 flood event at Huntly is not ideal however it is considered that the gauge data is in error and the calibration cannot be improved further. It is difficult to fit the calculated hydrograph due to the erroneous flattened peaks recorded in the gauge data. The difference in observed and estimated peak flow at Huntly is 72%, while the difference between estimated and observed flood volume is 19.5%. The fit of the calculated to observed rising and falling limbs is considered good at the Huntly gauge. It was not possible to calibrate at the Bendigo gauge due to poor gauge data including minimal flow readings throughout the March event.

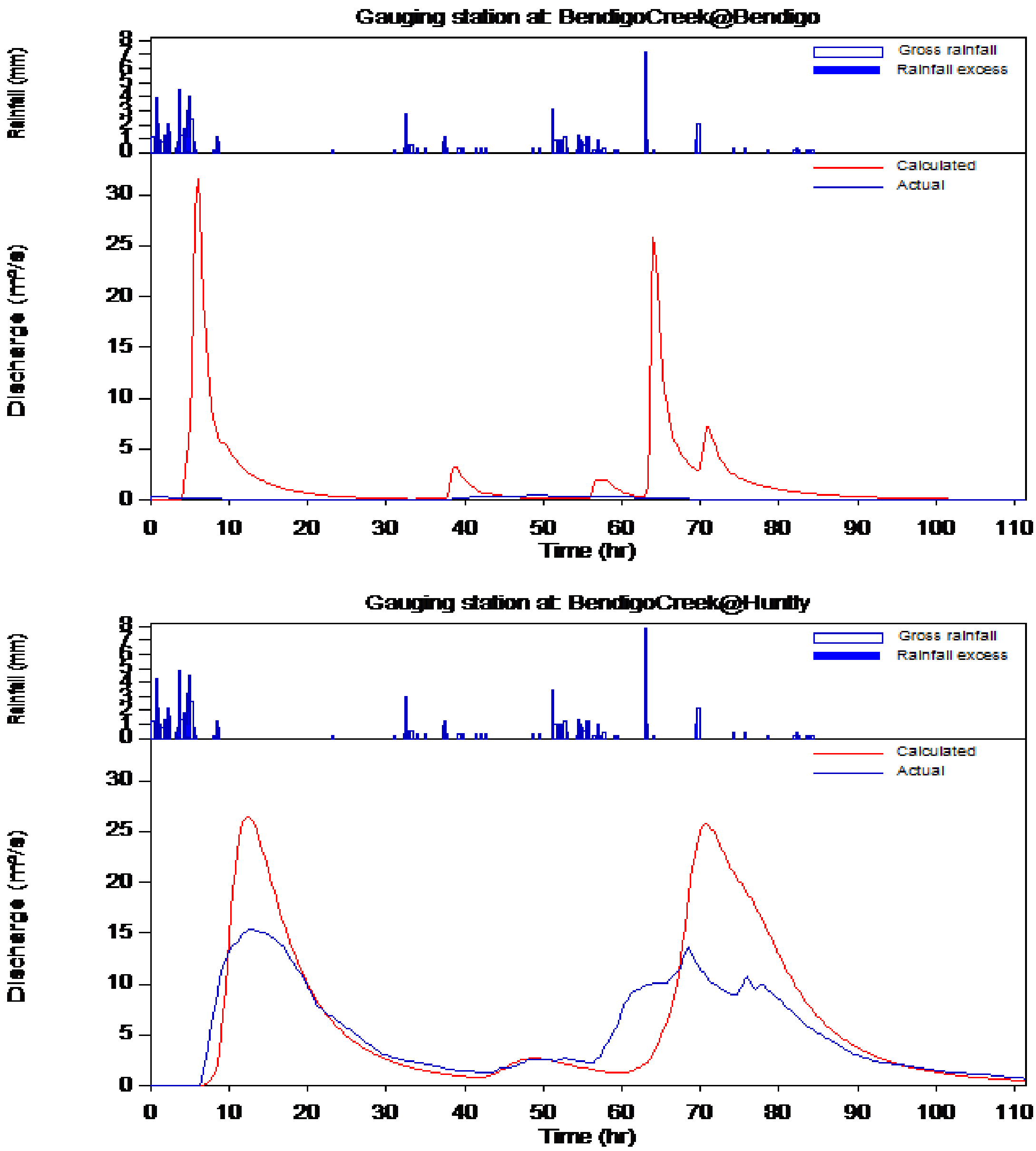


Figure 3-6 **RORB Calibration – Comparison of modelled and observed surface runoff hydrographs at Bendigo (407254) and Huntly (407255) for the March 2010 Event**

Table 3-3 **RORB Calibration Loss Parameters – March 2010**

Location	kc	Burst 1		Burst 2		Burst 3	
		IL	CL	IL	CL	IL	CL
Bendigo Creek @ Bendigo	17	50	6	30	2	25	5
Bendigo Creek @ Huntly	17	50	6	30	2	25	5

Table 3-4 RORB Calibration Peak Flows – March 2010

Location	Peak flow (m^3/s)		Volume (ML)	
	Observed	Calculated	Observed	Calculated
Bendigo Creek @ Bendigo	0.54	31.5	51	766
Bendigo Creek @ Huntly	15.36	26.5	2,100	2,510

3.3.5 September 2010 Flood Event Calibration

Based on examination of daily rainfall, pluviograph and streamflow data, the September 2010 event was modelled from 7:45pm on 3rd September 2010 to 12:00am on 6th September 2010, with the first burst considered to be from 7:45pm on 3rd September to 4:00am on 4th September, the second burst from 4:00am on 4th September to 2:00pm on 4th September and the third burst from 2:00pm on 4th September to 11:00pm on 4th September. Observed and calculated hydrographs at Bendigo Creek at Bendigo (407254) and Bendigo Creek at Huntly (407255) are compared in Figure 3-6. The Kc and loss values adopted are summarised in Table 3-5.

The RORB model calibration for the September 2010 flood event is considered good. The difference in observed and estimated peak flow is 12.8% at Bendigo and 4.5% at Huntly, while the difference between estimated and observed flood volume is 25.8% at Bendigo and 7.5% at Huntly. The fit of the calculated to observed rising and falling limbs is poor at Bendigo and very good at Huntly. The gauge data at Bendigo appears to be particularly erroneous later in the event with the third peak barely recorded.

It is worth noting that higher losses were generally required in the lower catchment to achieve the calibration. This is consistent with the land use across the catchments with the upper catchment containing a significantly greater urban area than the lower catchment.

Table 3-5 RORB Calibration Loss Parameters – September 2010

Location	kc	Burst 1		Burst 2		Burst 3	
		IL	CL	IL	CL	IL	CL
Bendigo Creek @ Bendigo	16	10	2	10	4	10	5
Bendigo Creek @ Huntly	18	20	3	20	2	20	1

Table 3-6 RORB Calibration Peak Flows – September 2010

Location	Peak flow (m^3/s)		Volume (ML)	
	Observed	Calculated	Observed	Calculated
Bendigo Creek @ Bendigo	44.53	50.22	1,260	1,590
Bendigo Creek @ Huntly	72.86	76.16	4,930	4,560

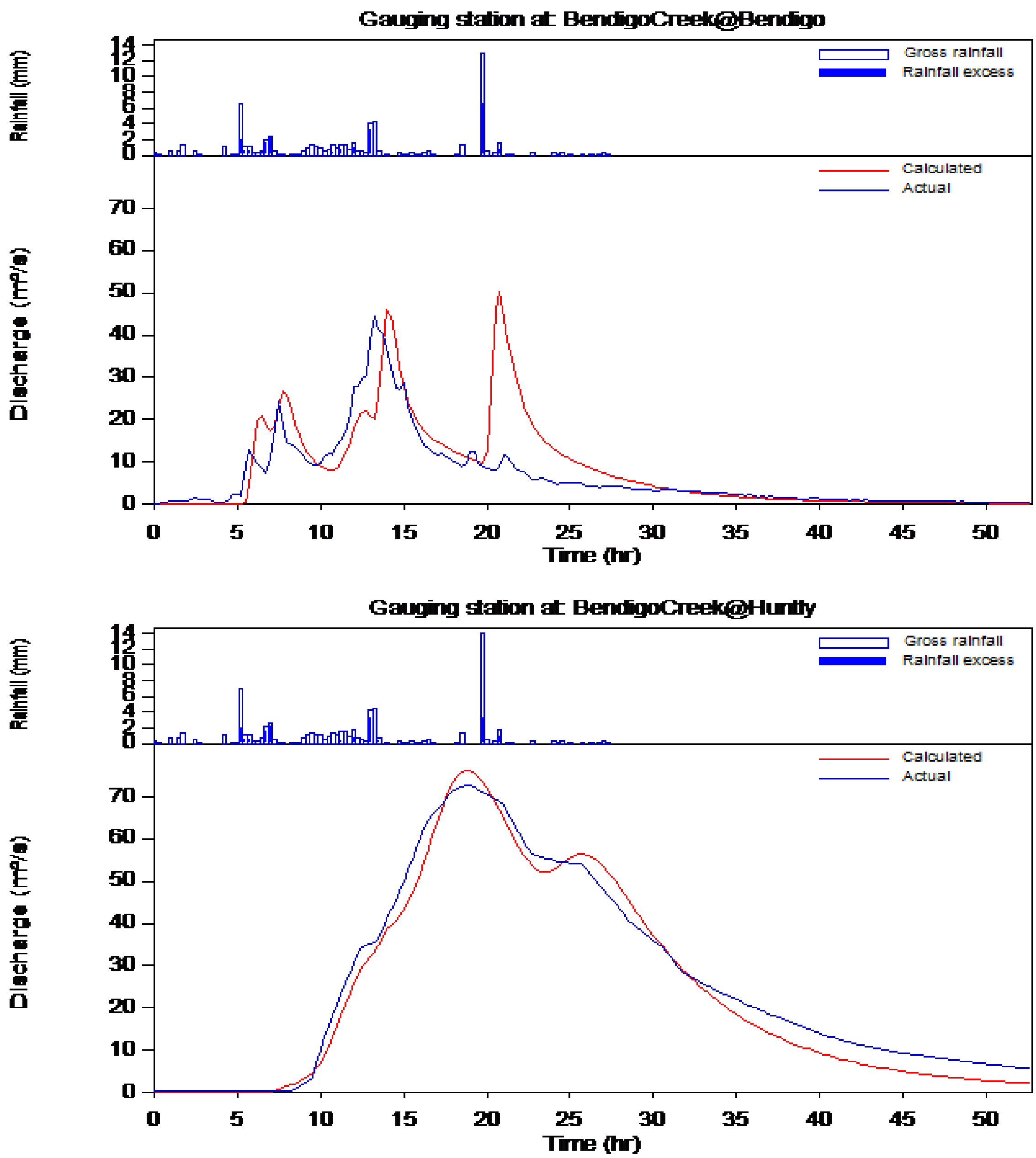


Figure 3-7 RORB Calibration – Comparison of modelled and observed surface runoff hydrographs at Bendigo (407254) and Huntly (407255) for the September 2010 Event

3.3.6 February 2011 Flood Event Calibration

Based on examination of daily rainfall, pluviograph and streamflow data, the February 2011 event was modelled from 5:00am on 3rd February 2011 to 9:00am on 8th February 2011, with the first burst considered to be from 5:00am on 3rd February to 3:30pm on 4th February, and the second burst from 3:30pm on 4th February to 5:00am on 5th February and the third burst from 5:00am on 5th February to 3:00pm on 5th February. Observed and calculated hydrographs at Bendigo Creek at Bendigo (407254) and Bendigo Creek at Huntly (407255) are compared in Figure 3-8. The Kc and loss values adopted are summarised in Table 3-7.

The RORB model calibration for the February 2011 flood event is considered generally poor but the quality of the calibration data does not allow a more accurate calibration to be achieved. The difference in observed and estimated peak flow is 57% at Bendigo and 81% at Huntly, while the difference between estimated and observed flood volume is 62% at Bendigo and 15% at Huntly. The fit of the calculated to observed rising and falling limbs is good at both Bendigo and Huntly. Again the flattened peaks in the gauge data makes fitting the full hydrograph difficult to achieve at both locations and the data record suggests that recorded flows have been underestimated at both gauge locations. It can also be seen that, as with the September 2010 calibration, lower losses were required in the predominantly urban upper catchment.

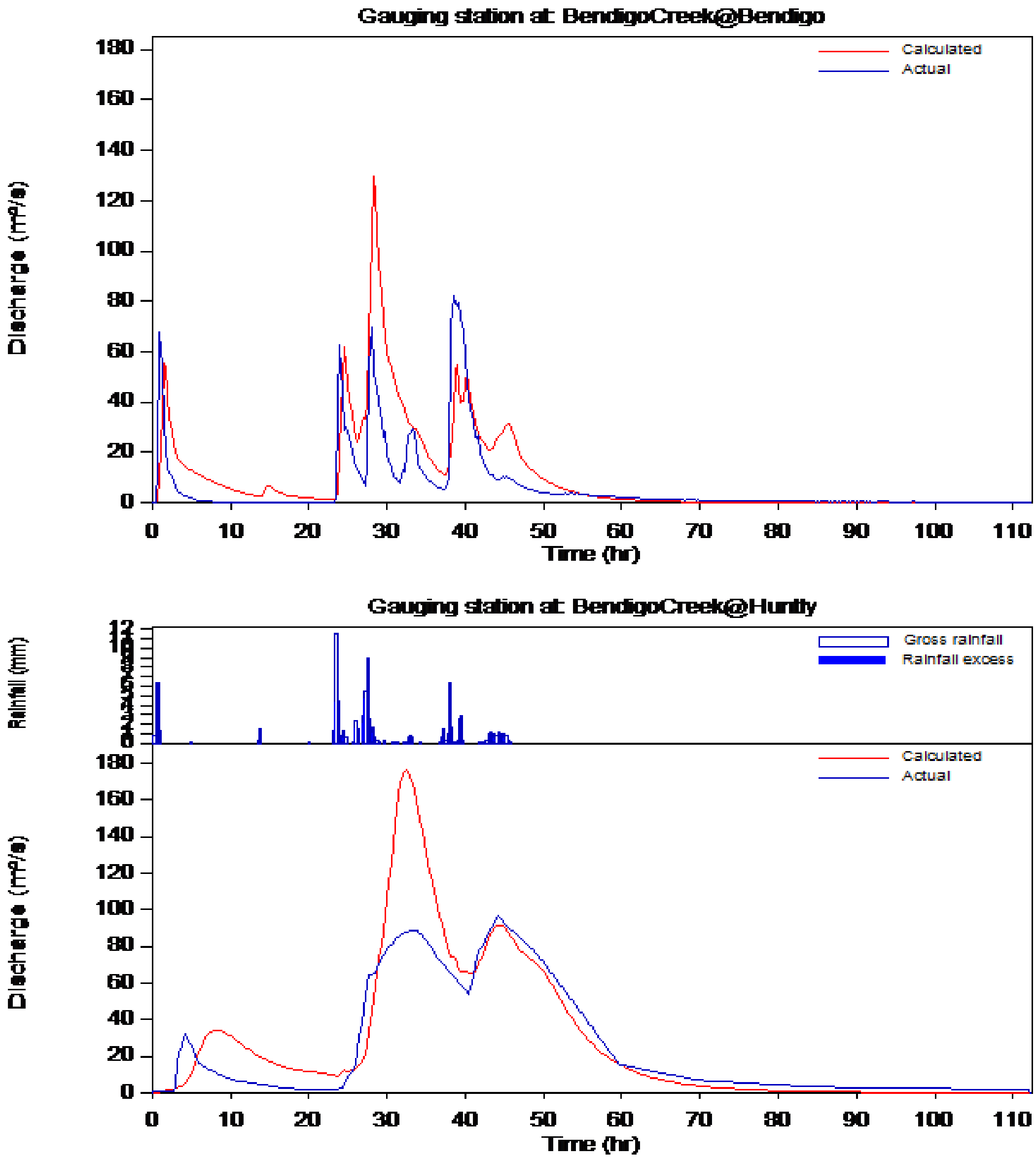


Figure 3-8 RORB Calibration – Comparison of modelled and observed surface runoff hydrographs at Bendigo (407254) and Huntly (407255) for the February 2011 Event

Table 3-7 RORB Calibration Loss Parameters – February 2011

Location	kc	Burst 1		Burst 2		Burst 3	
		IL	CL	IL	CL	IL	CL
Bendigo Creek @ Bendigo	14	5	2.5	10	2.5	0	2.5
Bendigo Creek @ Huntly	17	10	2.5	10	5	5	2.5

Table 3-8 RORB Calibration Peak Flows – February 2011

Location	Peak flow (m^3/s)		Volume (ML)	
	Observed	Calculated	Observed	Calculated
Bendigo Creek @ Bendigo	82.4	129.7	2,570	4,160
Bendigo Creek @ Huntly	97.2	176.4	9,650	11,100

3.4 Discussion

3.4.1 Routing Parameters

All events were calibrated with m set to 0.8. Book VI of Australian Rainfall and Runoff recommends that in cases where there is insufficient data to examine the potential variation of non-linearity with event magnitude that a value of 0.8 is adopted for extreme flood estimation. There appears no significant reason to vary it for the Bendigo Creek catchment and thus, 0.8 was adopted for design runs.

For all events, the routing parameters could be varied according to inter-station area, and the calibrated kc varied as shown in Table 3-9. The results indicate a reasonably consistent kc across the three flood events to which the RORB model was calibrated. An indication of the travel distance to the outlet is given by d^{av}. This is the weighted average flow distance from all nodes to the catchment outlet and is shown in the following table for the whole catchment and the two interstation areas.

Table 3-9: RORB model routing parameters

Area	d_{av}	March 2010		September 2010		February 2011	
		kc	kc / d_{av}	kc	kc / d_{av}	kc	kc / d_{av}
Bendigo Creek to Bendigo	7.81	17	2.18	16	2.05	14	1.79
Bendigo Creek to Huntly	11.16	17	1.52	18	1.61	17	1.52
Average:		17	1.85	17	1.83	15.5	1.66

Due to the poor quality of data available for calibration, the achieved fit of calculated to observed data was generally poor, particularly for peak flow. Therefore alternative methods to determine Kc values were investigated, to compare these estimates to the parameter estimates from calibration. This included regional equations (AR&R 1987) and the use of Andrews Curves (Grayson et al. 1996). The resulting Kc values are shown in Table 3-10.

Table 3-10 Additional regional prediction equation estimates of routing parameter

Method (from RORB manual)	Applicable Region	Equation	Predicted kc	
			Bendigo Creek @ Bendigo	Bendigo Creek @ Huntly
RORB default equation	Australia wide	$Kc = 2.2^* A^{0.5} {}^*(Qp/2)^{0.8-m}$	17.33	26.21
Regional Equation	For Areas where Annual Rainfall <800mm	$kc = 0.49^*A^{0.65}$	7.17	12.28
Regional Equation	For Areas where Annual Rainfall >800mm	$kc = 2.57^*A^{0.45}$	16.47	23.90
Pearse et al. (2002) after Dyer (1994)	Australia wide	$k_c = 1.14 \times d_{av}$	8.9	12.72
Pearse et al. (2002) after Yu (1989)	Australia wide	$k_c = 0.96 \times d_{av}$	7.5	10.71
Andrews Curves	Australia wide	See Grayson et al. 1996	7.82	5.65

A review of the kc values determined from alternative methods suggested that the parameters used in calibration were reasonable. It was deemed that additional sensitivity testing of appropriate kc values for design modelling was required, with results presented below in Section 3.5.3.

3.4.2 Losses

To achieve a reasonable fit between the observed and design hydrographs, significant losses were required, as shown in Table 3-11 to Table 3-13.

Table 3-11 RORB Calibration Loss Parameters – March 2010

Location	Burst 1		Burst 2		Burst 3	
	IL	CL	IL	CL	IL	CL
Bendigo Creek @ Bendigo	50	6	30	2	25	5
Bendigo Creek @ Huntly	50	6	30	2	25	5

Table 3-12 RORB Calibration Loss Parameters – September 2010

Location	Burst 1		Burst 2		Burst 3	
	IL	CL	IL	CL	IL	CL
Bendigo Creek @ Bendigo	10	2	10	4	10	5
Bendigo Creek @ Huntly	20	3	20	2	20	1

Table 3-13 RORB Calibration Loss Parameters – February 2011

Location	Burst 1		Burst 2		Burst 3	
	IL	CL	IL	CL	IL	CL
Bendigo Creek @ Bendigo	5	2.5	10	2.5	0	2.5
Bendigo Creek @ Huntly	10	2.5	10	5	5	2.5

The design losses were not based on the losses adopted in the calibration events. Losses applied for the March 2010, September 2010 and February 2011 are highly dependent on antecedent catchment conditions and are not suitable for design flood estimation.

3.5 Design Event Modelling

The goal of the RORB model design runs is to provide design flow hydrographs over a range of ARI's for input into the hydraulic model. For this study the 5, 10, 20, 50, 100 and 200 year ARI events were run. The design runs were modelled conservatively with the storages set to full, consistent with conditions during the calibration events. The inputs for the design flood estimation are described below.

3.5.1 Design Rainfall

Design rainfall depths

Design rainfall depths were determined using the IFD methodology outlined in AR&R Volume 2, (1987). The IFD parameters were generated for a location in Bendigo (144.2891E, -36.724S) and are shown in Table 3-14 below.

Table 3-14 Catchment IFD Parameters

$2I_1$ (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
19.55	3.62	0.93	39.74	6.99	1.83	0.17	4.34	14.97	2

Design temporal pattern

The temporal patterns used in the design events were obtained from AR&R (1987). The catchment is located within Zone 2 of the temporal pattern map as defined in AR&R (1987). The temporal patterns were filtered to remove embedded intensities of higher ARI. Bendigo sits within the boundary of Zone 2, and therefore design temporal patterns for this zone were used.

Design spatial pattern

A uniform spatial rainfall pattern (i.e. same rainfall depths applied to the entire catchment) was adopted for the generation of design flood hydrographs.

Areal reduction factor

Areal reduction factors convert point rainfall to areal estimates and are used to account for the variation of rainfall intensities over a large catchment. Reduction factors were applied to both the upper and lower catchment areas.[3]

3.5.2 Design Model Parameters

The design model parameters (kc and losses) were determined from calibration, sensitivity analysis and comparisons to flood frequency analysis.

Routing parameters

The following RORB parameters were adopted for the design modelling. These were determined as a result of extensive sensitivity testing described in Section 3.5.3.

Table 3-15: Adopted RORB Design Losses

Location	kc	Initial Loss (mm)	Continuing Loss (mm/h)
Upper Catchment	14	10	2.5
Lower Catchment	17	20	2.5

Design losses

This study adopted an initial loss of 10 mm for the upper catchment, 20 mm for the lower catchment and a continuing loss of 2.5 mm/hr. These values were determined based on the sensitivity described in Section 3.5.3 and validation of design flows against flood frequency analysis as described in Section 3.6. The loss parameters were applied across all ARI events and durations. The loss parameters adopted are consistent with regional design loss parameters set out within AR&R (1987) and Melbourne Water Guidelines[1] used in the urban rain on grid hydraulic modelling in this project.

The design losses were not based on the losses adopted in the calibration events. Losses applied for the March 2010, September 2010 and February 2011 events are highly dependent on antecedent catchment conditions and are not suitable for design flood estimation. Design losses for the March 2010 event in particular were quite large in an attempt to reduce the modelled streamflow hydrographs to match the observed gauges, but regardless of the losses applied the modelled hydrographs were still too high, this could have to do with the fraction imperviousness applied to the various model subareas.

3.5.3 Sensitivity Analysis of Kc and Design Losses

A sensitivity analysis was conducted on both kc and design losses. The initial testing utilised a kc of 17 in both the upper and lower catchment which was consistent with the March 2010 calibration. 13 combinations of design loss parameters were initially trialled to assess their impact on peak flows in Bendigo Creek at the location of the streamflow gauges. Changes in these parameters also impact the apparent frequency of historic events such as the three calibration events so this impact was

[33] Siriwardena and Weinmann (1996), *Derivation of Areal Reduction Factors For Design Rainfalls (18 - 120 hours) in Victoria*. Report 96/4, CRC for Catchment Hydrology, 60pp.

also assessed. The scenarios that were trialled and the results of testing are shown in Table 3-16 to Table 3-21.

To aim for consistency across the project it was proposed that an Initial Loss/Runoff Coefficient model may be more appropriate for use so both continuing loss and runoff coefficient models were trialled in the sensitivity analysis. A Runoff Coefficient model approach was utilised in the Rain on Grid urban modelling in this project, with values consistent with Melbourne Water Guidelines[1] used. Similar values were trialled in the sensitivity analysis.

Table 3-16 Design Loss Sensitivity Analysis –Initial/Continuing Loss Parameter Details

Scenario	Loss Parameter Details	kc (upper & lower catchment)	Initial Loss (mm)	Continuing Loss (mm/h)
1	AR&R design losses (upper end of range)	17	25	2.50
2	AR&R design losses (lower end of range)	17	20	2.50
3	Hill et al. losses using a Baseflow Index of 0.3	17	26.1	3.71
4	Hill et al. losses using a Baseflow Index of 0.2	17	28.6	2.91
5	Hill et al. losses using a Baseflow Index of 0.08	17	31.7	1.95

Table 3-17 Design Loss Sensitivity Analysis – Impact on peak flows and calibration event frequency at Bendigo Creek at Bendigo Gauge (Initial/Continuing Loss)

Scenario	Initial Loss (mm)	Continuing Loss (mm/h)	Bendigo Creek at Bendigo Gauge			
			Q100 (m^3/s)	Feb 11 ARI (yrs)	Sept 10 ARI (yrs)	March 10 ARI (yrs)
1	25	2.5	100	>200	<50	<50
2	20	2.5	111	187	<50	<50
3	26.1	3.71	95	>200	<50	<50
4	28.6	2.91	91	>200	<50	<50
5	31.7	1.95	89	>200	<50	<50

Table 3-18 Design Loss Sensitivity Analysis – Impact on peak flows and calibration event frequency at Bendigo Creek at Huntly Gauge (Initial/Continuing Loss)

Scenario	Initial Loss (mm)	Continuing Loss (mm/h)	Bendigo Creek at Huntly Gauge			
			Q100 (m^3/s)	Feb 11 ARI (yrs)	Sept 10 ARI (yrs)	March 10 ARI (yrs)
1	25	2.5	220	50	<50	<50
2	20	2.5	235	<50	<50	<50
3	26.1	3.71	181	93	<50	<50
4	28.6	2.91	196	77	<50	<50
5	31.7	1.95	219	63	<50	<50

Table 3-19 Design Loss Sensitivity Analysis – Initial Loss/Runoff Coefficient Parameter Details

Scenario	Loss Parameter Details	kc (upper and lower catchment)	Initial Loss (mm)	Runoff Coefficient (RoC)
6	Hill et al. IL of 30.7 (using a Baseflow Index of 0.08).Trial ROC of 0.7.	17	31.7	0.7
7	IL consistent with MW guidelines for rural catchments. ROC of 0.6 consistent with MW guidelines.	17	20	0.6
8	IL consistent with MW guidelines for rural catchments. Trial ROC of 0.5.	17	20	0.5
9	Trial IL of 17.5mm. ROC of 0.6 consistent with MW guidelines.	17	17.5	0.6
10	IL consistent with MW guidelines for rural catchments. Trial ROC of 0.7.	17	20	0.7
11	Trial IL of 17.5mm and ROC of 0.7.	17	17.5	0.7
12	Trial IL of 15mm. ROC of 0.6 consistent with MW guidelines.	17	15	0.6
13	Upper Catchment IL – 10mm, Lower Catchment IL – 20mm, ROC of 0.6 (consistent with Melbourne Water Guidelines[1])	16	10/20	0.6

Table 3-20 Design Loss Sensitivity Analysis – Impact on peak flows and calibration event frequency Bendigo Creek at Bendigo Gauge (Initial Loss/Runoff Coefficient)

Scenario	Initial Loss (mm)	Runoff Coefficient (RoC)	Bendigo Creek at Bendigo Gauge			
			Q100 (m^3/s)	Feb 11 ARI (yrs)	Sept 10 ARI (yrs)	March 10 ARI (yrs)
6	31.7	0.7	77	>200	<50	<50
7	20	0.6	84	>200	<50	<50
8	20	0.5	76	>200	<50	<50
9	17.5	0.6	87	>200	<50	<50
10	20	0.7	90	>200	<50	<50
11	17.5	0.7	95	>200	<50	<50
12	15	0.6	91	>200	<50	<50
13	10/20	0.6	95	>200	<50	<50

Table 3-21 Design Loss Sensitivity Analysis – Impact on peak flows and calibration event frequency at Bendigo Creek at Huntly Gauge (Initial Loss/Runoff Coefficient)

Scenario	Initial Loss (mm)	Run Off Coefficient (RoC)	Bendigo Creek at Huntly Gauge			
			Q100 (m^3/s)	Feb 11 ARI (yrs)	Sept 10 ARI (yrs)	March 10 ARI (yrs)
6	31.7	0.7	196	68	<50	<50
7	20	0.6	217	<50	<50	<50
8	20	0.5	191	72	<50	<50
9	17.5	0.6	222	<50	<50	<50
10	20	0.7	244	<50	<50	<50
11	17.5	0.7	249	<50	<50	<50
12	15	0.6	226	<50	<50	<50
13	10/20	0.6	225	<50	<50	<50

The results of the sensitivity analysis show that the design losses have a significant impact on flows in Bendigo Creek. Results using the Hill and Mein losses show considerably lower flows as a result of the higher losses used in that method compared with AR&R (1987) losses. The calculated initial loss in the Hill and Mein method is entirely a function of baseflow and regional maps indicate a low base flow of approximately 8% around Bendigo although higher baseflow values were also trialled. The reduction in flows observed when using Hill and Mein losses compared with AR&R (1987) causes the apparent frequency of the calibration events to increase significantly with the February 2011 event becoming a greater than 200 year ARI event at the Bendigo gauge in scenarios 3 to 5.

The results show that using a runoff coefficient instead of a continuing loss leads to an even greater reduction in flows. This also causes the apparent frequency of the calibration events to increase significantly with the February event becoming a greater than 200 year ARI event at the Bendigo gauge in every scenario. Interestingly, at the Huntly gauge the apparent frequency of the February event is considerably less regardless of which loss parameters are used with a range of <50 to a 93 year ARI event being determined. The results also indicate that the September 2010 and March 2010 events were relatively minor with their relative frequency being <50 year ARI in every scenario.

The results were also compared with the Flood Frequency Analysis (presented in Section 3.6.1) 100 year ARI flow of 133 m^3/s at Bendigo and 121 m^3/s at Huntly. As discussed previously the data records at both of these locations show significant periods of poor and extrapolated data and because of this it is strongly suspected that the Flood Frequency Analysis underestimates flows at both gauges. All of the scenarios trialled above resulted in 100 year ARI flows which were considerably lower than the Flood Frequency Analysis 100 year flow of 133 m^3/s. This does not correlate with the assumption that the 100 year ARI flow is likely to be higher than 133 m^3/s and raises doubt regarding the use of those parameters.

Based on the above reasoning it was deemed that none of the scenarios in the above testing provided satisfactory results for use in design modelling. It was decided that additional testing was required with an alternate design kc. A lower kc of 14 for the upper catchment was trialled with the lower catchment kc remaining at 17. These values are consistent with those used in the February 2011 event calibration. It is also consistent with the differing characteristic between the upper and lower catchments. The upper catchment has a lower D_{av} so a lower kc would also seem logical.

Both Continuing Loss and Runoff Coefficient models were trialled in the second phase of the sensitivity analysis. A number of scenarios were trialled including initial losses based on Hill and Mein methods, ARR (1987) regional initial loss values and Melbourne Water values outlined in their technical specifications for hydrologic modelling.

Table 3-22 Design Loss Sensitivity Analysis (Upper Catchment kc - 14) – Initial/Continuing Loss Parameter Details

Scenario	Loss Parameter Details	Initial Loss (mm)	Continuing Loss (mm/h)
14	IL of 10mm consistent with Melbourne Water Guidelines[1] for urban catchments	10	2.50
15	IL of 20mm consistent with Melbourne Water Guidelines[1] for rural catchments	20	2.50
16	Hill et al. losses using a Baseflow Index of 0.08	31.7	1.95
17	Hill et al. losses using a Baseflow Index of 0.2	28.7	2.91
18	Upper Catchment IL – 10mm, Lower Catchment IL – 20mm (consistent with Melbourne Water Guidelines[1])	10/20	2.5

Table 3-23 Design Loss Sensitivity Analysis ((Upper Catchment Kc - 14) – Impact on peak flows at Bendigo Creek Gauges (Initial/Continuing Loss (Model)

Scenario	Initial Loss (mm)	Continuing Loss (mm/h)	Q100 (m^3/s)	
			Bendigo Gauge	Huntly Gauge
14	10	2.50	152	296
15	20	2.50	120	244
16	31.7	1.95	98	206
17	28.7	2.91	105	193
18	10/20	2.5	157	261

Table 3-24 Design Loss Sensitivity Analysis (Upper Catchment kc - 14) – Initial Loss/Runoff Coefficient Parameter Details

Scenario	Loss Parameter Details	Initial Loss (mm)	Runoff Coefficient
19	IL of 10mm consistent with Melbourne Water Guidelines[1] for urban catchments, ROC of 0.6 consistent with Melbourne Water Guidelines[1]	10	0.6
20	IL of 10mm consistent with Melbourne Water Guidelines[1] for urban catchments, trail of higher ROC of 0.7	10	0.7
21	IL of 10mm consistent with Melbourne Water Guidelines[1] for urban catchments, trail of higher ROC of 0.8	10	0.8

Table 3-25 Design Loss Sensitivity Analysis (Upper Catchment kc - 14) – Impact on peak flows at Bendigo Creek Gauges (Initial Loss/Runoff Coefficient Model)

Scenario	Initial Loss (mm)	Runoff Coefficient	Q100 (m^3/s)	
			Bendigo Gauge	Huntly Gauge
19	10	0.6	111	230
20	10	0.7	126	268
21	10	0.8	137	298

The results again show that the use of a Runoff Coefficient model generally resulted in significantly lower flows than when a Continuing Loss model was used unless a very high runoff coefficient is utilised. It can be seen that a Runoff Coefficient of 0.8 was required to achieve a 100 year ARI flow at the Bendigo gauge greater than the Flood Frequency Analysis 100 year ARI flow at that location. A Runoff Coefficient of 0.8 is considered very high and is not consistent with values used in the urban Rain on Grid modelling which are in line with Melbourne Water Guidelines[1]. These results indicate that it is more appropriate to use a Continuing Loss model. This is supported by the fact that much of the broader catchment is either agricultural or forest and so it would seem logical that a Continuing Loss model is more appropriate.

The results of the sensitivity analysis using a Continuing Loss model generally resulted in flows which are more in line with the flows expected as a result of the Flood Frequency Analysis and Regional Methods discussed in Section 3.6. Some of the scenarios tested also utilised Initial Losses which were consistent with the urban Rain on Grid modelling and Melbourne Water Guidelines[1]. It was deemed that Scenario 18 was the most appropriate for use in design modelling. The initial losses of 10 mm for the upper catchment and 20 mm for the lower catchment used in Scenario 18 are consistent with the urban modelling in this project and reflects the fact that much of the land use in the upper catchment is urban while the lower catchment is predominantly rural. The resulting 100 year flow of 157 m^3/s at Bendigo is consistent with the flood frequency analysis and the likelihood that the Flood Frequency Analysis has somewhat underestimated flows due to the poor data record. The continuing loss of 2.5 mm/h in Scenario 18 is consistent with AR&R (1987) regional losses for the area.

Based on the results of the sensitive analysis Scenario 18 was selected as the most appropriate parameters. The adopted design losses and runoff coefficients are shown in Table 3-26. These parameters are consistent with those used in the urban Rain on Grid modelling and Melbourne Water Guidelines[1].

Table 3-26: Adopted RORB Design Parameters

Location	kc	Initial Loss (mm)	Continuing Loss (mm/h)
Upper Catchment	14	10	2.5
Lower Catchment	17	20	2.5

An alternative method to determine design losses is to fit the design flows to the results of Flood Frequency Analysis. This option was trialled however it was discovered that to fit the peak flow to the Flood Frequency Analysis flow at the upstream gauge requires considerably different losses than at the downstream gauge. At the downstream Huntly gauge excessively high losses were required to fit the 100 year ARI design flow to the 100 year Flood Frequency Analysis indicating that the Flood Frequency Analysis is underestimating flows. This is likely to be a result of poor gauging and the peaks of major flood events not being recorded. The results of this are shown in Table 3-27. It was concluded it was not possible to fit the design flows to the results of Flood Frequency Analysis in this study and that the losses determined using the sensitivity analysis above are more suitable.

Table 3-27 Design losses to fit Design flows to Flood Frequency Analysis

Location	FFA 100 year ARI (m^3/s)	Design Initial Loss (mm)	Design Continuing Loss (mm/h)
Bendigo	133	10	3
Huntly	121	25	7.25

3.6 Design Flow Verification

The design flows are largely dependent on the adopted RORB model design parameters. A number of checks were undertaken to verify the generated design flows.

3.6.1 Flood Frequency Analysis

A flood frequency analysis (FFA) allows the estimation of peak selected ARI flows based on a statistical analysis. FFA was undertaken for both the Bendigo Creek gauges to provide an estimate of a range of ARI flow events at these locations. An annual flood series was extracted from the available 34 years of instantaneous streamflow data, from 1977 to 2011, at both gauges. At the Bendigo Gauge no data was available for 1989-90, 1992-1999, 2000 and 2002-2004 and so these years were excluded from the analysis.

A statistical analysis software package, FLIKE, was used to perform the FFA. There are a number of probability distributions which can be used to best describe the historic streamflow peak data. AR&R recommends the 'Log Pearson III' distribution for general use, however the 'Generalised Extreme Value (GEV)' distribution is also used increasingly. Both distributions were tested with the data and the 'Generalised Extreme Value (GEV)' distribution produced a better fit for both streamflow gauges. The results of the GEV distribution FFA for Bendigo Creek at Bendigo is shown in Figure 3-9 and for Bendigo Creek at Huntly in Figure 3-10. The peak flow estimates based on these distributions for a range of ARIs is summarised in Table 3-28.

Considering the previous acknowledgement that both gauges are inaccurate at high flows it is suspected that the FFA will considerably underestimate flows. Given this assumption, it is suggested that the FFA should not be used to scale the design flows.

Table 3-28 FFA Peak ARI flood estimates (GEV)

ARI (Years)	Peak Design flow (m3/s)	
	Bendigo Creek at Bendigo	Bendigo Creek at Huntly
1.01	12.58	2.87
2	38.72	32.56
5	63.12	52.92
10	79.57	67.60
20	95.55	82.66
50	116.57	103.66
100	132.56	120.61
200	148.69	138.61
500	170.30	164.15
1000	186.88	184.92

The FFA at Bendigo indicates that the September 2010 and February 2011 flood events were approximately 2 and 10 year ARI events respectively which does not correlate with anecdotal evidence regarding the magnitude of these flood events. At Huntly the FFA indicates that the same events are greater than 1,000 year ARI events which again does not correlate with anecdotal evidence and suggests that the FFA estimates are significantly underestimated for the higher magnitude events. Both FFAs have significantly large confidence limits at the upper end of the fitted distribution due to the lack of available data and lack of large observed events.

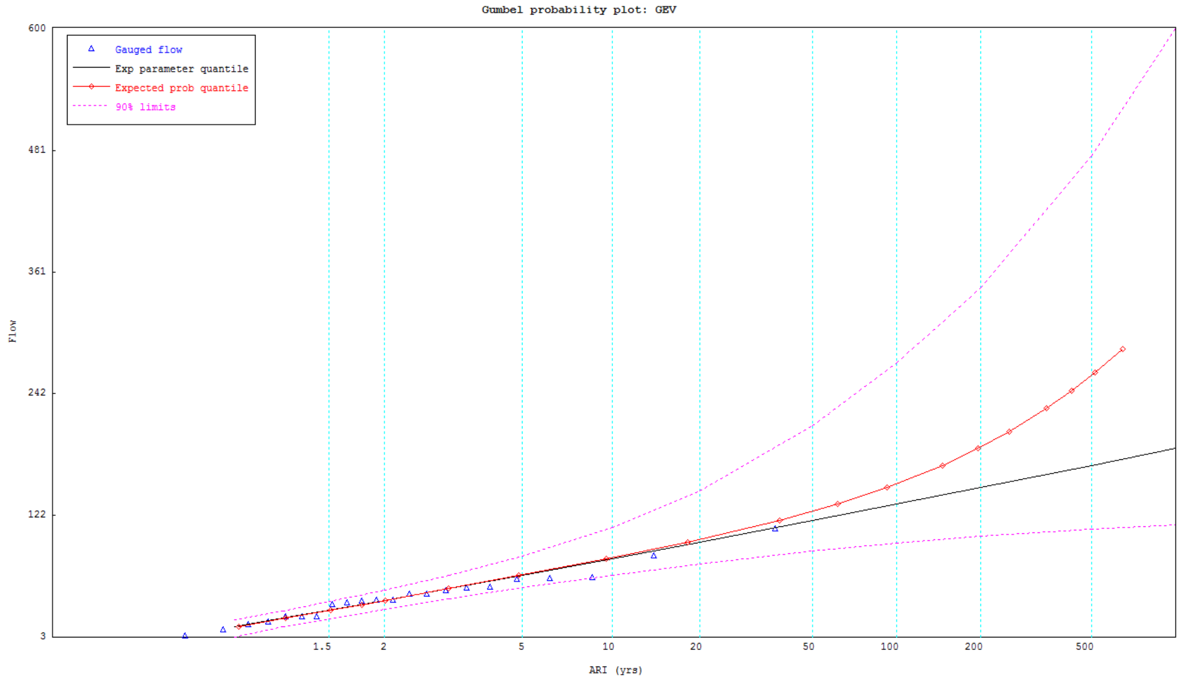


Figure 3-9 Generalised Extreme Value Flood Frequency Analysis – Bendigo Creek at Bendigo

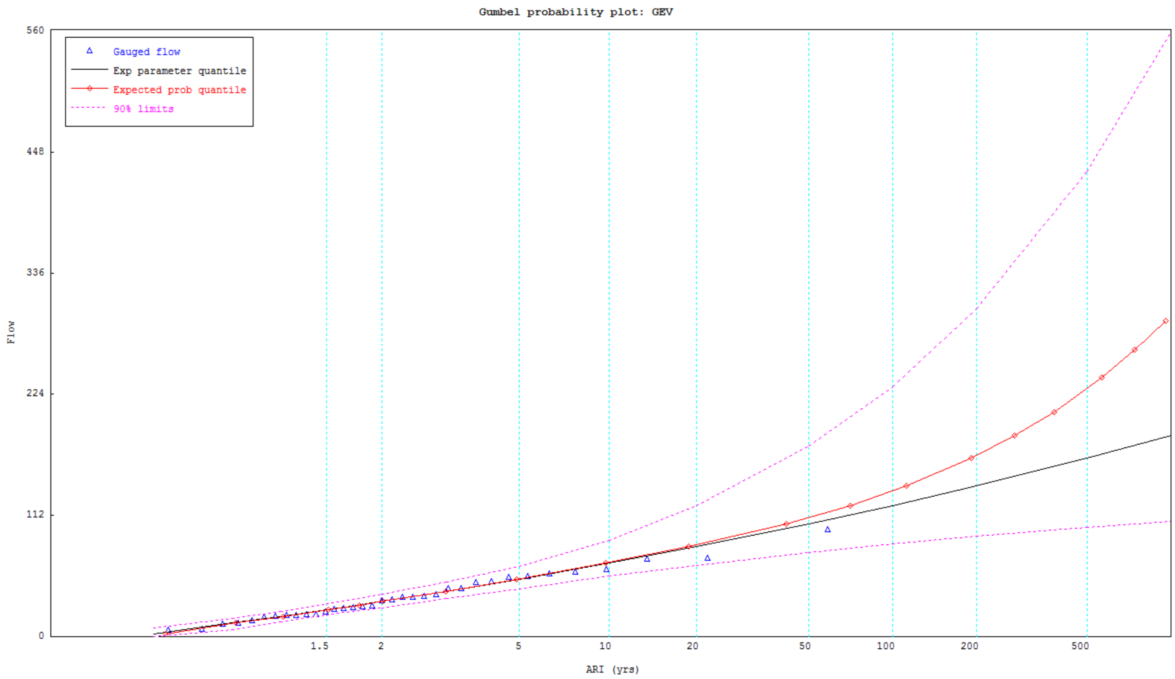


Figure 3-10 Generalised Extreme Value Flood Frequency Analysis – Bendigo Creek at Huntly

3.6.2 Comparison to Regional Methods

Due to the poor quality of data available for verification and the uncertainty about the magnitude of peak flows, the achieved fit of calculated flood peaks from RORB to observed flood frequency analysis was also poor. Therefore regional methods were used to estimate peak flows for comparison.

Rational Method

Rational Method calculations were performed as part of the analysis to compare against other methods. At the Huntly gauge the Rational Method estimated a high 100 year ARI flow of 317 m^3/s compared to the FFA 100 year ARI flow of 121 m^3/s and a design flow of 261 m^3/s from RORB modelling. The result of the Rational Method calculation adds further weight to the likelihood that the FFA has considerably underestimated flows due to the poor data record.

At the Bendigo Gauge the Rational Method estimates a 100 year ARI flow of 153 m^3/s which correlates very closely with the RORB design flow of 157 m^3/s. This also adds weight to the likelihood that that the FFA at the Bendigo gauge of 133 m^3/s is an underestimate.

Regional Method

The hydrological recipes – Estimation Techniques in Australian Hydrology (Grayson et al, 1996), provides a regional equation for the 100 year ARI event in rural catchments. The peak 100 year ARI design flow at Huntly determined using the Regional Method analysis was found to be 204 m^3/s for a rural catchment and 449 m^3/s for urban. Again, these flows are considerably higher than the FFA 100 year ARI flow of 121 m^3/s, however correlates to the RORB design flow of 261 m^3/s.

The peak 100 year ARI design flow at Bendigo determined using the Regional Method analysis was found to be 109 m^3/s for a rural catchment and 204 m^3/s for urban. These flows correlate very close to both the RORB design flow of 157 m^3/s as well as the FFA 100 year ARI flow of 133 m^3/s.

3.6.3 Comparison to Hydraulic Modelling

As a further comparison the flows from the calibration models were then run in the 1D TUFLOW hydraulic model and the results reviewed. The following comparisons were made:

Comparison of flood extents

Model extents were compared against observed flooding by North Central CMA and City of Greater Bendigo staff. Generally the modelled extents were consistent with observed flooding. Locations where inconsistencies were observed were generally a result of hydraulic model schematisation rather than issues with modelled flows. The conclusion of the review was that the flows used in the hydraulic model led to modelled flood extents which were consistent with known flooding and suggested that the RORB calibration flows were appropriate.

An example of the flood review for the February 2011 event modelled extent is shown in Figure 3-11. It can be seen in the figure that the extent has been identified as being inaccurate at several locations in the area but these were all identified as problems with mapping 1D results and hydraulic model parameters rather than indications of inaccurate flows. The problem areas were resolved in the hydraulic modelling phase of the project by altering the model to a predominately 2D model as opposed to earlier versions of the model which were largely 1D.

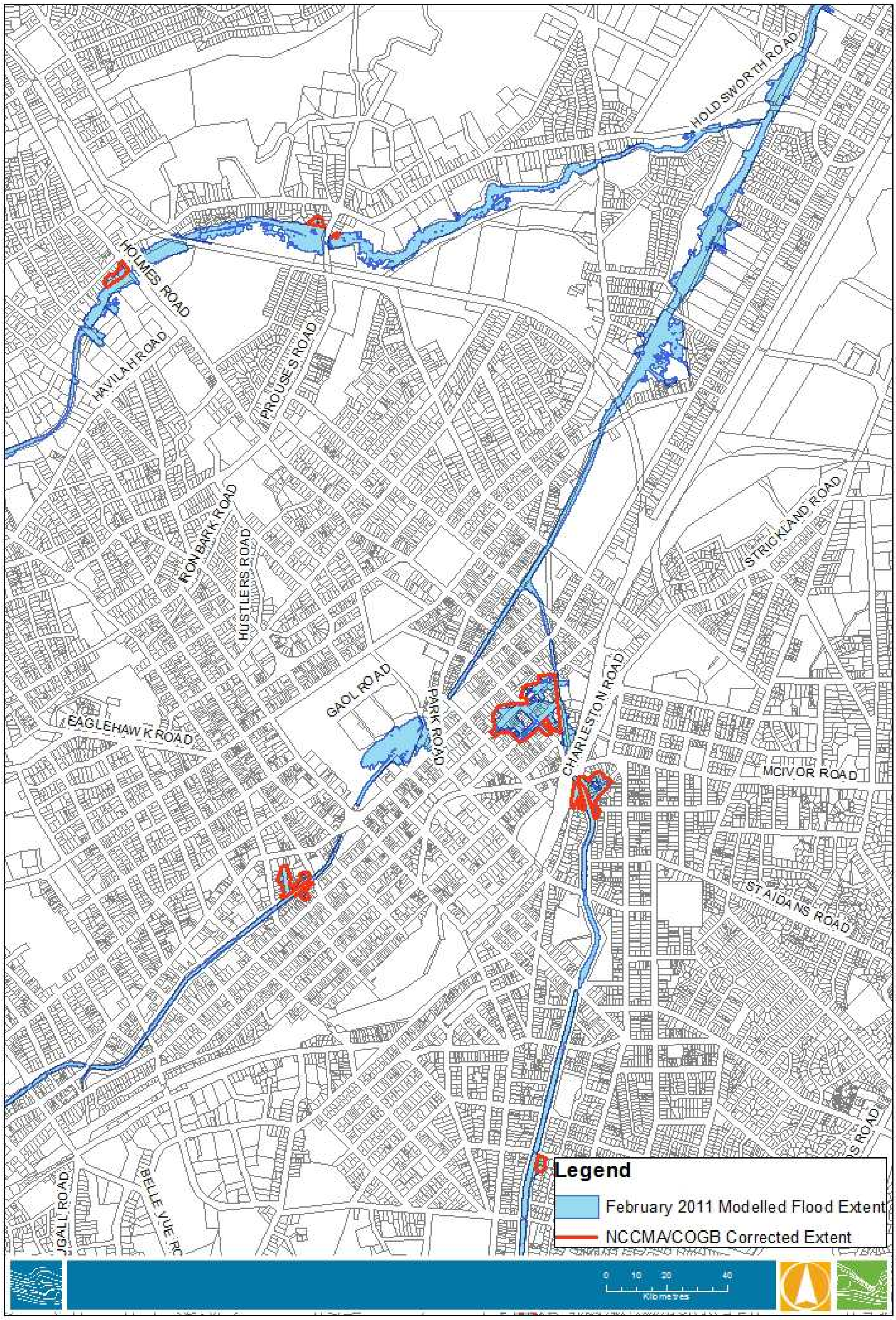


Figure 3-11 Example of the NCCMA/COGB review of the modelled flood extent for the February event around Central Bendigo.

Comparison of modelled levels and flows

Modelled peak water levels and flows were extracted at the Bendigo Creek at Bendigo Gauge and compared against recorded gauge levels and flows as well as flows from the RORB model.

The comparison between the hydraulic model and observed peak flood levels showed an excellent correlation for the March 2010 event and a poor correlation for the February 2011 and September 2010 events, however as previously discussed the recorded data during these events is of poor quality. It is difficult to draw any conclusions from this comparison. A comparison at the Huntly gauge was not possible as an accurate gauge elevation was not available. The gauge elevation recorded on the Victorian Data Warehouse indicates an elevation which is lower than the topography in the area. Further investigation of this data would need to occur for this comparison to be made.

Table 3-29: Comparison of Hydraulic Modelled and Observed Water Elevations at Bendigo Gauge

Event	Modelled Elevation (m AHD)	Recorded Gauge Depth (m)	Derived Gauge Elevation (m AHD)	Difference (Modelled – Observed) (m)
February 2011	205.28	2.71	206.15	-0.87
September 2010	204.77	2.44	205.88	-1.11
March 2010	204.50	1.40	204.54	-0.04

A comparison was also made between the hydraulic model and RORB hydrological model flows at both gauge locations as shown in Table 3-30. The results indicate a good correlation between the hydraulic and hydrologic flows at both locations for the February 2011 and March 2010 events and a moderately good correlation for the September 2010 event. This was an additional check to demonstrate that the RORB routing provided similar results to the 1D TUFLOW model at the Bendigo Creek gauge locations.

Table 3-30: Comparison of Hydraulic Model and RORB Hydrological Peak Flows at Bendigo Gauge

Event	Hydraulic Model Peak flow (m^3/s)		RORB Model Peak Flow (m^3/s)	
	Bendigo Gauge	Huntly Gauge	Bendigo Gauge	Huntly Gauge
February 2011	128	149	130	176
September 2010	75	96	50	76
March 2010	54	29	32	27

Comparisons with other available information

Modelled levels were also compared with other available evidence of flooding in those events including YouTube videos.

A video of the February 2011 event was observed showing the flood event in Bendigo Creek from the Holdsworth Road Bridge[4]. This is located approximately 1.5 km downstream of the Bendigo Creek at Bendigo Gauge. The video shows the rapid rise in water levels in the channel with the channel reaching approximately 40% of the channel capacity. The creek is still slowly rising by the end of the video so a peak level cannot be determined.

The model results were reviewed at the same location and it can be seen that the modelled flood event reaches a level of approximately 60% of the channel height. While this information does not allow for a direct, accurate comparison of levels it does provide some additional information which suggests that the flood event was well contained in the creek at this location adding further weight that the flows being used are appropriate.

Figure 3-12 **Cross-section at the location of the Holdsworth Road bridge with the peak modelled flood level marked with the blue line.**

Figure 3-13 **Screen shot from video of the February 2011 in Bendigo Creek at Holdsworth Road with significant flow in the channel visible.**

[4] http://www.youtube.com/watch?v=b0taOiyQG3E

A second video was sourced also taken during the February 2010 event at the Central City Caravan Park in Golden Square[5]. The video indicates that that the flood reached a level just below bank level. This correlates reasonably well with modelled flows which suggest a level approximately 30 cm below bank level at this location. The video also depicts some shallow water flowing through the caravan park which was also represented in the hydraulic model also indicating the modelled flows for this event are appropriate.

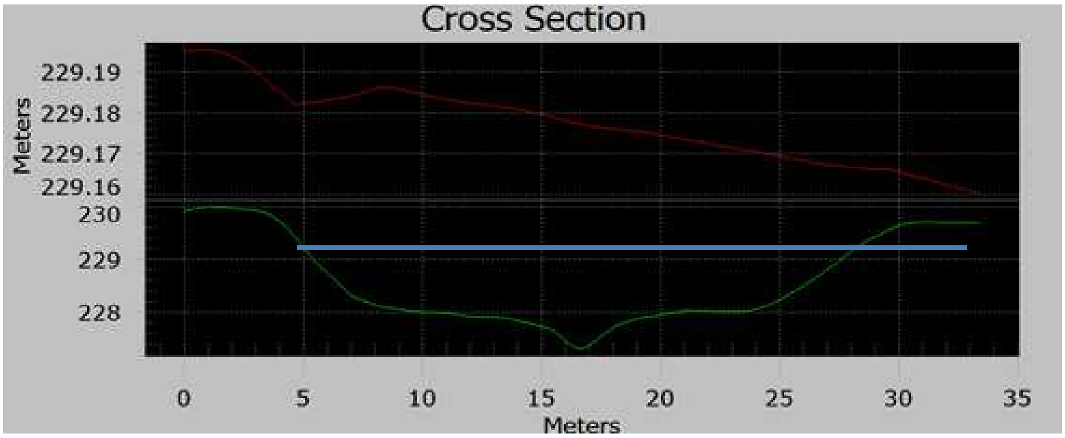


Figure 3-14 Cross-section at the location of the Central City Caravan Park bridge with the peak modelled flood level marked with the blue line.

Figure 3-15 Screen shot of the February event taken from the Central City Caravan Park with flood levels visible just below bank level.

[5] http://www.youtube.com/watch?v=tcNriAomuQc

Summary

The additional checks completed have generally supported the view that the RORB calibration flows are appropriate and are a good representation of the flows experienced in Bendigo during those flood events. Where comparisons were poor was generally a result of poor or unavailable data rather than an indication that the RORB calibration flows are inaccurate.

Unfortunately the Bendigo Creek catchment has very little high quality data to calibrate hydrological models to. Water Technology has undertaken extensive checks using alternative methods and has adopted design estimates that are reasonable.

3.6.4 Adopted Hydrology Parameters

Based on the hydrological analysis undertaken the following parameters have been adopted for design purposes:

- Design rainfall depths for Bendigo
- Zone 2 design temporal patterns
- Areal Reduction Factors for an area upstream of 203 km^2
- Uniform spatial rainfall pattern across the entire catchment
- kc of 14 for the upper catchment, 17 for the lower catchment
- Design losses; an initial loss of 10 mm for the upper catchment, 20 mm for the lower catchment and a continuing loss of 2.5 mm/hour
- Upper catchment defined as upstream of the Bendigo Creek at Bendigo gauge

3.6.5 Design Flood Hydrographs

Design flood hydrographs were extracted at 8 locations for input into the hydraulic 'spine' model. A range of storm durations were run (10min – 72hrs) to ensure the critical storm durations of the large branches and smaller tributaries were determined. Table 3-31 displays the calculated design peak flows and critical storm durations for various ARI events.

Table 3-31 RORB model design peak flows and critical storm durations at selected locations

	Bendigo Creek at Bendigo		Bendigo Creek at Huntly		Furness St, Kangaroo Flat Inflow (IF2 - 2)		Back Creek (Huntly) Inflow (IF7 - 41)		Eaglehawk Creek Inflow (IF8 - 27)	
ARI	Peak flow (m^3/s)	Critical Storm Duration (hrs)	Peak flow (m^3/s)	Critical Storm Duration (hrs)	Peak flow (m^3/s)	Critical Storm Duration (hrs)	Peak flow (m^3/s)	Critical Storm Duration (hrs)	Peak flow (m^3/s)	Critical Storm Duration (hrs)
5	63.3	12	75.8	6	8.8	12	3.6	72	4.0	6
10	79.5	3	104.6	6	11.5	3	5.3	72	5.4	12
20	101.6	3	148.0	6	15.0	3	7.6	72	7.6	12
50	132.7	3	209.9	6	20.4	3	11.3	48	10.0	3
100	156.9	3	260.7	6	24.9	3	14.4	48	12.4	3
200	182.3	3	315.0	6	29.6	3	17.3	6	14.9	3

*Note that critical design flows for Back Creek for the 5 year ARI to 100 year ARI are shown above as occurring for long duration storm events. The 6 hour duration storm event produced peak flows that were almost identical, only slightly lower than those shown in the Table.

The design flows indicate that the March 2010, September 2010 and February 2011 flood events were approximately <5, 5 and 50 year ARI events respectively in Bendigo Creek at Bendigo and Huntly.

3.7 Comparison to previous studies

There are two previous studies where the hydrology of Bendigo Creek has been investigated: the State Rivers and Water Supply Commission (1984) and SKM (2004). Both studies used different RORB models and different catchment extents; however some comparisons can be made, particularly to the 100 year ARI flow.

It can be seen that a number of parameters and characteristics correlate quite closely between the different studies. The kc of 14 used in the upper catchment in this study is higher than the kc of 10.1 used in the previous studies. The previous studies modelled a smaller catchment area which could account for the slightly lower kc value.

The 100 year ARI flows determined in the previous study of 165 m^3/s and 140 m^3/s correlate very closely with the 157 m^3/s determined in this study. The initial loss parameters are also of a similar magnitude. Overall it can be seen that broadly there is good consistency between this study and the previous hydrological studies of Bendigo Creek.

Table 3-32: Adopted RORB model parameters from previous studies

Parameter	SR&WSC (1984)	SKM (2004)	Water Technology (2011)	
			To Bendigo	To Huntly
Kc	10.1	10.1	14	17
m	0.8	0.8	0.8	0.8
D_{av}			7.81	11.16
IL (mm)	12-20	23.5	10 for upper / 20 for lower	
CL (mm/hr)	0.8	4.5	2.5	
Number of sub-areas	18	19	16	59
Catchment area	46	44	62	142
Q100 (m^3/s)	165	140	157	261
Location	Upstream of confluence with Back Creek (approx. 1 km downstream of Charing Cross)	Charing Cross	Bendigo Creek at Bendigo Gauge	Bendigo Creek at Huntly Gauge

3.8 Summary

A RORB hydrological model was used to generate design flows for the study. The RORB model developed for the catchment was calibrated to the March 2010, September 2010 and February 2011 flow hydrographs at two gauges on Bendigo Creek located at Bendigo and Huntly. The model was then used to generate design flows for the 5, 10, 20, 50, 100 and 200 year ARI events. The choice of hydrological model parameters used to generate design flows was comprehensively checked using alternative design flow estimation techniques and sensitivity testing, and is recommended for adoption in this study. The design flows indicate that the March 2010, September 2010 and February

2011 flood events were approximately <5, 5 and 50 year ARI events respectively in Bendigo Creek at Bendigo and Huntly.

4. HYDRAULIC MODELLING - SPINE MODEL

4.1 Overview

The hydraulic model routes the design flood hydrographs, obtained from the RORB modelling, along Bendigo Creek and its tributaries as well as any associated overland flow paths. The hydraulic model, TUFLOW, was employed in this investigation.

TUFLOW is a widely used model that is suitable for the analysis of overland flows in both urban and rural areas. The hydraulic model has three main inputs:

- Topography data;
- Roughness maps; and,
- Boundary conditions.

There are no existing hydraulic models within the Bendigo Creek catchment so a new TUFLOW model was constructed for this study. Flood extents, water levels, depths and velocities are the key TUFLOW model outputs. Major hydraulic structures such as culverts and bridges were modelled.

4.2 Hydraulic model construction and parameters

The TUFLOW model was constructed using MapInfo V11.5 and text editing software. This section details key elements and parameters of the TUFLOW model which comply with Melbourne Water 2D Modelling Guidelines[1].

4.2.1 Model Version

The double precision version of the latest TUFLOW release (as of May 2013) was used for all simulations (TUFLOW Version: 2012-05-AC-iDP-w64).

4.2.2 2D Grid Size and Topography

A single 2D domain was used with a grid resolution of 5 m. The 2d_zpt file was populated with elevations from the LiDAR data provided by North Central CMA.

4.2.3 1d Network

All significant bridges and culverts located on the main tributaries in the spine model were modelled in a 1D network using council plans and survey provided by North Central CMA and City of Greater Bendigo. A number of measurements of structures and channels were made during the site visit in October 2011. The survey and measurements were converted to electronic MapInfo tables for their use in the hydraulic model.

4.2.4 Roughness

For the 2D domain, 2d_mat files were produced based on land use zones, with further refinement through the use of aerial photographs and site visits. The Manning's values are specified in the .tmf TUFLOW model file. For the 1D domain, Manning's values are defined in the 1d_nwk file. Manning's 'n' roughness coefficients are listed in Table 4-1 below.

Table 4-1 Manning's Roughness Coefficient

TUFLOW .tmf Code	Land Use	Manning's n Roughness Coefficient
1	Pasture, some tall trees	0.040
2	Residential Parcel	0.200
3	Industrial Parcel	0.300
4	Carpark	0.050
5	Cemetery	0.150
6	Grassed areas, waterways	0.035
7	Paved Road	0.020
8	Unpaved Road	0.030
9	Ponds and other water bodies	0.030
10	Railways	0.040
11	Rural residential parcels/Schools	0.100
12	Dense bushland	0.100
13	Creeks with dense bush	0.080

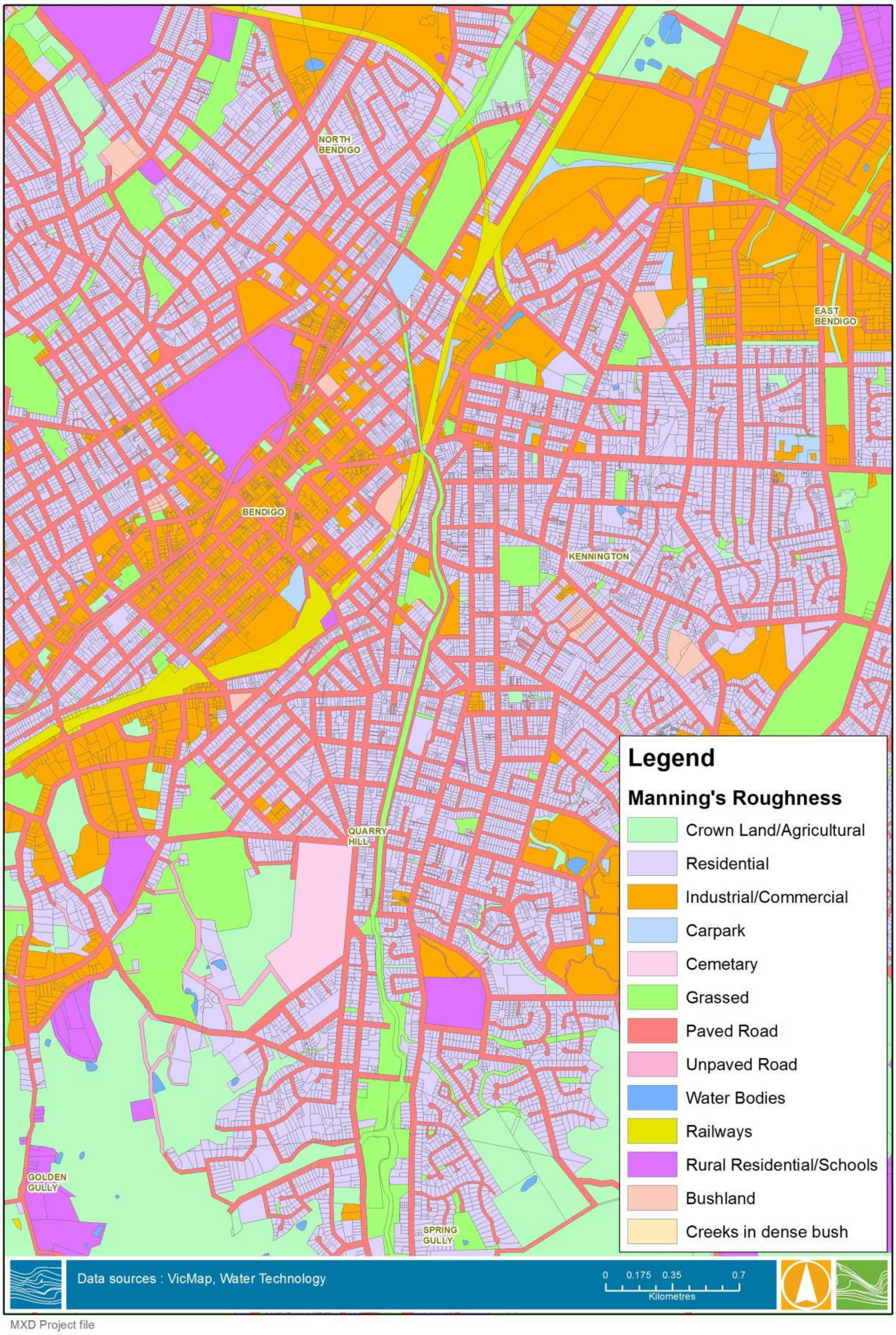


Figure 4-1 Roughness map of central Bendigo

4.2.5 Boundary Conditions

Upstream inflow boundary

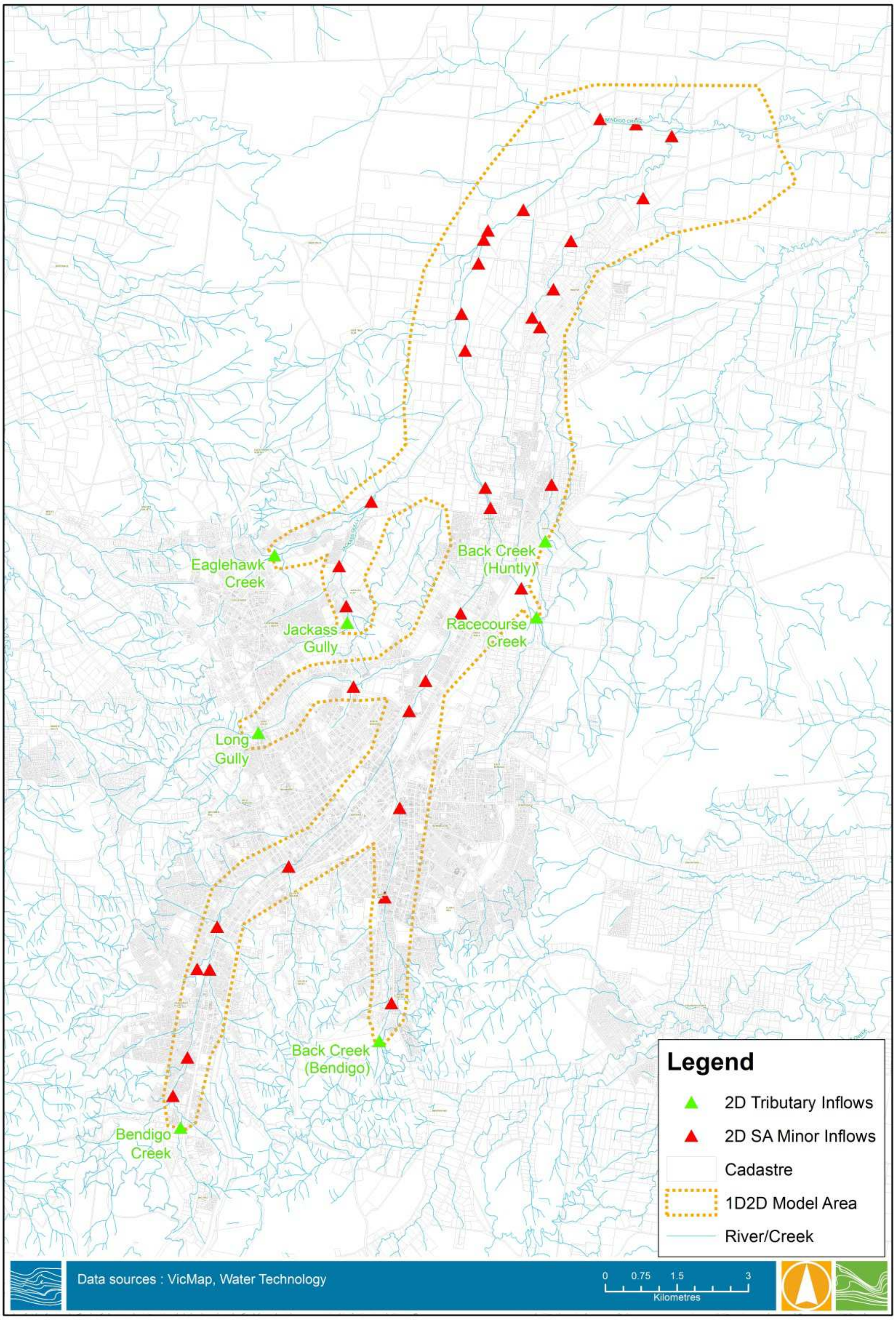
The spine model has 17 major inflow locations throughout the catchment. 7 of these boundaries are at the upstream ends of the major tributaries while the remainder are located at the outlets of smaller tributaries located throughout the catchment. The major tributary inflows were modelled using 2D_BC QT boundaries drawn as lines. The smaller inflows throughout the catchment were modelled using 2D_SA QT boundaries with the inflow distributed over several grid cells using a polygon. The locations of these boundaries are shown in Figure 4-2.

1D/2D boundaries

HX boundaries were used to link the 1D and 2D models upstream and downstream of the 1D structures. This allows water to freely flow into the 1D reach upstream of the structure and then back into the 2D domain downstream of the structure. Any overtopping and weir flow over structures was modelled in the 1D model and the results merged for mapping in the post-modelling processing.

Outlet boundary

At the lower end of the catchment, ‘HQ’ boundaries were used to convey the overland flow out the catchment in a steady manner.



MXD Project file

Figure 4-2 Hydraulic model extent and location of inflows

4.3 Hydraulic model application

The TUFLOW model was run for both the 3 hour and 6 hour duration events for each of the required design events under existing conditions. Preliminary results had indicated that the 3 hour and 6 hour durations were the critical events across much of the catchment including all areas of interest.

As a stage-discharge relationship was used as the downstream boundary condition, it was not necessary to vary the boundary condition for each ARI event simulated. The range provided in the relationship is capable of calculating an appropriate boundary level in all scenarios.

Inflow boundaries were varied for each ARI and duration by varying the flow boundaries to match the outputs from the RORB modelling.

All TUFLOW model runs were controlled through a TUFLOW Event File (.tef) and a series of batch files constructed for use in this project. The use of the .tef file and batch files ensures that the base .tcf (TUFLOW Control File) does not change between runs, with all event specific parameters specified in the .tef file. This reduces the potential for error and also assists in reducing model run and processing times.

4.3.1 TUFLOW model outputs

TUFLOW provided times-series of depths (m), water surface elevations (m AHD), flow velocities (m/s) and flood hazard (m/s/m) at each link location within the 1D element, and at the grid points within the 2D domain. These results were used to create maps and further analyse areas of concern regarding flooding within catchment areas. The model outputs were then processed as described in section 4.4.

4.4 GIS Processing

The raw model output data was processed in order for it to be easily viewed in GIS. Processing occurred in two stages; firstly processing the raw data using TUFLOW utilities and then processing the resulting data within a GIS environment. These processes are detailed below.

4.4.1 TUFLOW Data Processing

TUFLOW contains a number of utilities for processing output data. The following utilities were used:

- Dat_to_dat.exe: This utility has a number of functions and in this instance was used to extract the maximum value for depth, velocity and water elevation at each grid point across the twelve durations for each event. The maximum values are then placed in a new data file.
- TUFLOW_to_GIS.exe: This utility converts TUFLOW data into GIS formats and in this instance was used to convert TUFLOW data into the MapInfo mid/mif interchange format.

4.4.2 Results Processing

MapInfo was used to import and then compile the data into an appropriate format. Initially the depth, velocity, water surface elevation and duration layers were amalgamated into a single layer for each event. Separate 1D and 2D outputs were then merged into single layers. Final maps were produced from ASCII plots in Arc-GIS v10.

4.5 Discussion

The flood mapping deliverables consist of hardcopy plans, along with digital PDF maps showing flood extents, depth, velocity and hazard. Maps also include VFD and flood planning maps.

The flood mapping provides significantly more detail than any previous mapping of the Bendigo Creek and its tributaries. Given a very similar flow to the flows derived in both the 1984 and 2004 studies, the change in modelling technique to 2 dimensional analysis has yielded a much higher resolution output. This output can now be used to better manage both development within the Bendigo catchment, but also predict and manage flood conditions during times of emergency.

In reviewing the results of the modelling and mapping exercise the following points can be made:

- The mapping has been verified through a number of anecdotal and recorded methods providing a high level of confidence in the final results.
- The selected roughness parameters are within recommended limits and have been approved by the technical steering group.
- The LiDAR data collected for the project provides a high level of accuracy as the basis for the flood mapping
- The flows created from the RORB modelling, whilst having poor observed data to calibrate to have been verified and checked through a number of alternative methods. Finally these flows were reviewed by an independent technical review panel not associated with the project and approved for use.
- The modelling has been run for both the 3 and 6 hour events with the maximum flood depth for each grid point recorded and mapped. Again this provides a high level of confidence that the critical flood depth at any location throughout the catchment has been predicted.

5. HYDRAULIC MODEL – CATCHMENT RAINFALL ON GRID

5.1 Rainfall on Grid Overview

This section describes the catchment modelling of areas not influenced by Bendigo Creek away from the central spine model. To model these areas a technique described as direct rainfall, or Rainfall on Grid modelling has been used.

Rainfall on Grid (ROG) modelling is an integrated hydrological and hydraulic modelling computation that directly applies rainfall (minus losses) on the catchment to generate runoff which is simultaneously routed downstream across the topographic 2D grid. The focus of this modelling is for areas that are not influenced by the Bendigo Creek flooding.

The multipronged modelling approach reflects the differences in catchment behaviour across the study area. The lower reaches of Bendigo Creek behave much like any other creek in the region, and the upper urban catchment responding much quicker to rainfall within minutes to hours depending on the location within the catchment.

This section of the report covers the following:

- General description of the methodology used for the hydrologic and hydraulic assessment.
- Details of design rainfall inputs to the hydraulic model for the 5, 10, 20, 50, 100 and 200 year ARI events.
- Details of the hydraulic model schematisation and input data.
- Discussion of the overall modelling results.

Due to the large and complex nature of the study extent, the ROG modelling was delineated in to 28 sub-catchments including 21 urban and 8 semi-urban areas. The sub-catchment delineation was calculated using a number of topographical water sheds and computer computational limits. The model extent for each sub-catchment was enlarged beyond the delineated sub-catchment boundary to ensure all flows into a catchment were captured. This and the rectangular model requirements resulted in significant overlap between models. This technique also ensured a smooth and continuous transition of modelling results between sub-catchments. The sub-catchment delineation is shown in Figure 5-2.

ROG modelling combines hydrological and hydraulic computation in one model by directly applying rainfall onto study areas. In a ROG model a specified rainfall depth is applied to each cell, such that the model performs the function of both a hydrologic and hydraulic model.

Key advantages of ROG modelling compared to the traditional approach include:

- Ability to provide flood extents for the whole catchment whereas a traditional approach only shows flood extents starting at a point where a flow hydrograph can be generated.
- All routing is completed in a hydraulic model in which flows arriving at a location is based on the true topography at the time, minimizing hydrological and hydraulic assumptions.
- The 1d links (pipe network, culverts, and channels) are incorporated and dynamically linked to the 2D domain.

Major disadvantages of ROG method include:

- The modelling requires excessive simulation time. Simulation time for each of the urban Bendigo sub-catchments varies from 3 to 5 times real time. For instance, running a single 6-hour storm event can take up to 2 days. This is largely due to the high resolution grid size modelled.

- The modelling can become unstable for a large and complex model which has multiple pipe networks and structures such as bridges, retarding basins. Fixing the instability is often not straight forward and is a time consuming process.

A generic ROG modelling process is illustrated in Figure 5-1.

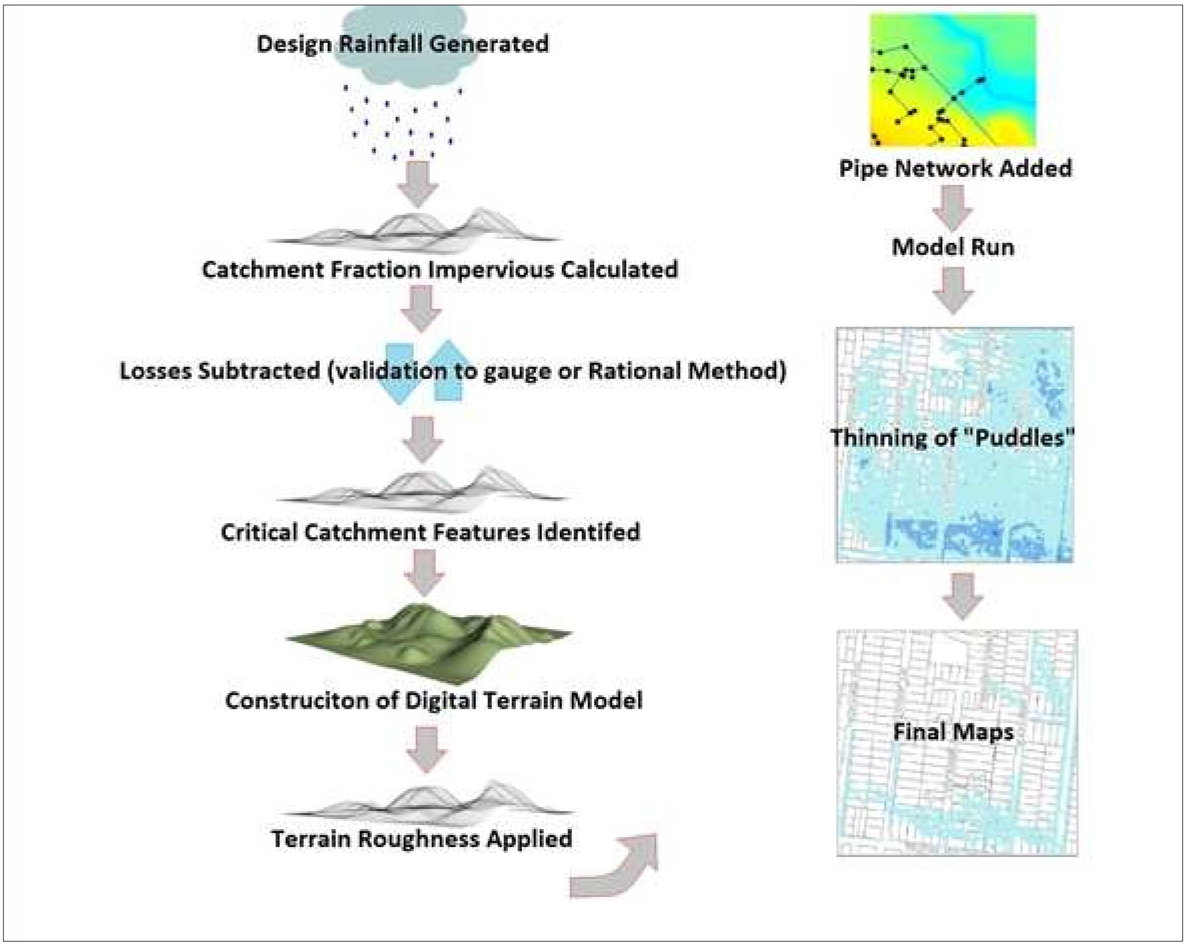


Figure 5-1 ROG modelling process

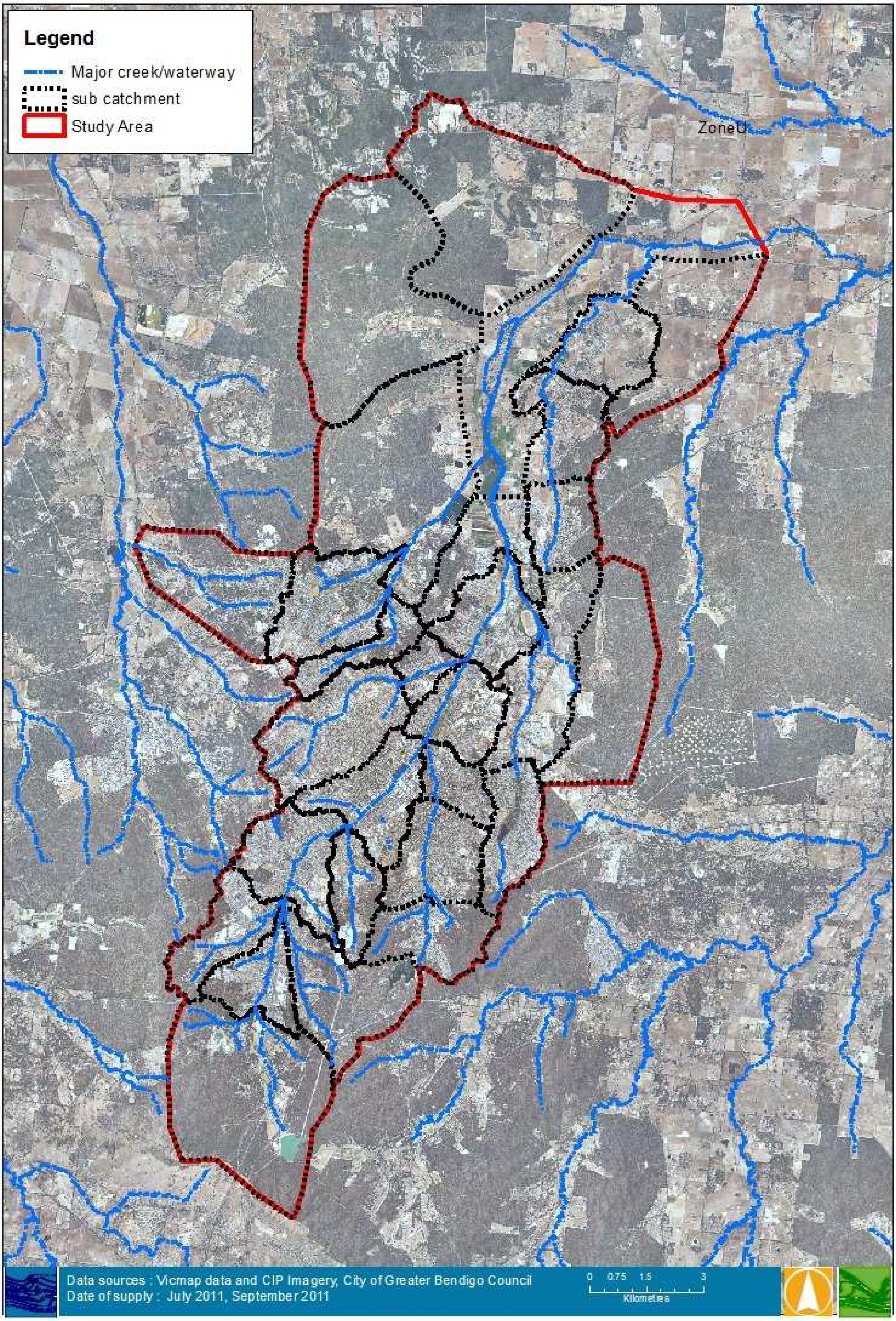


Figure 5-2 Catchment delineation

5.2 Hydrological modelling

The basis of the hydrologic model is the rainfall hyetographs that are used for the TUFLOW model input. The hyetographs for TUFLOW were built using the following procedures:

5.2.1 Intensity Frequency Duration (IFD) data

IFD data for the catchment was generated from the Bureau of Meteorology IFD Program. Due to the extensive study area, the IFD parameters were checked at extremities of the study area and found to have insignificant differences. The basic IFD parameters for North, South, East, and West areas of Bendigo are shown in Table 5-1.

Table 5-1 IFD parameters at North, South, East, and West Bendigo

Location	Log Normal Intensities (mm/hr)						Geographical Factors		
	2 year ARI			50 year ARI					
	1hr	12hr	72h	1hr	12hr	72h	Skewness (G)	F2	F50
North Bendigo (Epsom)	19.42	3.51	0.91	39.69	6.98	1.79	46.30	28.90	0.16
South Bendigo (Kangaroo flat)	19.81	3.90	0.99	39.85	7.01	1.97	46.70	29.00	0.18
West Bendigo (Maiden gully)	19.59	3.63	0.94	39.78	6.98	1.86	46.50	29.00	0.17
East Bendigo (Strathdale)	19.82	3.86	0.97	39.84	7.00	1.89	46.60	29.00	0.18

Given the minor spatial differences, the average IFD at central Bendigo was selected to represent the whole study area as shown in Table 5-2.

Table 5-2 Adopted IFD parameters

Log Normal Intensities (mm/hr)						Geographical Factors		
2 year ARI			50 year ARI					
1hr	12hr	72h	1hr	12hr	72h	Skewness	F2	F50
19.65	3.72	0.95	39.79	7.00	1.88	0.17	4.34	14.97

5.2.2 Catchment imperviousness

The excess runoff is influenced by Fraction Impervious (FI) which is factored to rainfall depth through the equation adopted from Melbourne Water Guidelines[1].

$$ROC_{final} = (FI \times 0.9) + ((1 - FI) \times ROC_{x\ years\ ARI})$$

Where:

ROC_{final} = Final runoff coefficient for ARI of x years

FI = Fraction Impervious of rainfall polygon

$ROC_{x\ years\ ARI}$ = Runoff Coefficient for ARI of x years

ROCx values were adopted from Melbourne Water Guidelines[1] as presented in Table 5-3 below.

Table 5-3 Runoff coefficient

ARI Event (years)	Runoff Coefficient (ROCx)
5	0.25
10	0.35
20	0.45
50	0.55
100	0.60
200	0.65

The FI values were essentially based on the ultimate landuse zoning and further refined using high-resolution aerial photos. The FI map used in the modelling is presented in Figure 5-3, displaying FI values in accordance with landuse types. The predominant residential developments account for FI values between 0.4 and 0.6. The highest FI values are in reference to commercial or industrial landuses, contrasting to the lowest values for farm lands and public reserves.

5.2.3 Initial Losses

For catchments with large pervious areas, the initial loss plays an important role in determining excess rainfall amount and critical storm durations. Different initial losses were used and calibrated in the preliminary modelling stage, and the values agreed and adopted for design purposes were 20 mm for forest and large open space, and 10 mm for all other land-use types. These losses are in line with the design RORB losses adopted in the Spine modelling.

5.2.4 Inter sub-catchment flows

Although the sub-catchments were split using the topographical water sheds there were areas with either relatively flat terrain where the sub-catchment boundary was not easily identifiable or very large sub-catchments that do not fit the computational limits. In such cases inter sub-catchment flows are expected to occur. To account for this condition, the upstream model discharge hydrographs were recorded and input into the downstream model as an external inflow hydrograph.

5.2.5 Model Reconciliation

Two methods of model reconciliation were undertaken during the study. Method one was to trial a number of catchments and refine parameters to meet Rational Method flow reconciliation. The second method was to compare a catchment to an existing flood study to measure flow differences.

Rational Method Reconciliation

Reconciliation of the TUFLOW model flows to Rational Method estimates can show the consistency of TUFLOW results with traditional empirical calculations. However, given that ROG modelling uses advanced computation technology and takes into account many catchment variables that affect hydrological and hydraulic characteristics, it is expected that the modelling results would not be in complete agreement with the Rational Method flow at every location in a catchment. Instead, the Rational Method is used as a means to check that TUFLOW input parameters such as losses; runoff coefficient and roughness values have been reasonably adopted. The reconciliation was performed for 100 year ARI storms only.

Selected Areas

There were 4 areas chosen for the flow reconciliation. The selected areas had well defined catchment boundaries with a distinctive discharge point, which is suitable Rational Method flow estimation. The TUFLOW flows were directly extracted from the models.

The selected areas in Zones F, H, R and U are presented in Figure 5-4 to Figure 5-6 respectively

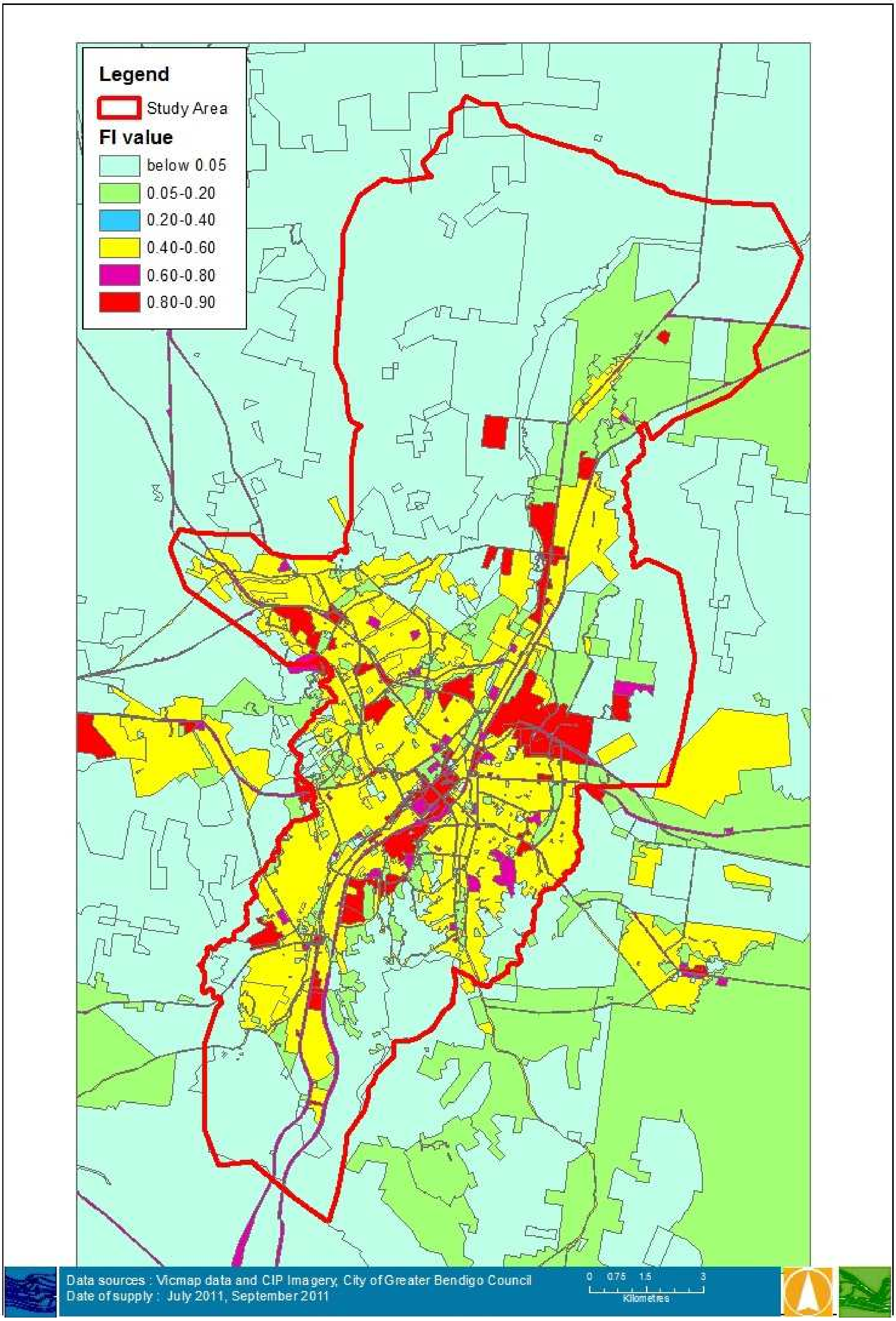


Figure 5-3 Catchment Impervious Fraction

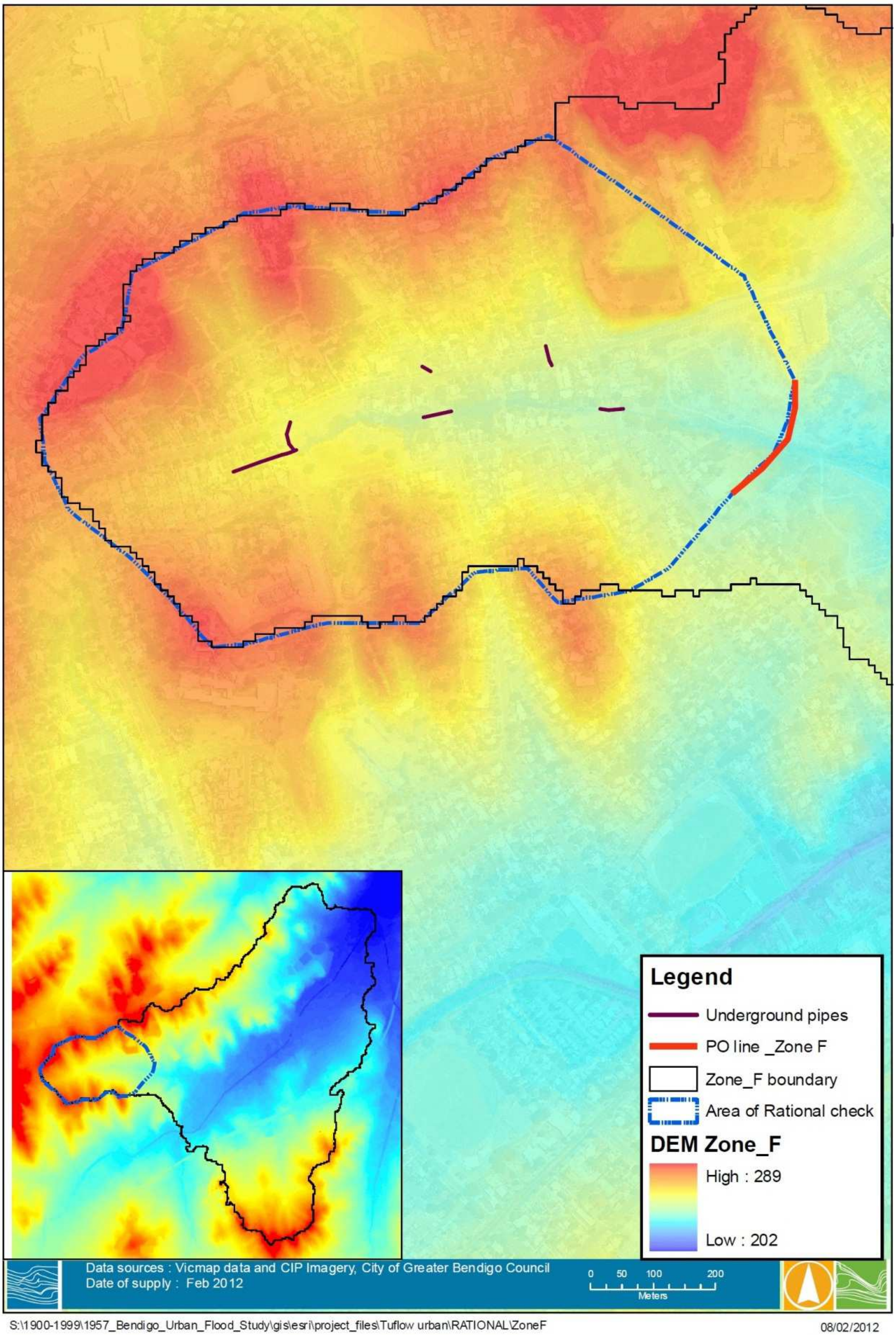


Figure 5-4 Zone F Reconciliation Location

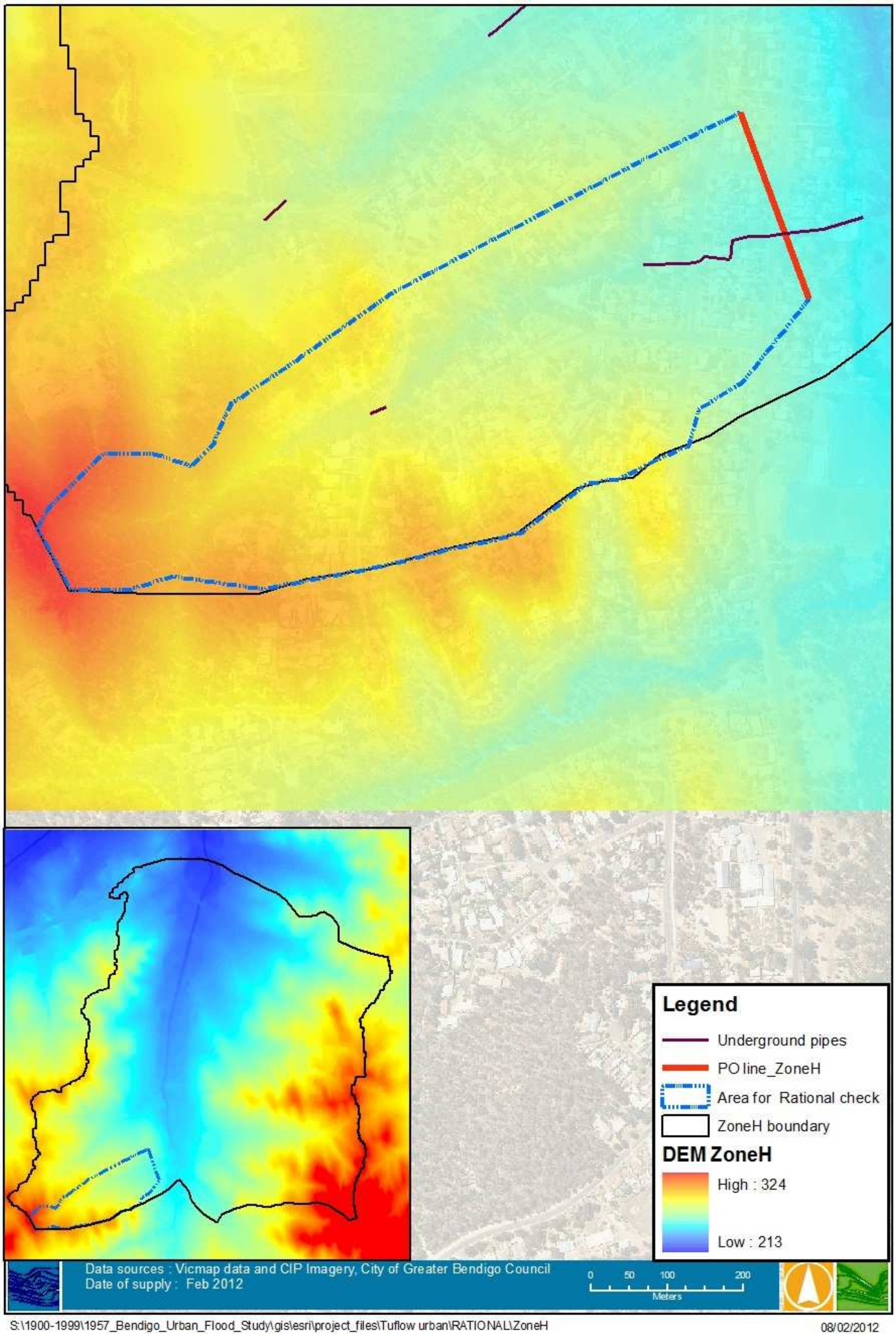


Figure 5-5 Zone H Reconciliation Location

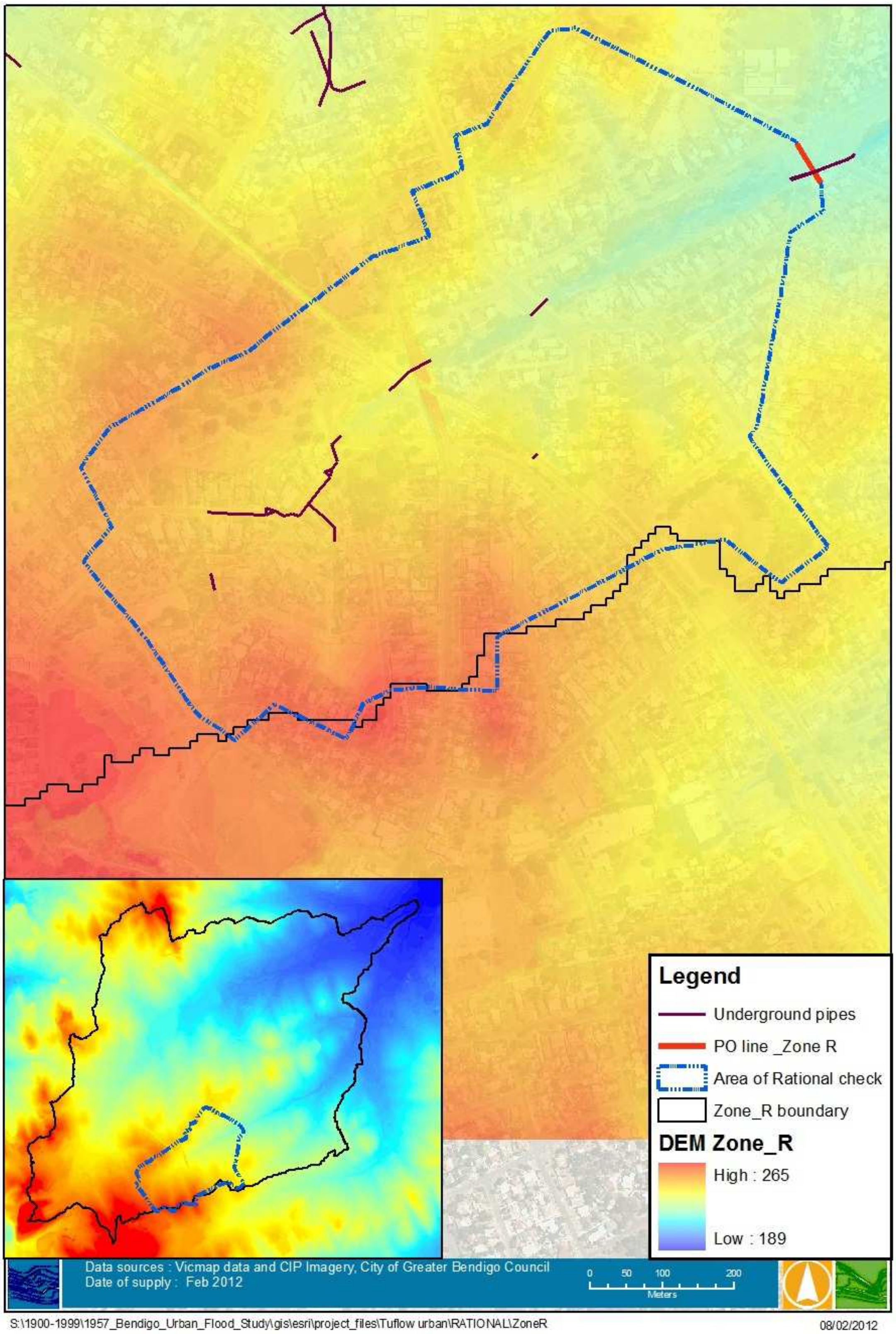


Figure 5-6 Zone R Reconciliation Location

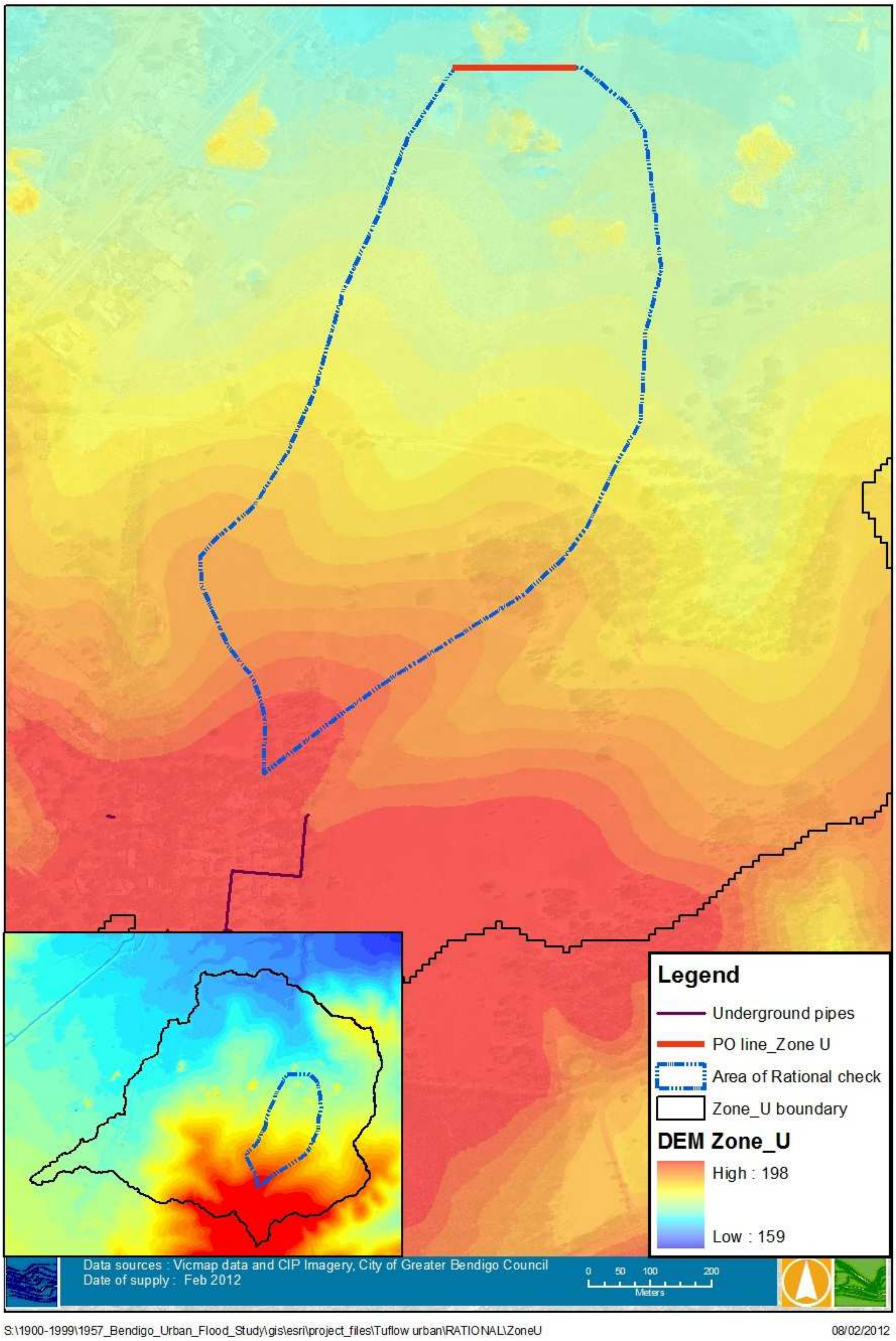


Figure 5-7 Zone U Reconciliation Location

Rational Method Calculation

- The Fraction Impervious (FI) value of the selected area was determined using the same methodology as outlined in the memo *"Proposed Hydrology Approach Urban" (Water Technology,21 October 2011).*
- The Time of Concentration (tc) was calculated using Adams Method, as shown below:

$$tc = t_{ini} + 0.76A^{0.36}$$

Where A = catchment area (km^2)

t_{ini}= initiation time , taken as 7 minutes

- The Rational Method flow rate was calculated at the outlet of each catchment through the use of the Rational Method shown below:

$$Q = \frac{C.I.A}{360}$$

Where Q = 100 year ARI peak flow rate (m^3/s)

C= Runoff coefficient, based on FI values and ARI storm events.

A=Catchment area (ha)

I =Rainfall intensity of the storm with duration of tc

Rational Method estimated flows are shown in Table 5-5.

TUFLOW Flows

The Runoff Coefficient and Initial Loss values used in the TUFLOW models are shown in Table 5-4.

Table 5-4 Initial Loss and Runoff Coefficients

Catchment	Initial Loss* (mm)	Runoff Coefficient 100 Year ARI
Catchment F	20 and 10	0.60
Catchment H	20 and 10	0.60
Catchment R	20 and 10	0.60
Catchment U	20 and 10	0.60

* as discussed in Section 5.2

TUFLOW results are presented in Table 5-6.

Reconciliation Results

The Rational Method flows were compared to the TUFLOW outputs for 100 year ARI storms. Successful reconciliation was judged to be no more than ±10% difference between the TUFLOW and Rational Method peak flows.

The flow calculations and comparison are shown in Table 5-5 and Table 5-6 below.

Table 5-5 Rational Method 100 Year ARI Flow Estimates

Zone	Selected Area (ha)	% Impervious	tc (minutes)	C_{100yr}	I (mm/hr)	Rational Method $Q^R(m^3/s)$
F	66.3	53.0	46.3	0.66	54.9	6.7
H	30.0	44.0	36.6	0.58	72.3	3.5
R	59.0	53.0	45.0	0.66	55.9	6.0
U	42.5	23.0	40.5	0.38	58.3	3.0

Table 5-6 Comparison of TUFLOW flows and Rational Flows

Zone	Critical Storm	Overland Flow (m^3/s)	Underground pipe flow(m^3/s)	Total (m^3/s)	Rational Method $Q^R(m^3/s)$	Difference (%)
F	1hr	6.8	-	6.8	6.7	**1.3**
H	1hr	1.9	1.3	3.2	3.5	**-9.4**
R	1hr	2.4	3.1	5.5	6.0	**-9.9**
U	1hr	3.0	-	3.3	3.0	**9.1**

The results shown in Table 5-6 indicate that the results extracted from the TUFLOW models have been reconciled to the Rational Method flows to within an acceptable 10% difference.

Mapped Reconciliation

The results were further verified through the modelling of the February 2011 event. The results of these models were thoroughly investigated by Council resulting in over 100 changes in roughness, pipe sizes and flow paths within the model. An example of the modelled results, and review process comments are shown below. Given this thorough examination of results, and individual analysis of flow paths across the Council, a high level of confidence in the results is expected.

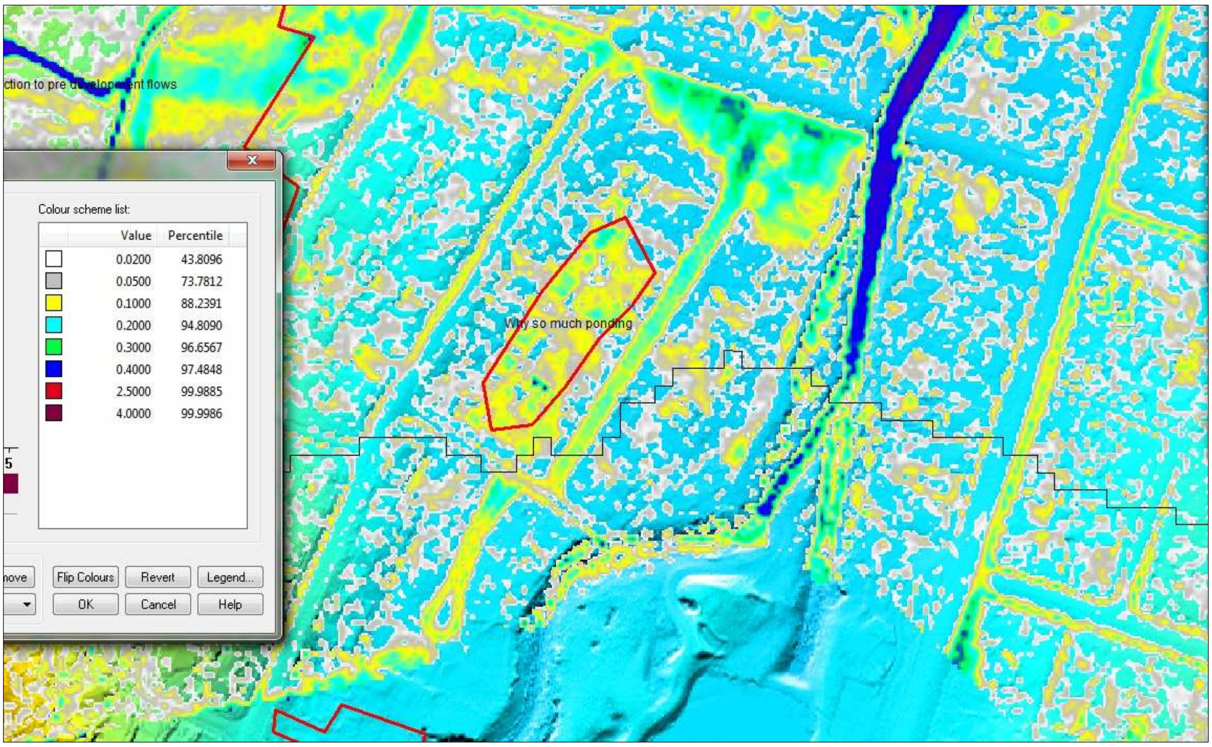


Figure 5-8 Example interrogation of modelling results

Reference	Notes	Response	Response_to_Response
83	Reserve	roughness value updated _n=0.04	
84	100 year pipe ????	downstream pipe system of 450mm was not included in the model. To be include	Will you modell?
85	Reserv e check roughness - spillway concr	currently used pasture roughness,n=0.04	Will the pipeline out of RB be modelled. refer to S1163
86	Reserve check roughness	roughness value updated _n=0.04	
87	100 year pipe but still shows overland flov	pipe was not fully linked to downstream pipes due to minor pipes less than 525	
88	100 year pipe but still shows overland flov	pipe was not connected to downstream pipes due to minor pipes less than 525 c	
89	100 year pipe but still shows overland flov	pipe was not connected to downstream pipes due to minor pipes less than 525 c	Model to Sandstone Rise RB
90	100 year pipe but still shows overland flov	pipe was not connected to downstream pipes due to minor pipes less than 525 c	
91	Reserve check roughness	roughness value updated _n=0.04	
92	100 year pipe + overland flows in laneway	pipe system less than 600dia was not included. To be included	
93	100 year pipeline	pipe was not connected to downstream due to the small pipe 450 downstream b	Model 450mm + pipeline??? Refer GB2163
94	Place easement pits in rear of properties	roughness value updated/ minor pipes less than 600mm were not included in the	
95	100 year pipe + overland flow along road	pipe system less than 600dia was disregarded in the model.To be included.	
96	Solid fence	a raised embankment to be introduced in the model	
97	100 year pipeline	pipe was not connected to downstream due to the small pipe 450 downstream b	Pipeline not modelled is 1200 X 450 BC Refer to GB
98	Crown reserve	a separate layer of Crown lands & reserve to be introduced in the model	
99	Driveway open area check roughness	roughness value updated _n=0.02	
100	Open area check roughess	roughness value updated _n=0.035	
101	100 year retardation basin	Harpin Place Retardation Basin ?_data not yet avaiable to Watech	REfer to Harpin Street RB GB903
102	Council reserve	roughness value updated _n=0.04	
103	Council reserve	roughness value updated _n=0.04	
104	Rec Reserve	roughness value updated _n=0.04	
105	Overland flowpath	currently used roughness of openspace_n=0.035	
106	Overland flow path covered by easement	roughness value updated _n=0.035	
107	Large area crown reserve	a separate layer of Crown lands & reserve to be introduced in the model	
108	Limited to 1500m2 lots check roughness /	roughness & FI=0.45 for rural residential (800 -4000 sq.m) is currently used;	Use FI=0.35 for rural residential
109	Unmaintained open drain / creek check rc	roughness value updated _n=0.04	
110	Rubbish tip check runoff coeff / roughnes	updated roughness value n=0.04	
111	Large areas of crown land	a separate layer of Crown lands & reserve to be introduced in the model	

Figure 5-9 Council's comments, Water Technology's responses, and Council's feedback

Reconciliation to other Flood studies

One study that is relevant to the ROG modelling is the Marnie Road Catchment Report (MCR) prepared by GHD in September 2008. The MCR focused on the estimation of the catchment flow using one-dimensional XP-RAFTS software and calculation of pipe flows for existing and mitigation scenarios. The 100 year ARI flows were extracted from the ROG model and found to be about 30% lower than in the past flood study. Different modelling techniques and input assumptions were mainly accounted for the differences. The TUFLOW ROG model seems to be more advanced and objective by using the true topographical routing in contrast to XP-RAFTS, where the modelling output is much more subjective to the modeller's inputs.

5.3 Hydraulic Modelling

A hydraulic model was constructed for each sub-catchment. The model grid size was 3 m for urban areas and 4-6 m for semi-urban areas. The selected grid sizes were in line with standard practice for TUFLOW ROG modelling. The 2D grid was used to compute overland flow behaviour and 1d links were used to represent bridges, culverts, pipes, and channels. The 1D elements were dynamically linked to the 2D grid at every simulation time step.

Key elements of a ROG hydraulic model include:

- Topography;
- Catchment roughness;
- 1d elements; and
- Boundary conditions.

5.3.1 Topography

Topography was represented in the model by a Digital Elevation Model (DEM) produced from the available LiDAR data.

5.3.2 Catchment Roughness

The catchment roughness values were used to represent overland flow resistance associated with different landuse types. After reviewing the preliminary modelling results, the roughness values were refined in consultation with NCCMA and Council. The roughness values are defined as Manning's n Roughness values and are listed in Table 5-7.

Table 5-7 Manning Roughness values

Model material No	Roughness value	Land use
1	0.04	Pasture & some tall trees
2	0.2	Residential
3	0.3	Industrial
4	0.025	Carpark
5	0.15	Cemetery
6	0.035	Grass
7	0.02	Paved road
8	0.03	Unpaved road, tennis court
9	0.03	Ponds and other water bodies
10	0.04	Railway
11	0.1	Rural residential
12	0.1	Dense bushed
13	0.08	Creeks with heavy vegetation

5.3.3 Boundary Conditions

For the 2DI domain, all the models had free flow discharge boundary conditions assigned at the downstream outfall locations. Inflow hydrographs were introduced in models with inter sub-catchment inflows. For pipe lines discharging to the Bendigo Creek, the peak creek flood level generated by the same storm event in the Spine modelling was applied as a tailwater condition. This is a conservative assumption and is expected to influence the water levels generated near the creek interfaces. It is thus assumed that a 45 minute 100 year ARI peak flow on a small catchment will be coincident with a 3 hour (the general maximum) peak water level in the creek.

5.3.4 Grid Extent and Resolution

The modelling extent covers catchments that drain to Bendigo Creek. The catchment delineation includes 21 Urban TUFLOW Catchments labelled from “Zone A” to “Zone U”, using a 3 m grid size, and 8 Rural TUFLOW catchments labelled from “Area1” to “Area8”, using 4-6 m grid sizes.

5.3.5 Topography Data

Topography is input to TUFLOW in the form of a Digital Elevation Model (DEM). The DEM was generated by LiDAR sourced from the DEPI dataset made available to Water Technology. In most cases, the original DEM as illustrated in Figure 5-10 does not contain newly built, ongoing or approved subdivision sites, or new Retardation Basins (RB). These changes to the topography are often important and need to be reflected in the modelling. Figure 5-10 shows a site in the study area in Thistle Street, Bendigo before and after an approved RB construction. Several hundred of these modifications were made to the model in line with discussions with CoGB.

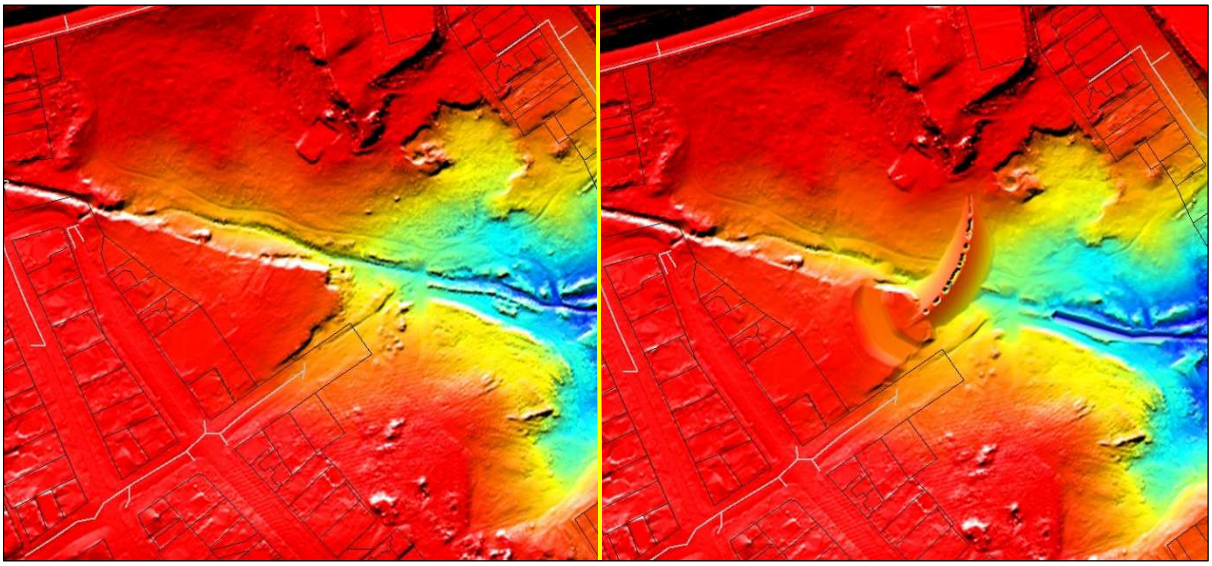


Figure 5-10 DEM before and after a Retardation Basin

5.3.6 Roughness

Manning’s Roughness values were assigned based on planning zones with refinement by aerial images and site inspections. The values were generally consistent with the standard practice in flood modelling. Further refinement was completed through a reconciliation process involving Council review of the preliminary modelling results of a 2 hour 100 year event.

Given that majority of the 2D domains would have shallow overland flow depths and that the main creek was modelled separately, variable Manning’s roughness values by depth were not applied on the 2D domains. The model roughness map is presented in Figure 5-11.

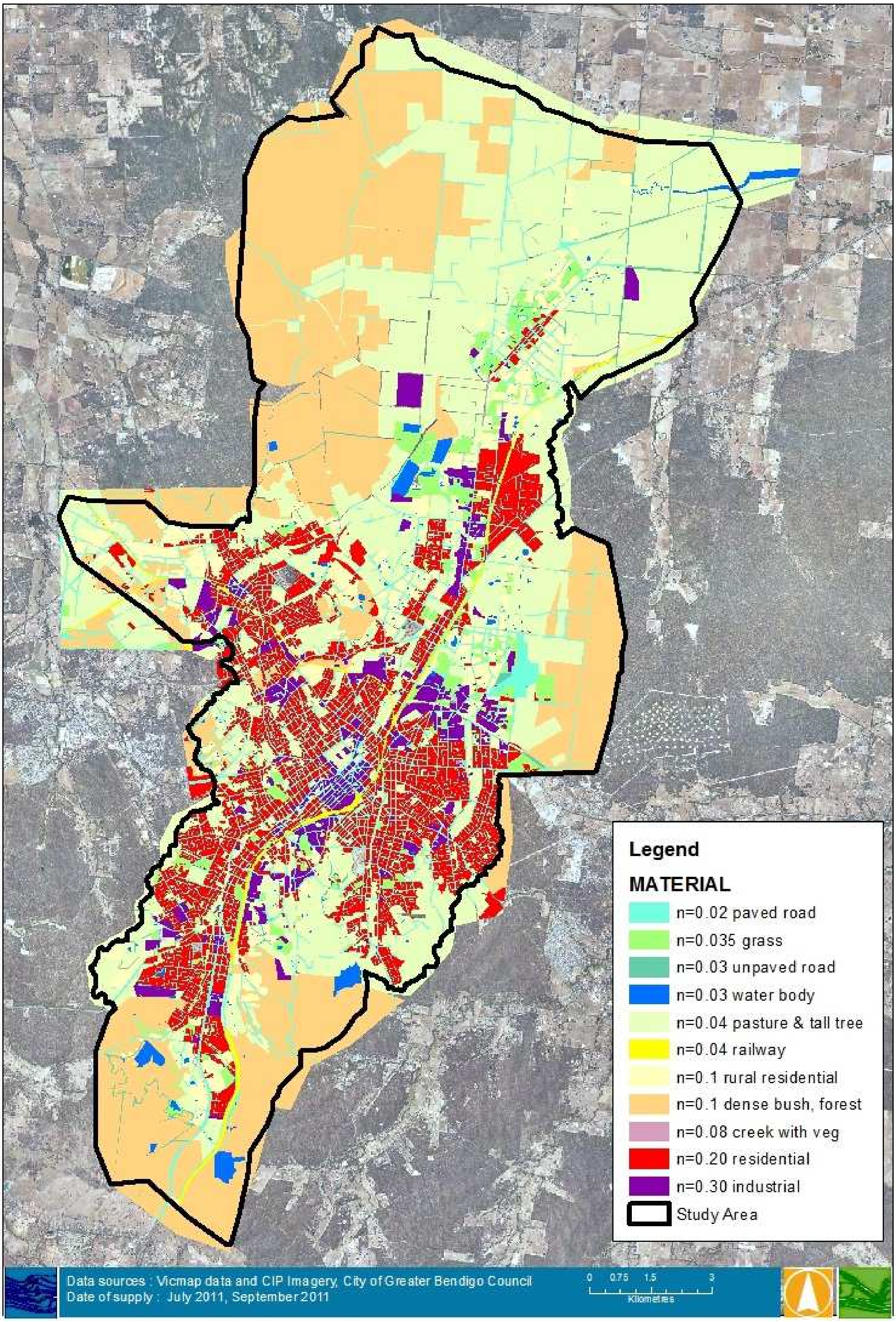


Figure 5-11 Model roughness map

5.3.7 1D Schematisation

Bendigo City Council has an extensive pipe and culvert network concentrated in the urbanised areas. All pipes, culverts, spillways and other structures were modelled in a 1D network using the plans and drawings provided by City of Greater Bendigo. These plans were converted to electronic MapInfo tables for use in the hydraulic modelling.

Originally, it had been proposed that only the major pipes of 600 mm diameter or above would be modelled assuming the smaller pipe sizes would have insignificant impacts to overland flows. However, the preliminary 100 year ARI results indicated unexpected and considerable pondage at some depressions with minor outlet pipes. The pondage was concluded to be due to accumulated inflow and absence of outlet pipe structures. As a result, the modelled 1d pipe network was revised to include more than 3,000 major pipes of 600 mm diameter or greater, and over 18,000 minor pipes of 300 mm to 525 mm diameter.

Pipe and pit specifications were obtained from the council MapInfo dataset. Where the pipe/pit inverts were not available, they were calculated as follows:

- The difference between DEM and pit depth provided in Council's MapInfo tables.
- Where pit depth was unavailable, it was computed using standard pipe cover (~600 mm).
- Refinement of pipe inverts to achieve continuous downhill gradient to downstream.

Each pipe end was connected to a pit or a discharge point, which was modelled in TUFLOW as a node. The node transfers water to and receives water from the 2D surface flow. The pits were configured as weir node types which facilitate the surface flow intake. In all cases it was assumed that the pipe capacity is the controlling element, not the pit inlet capacity. This may in some locations overestimate the flow in pipes, but does allow Council to easily identify capacity constraints. The 1d pipe network is presented in Figure 5-12.

5.3.8 Dams and Retardation Basins

There are numerous farm dams and reservoirs scattered throughout the study area. As a conservative approach all dams were assumed full by setting an initial water level at the spillway crest. The Retardation Basins, which were not assumed full, are distributed across the study area as shown in Figure 5-13 . The Retardation Basin outlet structures were extracted from the Council's design data.

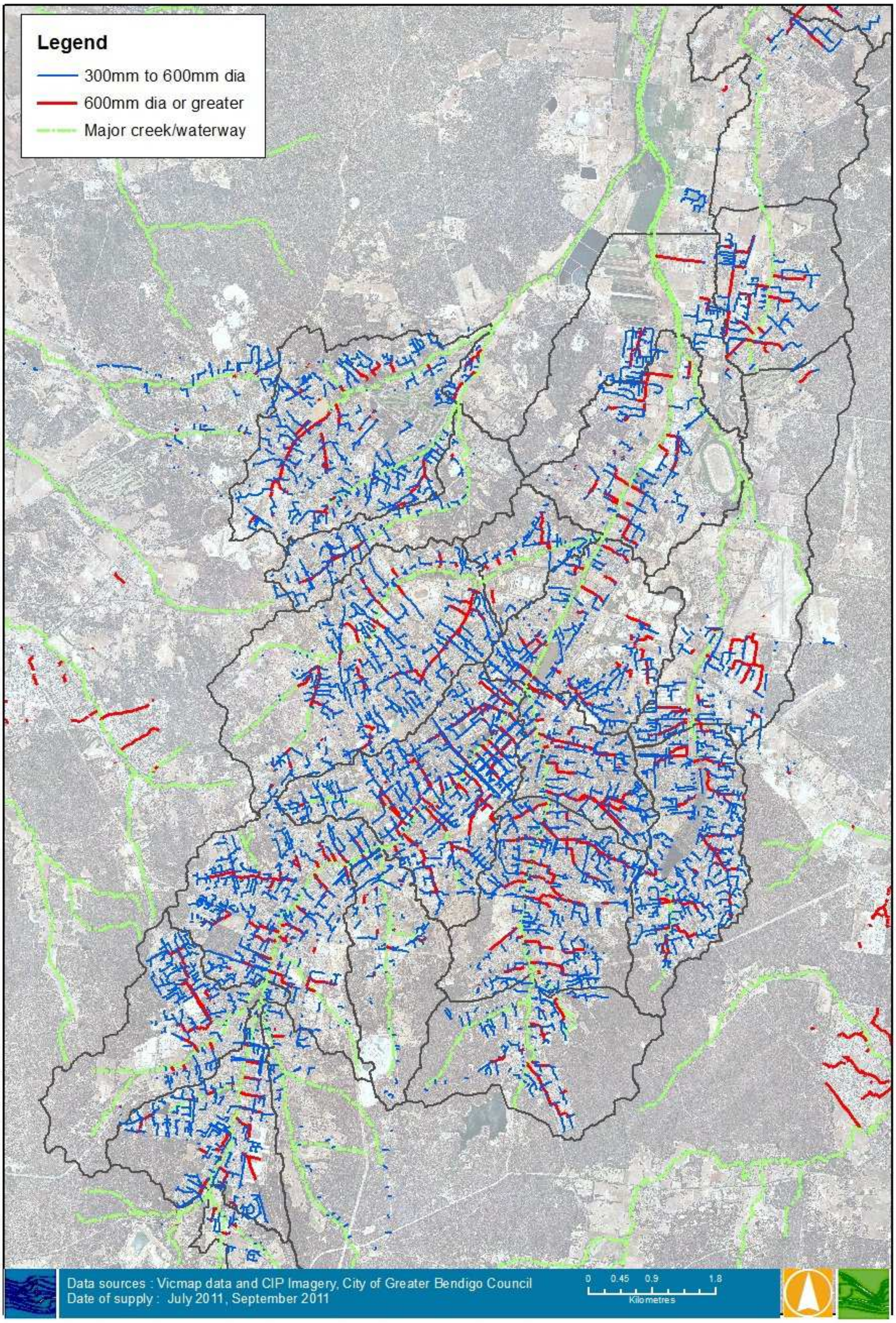


Figure 5-12 1d Pipe network

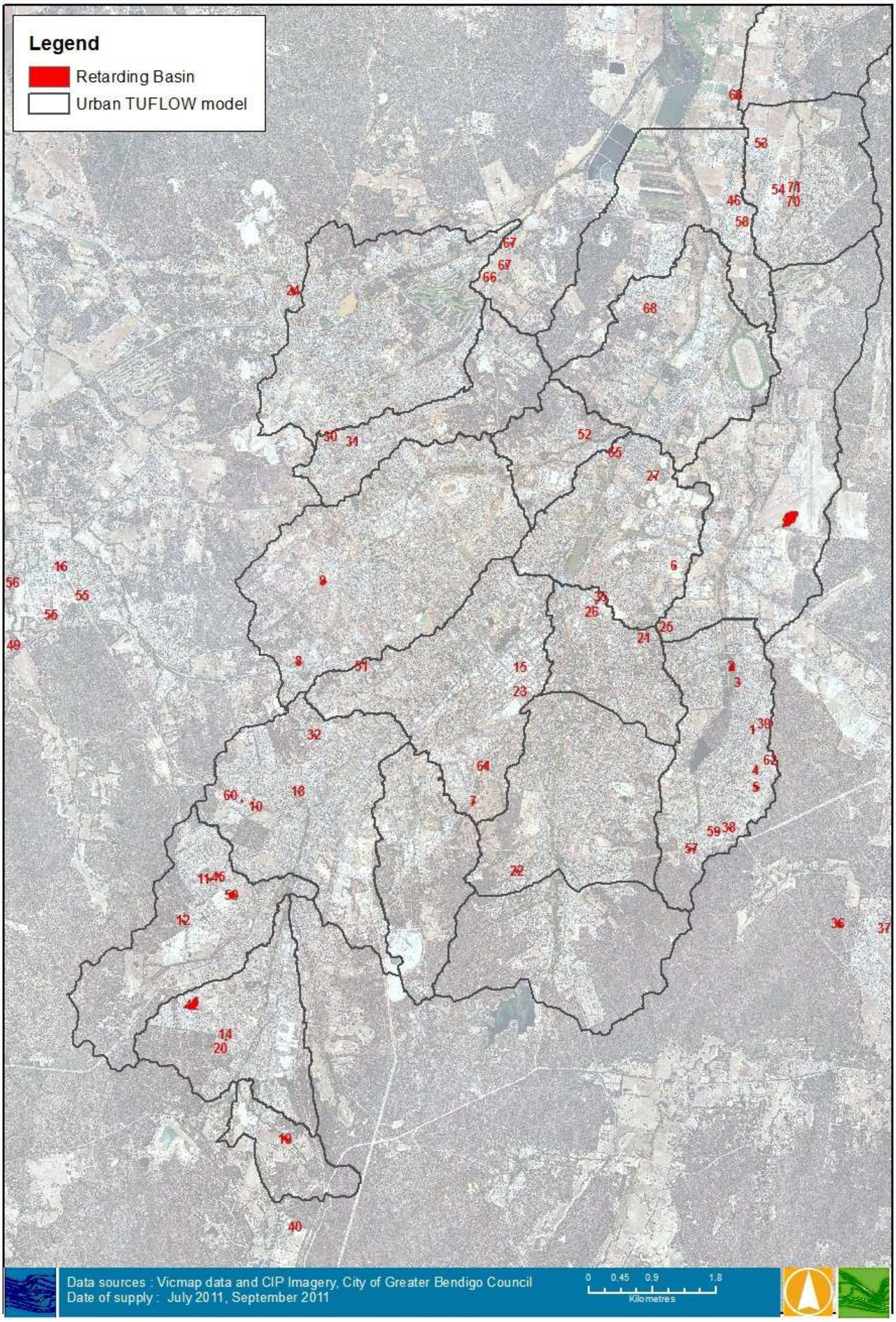


Figure 5-13 Retardation Basin (RB) locations

5.3.9 Simulation durations and events

The modelling was performed for 6 design storm events 5, 10, 20, 50, 100, and 200 year ARI. Each event comprised of 12 durations from 15 minutes to 9 hours, with the durations enveloped for each ARI event.

5.3.10 Model checks

The following checks were undertaken on TUFLOW model parameters and outputs and are based on Melbourne Water Guidelines[1] and the TUFLOW Manual.

- 2D grid size: Urban catchments had a 2D grid size of 3 meters, within the recommended range of 2-3 meters for urban catchments. The rural catchments and semi urban catchments had a 2D grid size of 4-6 meters, which is within the recommended range for rural land.
- 2D timestep: The 2D timestep for each model was between 0.5 and 1 second, and always no less than ¼ of the grid size and is hence within the recommended range.
- 1D timestep: The 1D timestep was set to equal the 2D timestep and is hence within the recommended range.
- Model mass errors: The Mass Errors are generally below 1% for all the models.
- No simulation errors.
- 2D Model extent: All the model extents and boundaries had been selected to avoid backwater influence from the model extremities.

Of the above TUFLOW checks, the controlled mass error and time steps were crucial to ensure that the modelling results were healthy and minimal rainfall excess was lost from the model due to errors. All models have passed the Quality Control points set by Water Technology based on advice from various guidelines and past experience.

5.3.11 Quality control

Given the large and complex nature of the flood study, the North Central CMA, CoGB and Water Technology exchanged, reviewed and updated hundreds of pieces of data throughout the modelling and refinement process. Additional survey works were also carried out to supplement missing or unavailable data. Two rounds of review and refinement were entered into with many modifications to the model during this stage. A number of quality control documents and databases have been included in the data transfer stage of the project.

5.3.12 Mapping outputs

The ROG methodology provides detailed hydrology to all parts of the modelled catchment. This can provide some difficulties with standard mapping and planning processes. Very shallow flood depths and non-connected depressions in particular can distract planners, regulators and home owners from the important flow paths and hazardous areas. As such a filtering process has been undertaken to provide the mapping outputs for the project. Filtering limits can be very subjective with many Council's and regulators around Victoria choosing different parameters. For the Bendigo study the following filtering parameters have been applied:

- All depths less than 0.05 m have been removed from the mapping
- Velocity x Depth areas less than 0.008 m^2/s have been removed from the mapping
- All puddles less than 100 m^2 have been removed from the mapping

These parameters are generally in line with other known studies throughout Victoria. It should be noted that all raw data grids have been provided to North Central CMA and CoGB for further analysis if required.

5.3.13 Flow line locations

To aid in the analysis of the results and future investigations a number of flow locations were input into the model. These flow lines record design flows at the given location for all design runs. A depiction of these flow locations can be found in Figure 5-14

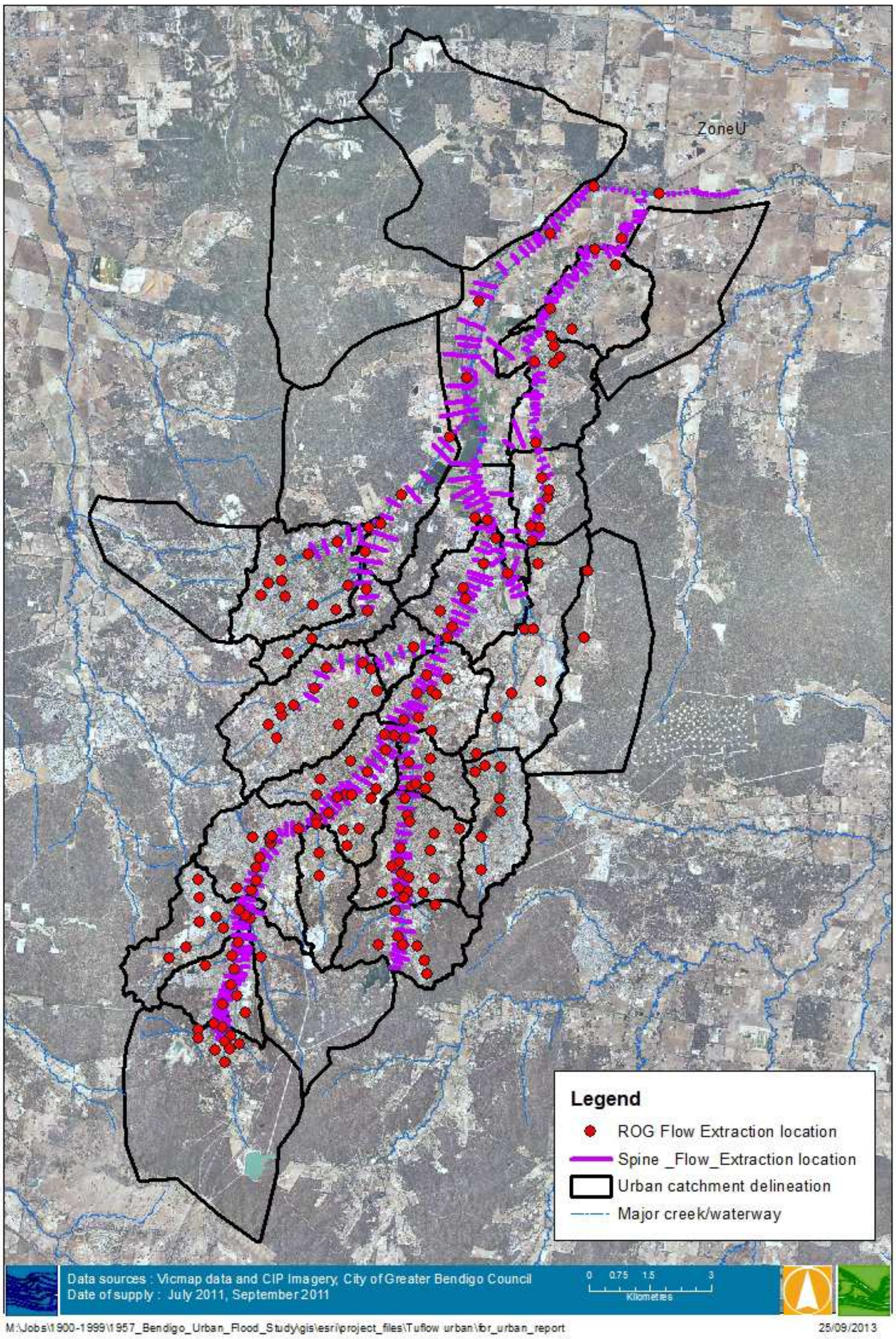


Figure 5-14 Flow output locations

5.4 Discussion

The processed results were converted into a number of mapping outputs. It should be remembered that the mapping depicts the maximum flood depth at any given location. The maximum flood depth is the deepest water recorded throughout any given ARI for all of the different duration events. This will tend to display maximum depths for short duration storms at the top of any given catchment, and maximum depths for the longer duration storms towards the bottom of any catchment.

The flood maps include flood extents, flood depths, overland flow velocities, and flood hazard. The flood hazard was categorised based on the current Melbourne Water Guidelines[1] as shown in Table 5-8 below. For convenience of displaying results, the study area was split into a number of A3 Sheets exhibiting the map in sufficient detail. A typical flood depth map is shown in Figure 5-15.

Table 5-8 Flood Hazard Category

Flood Risk	Depth (m)	Velocity x Depth (m^2/s)
Low	Below 0.4	Below 0.4
Medium	0.4-0.8	0.4-0.8
High	Above 0.8	Above 0.8

A number of results cannot or have not been included in the mapping including:

- 1 Dimensional outputs
  - Pipe flow
  - Pipe velocity
  - Pipe Capacity %
  - Peak Pipe flow
- Flow location outputs
- Bridge and culvert data
- Velocity vectors

These outputs were provided to the North Central CMA and CoGB for use in future investigations. Although remarkable effort has been made throughout the data process and modelling there remained a number of challenges, these included:

- The significant drawback of the methodology was the excessive simulation time required. On average it took 3 weeks to complete 72 simulations of one sub-catchment, not taking into account time for fixing errors and rerunning the model. Despite employing multiple simulations and advanced computer configurations, the overall run time for 29 sub-catchments was well behind the original schedule.
- The change in scope to include sub 600 mm diameter pipes increased the pipe input requirements by 6 times. This also made the 1D system and 1d network far more complicated.
- The 3 m grid size was not ideal for representing some sub 3 m flow paths. Creating 1d linkages to represent all small flow paths was not practical given the tremendous additional work involved. A compromise in resolution is always a challenge with flood modelling.
- The modelling approach using roughness values to holistically represent clusters of residential dwellings or buildings is suitable for large scale project. The actual effects of individual building blockages and open space such as driveways, backyards, gardens were not truly reflected.

Nevertheless the quality of the modelling results is considered excellent for decision making at a strategic level by generating a comprehensive flood map across the Bendigo urban development area. The flood maps are expected to provide Council the overall understanding of existing flood problems as well as potential future flood issues caused by the current planning strategy.

All of these results provide both the CoGB and North Central CMA an unprecedented amount of flood intelligence data. Using the ROG methodology combined with the Spine model provides the best of both worlds with respect to accessible outcomes. It should be noted that at interface areas between the two models it is expected that some minor differences in flows would be expected. This occurs as each methodology routes flows through the catchment differently. The differences in flow are reliant on a number of factors including catchment storage, catchment topography, length of flow path and others. Caution should be used when deriving a flow from the model at any of these interface locations.

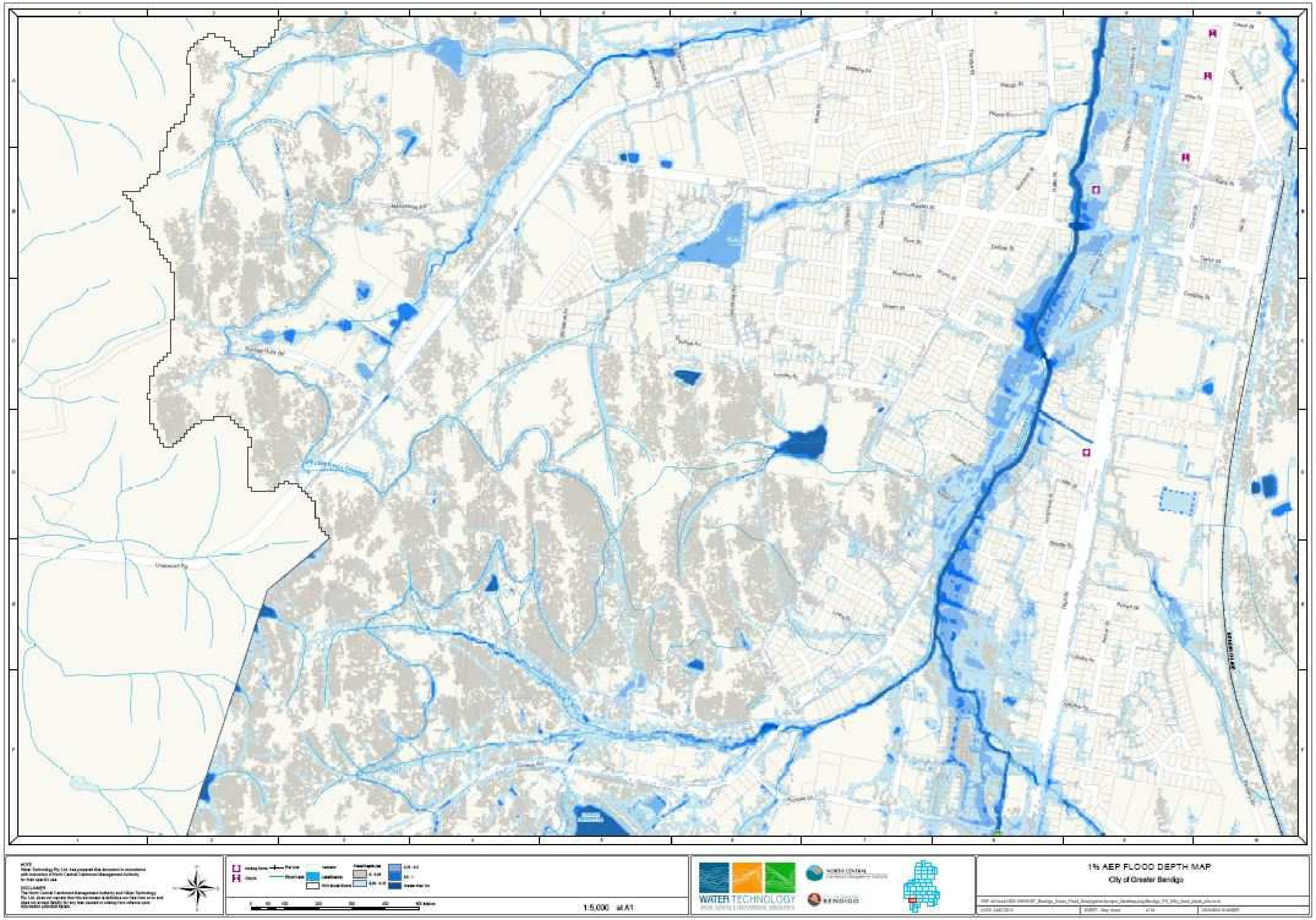


Figure 5-15 Typical depth map

6. MITIGATION

6.1 Overview

Three mitigation scenarios were modelled within this project. Given the nature of the flooding the mitigation modelling focussed on the Spine or major creek models only. It was deemed by the steering committee that the following three scenarios were the most appropriate options to model. In each of the scenarios both the 3 and 6 hour duration 100 year ARI events were run.

- Scenario 1 – Levee Breach
- Scenario 2 – Local structural works
- Scenario 3 – Flow retardation

6.2 Scenario 1 – Levee Breach

The aim of Scenario 1 was to gain a better understanding of the role that levees along Bendigo Creek continue to play in protecting part of Bendigo, particularly areas around Epsom and Huntly.

Currently levees exist on the east bank of Bendigo Creek from Scott Street in White Hills to the Bendigo-Tennyson Rd in Huntly, approximately 15 km downstream. It is believed that the levees play an important role in protecting large areas of Epsom and Huntly from inundation in large rainfall events. Currently there is no formal maintenance of these levees despite the important role they are believed to have.

Levee breaches were trialled along Bendigo Creek at the following three locations:

- Where the Sargeants Road easement intersects Bendigo Creek in Epsom.
- 50 metres south of where the Ironstone Road easement intersects Bendigo Creek in Epsom.
- Immediately north of Howard Street in Epsom.

These locations were chosen following a GIS analysis of the levee to determine low points which could be susceptible to future breaching. Longsections showing the levee are displayed below in Figure 6-1 and Figure 6-2. The locations of the breaches are shown in Figure 6-3.

The breaches were set to occur dynamically during the model run. The breaches commenced when flood levels rose to within 300 mm of the 1% AEP design flood level. The breaches were specified to develop over 30 minutes before reaching their final geometry.

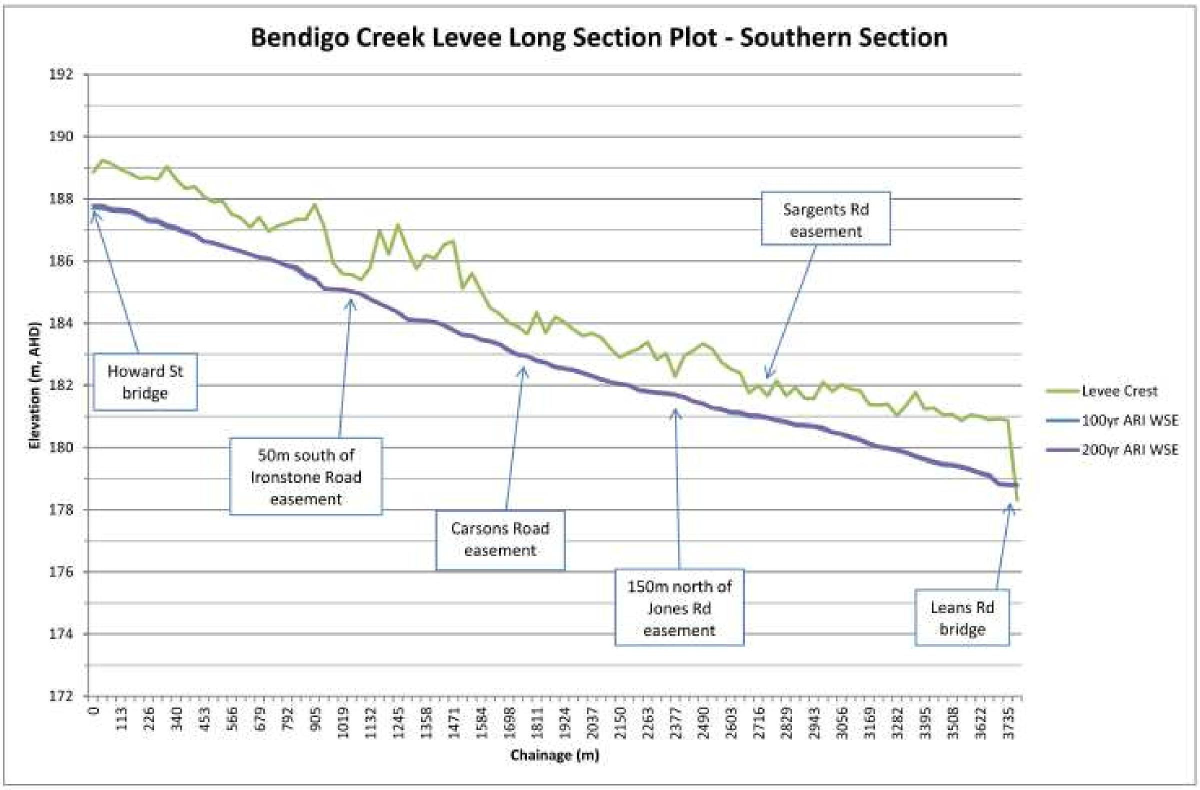


Figure 6-1 **Southern long-section of levee**

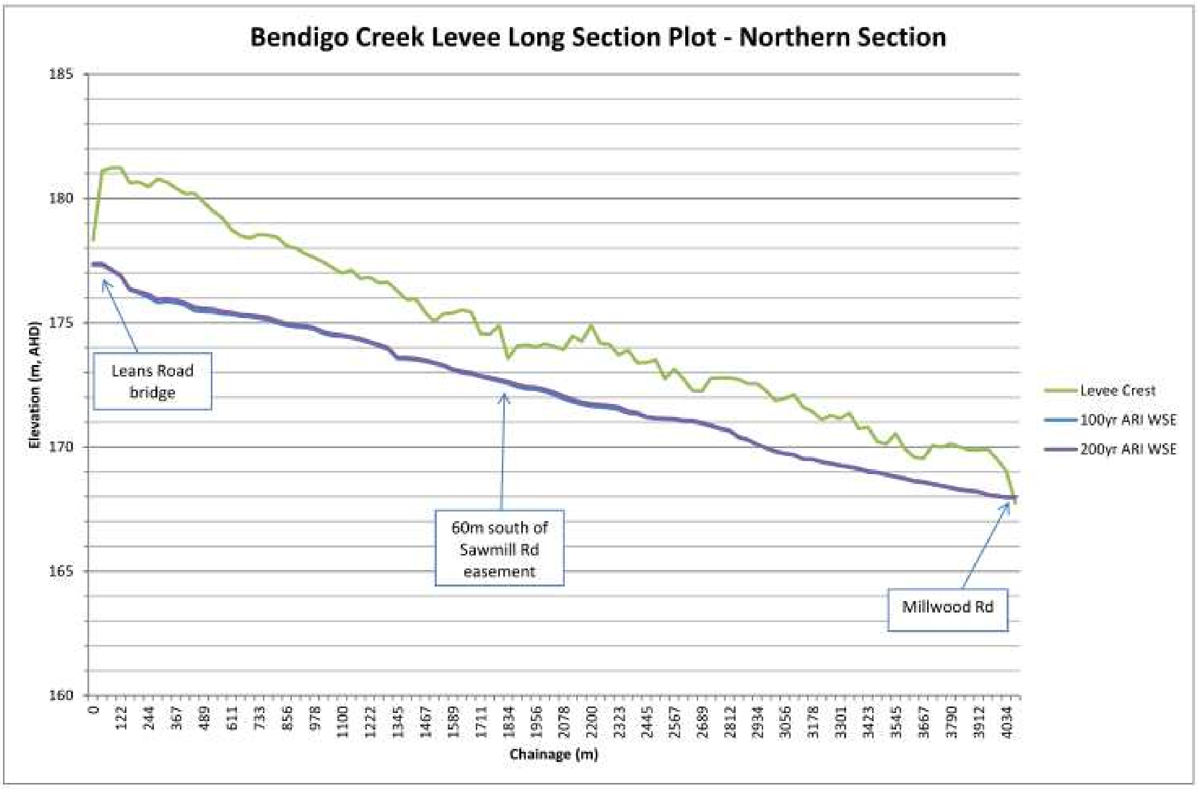


Figure 6-2 **Northern long-section of levee**

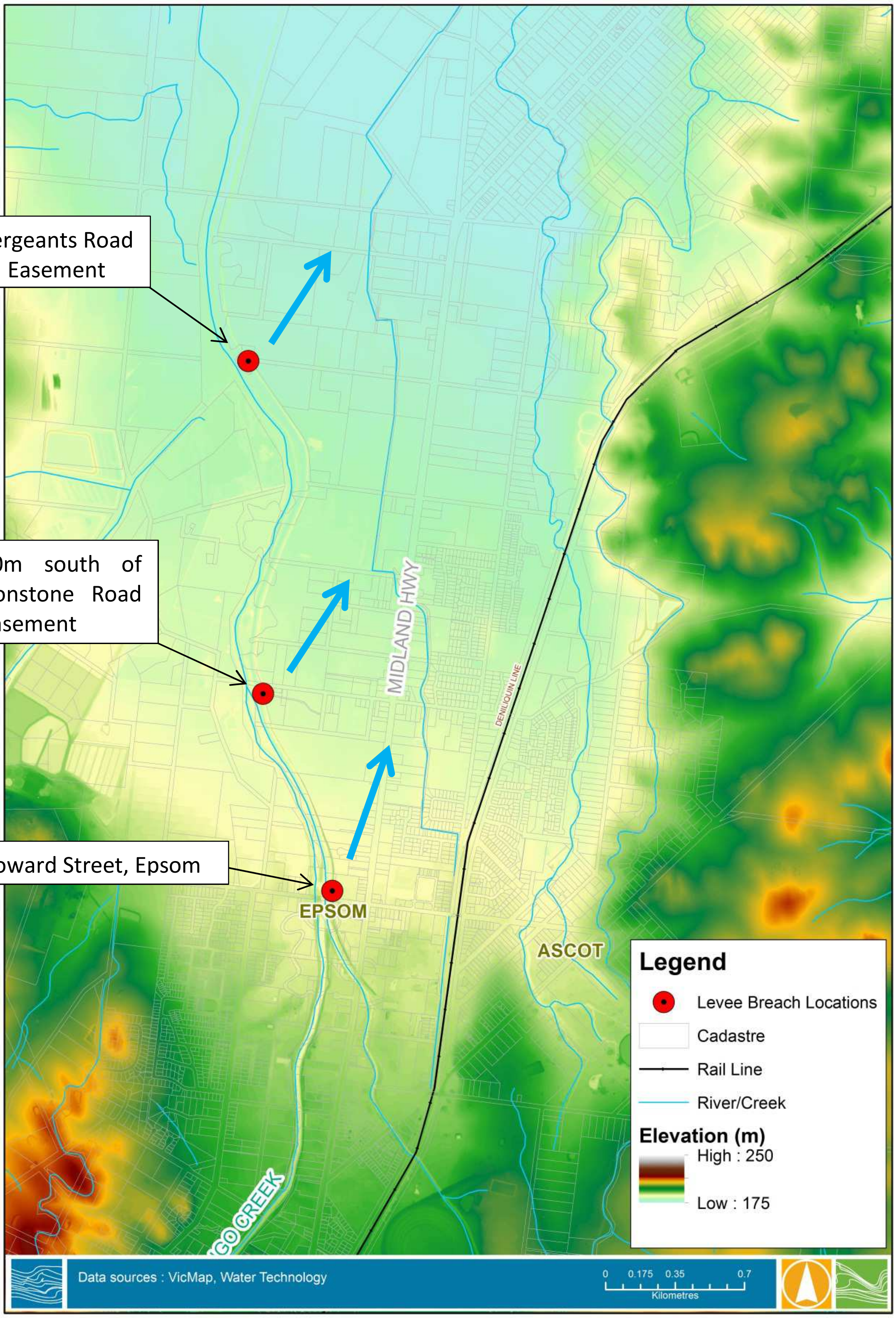


Figure 6-3 Location of modelled levee breaches

6.2.1 Results and Discussion

The scenario 1 modelling demonstrated that the Bendigo Creek levees continue to play an important role in protecting large areas of Epsom and Huntly from inundation in large flood events in Bendigo Creek.

Figure 6-4 provides a comparison of the 100 year ARI flood extents between existing conditions and the levee breach scenario. It can be seen that the levee breaches led to large areas of inundation through Epsom and Huntly that don't occur under existing conditions. Figure 6-5 shows depth results for the same event. It can be seen that much of the inundation through Epsom and Huntly in Scenario 1 is less than 250 mm however there are a couple of obvious flow paths where flows are deeper including adjacent to the Midland Highway and to the south of Leans Road. It can also be seen that much of the flow breaking out from the levee breaches ends up flowing into Back Creek. This is consistent with anecdotal reports from the area.

Scenario 1 has highlighted the importance of resolving the ownership and future maintenance requirements of the levee banks along Bendigo Creek to protect large areas of Epsom and Huntly from flooding in significant rainfall events.

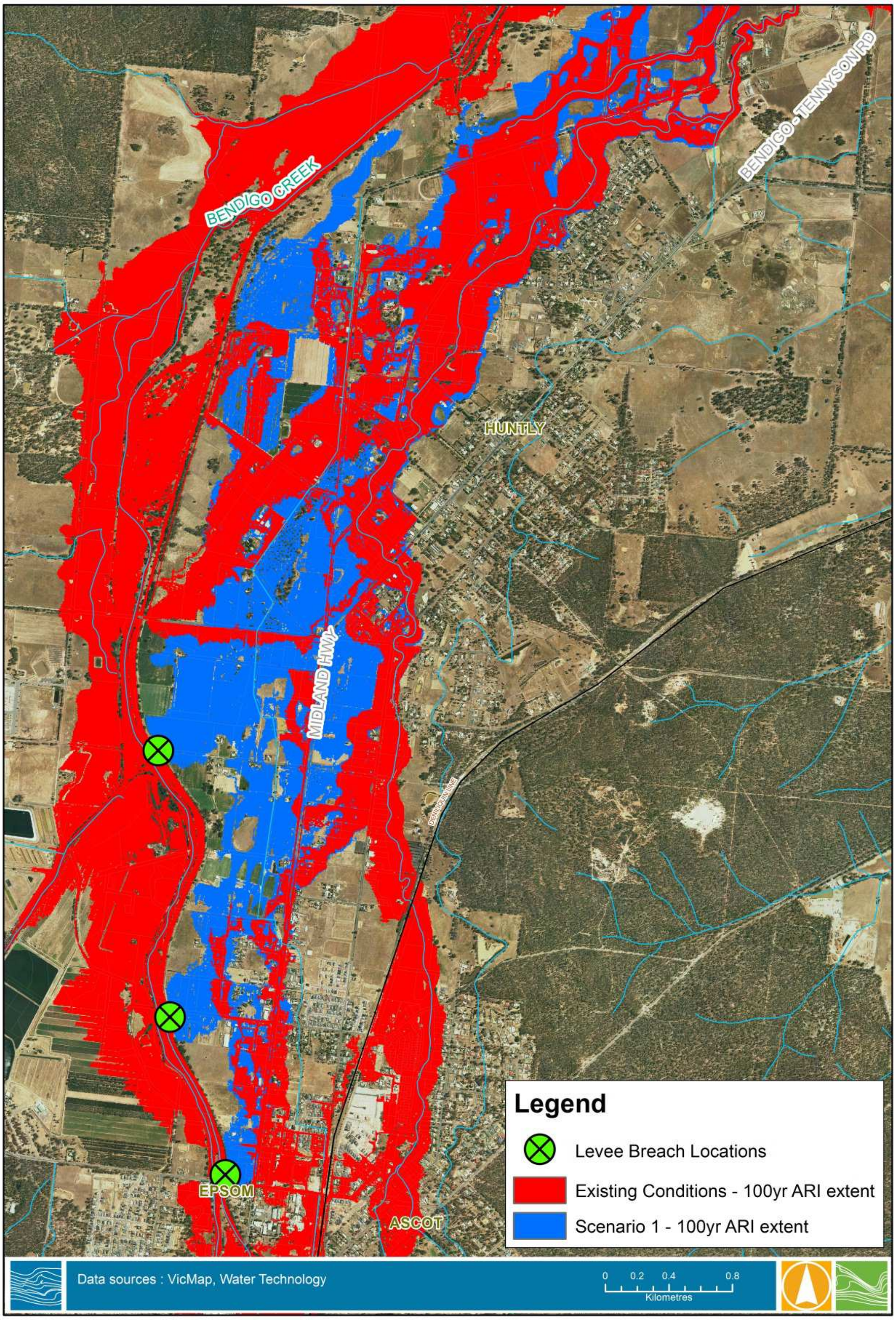


Figure 6-4 Mitigation Scenario 1 vs. Existing Conditions 100 year ARI Flood Extent

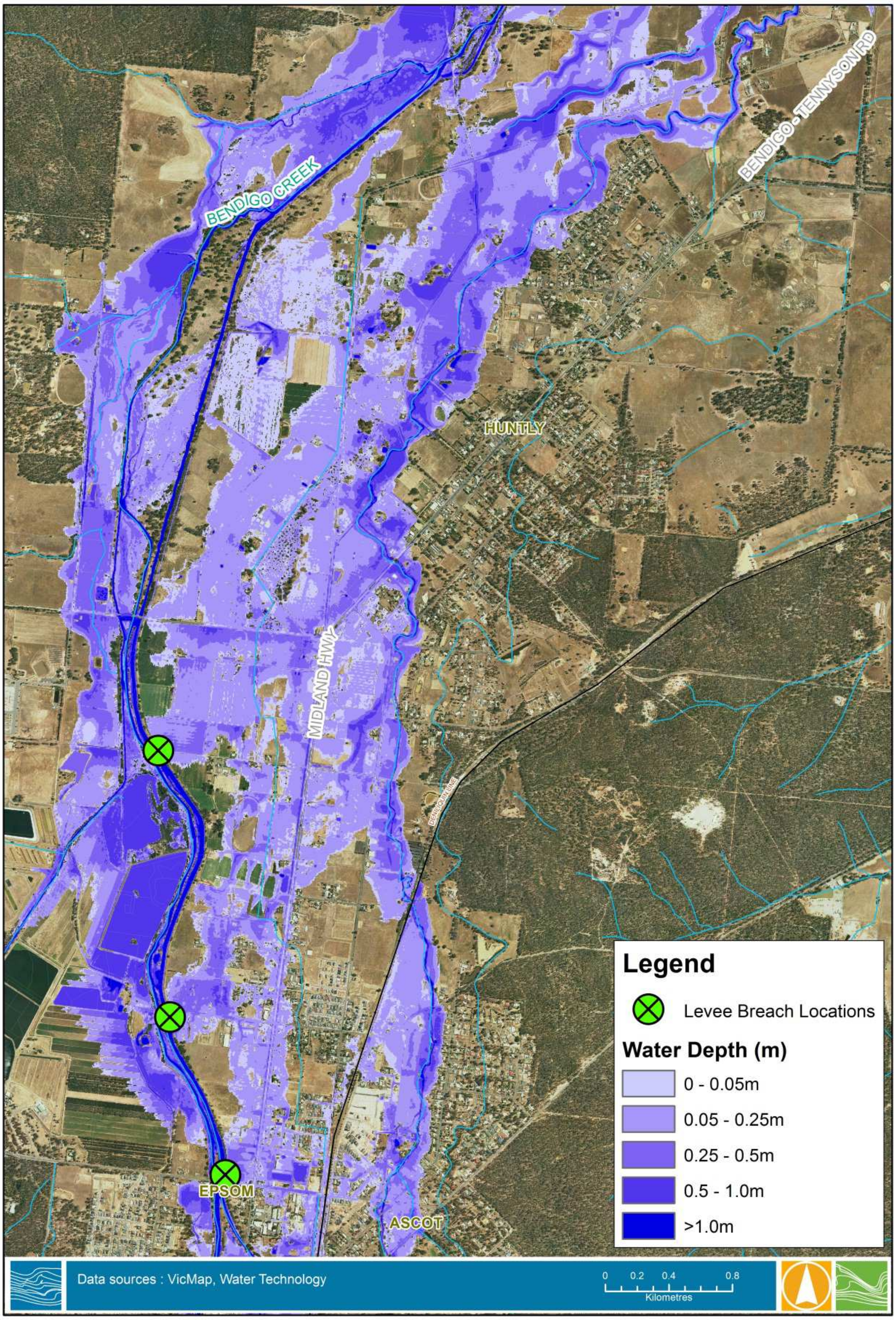


Figure 6-5 Mitigation Scenario 1 – 100 year ARI depth results

6.3 Scenario 2 – Local Structural Works

Scenario 2 involved testing a range of local structural mitigation options to protect areas from inundation. This list of options was developed based on input from a number of stakeholders including Water Technology, City of Greater Bendigo, North Central CMA and community groups. The options are described in Table 6-1.

All of the levees and bunds tested in Scenario 2 were modelled by setting the levee crest elevation several metres higher than the surrounding topography. This ensured the structures could not be overtopped during the modelling. The required design height was then established from the model results by taking the water surface elevation at that location and adding the required freeboard.

Table 6-1 Scenario 2 mitigation options

Waterway	Option Number	Location	Mitigation Details
Bendigo Creek	2a	Development at 15 Wesley Street, Kangaroo Flat	Inclusion of as-constructed survey in topography
	2b	Valley Estate, Kangaroo Flat	Inclusion of as-constructed survey in topography
	2c	Wesley Street bridge Kangaroo Flat	Inclusion of new Wesley Street road bridge in model (not built at commencement of design modelling)
	2d	Between High Street and Thistle Street, Golden Square	Trial of levee along north bank to protect from breakout
	2e	Park Road, Bendigo	Trial of levee (or raised road) to prevent breakout from gardens which flows along Bridge Street.
	2f	Weeroona Avenue, North Bendigo	Trial of levee or bund to protect properties near corner of Weeroona Ave and Caledonia St
	2g	Leans Road, Huntly	Trial of levee across road to prevent breakout through eastern bank levee
	2h	Millwood Road, Huntly	Trial of levee to prevent breakout through southern bank levee
Back Creek (Epsom)	2i	Taylor Street, Epsom	Trial levee parallel to Taylor Street and along eastern channel bank to prevent breakouts
	2j	Ascot Gums Estate, Epsom	Inclusion of as-contracted survey in topography
	2k	Ascot Landing Estate, Epsom	Inclusion of as-constructed survey in topography
	2l	Yellowgum Estate, Epsom	Inclusion of as-constructed survey in topography

Eaglehawk Creek	2m	Edgewater Close, Eaglehawk	Inclusion of as-constructed survey in topography
	2n	Evergreen Waters Estate, Jackass Flat	Inclusion of as-constructed survey in topography
Back Creek (CBD)	2o	Between McIvor Road and Havelock Street	Levees along both banks to prevent breakouts
Racecourse Creek	2p	Between Bendigo Racecourse and Bendigo Creek confluence	"Racecourse Floodway" consisting of levees on both banks to prevent breakouts
Long Gully	2q	Finn St and Holdsworth Road, White Hills	Small bund to protect properties inundated near corner of Finn St and Holdsworth Road, White Hills
	2r	William Street, Long Gully	Small bunds to protect properties on William Street which back onto Long Gully

6.3.1 Results and Discussion

The results of the modelling for each Scenario 2 option are presented in Table 6-2 below. It can be seen that most options have been effective in mitigating from inundation however it is likely that a number of options would not be feasible based on a benefit-cost analysis. Further analysis is required of those options which have been found to be effective and Council and North Central CMA feel are worthy of pursuing on a benefit-cost basis.

Figure 6-6 shows the locations of mitigation works in Racecourse Creek and Back Creek with the resulting 100 year ARI results overlayed. It can be seen that both sets of levees were effective in preventing significant breakouts and containing flow within the waterways.

Figure 6-7 shows the locations of mitigation works in central Bendigo with the resulting 100 year ARI results overlayed.

Figure 6-8 shows the location of the Millwood Road and Leans Road levee works and the impact this had on flood extents compared with existing conditions. It can be seen that the modelled levees have prevented large sections of Huntly from being inundated.

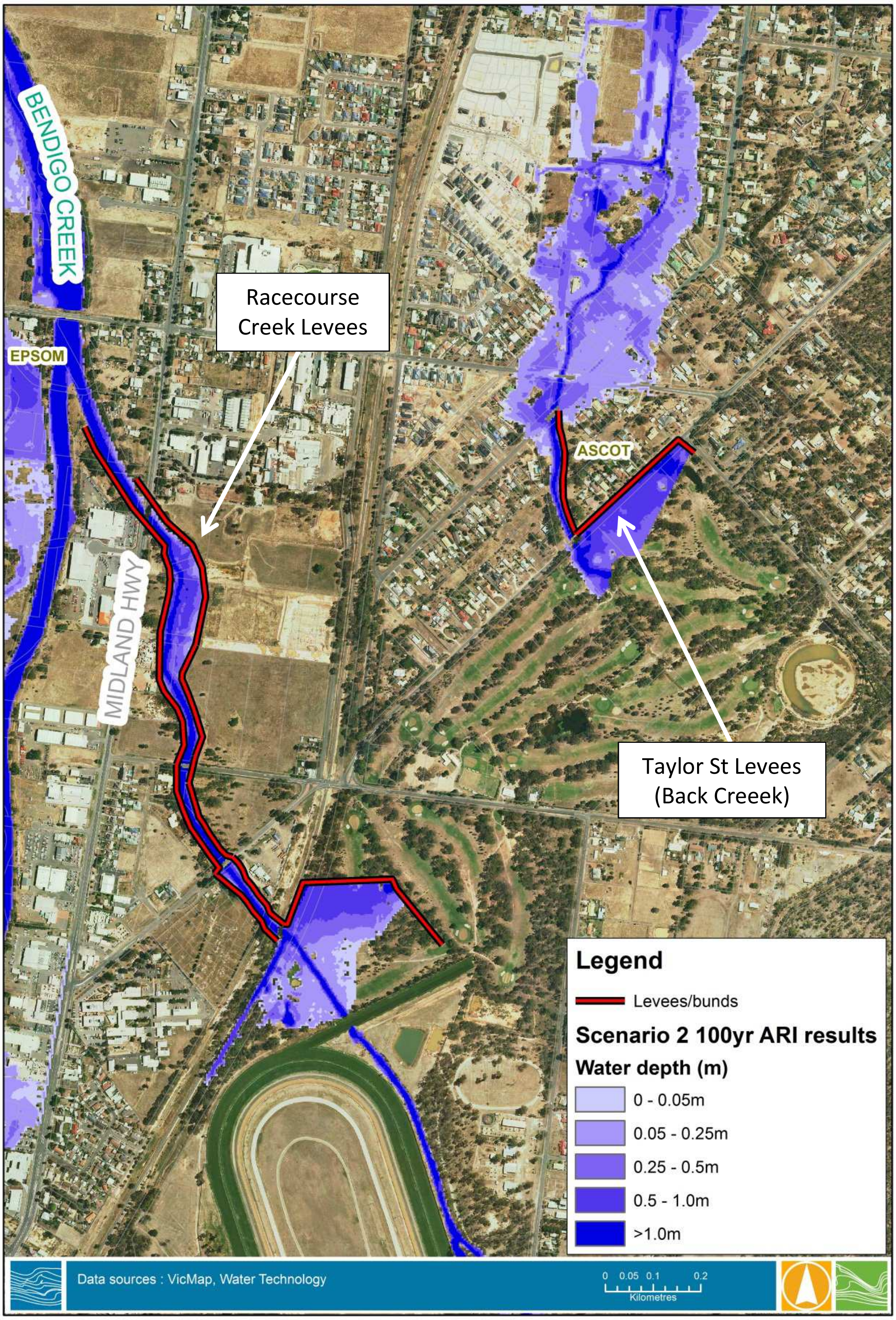


Figure 6-6 **Back Creek and Racecourse Creek Scenario 2 works and Scenario 2 100 year ARI results**

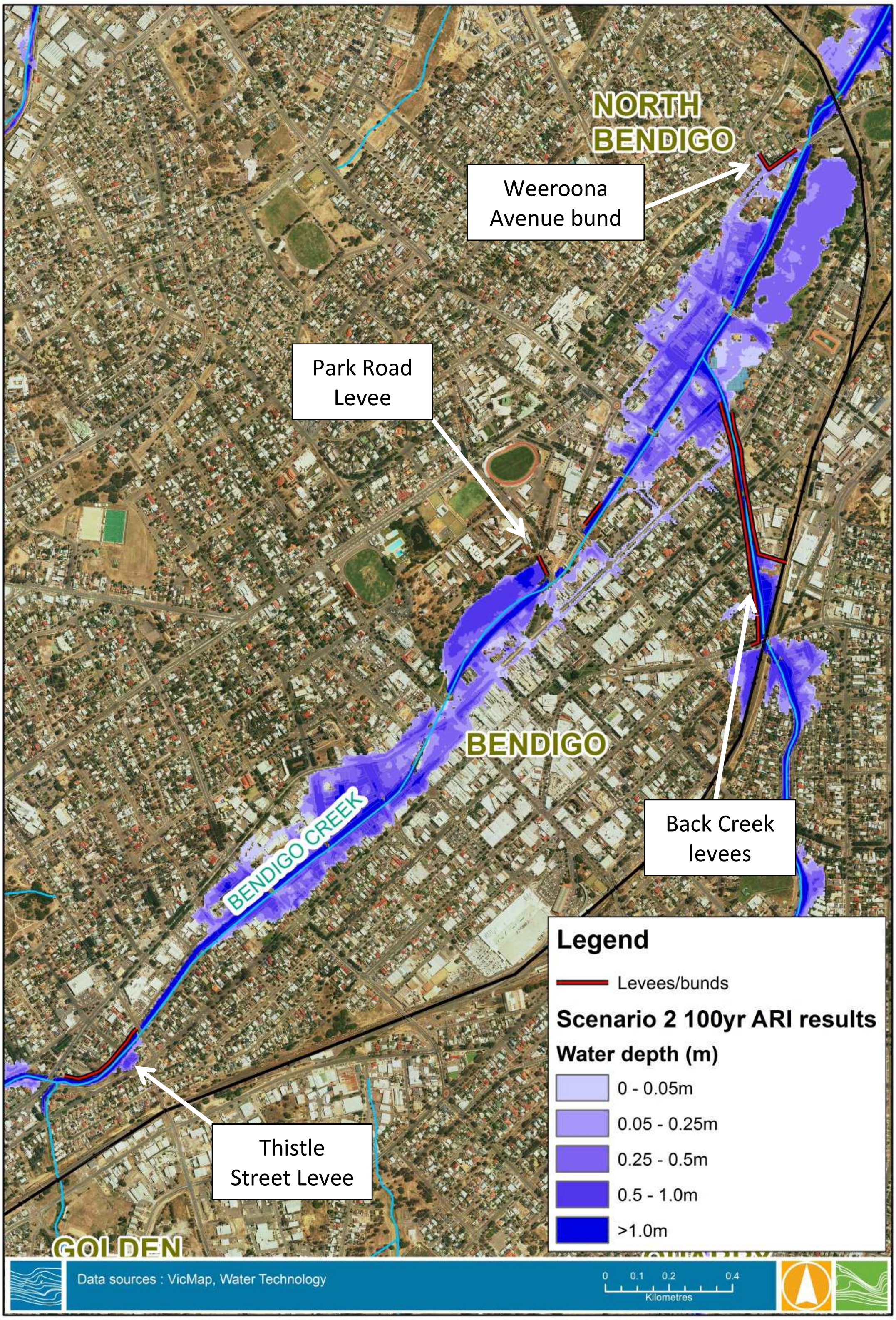


Figure 6-7 Central Bendigo Scenario 2 works and Scenario 2 100 year ARI results

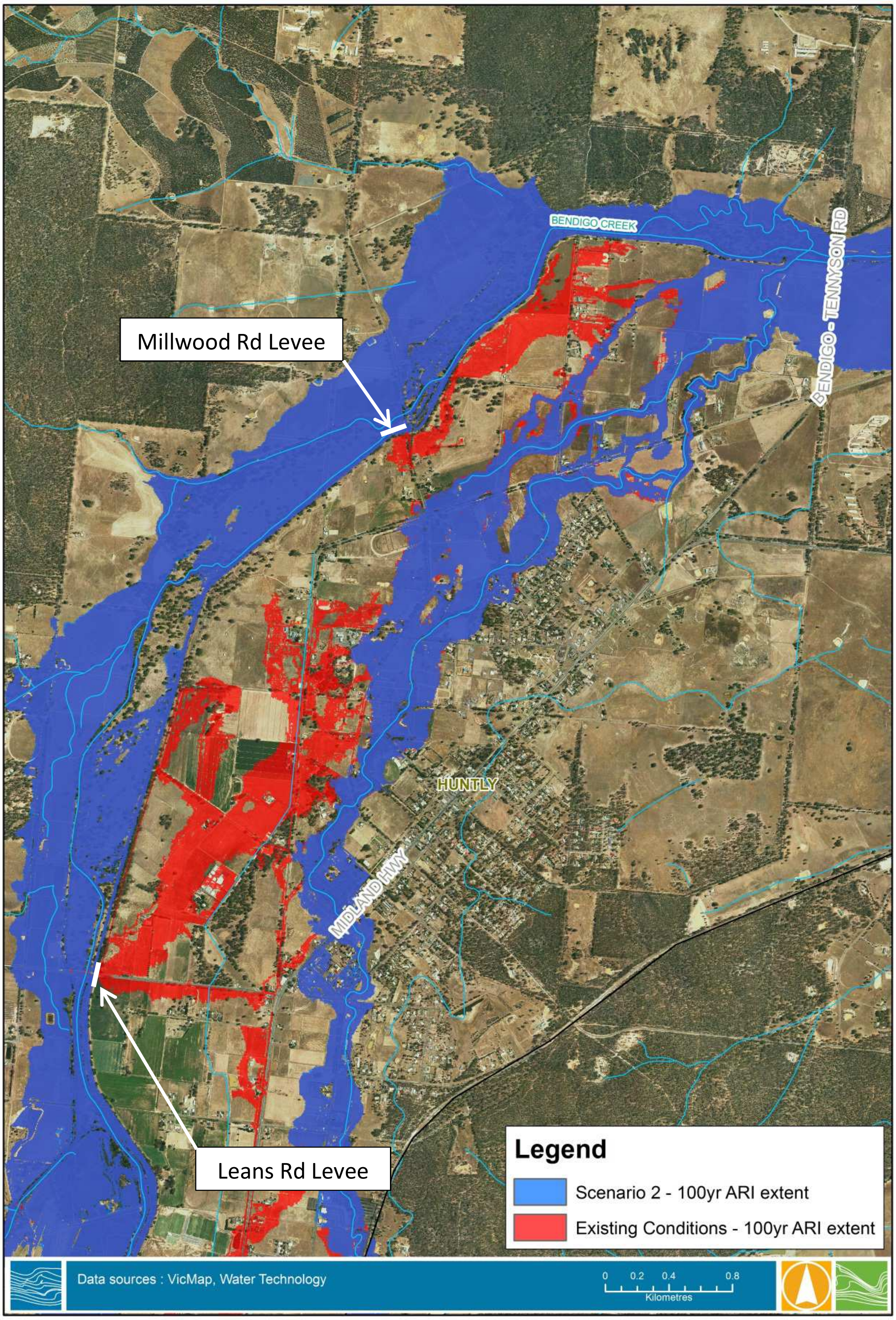


Figure 6-8 Impact of Leans Road and Millwood Road levees on flood extent

Table 6-2 Result of Scenario 2 mitigation modelling

Waterway	Option Number	Location	Mitigation Details	Result	100yr ARI Design Requirements
Bendigo Creek	2a	Development at 15 Wesley Street, Kangaroo Flat	Inclusion of as-constructed survey in topography	Several properties at southern end of development inundated up to 400mm	Not Applicable
	2b	Valley Estate, Kangaroo Flat	Inclusion of as-constructed survey in topography	Approximately 50 residential parcels inundated which includes 28 parcels with depths less than 50mm. 9 parcels with depths greater than 250mm.	Not Applicable
	2c	Wesley Street bridge Kangaroo Flat	Inclusion of new Wesley Street road bridge in model (not built at commencement of design modelling)	Upstream water levels lowered by 210mm	Not Applicable
	2d	Between High Street and Thistle Street, Golden Square	Trial of levee along north bank to protect from breakout	Effective at blocking breakout, protects approximately 30 properties.	Levee approximately 300m in length, height varying from 0.3m to 1.0m (includes 300mm freeboard)
	2e	Park Road, Bendigo	Trial of levee (or raised road) adjacent to Park Road to prevent breakout from gardens which flows along Bridge Street.	Effective at preventing breakout	Levee approximately 70m in length, height varying from 0.3m to 0.9m (includes 300mm freeboard).
	2f	Weeroona Avenue, Bendigo North	Trial of levee or bund to protect properties near corner of Weeroona Ave and Caledonia St	Effective at protecting several properties	Levee or bund approximately 150m in length, height varying from 0.4m to 0.7m (includes 300mm freeboard).
	2g	Leans Road, Huntly	Trial of levee across road to prevent breakout through eastern bank	Effective in preventing breakout	Levee crest elevation of 179.20m required for 300mm

Waterway	Option Number	Location	Mitigation Details	Result	100yr ARI Design Requirements
			levee		freeboard (1.7m lower than adjacent existing levee)
	2h	Millwood Road, Huntly	Trial of levee to prevent breakout through southern bank levee	Effective in preventing breakout	Levee crest elevation of 167.43m required for 300mm freeboard (1.6m lower than adjacent existing levee)
Back Creek (Epsom)	2i	Taylor Street, Epsom	Trial levee parallel to Taylor Street and along eastern channel bank to prevent breakouts	Effective at preventing breakout and protects approximately 16 properties from inundation. Existing 100yr ARI flood depths less than 150mm at impacted properties so likely to be predominately external inundation.	Levee along eastern bank of creek approximately 270m in length, height varying from 0.3m to 0.9m (includes 300mm freeboard). Levee parallel to Taylor Street approximately 330m in length, height varying from 0.9m to 1.2m (includes 300mm freeboard).
	2j	Ascot Gums Estate, Epsom	Inclusion of as-contracted survey in topography	Inundation predominately confined to roads and reserves. Inundation less than 200mm in depth impacting several properties at southern end of estate.	Not applicable
	2k	Ascot Landing Estate, Epsom	Inclusion of as-constructed survey in topography	Eastern half of estate inundated impacting approximately 55 properties. Deeper inundation confined to roads and reserves. Inundation on properties generally less than 150mm. 12	Not applicable

Waterway	Option Number	Location	Mitigation Details	Result	100yr ARI Design Requirements
				properties on eastern side of estate inundated up to 400mm	
	2l	Yellowgum Estate, Epsom	Inclusion of as-constructed survey in topography	Inundation confined to wetland and reserves. No properties inundated.	Not applicable
Eaglehawk Creek/Jackass Gully	2m	Edgewater Close, Eaglehawk	Inclusion of as-constructed survey in topography	Inundation confined to road and reserves adjacent to waterway. No properties inundated.	Not applicable
	2n	Evergreen Waters Estate, Jackass Flat	Inclusion of as-constructed survey in topography	Inundation confined to road and reserves adjacent to waterway. No properties inundated.	Not applicable
Back Creek (CBD)	2o	Between McIvor Road and Havelock Street	Levees along both banks to prevent breakouts	Effective at preventing breakouts from both banks. Protects approximately 30 properties on eastern bank and 80 properties on the western bank. Impacts continue downstream with depths at properties near the confluence with Bendigo Creek lowered by 100mm.	Levee along eastern bank of creek approximately 550m in length, height varying from 0.4m to 1.4m (includes 300mm freeboard). Levee along western bank of creek approximately 800m in length, height varying from 0.4m to 1.4m (includes 300mm freeboard). Levees were modelled across both McCrae and Hargreaves Streets so solutions would have to be determined at those locations. Options could include raising roads, automatic levees or temporary structures such as

Waterway	Option Number	Location	Mitigation Details	Result	100yr ARI Design Requirements
					drop boards.
Racecourse Creek	2p	Between Bendigo Racecourse and Bendigo Creek confluence	"Racecourse Floodway" consisting of levees on both banks to prevent breakouts	Effective at preventing breakouts from both banks. Prevents the breakout from the north bank which flows 3-4km northwards through Epsom and into Back Creek impacting up to 200 properties in the 100yr ARI event.	Levee along eastern bank of creek approximately 550m in length, height varying from 0.4m to 1.4m (includes 300mm freeboard). Levee along western bank of creek approximately 800m in length, height varying from 0.4m to 1.4m (includes 300mm freeboard).
Long Gully	2q	Finn St and Holdsworth Road, White Hills	Small bund to protect properties inundated near corner of Finn St and Holdsworth Road, White Hills	Effective at preventing breakout, protects 5 properties from shallow inundation	Levee/bund along northern bank of creek approximately 180m in length, up to 500mm in height (includes 300mm freeboard).
	2r	William Street, Long Gully	Small bunds to protect properties on William Street which back onto Long Gully	Effective at preventing breakout, protects 4 properties from inundation	Levee/bund behind properties adjacent to creek and to west of properties approximately 140m in length, up to 750mm in height (includes 300mm freeboard).

6.4 Scenario 3 – Flow Retardation

The aim of Scenario 3 was to determine if there was any potential to reduce peak flows in some of the main tributaries in the Bendigo area using structures to retard the flow. Retarding basins were trialled upstream of both Bendigo and Back Creeks and the potential for Crusoe Reservoir to attenuate flow was examined.

The Scenario 3 options are described in more detail in Table 6-3 below.

Table 6-3 Scenario 3 options

Waterway	Option Number	Location	Mitigation Details
Bendigo Creek	3a	Crusoe Reservoir	Testing the mitigation potential of Crusoe Reservoir by modelling the storage in RORB using the original stage-storage charts as provided by Coliban Water. The reservoir was altered following its decommissioning and an accurate stage-storage chart for the current arrangement is not available.
	3b	Granter Street, Kangaroo Flat	Trial of a retarding basin in the RORB model to determine what reduction in peak flows in Bendigo Creek could be achieve given the area that could be utilised to build such a structure
Back Creek (Epsom)	3c	Bendigo Golf Course, Epsom	Trial of a retarding basin in the RORB model within Bendigo Golf Course to determine what reduction in peak flows in Back Creek could be achieve given the area that could be utilised to build such a structure

The locations of the three modelled options are shown in Figure 6-9 and Figure 6-10. Additional details of the Scenario 3 measures are discussed below.

6.4.1 Crusoe Reservoir

In the design modelling Crusoe Reservoir was set to full capacity and provided minimal attenuation to flows. This was a conservative approach and deemed appropriate for design conditions. A review of the original charts for Crusoe Reservoir show that when operating as a Coliban Water storage it provided significant attenuation even when at full capacity. Following decommissioning the reservoir underwent a number of changes including the construction of catch drains and a reported lowering of the spillway. Stage-discharge curves do not exist for the current arrangement and so its ability to attenuate flows is unknown.

The Scenario 3 modelling aimed to understand what impact there would be on downstream inundation if Crusoe was able to attenuate flows as effectively as when it was fully operational. The original charts were input into the RORB model and the resulting flows were used in the hydraulic model.

6.4.2 Kangaroo Flat Retarding Basin

It was deemed that a retarding basin in Kangaroo Flat upstream of Furness Street could reduce flows into Bendigo Creek. A potential site was chosen near Granter Street based on aerial photography and topographical information. It should be noted that Water Technology does not propose this site as a genuine proposed location for a retarding basin but was simply investigating what could be achieved if a retarding basin was constructed in the area.

The retarding basin's volume and geometry were determined based on the size of the chosen site. The basin was added to the RORB model as a storage, with RORBs storage design capabilities used to determine the pipe outlet design.

6.4.3 Bendigo Golf Course Retarding Basin

It was deemed that a retarding basin in Ascot upstream of Taylor Street could be an appropriate location for a retarding basin to reduce flows into Back Creek. A potential site was chosen within Bendigo Golf Course based on aerial photography and topographical information. Again it must be emphasised that this site is not a genuine proposed location for a retarding basin.

As with Kangaroo Flat the basin's volume and geometry was determined based on the size of the chosen site and RORB's storage design capabilities were used to determine the pipe outlet design.

The model was then run for the 3 and 6 hour duration 100 year ARI events.

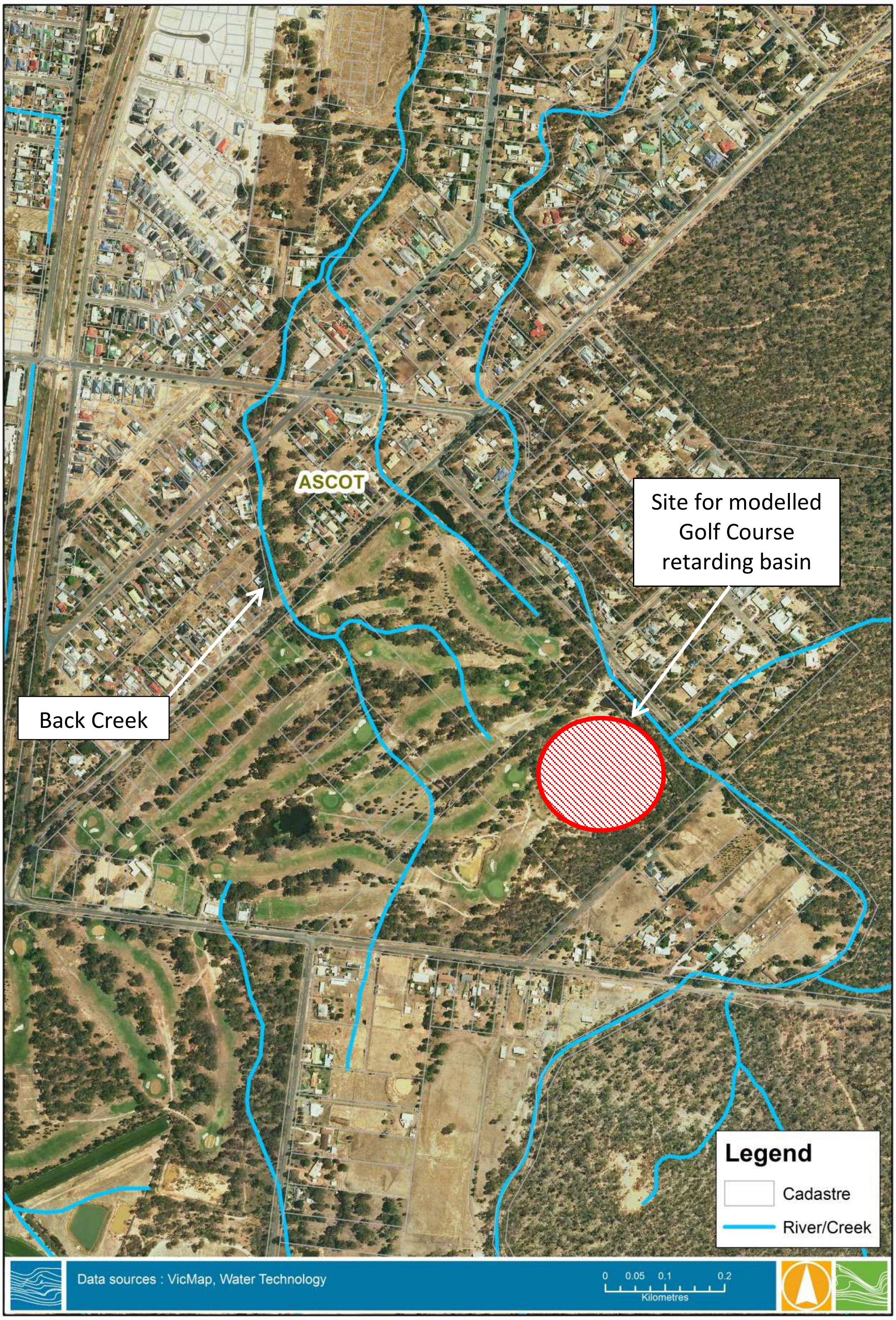


Figure 6-9 Location of modelled retarding basin on Bendigo Golf Course

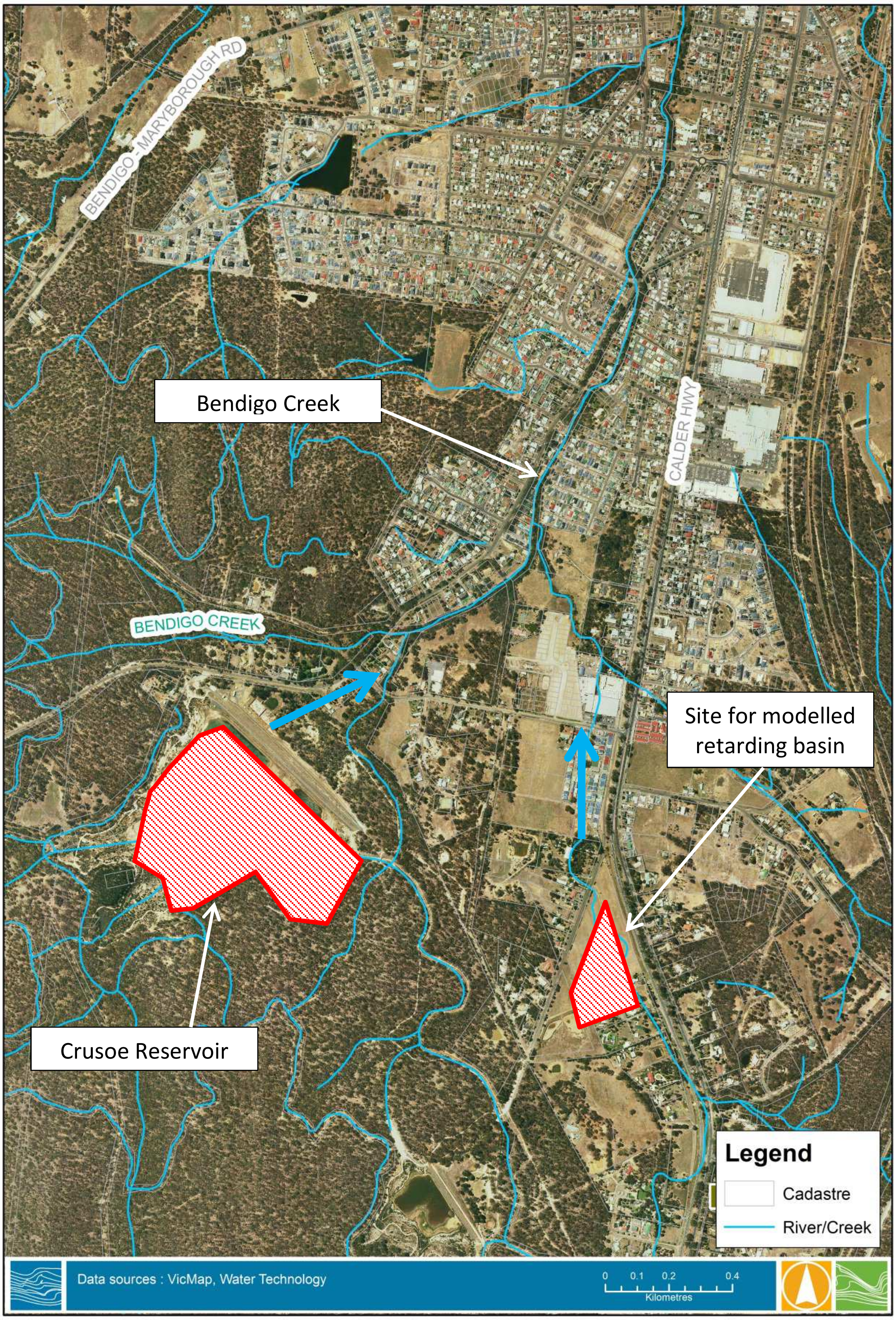


Figure 6-10 Location of modelled retarding basin in Kangaroo Flat and Crusoe Reservoir

6.4.4 Results and Discussion

The results showed that significant reductions in peak flows could be achieved in upper Bendigo Creek resulting in much improved flood depths and extents in the catchment around Kangaroo Flat. The Kangaroo Flat retarding basin has a modest impact on flows in Bendigo Creek however the reduction in flows out of Crusoe Reservoir was quite significant.

At Crusoe Reservoir a 90% reduction in flow was achieved through remodelling the reservoir using the original operational charts. The combined reduction in flow from the retarding basin and Crusoe Reservoir resulted in much improved flood extents and depths. The impacts are evident for approximately 5 km downstream as can be seen in Figure 6-11 with reduction in flood levels of up to 400 mm. With regards to the Kangaroo Flat Retarding Basin, despite a large structure being trialled only modest results were achieved. It is likely that a benefit-cost analysis of such a structure would yield poor results in terms of feasibility. The largest benefits to flood risk were a result of the remodelling of Crusoe Reservoir and it is recommended that further analysis be conducted to better understand the reservoir's ability to attenuate flow in its current state. It is also possible that modifications to the reservoir, such as a low flow outlet to keep storage levels lower, could result in further improvements to flood risk downstream.

Improvements in flooding in Back Creek were not as successful with the Golf Course retarding basin having a smaller impact on flows. The resulting impacts on flood depths and extents through Epsom and Ascot were minimal. It is likely that a benefit-cost analysis of such a structure would deem it unfeasible and there are also likely to be issues around practicality of building a structure of the required size in the vicinity of the golf course.

Table 6-4 Impact of Scenario 3 options on hydraulic model inflows

Option	Event	Peak Flow: existing conditions (m3/s)	Peak Flow: Scenario 3 (m3/s)	Reduction in flow (%)
Crusoe Reservoir	100yr, 3hr	18.1	1.2	93%
	10yr, 6hr	17.0	1.9	89%
Kangaroo Flat Retarding Basin	100yr, 3hr	24.9	15.6	37%
	100yr, 6hr	24.3	16.9	30%
Golf Course Retarding Basin	100yr, 3hr	13.1	10.4	21%
	100yr, 6hr	14.01	12.2	13%

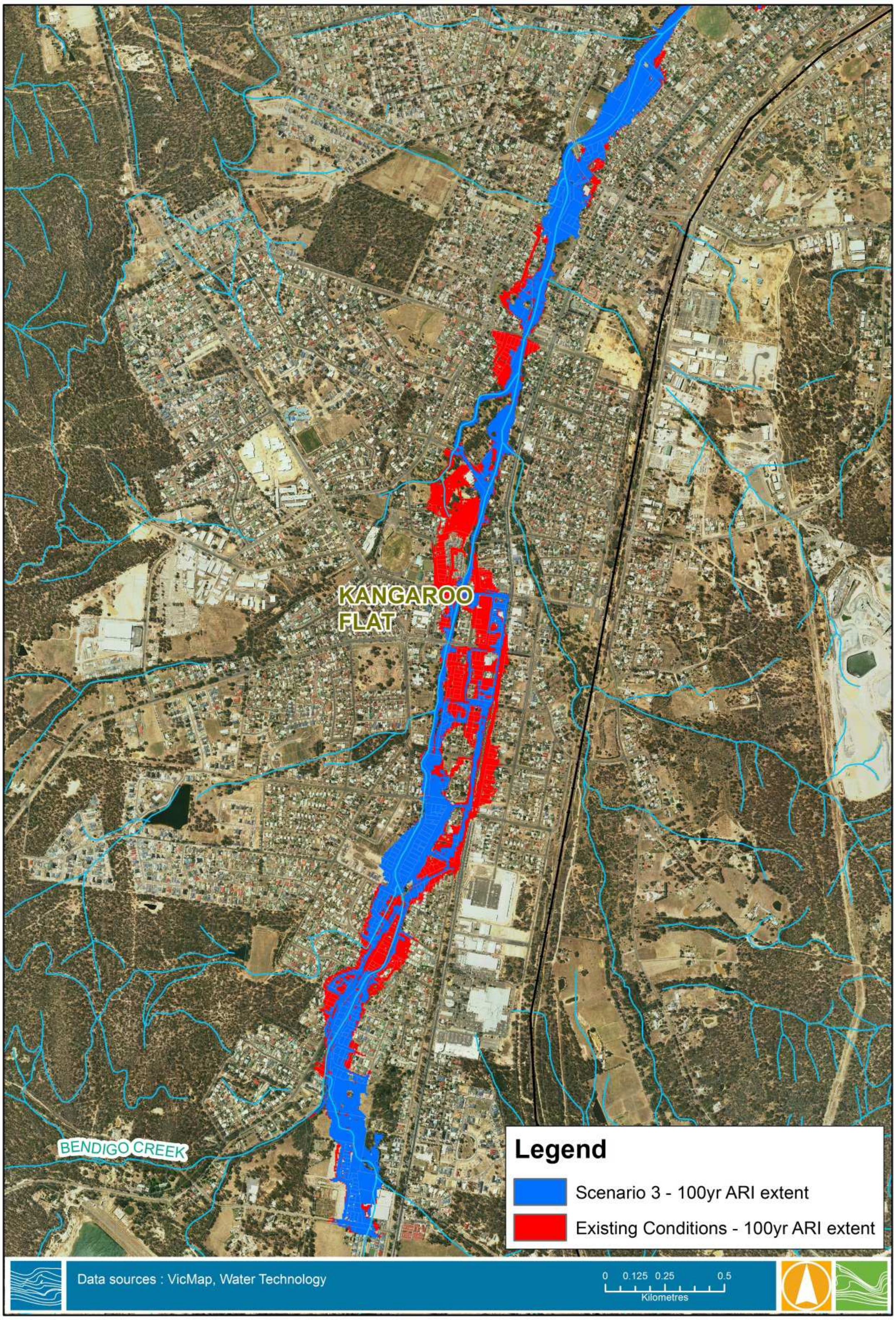


Figure 6-11 Mitigation Scenario 3 vs. Existing Conditions 100 year ARI Flood Extent in upper catchment

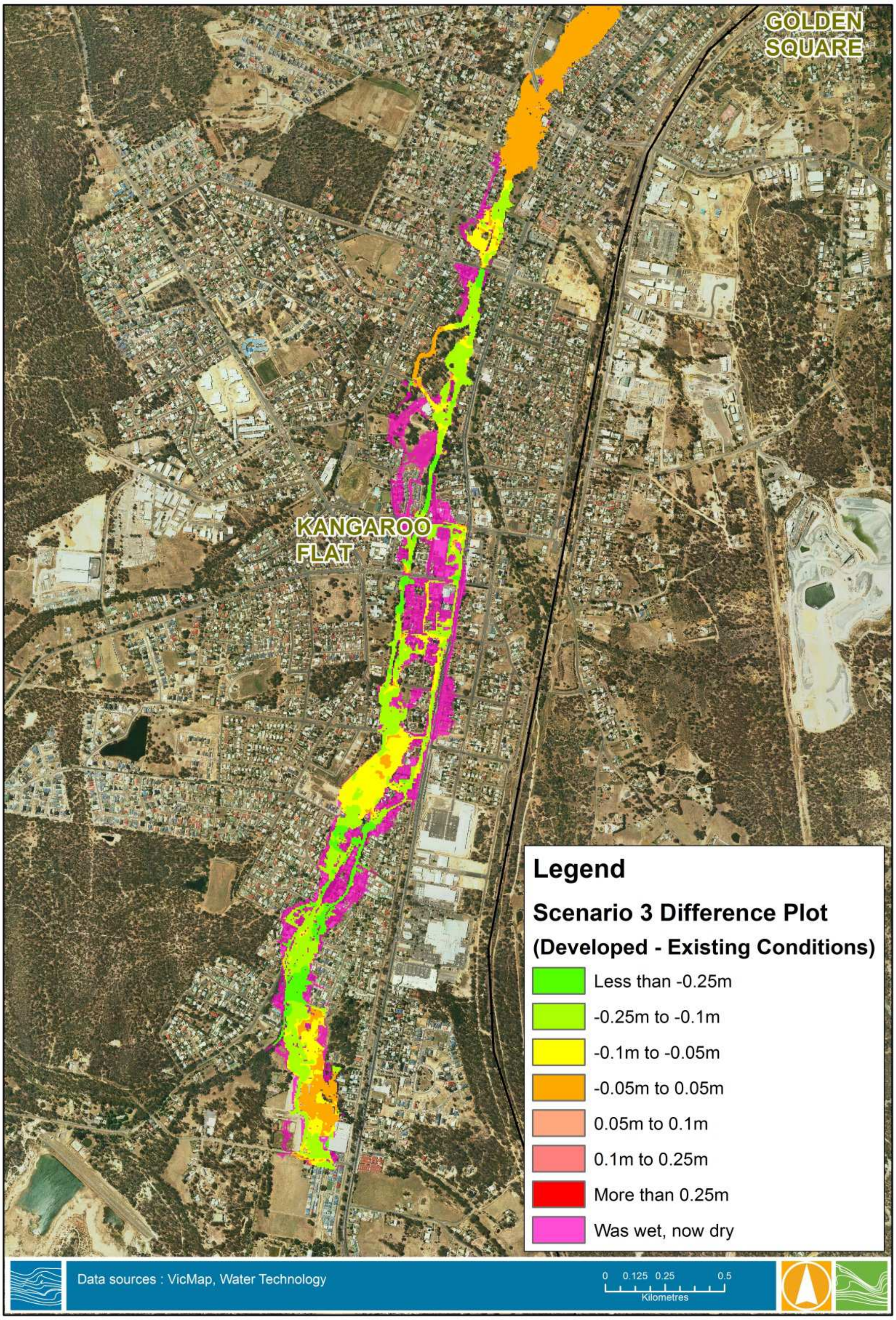


Figure 6-12 Scenario 3 Difference Plot

6.5 Summary

Mitigation modelling at selected locations has identified that there are a number of measures which can reduce flood risk in Bendigo. It is recommended that the City of Greater Bendigo and North Central CMA further investigate and undertake benefit-cost analysis on those options which have been found to be effective.

From the mitigation modelling several conclusions can be made:

- The levees along Bendigo Creek continue to play an important role in protecting parts of Epsom and Huntly from inundation in large flood events. It is essential that there is a clear plan to maintain the existing benefit provided by the levees.
- Flood risk can be reduced at a number of locations around Bendigo through the use of local structural works such as levees and bunds, provided further investigation can demonstrate that there are no detrimental impacts to other properties
- The construction of new retarding basins is unlikely to be feasible due to the level of retardation required and associated cost.
- Crusoe Reservoir is likely to have significant potential to attenuate flows in Bendigo Creek resulting in reduced flood extents in Kangaroo Flat. Further analysis is needed to better understand this potential.

The scope of the project was to propose a number of low-detail mitigation options to provide the basis for further investigation beyond the life of this project. The number of options examined are not exhaustive and it is recommended that a more detailed investigation into further mitigation options could yield a greater list of viable options for future analysis and investment.

7. FLOOD DAMAGE ASSESSMENT

7.1 Overview

A flood damages assessment was undertaken across the study area for existing floodplain conditions. The flood damage assessment determined the monetary flood damages for design floods (5, 10, 20, 50, 100 and 200 year ARI events).

Water Technology has developed an industry best practice damage assessment methodology that has been utilised for a number of studies in Victoria. In the absence of floor level survey the study methodology was adjusted slightly, following the Rapid Appraisal Methodology more closely.

The Rapid Appraisal Methodology (RAM) was published in 2000[6] and provides an approach requiring a simple count of the total number of buildings within the flood extent. The Vicmap land parcels from September 2013 were used for this approach thereby avoiding lengthy digitising of building footprints. To improve the data set, aerial imagery from March 2013 was reviewed and all land parcels that did not contain a residential or community/commercial building were removed. In addition a number of overlapping or duplicate parcels were removed from the dataset to remove double counting, and common land such as driveways within subdivisions was also removed. Any parcels that were inundated by less than 5% of the total area were excluded from the analysis. This ensured that properties adjacent to a roadway conveying flow or properties with a small amount of water across a corner of the block were not overinflating the damage cost.

The RAM damage estimate of $20,500 per inundation was adopted for all buildings except large non-residential buildings. Adjusted for CPI to June 2013 this is $30,500[7]. Large non-residential buildings are classified as those that are > 1,000 m^2. A number of large non-residential properties were identified in the imagery.

Table 7-1 Suggested damages for large non-residential buildings (> 1,000 sq m) (RAM, 2000)

Value of contents	Mean potential damages per square metre (RAM, 2000)	Adjusted to 2013 CPI
Low (offices, sports pavilions)	$45	$67
Medium (libraries, caravan parks)	$80	$120

Recognising that damage reduction measures can be implemented during an emergency, an actual to potential damages ratio was applied.

Table 2 Actual to potential damages ratio (RAM, 2000).

Warning Time	Experienced Community	Inexperienced Community
<2 hours	0.8	0.9
2 to 12 hours	Linear reduction from 0.8 to 0.4	0.8
> 12 hours	0.4	0.7

It was assumed that Bendigo could be categorised as an inexperienced community in terms of floods. For Bendigo a ratio of 0.85 was applied based on the rationale that the smaller catchments

[6] Rapid Appraisal Method (RAM) for Floodplain Management. DNRE Victoria, May 2000.
[7] $30,497.82

have a warning time less than 2 hours (a factor of 0.9) and Bendigo Creek has a warning time of greater than 2 hours (a factor of 0.8).

The estimated damage of roads was calculated by intersecting the Vicmap Roads data layer with the flood extents and applying the cost table below. These were added to the estimated building damages.

Table 7-2 Cost of repairing flood inundated roads ($/km) from RAM

	Initial Repairs	Accelerated deterioration	Bridge repairs	Total cost
Major sealed roads	$32,000	$16,000	$11,000	$59,000
Minor sealed roads	$10,000	$5,000	$3,500	$18,500
Unsealed roads	$4,500	$2,250	$1,600	$8,350

Table 7-3 Cost of repairing flood inundated roads ($/km) factored up by CPI for 2013

	Initial Repairs	Accelerated deterioration	Bridge repairs	Total cost
Major sealed roads	$47,596	$23,798	$16,361	$87,756
Minor sealed roads	$14,874	$7,437	$5,206	$27,517
Unsealed roads	$6,693	$3,347	$2,380	$12,420

It was assumed that a 50% AEP event resulted in zero flood damage. Non indirect costs such as clean-up costs, emergency response or relocation costs were included in this assessment.

It must be clearly noted that this damage assessment is very different to the standard flood damage assessment that is generally carried out on riverine flood studies throughout Victoria. This study is considering potential flooding from stormwater not just riverine flooding from major creeks and waterways. As such the damage assessment is including many more properties than would traditionally be the case, resulting in very high flood damage estimates. These estimates should not be used for any future financial risk planning, as it is highly unlikely that in the event of a flood that the entire study area would be flooded. These flood damage estimates will be an over estimate by nature of the method employed to flood map the area.

7.2 Existing conditions

Using the modelled water surface elevation grids for each of the design events, flood damages were calculated as described above. Table 7-4 below includes the damage summary.

Table 7-4 Existing conditions flood damage estimate

AEP (%)	0.5%	1%	2%	5%	10%	20%	50%
Large buildings flooded	166	154	144	132	110	98	-
Properties flooded	17,830	14,846	12,101	8,908	6,272	4,494	-
Total Properties Flooded	**17,996**	**15,000**	**12,245**	**9,040**	**6,382**	**4,592**	**-**
Potential Large Buildings Damage Cost	$70.4 M	$67.8 M	$65.9 M	$61.5 M	$55.3 M	$51.6 M	$ -
Potential Property Damage Cost	$543.8 M	$452.8 M	$369.1 M	$271.7 M	$191.3 M	$137.1 M	$ -
Total Direct Potential Damage Cost	$614.2 M	$520.6 M	$435.0 M	$333.2 M	$246.6 M	$188.7 M	$ -
Total Actual Damage Cost *(0.8*Potential)*	$491.4 M	$416.5 M	$348.0 M	$266.5 M	$197.3 M	$151.0 M	$ -
Infrastructure Damage Cost	$9.4 M	$7.7 M	$6.1 M	$4.4 M	$3.2 M	$2.3 M	$ -
Total Cost	**$500.8 M**	**$424.2 M**	**$354.1 M**	**$270.9 M**	**$200.5 M**	**$153.3 M**	**$ -**
Average Annual Damage (AAD)	**$68.0 M**						

The above damages were compared to very basic estimates of damages for the Bendigo urban area in the RAM (2000) [6] report. In the RAM report an Average Annual Damage of $1.1 M was estimated, with a damage of $53 M associated with the LSIO at the time (approximate 100 year ARI flood estimate for Bendigo Creek only). The RAM flood damage estimate was only for the area impacted by Bendigo Creek directly, not the wider urban area impacted by tributaries and stormwater. The RAM flood damage assessment estimated that 1,877 buildings were affected, with 194 buildings affected within the floodway (floodway often defined as 10 year ARI). In comparison to this previous estimate, this study estimates 2,437 properties impacted by the 1% AEP event along Bendigo Creek (Spine Model), at a total damage cost of $66.1 M. This is comparable to the estimates made during the RAM study in 2000.

7.3 Non-Economic Flood Damages

The previous section relating to flood damages has primarily 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 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.*

Whilst Bendigo has been fortunate in its avoidance of major flood events in recent times, the flooding of this major regional centre would have far reaching non-economic impacts. Consideration of these impacts should be taken into account in any overarching consideration of flood hazard within the township.

8. CONCLUSIONS

The flood mapping of the Bendigo Creek Catchment has been one of the most technically comprehensive studies ever undertaken in Victoria. Water Technology believes that this study is a landmark study for flood mapping of large urban areas, it is the first of its kind, setting the benchmark for future work of this nature. Mapping of the creek systems using traditional methods combined with the Rain on Grid mapping of the greater catchment has provided North Central CMA and City of Greater Bendigo an unprecedented amount of flood intelligence and data.

Three major models have been built for this study, these include:

- A hydrological model calibrated to known events and verified by an external, independent expert panel.
- A detailed 1D-2D flood model of all the major waterways within the study area. This provides a high resolution flood map and associated data for future flood intelligence requirements.
- Comprehensive high resolution Rainfall on Grid models providing exceptional flood intelligence at a very fine resolution. This mapping will provide Council with a highly valuable dataset to base future development decisions on.

These models were all run for a series of historic calibration events and the 5, 10, 20, 50, 100 and 200 year ARI design events with multiple durations. PDF flood mapping products and digital mapping deliverables were produced and supplied along with the study report, and should be viewed in conjunction to this report.

The flood damages estimated during this study is very different to that estimated for other riverine flood studies across Victoria. Due to the nature of this study investigating not only riverine flooding, but flooding of urban overland flow paths, the total flood damages are much greater than traditional studies. The 1% AEP has an estimated 15,000 properties impacted at a total flood damage cost of $424.2 M. The Average Annual Damage was calculated at $68.0 M. This very large flood damage cost reflects the risk of flooding over the entire Greater Bendigo catchment, however the dollar value should not be used for financial risk planning as it is an overestimate due to the nature of the urban stormwater flood mapping methodology.

A number of scenarios were modelled, testing various mitigation options. The first scenario considered levee breaches in the downstream section of Bendigo Creek around Epsom and Huntly, clearly demonstrating the large area protected by these levee systems, strengthening the need to resolve the ownership and future maintenance requirements of this critical flood mitigation infrastructure. The second scenario considered numerous local flood mitigation measures, many of which were shown to have some merit, some would most likely not pass a benefit-cost test, but some are worth considering further. The third scenario looked at retardation basins and using the Crusoe reservoir to store flood flows. This was shown to have significant downstream benefits and should be considered further, although the benefit-cost ratio may prove low. The assessment of mitigation options for Bendigo was not extensive and covered a handpicked number of scenarios. It is recommended that a wider flood mitigation assessment be considered. This may provide significant benefits to Bendigo in terms of reducing the current legacy flood risk, but may also allow future development to be progressed in flood protected areas, facilitating future development in growth areas.

Using the outcomes of the data review, modelling and flood mapping, a flood warning discussion paper was developed to allow both the CoGB and NCCMA to consider their options regarding flood warning. This is included as an appendix to this report and should be read in conjunction with both this report and the flood mapping outputs.

Appendices to the Municipal Flood Emergency Plan were also developed and should be reviewed by VICSES and uploaded into the Council's Municipal Flood Emergency Plan.

The flood mapping outputs should now be used to update the Greater Bendigo Planning Scheme. The new data will help to define better controls on development within both the major floodplain and other overland flow paths throughout Bendigo. Appropriate planning tools should be considered for the various flood depths and hazards that have been shown in the maps associated with this report. Stronger controls should be considered for the greater depths and hazardous areas, with lesser controls on the more manageable flow paths and flood fringe areas – in accordance with the Department of Planning and Community Development Practice Notes. The provision of a fully functional flood model will enable the CMA and Council to undertake rigorous feasibility assessment on major developments within the floodplain or any proposed changes to local stormwater infrastructure prior to approval or construction. This will ensure that new development is designed appropriately, that the flood risk to existing development is not exacerbated, and that proposed changes to local stormwater infrastructure meet relevant industry standards or local community expectations.

Finally given the high level of rigour associated with this study it is hoped that a level of confidence can be shown to the community surrounding the understanding of flood behaviour within the limits of the study area, providing backing for Council decision making.

Water Technology would like to take this opportunity to thank North Central CMA, City of Greater Bendigo, all agency members of the steering committee and the Greater Bendigo community for their assistance and contribution to the development of the deliverables of this study.

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VICSES, MFEP

APPENDIX A FLOOD WARNING DISCUSSION PAPER AND RECCOMENDATIONS

Michael Cawood & Associates Pty Ltd

MCA

BENDIGO URBAN FLOOD STUDY

FLOOD WARNING SYSTEM FOR BENDIGO CREEK

DISCUSSION PAPER

1 - PURPOSE

This Discussion Paper arises from dialogue at the 14 June 2013 meeting in Bendigo of the Bendigo Urban Flood Study Steering Committee where it was determined that additional background and perspective were required to enable an informed conversation about flood warning systems as a preferred flood mitigation strategy for Bendigo. In that context, the purpose of this Paper is to:

- Provide a summary of what the Flood Study aimed to deliver with respect to flood warning;
- Introduce the Total Flood Warning System (TFWS) concept;
- Consider the flood risk at Bendigo in the context of flood warning as a flood mitigation strategy;
- Provide an overview of roles and responsibilities in relation to flash flood warning systems;
- Outline a number of available options for alerting and notifying the Bendigo community of conditions likely to lead to and the occurrence of rapid onset (flash) flooding;
- Present potential solutions for other TFWS elements;
- Suggest a staged approach to the development of a flash flood warning system for Bendigo; and
- Pose questions fundamental to system development.

2 - BACKGROUND – FLOOD STUDY DELIVERABLES

The study team undertook to provide broad recommendations, in terms of the eight building blocks making up the Total Flood Warning System, regarding the development of a (flash) flood warning system for the creek at Bendigo. The recommendations were to have due regard for assets at risk, the warning time available and existing proven flash flood warning systems. A number of pages of text and a table were envisaged with broad recommendations against each building block on what could be done along with cost estimates for the capital items needed to support such a system.

3 - FLOOD WARNING SYSTEMS

A Floodplain Management Context

With the shift to a risk based approach to floodplain management within Australia, the emphasis has moved from the implementation of structural solutions for flooding to 'softer' non-structural solutions that recognise the value of floodplains and their processes as well as the economic and social benefits that flow from their development. The emphasis now is on modifying how floodplains are developed (i.e. the human interface) rather than on modifying the floodplain so that it can be developed.

The value of floodplains to the community and to State and National economies is well recognised in Australia (e.g. DNRE, 1998; EMA, 2009; ARMCANZ, 2000). It is also recognised that the benefits that flow from the use and habitation of floodplains come at some costs.

The challenge then is to reduce those costs while maintaining the benefits: in effect to make it easier for communities to live with flooding.

Effective flood warning systems in conjunction with (perhaps) physical mitigation measures, a regime of appropriate land use management practices and instruments and the necessary emergency management measures are increasingly being recognised as representing good practice. It is the totality and proper mix and balance of measures that produce effective containment of the negative consequences of flooding. Appropriate flood warning practices are a vital ingredient to that mix.

The high level of development and the large number of properties at risk of flooding within Greater Bendigo make it difficult to implement suitable structural mitigation measures across the entire area. Flood warning services, however, remain applicable and offer opportunities to reduce flood related damages and flood related risk to personal safety.

Flood warning systems are integral to the objective of floodplain management. However, development of an effective flood warning system is not a simple matter.

Aim and Function

Put simply, flood warning systems provide a means of gathering information about impending floods, communicating that information to those who need it (those at risk) and facilitating an effective and timely response. Thus flood warning systems aim to enable and persuade people and organisations to take action to increase personal safety and reduce the damage caused by flooding[8]. Effective flood warning systems maximise the opportunity for the implementation of public and private response strategies aimed at enhancing the safety of life and property and reducing avoidable flood damage.

Fully developed 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 and in words that elicit appropriate responses based on well developed mechanisms that maintain flood awareness.

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.

The 'flood warning coupled with flood awareness and preparedness' theme is reiterated in BTRE (2002) where it is stated (p. 69) that "*Community awareness and preparedness together with reliable and timely flood warning systems play an important role in the success of (flood) mitigation (activities)*." The theme is also present in the list of principles for the application of early warning at national and local levels introduced and discussed in UN (1997).

Flood warning systems should respond appropriately to the risk being addressed. Thus, a sophisticated and possibly expensive system may not be suitable for a location or area where flooding results mainly in disruption and only the larger floods inundate a proportionally small number of properties above floor level.

Limitations of Flood Warning Systems

No single floodplain management measure is guaranteed to give complete protection against flooding. For example, levees can be overtopped (when a flood exceeds design height, as happened at Nyngan in 1990) or fail (when construction standards are poor or maintenance is inadequate). Likewise, flood response plans can be poorly formulated or applied ineffectually.

Flood warning systems are, by their very nature, complex. They are a combination of technical, organisational and social arrangements. To function effectively they must be able to forecast coming floods and their severity (using data inputs that may include rainfall and / or upstream river heights and / or flows along with modelling techniques or forecasting tools) and the forecast must be available / transmitted available to those who will be affected (the at-risk communities) in ways that they understand and which result in appropriate behaviours on their part (for example, to protect assets or to evacuate out of the path of the floodwaters).

It is not surprising, given the above, that flood warning systems often work imperfectly and have, on occasions, failed. Indeed, as Handmer (2000) points out, "*flood warnings often don't work well and too frequently fail completely - and this despite great effort by the responsible authorities*." While in some cases the problem is the result of a physical, mechanical or technical failure (for example of gauges or telemetry or of communications equipment during a flood event), or perhaps in defining what constitutes success (or failure), the more common reason is that the flood warning systems have not been properly conceptualised at the design stage and in terms of their operation, despite the considerable and conscientious efforts of those involved. All too often, too little attention has been paid to issues of risk communication. In particular:

- To building a local awareness of flood risk along with knowledge of what can be done to minimise that risk;
- Determining what information is required by the at-risk community and with what lead times;
- How warnings and required information will be distributed to and within the target communities; and
- Ensuring that recipients of warning messages understand what the message is telling them and what it means for their property and individual circumstances in terms of the damage reducing actions they need to take.

The outcome of the above is that many flood warning systems have an inbuilt likelihood of failure.

[8] More generally, the objective of early warning is to empower individuals and communities, threatened by natural or similar hazards, to act in sufficient time and in an appropriate manner so as to reduce the possibility of personal injury, loss of life and damage to property, or nearby and fragile environments (UN, 1997).

In numerous cases where flood warning systems have been developed, the bulk of the effort has been devoted to creating and strengthening data collection networks, devising and upgrading forecasting tools and facilities and utilising new dissemination technologies to distribute the forecast to at-risk communities. While all these things are important, they are never sufficient by themselves to ensure that flood warnings are heeded by those who receive them. Other equally vital elements of the system such as risk communication and the comprehension that people have of the flood problems they may face (and the value that warnings can offer) need at least as much attention at the design stage and in system operation. Systems need to also be appropriate to the circumstances. The lesson from many studies of flood warning systems (e.g. Smith and Handmer, 1986; Phillips, 1998; Handmer, 1997, 2000, 2001 & 2002; Comrie, 2011) is that the status of all elements of the system must be given appropriate attention (and resourcing) if the system is to be made capable of functioning effectively.

Studies of flood warning system failures (e.g. Brisbane in 1974, Charleville and Nyngan in 1990, Benalla in 1993, Canada in 1997, England in 1998, Kempsey and Grafton in 2001, New Zealand in 2005) suggest that the most common reasons for poor system performance are that those in the path of floods, whether emergency responders, householders, the owners of businesses or the operators of infrastructural assets, have either not understood the significance of the warnings they have received or have not known that there were things (or the most appropriate things) they could do to mitigate the effects of flooding. The result has all too often been unnecessary loss of private belongings and commercial and industrial plant, stock and records (for example, through late or non-existent responses) and / or unnecessary risk to life (for example, due to evacuation after it became dangerous rather than when it was relatively safe). Most studies report that warnings were of an adequate technical standard (that is, they were accurate and delivered with good lead times), but the information was poorly communicated and not understood by the target communities. As reported by Anderson-Berry (2002) and Soste & Glass (1996), there is often insufficient attention to ensuring that people in flood liable areas understand the flood gauge or forecast heights which are incorporated in warning messages. The result is that those who have been warned fail to appreciate that the information contained in the message has meaning for their own circumstances. Consequently, they fail to take appropriate or adequate protective measures. Such people often claim afterwards that they received no flood warnings. In many cases warnings were issued but the gap between the information provided and what was understood by those at risk was too large. The problem is one of poor communication.

It is clear that a major problem with many flood warning systems is one of inadequate conceptualisation. Flood warning systems (and investments in their implementation) that over-emphasise the collection of input data and / or the production of flood forecasts relative to the attention given to other elements (such as message construction, the information provided in the messages and the education of flood prone communities about floods and flood warnings) will fail to fully meet the needs of the at-risk communities they have been set up to serve.

The Total Flood Warning System Concept

In 1995 the Australian Emergency Management Institute, following a national review of flood warning practices after disastrous flooding in the eastern states in 1990, published a best-practice manual entitled '*Flood Warning: an Australian Guide* (AEMI, 1995). In describing practices for the design, implementation and operation of flood warning systems in Australia, the manual introduced the concept of the "total flood warning system" (TFWS). It also re-focused attention on flood warning as an effective and credible flood mitigation measure but made it clear that successful system implementation required the development of some elements that hitherto had been given little attention as well as the striking of an appropriate balance between each of the elements. In particular, it was noted that more attention needed to be given to risk communication and the education of communities about the flood risk, the measures that people could take to alleviate the problems that flooding causes and the place of warnings in triggering appropriate actions and behaviours. In other words, implementing a flood warning system involves much more than the installation of a data collection network, the development of a forecast tool and the forwarding of predicted flood levels and times to key agencies. The Guide (AEMI, 1995) also clearly enunciated the need for several agencies to play a part, with clearly-defined roles and with the various elements carefully integrated, and for the members of flood liable communities to be involved. Put another way, "*effective warning systems rely on the close cooperation and coordination of a range of agencies, organisations and the community*" (DoTARS, 2002).

While the original manual has been updated and republished as Manual 21 of the Australian Emergency Manuals Series (EMA, 2009), the concepts, practices and key messages from the original manual endure.

The philosophy that underlies the TFWS concept coupled with the need for a coherent set of linked operational responsibilities and overlapping functions is documented and discussed in the context of guiding principles for effective early warning in UN (1997).

In Australia, flood warning services are provided within a wider floodplain management, flood mitigation and emergency management environment where a variety of Commonwealth, State and local players as well as regional catchment management authorities have significant roles. The picture at both National and State level is quite complex.

Total Flood Warning System Building Blocks

An effective flood warning system comprises much more than a data collection network, forecasting tool or model and flood level (or flow) prediction.

An effective flood warning system is made up of several building blocks. Each building block represents an element of the Total Flood Warning System. The blocks (derived from EMA, 2009) along with the basic tools to facilitate delivery against each of the TFWS elements are presented in Table 7-1.

Experience shows that flood warning systems, and this applies even more so to flash flood warning systems, that are not designed in an integrated manner and that over-emphasise flood detection (say) at the expense of attention to the dissemination of warnings, local interpretation and community response inevitably fail to elicit appropriate responses within the at-risk community. It is essential that the basic tools against each of the building blocks are appropriately developed and integrated. Such a system considers not only the production of a timely alert to a potential flash flood but also the efficient dissemination of that alert to those, particularly the threatened community, who need to respond in an appropriate manner. A community that is informed and flood aware is more likely to receive the full benefits of a warning system.

It follows therefore that actions to improve flood response and community flood awareness using technically sound data (such as produced by the Bendigo Urban Flood Study) will by themselves result in some reduction in flood losses.

4 - BENDIGO AND FLOODING

Introduction

The Bendigo Creek catchment within the City of Greater Bendigo has an area of around 203km^2 and is considered, for the purposes of this study, to comprise all of the area and watercourses upstream of the Bendigo Creek at Huntly stream gauge[9]. This includes the main stem of Bendigo Creek along with its many tributaries as well as the stormwater drainage systems within the many sub-catchments.

There are fourteen (14) main tributary creeks comprising Long Gully Creek, Golden Creek, Spring Creek, Back Creek, Ironbark Creek, California Gully Creek, Jobs Creek, Shepherds Hut Gully, Tipperary Gully, Sunrise Gully, New Chum Gully, Grassy Flat Creek, Eaglehawk Creek and Racecourse Creek. There are also a number of channels and gullies, such as Dead Bullock Gully, that transfer runoff to the creek system but are not formal creeks.

There are five (5) minor water storages, all owned and operated by Coliban Water, within the catchment:

- Crusoe Reservoir;
- No 7 Reservoir;
- Spring Gully Reservoir;
- Sandhurst Reservoir; and
- Gateway Park Lake

All the storages (except Crusoe) are considered to be off-line as they have catch drains that divert water from their upstream catchments around the reservoir and back into the water course. The catch drains at Crusoe have been modified so that the reservoir now receives an inflow from its catchment. Crusoe is also the largest storage in the catchment with a capacity of 890ML and a catchment of 320ha (3.2km^2).

[9] The catchment area upstream of central Bendigo is approximately 62km^2.

The Bendigo Creek catchment is described in more detail in other volumes of this study report. A brief history of past floods is also provided in those volumes.

Flood Risk in the Bendigo Creek Catchment at Bendigo

Most of the creeks within the Bendigo Creek catchment have been modified with buildings constructed in close proximity. The creek channels are not large, some sections are bluestone and / or concrete lined and there are numerous road crossings. Floodwaters flow quickly and debris can cause blockages which cause localised increases in flood depths.

Bendigo Creek and its tributaries have a history of flash flooding. Floods occurred in 1974, on 16 March 1996, 26 December 1999, in October 2000, on 5 March and 4 September 2010 and again on 5 February 2011.

Large floods within the urban area of Bendigo typically occur after summer thunderstorms although they have also resulted from more general heavy rain events. The heavy rainfall causes a rapid rise in floodwaters which pass quickly through the hilly upper and middle parts of the creek catchments. Water is usually not very deep but moves very quickly and can be dangerous. Around Epsom and Huntly where the landscape is relatively flat, flood water spreads out more, is deeper and travels more slowly.

Flooding has been recorded from Kangaroo Flat, through central Bendigo and on through Epsom and Huntly. The central business district (CBD) is particularly vulnerable and there are numerous reports of Pall Mall and Charing Cross being under water with many business premises affected. Many roads have also been inundated, some by fast flowing water at a depth that represents a significant hazard. Roads considered hazardous during flood events can be seen on the hazard maps delivered by the Bendigo Urban Flood Study and are detailed in the Municipal Flood Emergency Plan (MFEP).

The analyses undertaken in support of the Bendigo Urban Flood Study suggest that typically, the time from the beginning of heavy rain on a wet catchment to the start of rises within the upper parts of the creek system is very short: generally less than an hour. In the vicinity of the CBD, time ranges from around 1 to 2 hours while at Huntly it ranges from around 2 hours in big floods to around 5 hours for small floods. Creek levels rise quickly with flooding / overbank flows likely to begin for a big flood within an hour or so of the initial rise[10].

The Bendigo Urban Flood Study has estimated that around 30,000 properties (industrial, commercial and residential) would be affected in Bendigo by a large flood.

Flood Mitigation Options

There are a range of structural and non-structural flood mitigation options available. Structural options are discussed and explored in other volumes of this study report along with land use planning and related options. The flood warning option is discussed in the following sections.

Existing Flood Warning System

A flood warning system does not currently exist for any locations or streams within the City of Greater Bendigo.

Two stream gauges exist within the catchment:

- Bendigo Creek at Bendigo (407254); and
- Bendigo Creek at Huntly (407255)

The Huntly site is instrumented with a logger and 3G telemetry while the Bendigo site is similarly equipped but without telemetry.

There are no other stream gauges within the catchment: the tributary creeks are not instrumented. A number of stream gauges (some telemetered) are operational downstream of Huntly.

[10] It is emphasised that these times are approximate only and are for heavy rain on a wet catchment. Lighter rain or rain on a drier catchment result in much slower response times. In addition, a multi-burst rain event that extends over a number of days will obscure response times: initial rain will wet up the catchment and later (heavy) rain will cause very quick and significant rises in creek levels with possible areas of flooding.

The only rain gauge within the general vicinity of Bendigo (it is also within the Bendigo Creek catchment) that reports in time increments that could be considered useful for a flash flood warning system is the BoM operated Automatic Weather Station (AWS) at Bendigo Airport (81123). This station routinely reports incremental rainfall totals every 30 minutes and more frequently during significant events. Data from the station is available in near real-time from the BoM website.

A Municipal Flood Emergency Plan (MFEP) that includes intelligence on flood impacts within the Bendigo Creek study area (i.e. from the upper catchment down to Huntly) has been prepared for the City of Greater Bendigo as part of this study.

5 - FLASH FLOOD WARNING

A Definition of Flash Flooding

There are a number of differing views on what constitutes flash flooding; from temporary exceedance of urban stormwater drainage system capacity through to large and very rapid rises in both rural and urban streams, sometimes as a result of urban stormwater being discharged to the stream. The trigger for flooding is considered to be essentially the same – high intensity short duration rainfall emanating from severe thunderstorms or rain bearing weather systems that are locally intense and slow moving.

A flash flood is defined in Australia as a flood that occurs within about 6 hours of the start of the rain that causes it (BoM, 1996). The source of flooding, whether the result of urban stormwater system capacity constraints or overflow from a watercourse, is not addressed by the definition: the key issue is time between cause and effect.

Roles and Responsibilities

The BoM provides generalised warnings of weather conditions likely to lead to flash flooding. It does not provide flash flood warnings for specific creeks and locations (i.e. where the catchment response, the time between rainfall and flooding, is less than six hours). A more detailed description of flash flood warning related service provided by the BoM is provided in BoM (1996)[11].

While the task of issuing warnings of weather conditions likely to lead to flash flooding is a BoM responsibility, the task of issuing catchment or location specific flash flood warnings (to the at-risk community, the media or other entities) is a local government responsibility. This division of responsibilities is very different from those associated with the issue of non-flash flood forecast and warnings (which sit firmly with the BoM) and is understood to relate mainly to the need to maximise available warning lead time. A rapid local response is often required.

The division of responsibilities detailed above was formalised in working arrangements for the provision of flood warning services approved by the Commonwealth Government in 1987 (BoM, 1987) and agreed to in-principle by the Victorian Government through the State Disaster Council in early 1988. The arrangements were reiterated and aspects clarified in *Arrangements for Flood Warning Services in Victoria* (VFWCC, 2001)[12] and then endorsed by the relevant Ministers at both State and Federal level.

11 The BoM's flash flood warning service is comprised of four components that depend on the sophistication of available monitoring and forecast capabilities as follows:

- Generalised warnings (issued to the general public and emergency management organisations, generally as a regional severe weather warning) associated with the onset of heavy rainfall. The threshold in Victoria is 25mm in an hour which is around the average 10-year 1-hour rainfall for Victoria.
- Radar based warnings of rainfall (issued to identified agencies and user groups as a severe thunderstorm warning at a space scale, where feasible according to BoM, of a typical local government area) that could lead to flash flooding within specific areas, but only where those areas are covered by suitable weather watch radar and where a threshold intensity, chosen such that its exceedance will produce flash flooding irrespective of existing antecedent catchment conditions, is expected to be equalled or exceeded. In Victoria the current threshold is 20mm in half an hour.
- Area specific predictions of rainfall intensities (issued to local flash flood warning groups where a local warning system has been established) but only in areas covered by suitable weather watch radar.
- Support and advice to local authorities in the establishment of automated flash flood warning systems (for example, ALERT systems) and related matters.

12 Comrie (2012) noted that the arrangements described by VFWCC (2001) are not couched in TFWS terms and fail to address system elements that do not have a technical basis.

What this means is that any flood warning system established for a stream or location considered to be subject to flash flooding will need to be purchased, installed and maintained by the local council but that the BoM will provide advice aimed at assisting the council establish and develop the technical aspects of the system. Operational responsibility, and thus message construction and dissemination, will also reside with council. The BoM will, however, assist through the supply of operational software for data management and alerting and continue delivery of existing severe weather and flood warning related services. While it is not specifically stated where responsibilities for other elements of the TFWS reside, it is apparent that arrangements in place for non-flash flood warning systems apply. Thus delivery on a number of TFWS elements, including the development and application of flood response plans as well as (flash) flood education and awareness programs[13], is a shared state and local government responsibility.

Funding to establish local flash flood warning systems has been available through the Natural Disaster Resilience Grants Scheme (NDRGS). While the initial contribution from councils can range from zero to 33 per cent of capital cost, they are required, as part of the funding agreements, to maintain infrastructure which includes gauges as well as monitoring and warning equipment.

The principles applying to the provision of flash flood warning services can be summarised as:

- The BoM has a responsibility to provide predictions of weather conditions likely to lead to flash flooding.
- Local government has prime responsibility for flash flood warnings extending from system establishment and operation through to the provision of predictions of stream levels if required.
- The BoM will provide specialist technical assistance and advice to local government to assist in system establishment and in relation to flood prediction techniques.
- Arrangements for the delivery on other TFWS elements, including the development and application of flood response plans along with (flash) flood education and awareness programs, is a shared state and local government responsibility, the same as for non-flash flood warning systems.

Possible Changes to Roles and Responsibilities

While there is always the potential for change, it is considered unlikely in the short term that there will be any significant changes to the roles and responsibilities outlined above. This statement is based on consideration of the Victorian Government's White Paper on Emergency Management Reform (Victorian Government, 2012) and particularly the statement on page 30 that "*local government will retain its current responsibilities to fund specific mitigation activities (such as flood warning systems ….)*."

It is noted that the Department of Environment and Primary Industries (DEPI) is about to initiate a project in response to recommendation 5 of the Victorian Floods Review (Comrie, 2011)[14]. The project will in part consider which agency is responsible for flash flood warning and which agencies are responsible for various TFWS elements associated with flash flood warning systems. It is assumed that results from this project are unlikely to be available to inform the delivery of recommendations for flash flood warning within the City of Greater Bendigo.

6 - THE TASK FOR BENDIGO

Introduction

Consideration of outputs from the Bendigo Urban Flood Study indicate that there are three critical flooding issues for Bendigo:

- The speed with which floods develop and propagate through the Bendigo Creek catchment to Huntly;
- Flooding of the CBD;

[13] Due to the relatively short warning lead times for flash floods, it is critical that people are aware of the potential consequences prior to an event. It is therefore important that in areas with a history of flash flooding, VICSES and councils adopt flash flood education and awareness programs.

[14] Recommendation 5: The VFR recommends that the state engage with the Bureau of Meteorology to establish a joint initiative to review existing flash flood warning systems in Victoria and identify where additional systems are needed, with a particular focus on urban centres with a history of flash flooding. This review should seek to achieve outcomes similar to those implemented in NSW. Subject to those outcomes being implemented, the state should determine which agency is responsible for flash flood warnings.

- Over-floor flooding of buildings; and
- The hazard caused by floodwater flowing quickly over roads.

Floods develop and rise quickly in the Bendigo Creek catchment, more so when the area is wet: catchment response times are less than 6 hours (see Section 4.2). This places the catchment in the flash flood category[15] with a need for any rain and water level data to be available locally in real-time. The categorisation also determines where responsibilities lie with respect to the purchase, installation and maintenance of any data collection equipment to support flood warning systems for Bendigo's communities[16]. In summary, these responsibilities reside at the local level (i.e. with Council) although the BoM will provide technical assistance[17].

It is suggested that in view of the likely cost - benefit ratio (i.e. sustainable economic metrics), the likelihood of securing State and Federal funding support for the purchase, installation and development of a sophisticated flash flood warning system would be reasonably positive. However, under existing arrangements, there would need to be commitment from Council to contribute to capital and other establishment costs as well as to the operation and maintenance of all equipment associated with the system. That would include all on-going costs.

If an effective flash flood warning system is to be established for the Bendigo Creek catchment, attention will need to be given to each of the TFWS building blocks. Installing rain and / or river gauges will not be sufficient. Practical information on what to do in response to flash flooding is critical (Environment Agency, 2009). It is important that attention is paid to issues of risk communication including:

- Building local awareness of flood risk along with knowledge of what can be done to minimise that risk;
- Determining what information is required by the at-risk community and with what lead times;
- How warnings and required information will be distributed to and within the at risk communities;
- Ensuring that recipients of warning messages understand what the message is telling them and what it means for their property and individual circumstances in terms of the damage reducing actions they need to take.

In other words, attention will need to be given to all elements of the TFWS.

The following sections outline how each of the TFWS elements could be addressed in order to implement an appropriate, functional and sustainable flash flood warning system for Bendigo Creek. An integrated and complete system is proposed in Section 7. A staged approach to implementation of the proposed response to each TFWS element, aimed at achieving balanced TFWS growth along with early and best benefit as quickly as possible, is presented in Section 9. Indicative costings are provided in Section 8.

Data Collection and Collation

Introduction

There is a variety of equipment available that will "collect" rain and river level data and make it available to a single entity or to a group of entities, either from the site, through a post box or delivered to a predetermined address. There are a number, but fewer, systems that collect the data, make it available in the desired format at the desired location(s), provide an alert of likely flooding (i.e. detect or predict the likelihood of flooding) after checking the data against pre-determined criteria and that also quality check and collate the data so that it is ready for use. Some of these systems are "turn key" while others are user built. All are modular in that fault-fix maintenance is generally via component plug-out / plug-in and expansion easy to achieve.

15 A flash flood is defined as a flood that occurs within about 6 hours of the rain that causes it (BoM, 1996).

16 Arrangements for the provision of flood warning services in Victoria were formalised in working arrangements approved by the Commonwealth Government in 1987 (BoM, 1987) and agreed to in-principle by the Victorian Government through the State Disaster Council in early 1988. These arrangements were reiterated and aspects clarified in *Arrangements for Flood Warning Services in Victoria* (VFWCC, 2001) and then endorsed by the relevant Minister at both State and Federal level. State and local entity responsibilities are addressed in the Emergency Management Manual Victoria as well as in applicable State legislation.

17 What this means is that any flood warning system established for a stream or location considered to be subject to flash flooding will need to be paid for and managed by the local council but that the BoM will provide advice aimed at assisting the council establish and develop the technical aspects of the system. Operational responsibility, and thus message construction and dissemination, will also reside with the council. The BoM will, however, assist through the supply of operational software for data management and alerting and continue delivery of existing severe weather and flood warning related services. While it is not specifically stated where responsibilities for other elements of the TFWS reside, it is assumed that arrangements in place for non-flash flood warning systems apply.

Turnkey Systems

Introduction

Turnkey systems are 'complete' or integrated systems. The vendor provides all equipment including the base station software and then installs and configures all components. Maintenance is usually undertaken under contract to the vendor. Systems are generally scalable.

Greenspan

Greenspan (part of TYCO Integrated Systems) is am Australian based supplier of turnkey flood warning systems. Standard or customised solutions are offered that include site investigation, system design services, installation, testing, commissioning, operation and maintenance. Solutions are tailored to the location and can include integrated hydrologic and hydraulic modelling. In such systems, processing is generally done off-site in Greenspan's office and authorised users log-in to obtain data and forecasts. Alarms set within the system enable SMS and email messages to be sent to nominated persons. Systems can also be configured to initiate remotely controlled (radio linked) warning signs.

A number of flood warning focussed systems are in operation and include:

- Sipan Sihaporas Hydro Electric Power Scheme in Indonesia;
- San Roque Dam and Hydro Power Scheme in the Philippines;
- SMART (Stormwater Management and Road Tunnel) in Kuala Lumpar in Malaysia;
- Public protection system for the Bruce Highway at Proserpine for Queensland Main Roads;
- Flash flood warning system for Warringah Mall in Brookevale in NSW.

Capital and operating costs are not available "off the shelf" but are generally more expensive than the ERTS equipment generally favoured by the BoM. The technology and equipment used however offers significantly more functionality.

Other Automated Data Collection and Alerting Systems

Introduction

Other systems in the context of this discussion paper are those that are built up by the system owner using readily available hardware that is compatible with existing hardware and that can easily operate with existing data interrogation and storage software.

Campbell Data Logger

Campbell data loggers provide a level of functionality and reliability that has seen them installed at many water resources sites across Victoria over the past 10 years or so.

They generally collect data at a combination of predetermined frequencies and exceedance criteria. When paired with a 3G modem, they can be interrogated by computer via the telephone system (fixed and mobile). They can also be set to dial out or SMS to one of a number of pre-determined telephone numbers or to email to one or more addresses when alarm criteria (either single or multi-parameter with simple or conditional rules) are exceeded. The alarm rules are user-specified and can be used (say) to alert to the likelihood of flooding and the detection of flooding.

It is understood that both the Bendigo and Huntly stream gauge sites are instrumented with one of these loggers (see Section 4.4).

Quality control of data accessed direct from site is an end-user responsibility. Any data loaded to the State Data Warehouse for long-term archive is subject to rigorous quality control and correction.

Other Data Loggers

A variety of other data loggers with similar functionality and pricing are readily available within Australia, mostly off-the-shelf. However, they are not as widely used as the Campbell logger within Victoria. It is suggested that while there are no functional reasons for not considering these alternatives for the Bendigo Creek catchment, there are likely to be additional costs associated with their use. These are likely to include, for example, additional capital cost associated with stocking the equipment maintenance pool, additional installation costs due to need to gain familiarity with logger setup, and additional on-going operating and maintenance costs due to the need to establish new procedures for data retrieval and on-site activity.

There are also a number of low cost options becoming available on the market for collection of rainfall and streamflow data. While this equipment has not been as widely tested and used as the Campbell data logger, it may be of interest to Council for Bendigo Creek.

Event Reporting Radio Telemetry System

Event-Reporting Radio Telemetry System (ERTS) equipment has been installed at a number of sites across Victoria Base stations are operational at agreed local offices and at the BoM office in Melbourne. All base stations host BoM supplied and maintained Enviromon software. This software manages all the data checking, collation and alerting functions.

Each ERTS flood monitoring system gauge sends a signal by radio to one or more base stations every time there is a change in state of the parameter being measured – each increment of rainfall (can be 0.2mm, 0.5mm or 1mm) and a predetermined rise in stream level (usually every 10mm).

Quality and other checks are performed automatically against pre-determined parameters (threshold checking and alerting) on the data as it is received in real-time at each base station. These checks include a comparison of rainfall and river level data received from each of the stations against a pre-set rainfall amount in a specified time period and / or against a pre-set river level threshold. The values selected reflect typical catchment response times as well as catchment and stream characteristics.

For Bendigo, a useful rainfall trigger may be the rainfall intensity over the time of concentration for the catchment or the critical duration that produces the first overbank flows in the vicinity of the nearest (downstream) at-risk location. Any creek height thresholds would be set based on consideration of a range of factors particular to each gauge location. Trigger values can be adjusted based on experience so that alarms do not trigger unnecessarily or too often but do provide sufficient lead time on a potential flash flood event.

The base station can be programmed to initiate an SMS message to the mobile phone (or pager) of key personnel[18] as soon as the trigger rate / value is exceeded. The SMS alert provides a 'heads up' to a possible flash flood situation. It is aimed at flagging the need for people to more closely monitor rainfall and other flood indicators (e.g. continuing heavy rain and other local indicators of a developing flood, including radar imagery and rainfall data available from the BoM website, etc), and at enabling early activation of flood response and related plans in order to minimise the risk to life and property. The 'heads up' also provides the trigger to use a proposed quick look 'flood / no flood' tool that will be developed and included in the Municipal Flood Emergency Plan Appendices.

A more detailed explanation of ERTS systems and their benefits when used in flash flood situations is provided by Wright (1994).

Manual Data Collection and Alerting

Due to the quick response of Bendigo Creek and its tributaries to heavy rain, it is not recommended that manually read rain gauges be deployed and locals co-opted to provide readings during heavy rain. There is insufficient time for this to occur with any certainty of success, where success is deemed to be the provision of rainfall information and / or an indication of the scale of likely flooding to those likely to be affected with sufficient lead time to enable implementation of damage reducing actions.

Possible Data Collection Sites and Base Stations

There is only one (1) rain gauge within (or within the vicinity of) the Bendigo Creek catchment that provides data at a time scale suitable for flash flood warning purposes: the AWS at Bendigo Airport. Data is available from the BoM website at approximately 30 minute intervals.

In the context of flash flood warning and with due consideration of where avoidable flood damage occurs (e.g. houses flooded over-floor, danger to road users, the CBD, etc), the topography and likely flood producing weather mechanisms and conditions, the spatial and temporal coverage that this gauge provides is considered to be less than ideal. As a consequence, there is an argument for improved coverage through the upper and middle parts of the catchment. ERTS rain gauge installations are proposed as follows with the number and spread of sites aimed at providing solid coverage of the Bendigo Creek catchment within Bendigo:

[18] Key personnel could include members of the at-risk communities.

- In the general vicinity of Diamond Hill;
- At Spring Gully Reservoir or perhaps in the vicinity of One Tree Hill;
- At Reservoir No 1 or perhaps in the vicinity of Flora Hill;
- In the general vicinity of Kangaroo Flat but in an elevated location;
- At Specimen Hill;
- In the general vicinity of Golden Square;
- At Long Gully or California Gully or somewhere in between;
- In the Whitehill area; and
- At the Racecourse.

It is appreciated that nine (9) new rain gauge sites may appear excessive. However, the network is proposed on the basis of thunderstorm activity, rather than widespread general rainfall events, leading to flooding. It is stressed that the above sites could be instrumented progressively with two (2) additional sites considered the minimum feasible. This would enable initial capital and effort to be directed to a sub-set of these sites.

The cost of adding a rain gauge to a stream gauging site is not prohibitive. It is therefore suggested that while location and exposure may not be ideal, a rain gauge could be added to the existing Bendigo Creek at Bendigo site (407254). If this is done, ERTS telemetry should also be added to the site.

Data from these sites should be captured by the base stations at the BoM offices and displayed on the BoM website. While this will enable data to be accessed by the local community, it is suggested that Council also establish a local base station and consider whether there is a need to make data more available locally and how that might be achieved. The local base station will also enable Council to develop a forecasting capability (see Section 6.3 below).

Stream gauges are not proposed at this stage. Council may wish, at a later time, to consider their installation to assist in the recognition and scaling of likely flooding, perhaps as an aid to the further development of a forecasting capability. However, as flooding occurs very quickly and travel times are short, it is suggested that any benefits to be gained from stream gauges are unlikely to be substantial, at least in the near to medium term. If river gauges were being considered, a suggested first installation would be immediately upstream of the CBD.

Staff gauges are also not proposed at this stage although their installation at key locations (e.g. upstream of key road crossings and in the vicinity of the CBD) could assist in the recognition and scaling of likely flooding and with operational monitoring during an event. Data from these sites would also aid post-event analyses[19].

Note that even without the installation of the proposed rain gauges, the indicative quick look “flood / no flood” tool developed as part of this project (refer to Appendix A of the MFEP) will be able to be used during general rain events with Bendigo airport rainfall data to provide an initial heads-up with some lead time of the likelihood and scale of possible flooding within the catchment.

Flood Detection and Prediction

An overview of flood warming services provided within Victoria by the BoM is available at Appendix A.

There are currently no flood warning systems or arrangements in place for the Bendigo Creek catchment. As the catchment is subject to flash flooding (see Section 6.1), Council has a lead role in system development, operation and maintenance. This includes flood prediction.

Normally and as part of a more comprehensive forecasting capability, a rainfall – runoff model that makes use of rain and river data telemetered from each of the proposed data collection sites would be proposed. This type of model provides a prediction of flow and gauge height at key locations using measured and / or predicted rainfall. It generally requires a stream gauge at each forecast location so that initial conditions can be fed into the model and the forecast hydrograph (or levels) can be tracked against the actual stream response in terms of timing and levels. Forecast levels then need to be translated into areas affected. This can be done through a linked hydraulic model or through reference to comprehensive flood inundation maps.

[19] Post-event ground survey of flood extents also informs post-event and other analyses.

The response time for Bendigo Creek is very short. The comprehensive TUFLOW hydraulic models developed as part of the Bendigo Urban Flood Study take longer to run than the creek takes to respond. It is not therefore proposed that the TUFLOW hydraulic models be used for operational flood forecasting. If an operational hydraulic model was required for flood forecasting purposes it is recommended that a simple 1D hydraulic model such as HECRAS or MIKE11 be used in conjunction with a hydrological model such as RORB which estimates the streamflow. Water Technology has demonstrated that such a model can be developed for complex environments, with a trial model on the Gippsland Lakes providing proof of concept for the Bureau of Meteorology.

Other approaches to flood forecasting have used measured and predicted rainfall to determine an input field (in terms of IFD) and then matched the rainfall to a flood profile (e.g. extent, depth, velocity, hazard) determined from the predetermined design event flood mapping.

It is suggested that a GIS based forecasting approach may have application for Bendigo. Rainfall data from each gauge would need to be assessed in real-time against IFD criteria (i.e. looking at the intensity and return period of recorded rainfall over a range of durations around the critical durations for each stream) and then matched up against the inundation mapping produced by the study. The inundation maps would need to be segmented so that different exceedance probability extents could be predicted for the various segments of the streams and for downstream areas. Using the areal extent as a trigger, the GIS could also extract the addresses of properties and / or other assets likely to be flooded over-floor (based on depth of flooding as floor level information was not available to the Bendigo Urban Flood Study) and the names / locations of streets likely to experience high hazard flooding (i.e. where the velocity – depth product is (say) greater than 0.3).

There are many commercial systems that can provide this kind of real-time hydrological analysis, flood risk assessment, visualisation of results and message dissemination. Water Technology is the Australian distributor of HydroNET (www.hydronet.com.au), a product that has proven itself in Europe and is rapidly expanding its user group. Water Technology is currently in discussion with a number of Victorian authorities regarding the implementation of HydroNET[20].

It is noted that DEPI is currently working on the development of a flood mapping access and enquiry tool, FloodZoom. It is possible that FloodZoom may offer some scope for the City of Greater Bendigo to utilise it to assist flash flood prediction capacity.

Regardless of the above, as a first step and in the absence of a formalised flash flood forecasting system, it is suggested that the indicative quick look 'flood / no flood' tool located in Appendix A of the MFEP should be made available to at-risk communities within Bendigo. The tool does provide some guidance on the likelihood and possible severity of flooding within the Bendigo Creek catchment. Rainfall depths from the upper parts of the catchment and / or from the general vicinity of the location are used in the tool to determine the likelihood and severity of flooding through a link to the flood inundation maps delivered as part of the Bendigo Urban Flood Study. It is suggested that the inundation maps, quick look tool and associated instructions for its use should be loaded to the City of Greater Bendigo website where they can be accessed and used by individuals with the at-risk communities.

Flood class levels, determined against standard definitions[21], are used to establish a degree of consistency in the categorisation of floods. In order to assist the flash flood warning process and increase awareness of flooding within the community, particularly if the Bendigo Creek at Bendigo site is telemetered and / or a stream gauge is installed on Bendigo Creek upstream of the CBD, flood class levels should be established for telemetered stream gauge sites in the catchment.

Interpretation

The flood inundation maps and MFEP Appendices developed as part of the Bendigo Urban Flood Study provide the base information to enable the community (and stakeholder agencies) to determine the likely effects of a

[20] HydroNET has additional functionality which would allow it to ingest rainfall data in real-time and identify areas at risk (based on consideration of depth and velocity). These areas could be available and shown in real-time, using a traffic light or similar system, to the community through a web portal. The system could be searchable by address. Consideration would however need to be given to the number and location of rain gauges installed to support HydroNET.

[21] Standard definitions for minor, moderate and major flood class level are available from the BoM website.

potential flash flood. This means however that the flood inundation maps and relevant MFEP Appendices would need to be readily available to the Bendigo community. Without this the proposed flash flood warning system would be severely compromised.

Message Construction and Dissemination

Background

According to Rogers and Sorensen (1988), warning people of impending danger encompasses two conceptually distinct aspects—alerting and notification. Alerting deals with the ability of emergency officials to make people aware of an imminent hazard. Alerting frequently involves the technical ability to break routine acoustic environments to cue people to seek additional information. In contrast, notification focuses on how people interpret the warning message. It is the process by which people are provided with a warning message and information.

Discussion

There are a number of alerting and notification tools and technologies available, some of which both alert and notify. Molino et al (2002) provide a summary worth considering in the context of Bendigo and flash flooding. Only those that can very quickly provide property owners and occupiers with an alert or notification have been considered herein due to the quick response time associated with flooding through Bendigo.

A summary of available tools / technologies and their applicability to the Bendigo area is provided below.

- Those that alert only:
  - Sirens / alarms – do not alert those who live outside the immediate area and possible confusion with the Country Fire Authority siren
  - Aircraft – impractical due to time, weather and noise limitations
  - Modulating electrical supply voltage – frequent false alarms
  - Modulating electrical supply frequency (e.g. NZ MeerKat system) – unlikely to be cost effective
  - Coded visual signals (cf. fire danger signs) – not practical due to rapid onset of flooding
  - Laser lights – health risks and high potential for theft of equipment
- Those that alert and notify:
  - Personal notification – impractical due to rapid onset of flooding and resources needed
  - Fixed and mobile public address systems – only serves immediate area
  - Tone alert radios – not cost effective for a small area
  - Dial-out systems and related technologies – worth considering
  - Enhanced dial-out system – similar to above but more expensive and reliant on local power supply
  - Paging and mobile phones – potential if local community is flood aware
- Those that provide notification only:
  - Mass media (radio, television) - already used, for example ABC radio (1026AM and 774AM)
  - Internet – BoM website displays warnings[22] and data from local rain and river sites[23]
  - FM-88 with community awareness program – worth considering

It is likely that for a (small) number of Bendigo residents, the initial alert of likely flash flooding will come from environmental indicators (i.e. heavy rain) and from application of the quick look "flood / no flood" tool (i.e. likely severity and impact of expected flooding). The message in relation to likely consequences and required actions will be as derived by the individual as a result of their consideration of information provided by the tool, the MFEP and the flood inundation maps. There is a need however to alert the Bendigo community to the likely on-set of flooding and to then back this up with information about likely consequences. This will enable individuals to initiate appropriate damage reducing actions.

The need to alert communities to flash flooding is not restricted to Bendigo. While a number of flash flood warning systems have been installed in NSW, the community alerting task in Victoria is a VICSES responsibility

[22] While the Bureau does not provide a flash flood warning service for the Bendigo Creek catchment, it does issue severe storm and thunderstorm warnings, phenomena that often lead to flash flooding in similar catchments.

[23] Rain and water level data from AWS's and other telemetered sites are available on the BoM website in near real-time.

and, when time permits, is usually achieved via local radio announcements. Active alerting is only undertaken occasionally and generally involves door knocking and loud hailer street announcements. Other States, with the exception of Victoria and to some extent South Australia and Queensland, do not appear to have as yet addressed the issue. In South Australia and Queensland, the Bureau of Meteorology alerts and notifies selected stakeholder agency staff using an SMS message initiated by Enviromon and delivered by service provided by StreetData. Within Victoria, many of the Councils involved in flood warning system upgrades in recent years have implemented Premier Global Services' Xpedite VoiceREACH system to alert and notify residents and property owners in flood-prone urban areas. Melbourne Water are piloting an in-house developed SMS alerting system for residents in an area subject to flash flooding alongside Brushy Creek in the City of Maroondah and in Laburnum in the City of Whitehorse (Rasmussen, 2013) both of which are triggered by the exceedance of rain or water level alarm criteria[24].

Both Xpedite (www.premiereglobal.com.au/voicereach/voicereach_broadcasting.htm) and StreetData (www.streetdata.com.au) are available and operational within Victoria. Both use existing technology, are quick and effective and are relatively cheap to implement and maintain, but require good quality broadband internet access from the host computer. For either to be truly effective, the at-risk or target community needs to be flood aware.

The Early Warning Network (www.ewn.com.au) is a multi-channel (SMS, email, Facebook, Twitter, Apps) geographic based distribution system for warnings and incidents issued by government agencies and other sources. Alerts via the SmartPhone Apps and via email are free while the SMS'ed alert service incurs an annual fee. A number of Councils (e.g. Brisbane City Council) pay an annual fee in order to provide the SMS service free to their residents. Subscription costs vary depending on the features required and the number of people registered under a particular subscription. A Council can also provide information (e.g. flash flood warnings) to the Early Warning Network for delivery to those residents in the impact area who have registered or subscribed to the service.

The national Emergency Alert (EA) system provides VICSES with a means of delivering short messages to selected areas. While the EA has application for all emergency situations, it is unlikely for a number of reasons to be used during smaller flood events. It may also not be suitable as a means of warning residents in the Bendigo Creek catchment of possible severe flash flooding events due to the short lead times available.

Expedite VoiceREACH

A number of Councils within Victoria have had to address the issue of how best to alert their flood–prone urban communities to the on-set of flooding. In all cases (City of Greater Shepparton for Shepparton and Mooroopna, Latrobe City for Traralgon, Strathbogie Shire for Euroa, Moira Shire for Nathalia, City of Benalla for Benalla, City of Geelong for selected areas within the Municipality and City of Maribyrnong for Maribyrnong Township) Premier Global Services' Expedite VoiceREACH system was selected to perform the alert and notify task.

VoiceREACH is simple to set up, implement, use and maintain. When flooding is likely, a message is scripted by Council staff and, following log-in (from any computer with broadband internet access) to the VoiceREACH website, is read into a file by the user. The message is confirmed via playback and either edited or accepted for transmission. On acceptance for transmission, VoiceREACH delivers the voice message almost simultaneously to all telephone numbers in the user-managed telephone number file[25] located on the VoiceREACH website.

VoiceREACH provides a message despatch report and delivers (by email to the user) a delivery success or failure report for each number in the telephone number file. This provides a template for follow-up door knocking or other personal approaches, if and as appropriate.

While not confirmed, it is understood that VoiceREACH message delivery may be able to be initiated by

[24] In addition, Melbourne Water and the Cities of Maroondah and Whitehorse collaborated with VICSES on the roll-out of a StormSafe program for residents affected by flash flooding along a reach of Brushy Creek and within a part of Laburnum. This has included helping residents develop personal residential flood response plans and supplying fully equipped household flood kits.

[25] The telephone number file is established and managed by the user. Numbers can be added and deleted online. Experience at Shepparton and Nathalia suggests that residents in at-risk areas should be invited to opt-out (rather than opt-in) to the system and receipt of alerts.

Enviromon through delivery of a pre-formatted voice file on triggering of a field station sensor alarm level. Enviromon has the capability. The issue is whether VoiceREACH requires real-time interaction with the user or whether it can be automated. If it can, automatic activation driven by river and rainfall alarms should be possible. This would, however, require additional configuration of the existing Enviromon software and the establishment of a base station within the City of Greater Bendigo. At this stage, it is not clear how soon or to what extent BoM would be able to assist with this.

StreetData

StreetData offers an SMS delivery service[26]. The disadvantage of StreetData that it can only deliver an SMS message. This means that unless a telephone handset recognises SMS protocols, only mobile phone owners can receive the message[27]. Further, there is no guarantee of delivery, delivery is not necessarily immediate and there is no confirmation that the message has been received: it is essentially a "fire and forget" system.

When coupled with Enviromon, StreetData can deliver a pre-scripted SMS message to a local user-maintained list of telephone numbers on the exceedance of alarm criteria on each sensor reporting into (or interrogated by) the base station. The alarm system operates on filtered rather than raw data which reduced but does not eliminate the opportunity for errors.

To set up the system, alarm criteria are set for each sensor, message scripts are developed and loaded to Enviromon and a StreetData account is opened. BoM has established a streamlined procedure with StreetData that makes this last step very easy. Essentially, all that is required is a credit card with which to purchase initial credits.

Enviromon can be set up to send the message to StreetData with a single, block of or all listed telephone numbers[28]. BoM recommends however that the message is sent to StreetData for each telephone number. This reduces the risk of message loss as, if there is a failure, only single, rather than many recipients fail to receive the message.

Enviromon can be configured to automatically drive the alerting process. It will monitor data from each sensor at each site[29] and can drop real time data into the pre-scripted messages.

StreetData credits expire at the end of each 12-month period unless further credits are purchased in which case they roll-over for a further 12-months. StreetData send a reminder email when credits are about to expire. Costs per call reduce with the number of credits purchased.

The Bureau is in the process of finalising documentation for the use of StreetData with Enviromon[30].

FM-88

A number of the Municipalities utilising Xpedite also secured an FM-88 licence and associated equipment in order to provide a means of distributing flood and other emergency messages more widely, including to visitors, road users, etc.

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[26] There are a number of alternative SMS message service providers. Generally, these either have a higher minimum monthly spend or are domiciled outside Australia. StreetData has a flexible credits program that accommodates low usage without imposing a high cost and is fully based in Australia.

[27] This gap could be covered if flood wardens were appointed and given the responsibility of passing on information to groups of people without a mobile phone. Robyn Betts (OESC) suggested that flood wardens could also assist other community members in interpreting messages. However, lack of time coupled with liability and other issues may mitigate against the appointment of and utility of wardens.

[28] There is a limit of 250 telephone numbers per message.

[29] This enables both data and system alerts to be generated. For example, if any pre-set alert criteria were exceeded an SMS message could be sent to a Duty Officer to prompt activation of Xpedite to alert the community to potential (or actual) flooding. An SMS message could also be sent to a Duty Officer if there was no activity on a sensor over a set period, thereby assisting local monitoring of system integrity.

[30] Enviromon can accommodate other programs that initiate other actions provided that an interface is available or developed. This means that if the City of Greater Bendigo wished to initiate a siren (say) on exceedance of alarm criteria, provided there was a program available to activate the siren and provided that an interface was prepared, the Enviromon alarm function could be used to sound the siren.

Community Involvement

It is generally recognised that a critical issue in developing and maintaining a (flash) flood warning system is the active and continued involvement of the flood-liable community in the design and development of the total system so that their warning needs are satisfied. It is therefore suggested that the City of Greater Bendigo give strong consideration to championing the formation of a community flash flood action group (or similar).

Members of this group could play a key role in local flash flood warning operations and review.

Response

The Bendigo MFEP Appendices have been populated for the Bendigo Creek catchment as part of the Bendigo Urban Flood Study. Information in the MFEP includes all available intelligence relating to flooding in the Bendigo Creek catchment upstream of Huntly along with indicative quick look "flood / no flood" tool based on local and upper catchment rainfall depths. Flood inundation extent and depth maps are included together with a list of areas and roads likely to be flooded. A flood intelligence card has also been prepared.

Community Flood Awareness

Following is a list (not exhaustive) of some of the more common misconceptions held by people who live in flood-prone areas. These misconceptions often act as a major barrier to improving flood preparedness and awareness within the community and thus hinder efforts to minimise flood damages and the potential for loss of life.

- The largest flood seen by the community / individual is often confused with the maximum possible flood (i.e. the next flood couldn't be bigger). This idea becomes more entrenched the bigger the flood witnessed previously.
- Areas that haven't flooded before will not flood in the future. This is an extension of the first bullet point.
- The stream cannot be seen from the house so the house couldn't possibly be at risk of flooding.
- A levee designed to hold the 1% Annual Exceedence Probability (AEP) flood will protect the community from (all) flooding and therefore a flood warning system is not required.
- The 1% AEP flood (i.e. the 100-year ARI flood), once experienced, will not occur for another 100 years.
- The statistics and estimates that underpin hydrology are exact.

Studies repeatedly show that communities that are not aware of flood hazard are less capable of responding appropriately to flood warnings or alerts and experience a more difficult recovery than a flood-aware community. Plain language flood awareness campaigns[31] should aim to erase these misconceptions

There are a number of activities that could be initiated to maintain and renew flood awareness within the urbanised parts of the Bendigo Creek catchment. The emphasis should be on an awareness of public safety issues (including the flash flood monitoring system) and on demonstrating what people can do to stay safe and protect their property from flooding. Typical initiatives include:

- Making the MFEP publicly available (Council offices, library, website) with a summary provided in Council welcome packages for new residents and business owners and with annual rate notices.
- Championing a community flash flood action group (or similar).
- Periodically providing feature articles to local media on previous flood events and their effects on the community.
- Installing flood markers indicating the heights of previous floodwaters (e.g. on power poles, street signs, public buildings, sides of bridges, etc).
- Preparing and distributing property specific flood depth charts for all properties likely to be affected by flooding within the urbanised parts of the Bendigo Creek catchment[32]. This information could also be included in the Bendigo MFEP.

[31] Such as the VICSES Local Flood Guide program.

[32] In order to develop property specific flood depth charts for properties likely to be affected by flooding in Bendigo, a large number of floor levels would need to be surveyed. Water levels would also need to be extracted from the model results for each property.

- Installing flood depth indicators along the edge of roads where there is an appreciable danger to human life due to flood depth and / or velocity (e.g. at strategic locations as indicated by the flood hazard maps delivered by the Bendigo Urban Flood Study).
- Photo displays of past flood events in local venues (these could be permanent).
- Preparing and distributing (as an on-going program) a flash flood action guide or brochure (e.g. Local Flood Guide and as described by Crapper et al (2005), in relation to Shepparton and Mooroopna) aimed specifically at encouraging local residents and businesses to take a pro-active role in preparing their property and themselves for a flood as well as describing what needs to be done during a flash flood event. These could be given out at local events, to schools and with council rate notices and / or other council communications.

7 - SUGGESTED SYSTEM FOR BENDIGO

Table 7-1 provides a brief description of the basic tools needed to deliver against each TFWS building block together with an outline of possible solutions applicable to the Bendigo Creek catchment upstream of Huntly. The solution has regard for:

- The flash flood nature of the catchment and the very limited lead time available between heavy rain and stream rises;
- The character of the flood risk (i.e. rapid onset, flooding of the CBD, over-floor flooding of buildings, high hazard along a number of roads, etc); and
- Economic metrics (i.e. likely cost – benefit based on consideration of the contribution of avoidable damages to the value of average annual damages).

Table 7-1 Flash Flood Warning System Building Blocks and Possible Solution for the Bendigo Creek catchment upstream of Huntly with due regard for the EMMV, Commonwealth-State arrangements for flood warning service provision (BoM, 1987; VFWCC, 2001; EMA, 2009)

Flood Warning System Building Blocks	Basic Tools	Possible Solution for the urbanised part of the Bendigo Creek catchment
DATA COLLECTION & COLLATION	Data collection network (e.g. rain and stream gauges)	Install a minimum of 2 and up to 9 x new ERTS rain gauges. Consider adding rain gauge and ERTS telemetry to stream gauge at Bendigo Ck at Bendigo. No new stream gauges proposed although could add stream gauge upstream of CBD. No staff gauges proposed although could add gauge boards at key road crossings and CBD.
	System to convey data from field to central location and / or forecast centre (e.g. radio or phone telemetry).	ERTS is a commercially available radio telemetry data collection system that reports any change in the parameter being measured by radio in real-time to a base station. BoM base station in Melbourne will receive data. Ideally, local base station would be installed in Bendigo.
	Data management system to check, store, display data.	ENVIROMON – base station software provided and maintained by BoM. Will require BoM to add new rainfall sites to data tables accessible via the BoM website. Council to consider whether there is a need to make data more available locally and how that might be achieved.
	Arrangements and facilities for system / equipment maintenance and calibration. For example, the Regional Surface Water Monitoring Partnership, data QA'ing and warehousing, etc.	Commercial arrangement between Council and a service provider for maintenance. Ideally this would be achieved through the Surface Water Monitoring Partnership as that would also ensure that all data was QA'ed and archived. Include all capitalised system components on Council's asset management register.
DETECTION & PREDICTION (i.e. Forecasting)	Rainfall rates and depths likely to cause flooding together with information on critical levels / effects at key and other locations.	INITIALLY: Using the tools described below together with data from nearby rainfall stations, individuals and agencies determine the likelihood and scale of possible flooding at key locations.
	Appropriately representative flood class levels at key locations plus information on critical levels / effects.	Establish flood class levels for telemetered stream gauge sites within the catchment. LATER: In order to initiate local alerting of potential flooding, use rainfall rates and depths from the MFEP tools to set rainfall gauge alarm criteria. This will necessitate consideration of who should be alerted and what they should do following the alert.
	Flood forecast techniques (e.g. hydrologic rainfall - runoff model, stream flow and / or height correlations, simple nomograms based on rainfall).	The indicative quick look "flood / no flood" tool developed for Bendigo and included in the Bendigo MFEP provides guidance on the likelihood and scale of possible flooding. Council responsible for maintaining the tool. Decide how the tool is to be used and who by – Council, VICSES? NCCMA? community? GIS based forecasting approach or HydroNET (www.hydronet.com.au)may have application for Bendigo. Could involve assessing real-time rainfall against IFD criteria and matched up against inundation mapping for sections of the creek system. Using the areal extent as a trigger, GIS could identify properties and other assets likely to be inundated or experience high hazard flooding. Will need to be developed.

Flood Warning System Building Blocks	Basic Tools	Possible Solution for the urbanised part of the Bendigo Creek catchment
INTERPRETATION (i.e. an ability to answer the question "*what does this mean for me - will I be flooded and to what depth".*	Interpretative tools (i.e. flood inundation maps, flood information cards, flood histories, local knowledge, flood response plans that have tapped community knowledge and experience, flood related studies and other sources, etc).	Deliverables and intelligence arising from the Bendigo Urban Flood Study have been captured to the Bendigo MFEP. This includes flood extent, depth and hazard mapping together with information about which areas / roads are likely to be affected along with guidance on the expected depth of that flooding. The quick look tool (see above) together with the MFEP enable those at risk to determine, with some lead time, whether they are likely to be flooded. In order to enable community members to determine the likely effects of a potential flood, Council to make the flood inundation maps and relevant Appendices of the MFEP readily available to Bendigo communities. This will also inform their development of individual flood response plans (see below). If and after additional rain gauges have been installed, Council to review the quick look tool to ensure that the tool is making best use of available data. Council to periodically (and after each major flood event) review the quick look tool and update / refine as necessary as part of maintaining a strong awareness of and engagement in the FFWS and its continuous improvement.
MESSAGE CONSTRUCTION	Warning messages / products and message dissemination system.	Short hydrologic response time, hence simple automated messaging is likely to work best, if required. In severe flood situations, the Emergency Alert would be used to disseminate critical information and key messages.
MESSAGE DISSEMINATION (i.e. Communication and Alerting)	Formal media channels[33] – TV, radio and print. Fax / faxstream, phone / pager (e.g. SMS, voice), voice messaging systems (e.g. Xpedite), tape message services, community radio, internet (e.g. BoM & VICSES websites, email, social media), national Emergency Alert system. Flood wardens Door knocking Informal local message / information dissemination systems or "trees".	If considered beneficial, Council to establish and champion a community flash flood action groups(s) and ensure that terms of reference are appropriate and agreed. Environmental indicators (i.e. heavy rain) and awareness following application of the quick look "flood / no flood" tool (i.e. likely severity and impact of expected flooding) will alert individuals to likely flooding. This alert could be shared within the community, either informally or more formally through the flash flood action group(s). Likely consequences and required actions will be as derived by the individual (or group) as a result of consideration of information provided by the quick look tool, MFEP and flood inundation maps. VICSES as the Control Agency for flood also issue flood warning messages that include more detailed information including flood consequences to the media and to a wider audience via the

[33] ABC Radio has entered into a formal agreement with the Victorian Government and the Bureau of Meteorology to broadcast, in full, weather related warnings including those for flood. The agreement provides for the interruption of normal programming at any time to allow the broadcast of warning messages. This agreement will ensure that flood (and other) warnings issued by the Bureau are broadcast in their entirety and as soon as possible after they are received in the ABC's studio.

Flood Warning System Building Blocks	Basic Tools	Possible Solution for the urbanised part of the Bendigo Creek catchment
	Opportunity for at-risk communities to confirm warning.	electronic media, websites and social media. LATER - consider each of the following and action if and as appropriate: a) Adopt HydroNET (www.hydronet.com.au) and develop a publically available web portal to display areas likely to experience hazardous flood conditions within Bendigo in real-time. b) Either encourage residents to subscribe for the free alerting service from the Early Warning Network (www.ewn.com.au) or subscribe to the service so that residents receive free alerts. c) Establish threshold criteria for each rain gauge and initiate an SMS (or similar) alert to key personnel (and perhaps members of at-risk communities) in order to achieve more lead time on possible flooding. d) Implement Premier Global Services' Xpedite VoiceREACH system to alert and notify residents and property owners in flood-prone urban areas in the lead up to heavy rain and / or on the exceedance of threshold criteria at rain gauges. e) Implement the SMS alerting system developed by Melbourne Water for pilot flash flood communities in Melbourne. f) Secure an FM-88 licence and associated equipment in order to provide a means of distributing flood and other emergency messages more widely, including to visitors, road users, etc. Alternative alerting mechanisms could include use of a siren or similar
RESPONSE	Flood management tools (e.g. MFEP complete with inundation maps and "intelligence", effective public dissemination of flood information, local flood awareness, individual and business flood action plans, etc). Flood response guidelines and related information (e.g. Standing Operating Procedures). Comprehensive use of available experience, knowledge and information.	Evacuation arrangements / planning (Appendix E of the MFEP) remain to be completed. The MFEP remains to be reviewed and signed-off by Council MEMPC. Initiate a community engagement program to communicate how the FFWS will work. Following (or perhaps in concert with) acceptance of the MFEP, encourage and assist residents and businesses to develop individual flood response plans. A package that assists businesses and individuals is available from VICSES and provides an excellent model for community use.
REVIEW	Post-event debriefs (agency, community), etc. Data from Rapid Impact Assessments. Flood "intelligence" and flood damage data from the event collected by residents, Council, NCCMA, VICSES, etc. Review and update of personal, business and other flood action plans.	Review and update of alarm criteria (if established), local flood intelligence (i.e. flood characteristics, impacts, etc), local alerting arrangements, response plans, local flood awareness material, etc (initially) after every (severe) flood. Best done by Council with input from VICSES, NCCMA and (if established) the Council championed community flash flood action group(s). Council to develop review and update protocols => who does what when and process to be followed to update material consistently across all parts of the flash flood warning and response system, including the MFEP. Ensure that as part of the above, information contained in Rapid Impact Assessments is captured to the MFEP.

<table>
<tr><th>Flood Warning System Building Blocks</th><th>Basic Tools</th><th>Possible Solution for the urbanised part of the Bendigo Creek catchment</th></tr>
<tr><td rowspan="5">AWARENESS</td><td>Identification of vulnerable communities and properties (i.e. flood inundation maps, information on flood levels / depths and extents, etc).</td><td rowspan="5">Studies repeatedly show that communities that are not aware of flood hazard are less capable of responding appropriately to flood warnings or alerts and experience a more difficult recovery than a flood-aware community. Thus, the emphasis of activities that aim to maintain and renew flood awareness across the urbanised part of the Bendigo Creek catchment should be on an awareness of public safety issues and on demonstrating what people can do to stay safe and protect their property from flooding.
Flood intelligence delivered by the Bendigo Urban Flood Study has been captured to the MFEP.
Develop, print and distribute flood awareness material (Local Flood Guide, property specific flood depth charts, etc), including information on how the FFWS operates using information collated for the MFEP and available within the Bendigo Urban Flood Study report and more generally from the web.
Council to ensure that the MFEP (including the quick look tool, inundation and hazard maps, etc) is publicly available (Council offices, library, website) with a summary provided in Council welcome packages for new residents and business owners and possibly also with annual rate notices.
Council to load and maintain other flood related material on their website with appropriate links to relevant useful sites (e.g. the Flood Victoria website http://www.floodvictoria.vic.gov.au/centric/home.jsp).
Routinely revisit and update awareness material to accommodate lessons learnt, additional or improved material and to reflect advances in good practice.
Establish and implement protocols for routinely repeating distribution of flood awareness material.
Decide whether to alert residents and visitors to the risk of flooding in more direct ways. This could include the installation of flood depth indicator boards at strategic locations along key roads (e.g. as indicated by the flood hazard maps delivered by the Bendigo Urban Flood Study).</td></tr>
<tr><td>Activities and tools (e.g. participative community flood education, flood awareness raising, flood risk communication) that aim to build flood resilient communities (i.e. communities that can anticipate, prepare for, respond to and recover quickly from floods while also learning from and improving after flood events).</td></tr>
<tr><td>Community education and flood awareness raising including VICSES FloodSafe and StormSafe programs.</td></tr>
<tr><td>Local flood education plans – developed, implemented and evaluated locally (e.g. Cities of Maroondah, Whitehorse, Wodonga, Benalla and Greater Geelong).</td></tr>
<tr><td>Flood response guidelines, residents' kits, flood markers, flood depth indicators, flood inundation maps and property listings, property specific flood depth charts, flood levels in meter boxes and on rate notices, etc for properties identified as being subject to flooding.</td></tr>
</table>

8 - ESTIMATED COSTS FOR THE FFWS

The following table provides indicative costs associated with the implementation and on-going operation of each of the TFWS elements proposed for the Bendigo Creek catchment flash flood warning system as discussed above.

Table 8-1: Estimated cost associated with implementation of the Flash Flood Warning System

Item	Estimated cost as at January 2014 (excl GST)	Comments
In-kind estimates developed using at-cost (not commercial) rates for time, consumables, etc		
1. Data Collection and Collation		
Input from BoM, comprising assistance with site selection, radio path testing and advice on necessary and appropriate equipment for up to nine (9) x ERTS rainfall only stations (see below) and possible upgrade of the Bendigo Creek at Bendigo stream gauge site.	In-kind estimate ~$10,000 total	Subject to operational and other workloads.
Up to nine (9) x ERTS rain only installations. Includes steel instrument housing, BoM spec TBRG, ERTS canister, logger, solar panel, antenna, cabling.	$12,000 per site ~$110,000 total	Cost covers supply, installation, commissioning and maintenance of equipment for the first 12-months along with the establishment of long term maintenance and data archival arrangements. It also includes estimated allowances for cultural heritage assessment and service checks and marking at site.
BoM to ingest data and display it via website bulletins, data tables and other related products.	In-kind estimate ~$500 total	Timing subject to operational and other workloads.
Add ERTS telemetry and rain gauge to Bendigo Creek at Bendigo gauging station. Includes BoM spec TBRG, bird guard, enclosure, lightning protection, modem, antenna, cabling.	$8,000	Cost covers supply, installation, commissioning and maintenance of equipment for the first 12-months along with the establishment of long term maintenance and data archival arrangements. It also includes estimated allowances for cultural heritage assessment and service checks and marking at site. New station cost could be reduced by ~$2,000 if a less robust instrument housing was used.
New gauging station immediately upstream of the Bendigo CBD. Includes concrete instrument housing on concrete pad, HS dry bubbler and pressure transducer, Campbell logger, modem, solar panel, antenna, cabling, ERTS telemetry.	$25,000 total	
New staff gauges at key road crossings and in the vicinity of the CBD.	$2,000 per site	Cost includes supply and installation as well as survey to AHD.
Recurrent costs for data collection network: ➢ ERTS rain only site. ➢ Rain - river site (no gauging). ➢ Staff gauge site.	$1,000/year/site, $4,000/year/site and $800/year/site respectively but could be as low as $500, $2,000 and $500/year/site.	Indicative costs only and dependent on the work scope and whether the sites are brought into the Surface Water Monitoring Partnership.
2. Flood Detection and Prediction		
Council (perhaps with input from VICSES, NCCMA and communities) to determine how the indicative quick look "flood / no flood" tool is to be used and who by.	In-kind estimate ~$2,000 total across all agencies	Expenditures relate to time costs. Timing subject to operational and other workloads

Item	Estimated cost as at January 2014 (excl GST)	Comments
In-kind estimates developed using at-cost (not commercial) rates for time, consumables, etc		
The indicative quick look "flood / no flood" tool together with the MFEP enable those at risk to determine the likelihood and scale of possible flooding with some lead time.	In-kind estimate ~$3,000/flood	Council to maintain the tool. This could be done by plotting flood producing rainfall events and resulting flooding on the chart along with the event date. This may allow some refinement of the tool over time. MFEP intelligence will also need to be updated following flooding in the Bendigo Creek catchment.
Establish and set rain and creek level triggers for each telemetered site.	Establishment: In-kind estimate ~$500 total	
Establish flood class levels for (say) 2 x stream gauging sites.	In-kind estimate ~$1,500 total across all agencies	Expenditures relate to time costs. Timing subject to operational and other workloads
Longer term and as part of a "best possible" system, establish a GIS based forecasting capability or HydroNET system with web portal.	Estimated at ~$50,000 to setup. Survey, operational and ongoing costs not included.	No indication of likely timetable for this as will depend on identification of responsible entity to develop, run and maintain the model / system.
3. Interpretation		
Make relevant parts of the MFEP and flood inundation and related mapping available to Bendigo communities.	In-kind estimate ~$3,000	Council to work with communities on how best to achieve access.
The indicative quick look "flood / no flood" tool together with the MFEP enable those at risk to determine whether they are likely to be flooded with some lead time.	Costed above	MFEP intelligence will need to be updated following flooding at Bendigo.
4. Message Construction and Dissemination		
Council to champion and oversee the establishment of a flash flood action group(s)	In-kind estimates ~$5,000 to set up ~$500/y ongoing	Will need to clearly establish the role for the group(s) along with authority and structure. VICSES should be invited to be involved in setting up the group(s). Liability issues may need to be considered and resolved.
Program the base station to send an SMS message to key Municipal (and perhaps members of at-risk communities) in order to achieve more lead time on possible flooding.	Establishment: In-kind estimate ~$2,000 total	Is an extension of action identified under 'flood detection and prediction'.
Establish and implement Xpedite to alert and notify residents and property owners in flood-prone urban areas in the lead up to heavy rain and / or on the exceedance of threshold criteria at rain gauges.	Establishment: ~$10,000 total ~$500/y ongoing	Adopt an opt-out approach. Melbourne Water approach suggested as an alternative in Section 7 above but not costed.
Secure an FM-88 licence and associated equipment in order to provide a means of distributing flood and other emergency messages more widely, including to visitors, road users, etc.	Establishment: ~$10,000 + Licence ~$500/y ongoing	Need to establish whether the licence is available and whether a broadcast location can be established.
Longer term and as part of a "best possible" system,	Estimated at	

Item	Estimated cost as at January 2014 (excl GST)	Comments
In-kind estimates developed using at-cost (not commercial) rates for time, consumables, etc		
establish a HydroNET driven web portal.	~$50,000 to set up.	
5. Response		
VICSES, VicPol and Council to complete the documentation / planning of evacuation arrangements for at-risk communities with the urbanised part of the Bendigo Creek catchment (Appendix E of the MFEP)	In-kind estimate ~$2,000	A required element of the MFEP.
Council and VICSES, with input from others as required, to populate the "required actions" column of the Flood Intelligence Card within the MFEP.	In-kind estimate ~$2,000	A required element of the MFEP.
Council and / or VICSES to share relevant parts of the MFEP with the Bendigo Creek catchment communities.	In-kind estimate ~$500 to set up	Will assist the implementation of an informed local response when it next floods.
Initiate a community engagement program to communicate how the FFWS will work.	In-kind estimate ~$3,000 to start ~$1,000 to repeat	VICSES with assistance from Council. Will need to be repeated as the system matures.
Encourage and assist residents and businesses to develop individual flood response plans.	In-kind estimate $500 to promote	VICSES and Council.
6. Review and Keeping the System Alive		
Post-event review and on-going maintenance of the system in order to keep it alive within the community (e.g. exercises to test procedures, website maintenance, asset replacement, operational costs, involvement with a community flash flood action group(s) and so on). Assuming that replacement spares were purchased as part of the initial capital investment, asset replacement expenses are considered to be included in site recurrent costs.	In-kind estimate ~$2,000/year for activities. Operational costs are assumed absorbed into incident management activities.	Costs will vary year to year and will depend on rainfall and seasonal conditions.
7. Community Flood Awareness		
Develop and distribute a Local Flood Guide for the urban communities within the Bendigo Creek catchment.	Up to $12,000 but expected to be covered by other funding through VICSES	Cost will depend on how much of the work is out-sourced and how much is done by VICSES as an in-kind contribution.
Load and maintain flood related material (including the MFEP) Council's (and perhaps also VICSES') website.	In-kind estimate per Council ~$1,000 to cover initial load ~$500 ongoing	
Council to develop, review and update protocols in conjunction with VICSES and with input from NCCMA and other stakeholders as required => who does what when and the process to be followed to update material consistently across all parts of the flood warning and response system, including the MFEP, quick look tool and personal / business flood action plans. This should include the capture of information contained in Rapid	In-kind estimate $5,000	Cost will depend on how much of the work is out-sourced.

Item	Estimated cost as at January 2014 (excl GST)	Comments
In-kind estimates developed using at-cost (not commercial) rates for time, consumables, etc		
Impact Assessment reports.		
Develop, print and distribute property-specific flood depth charts for Bendigo Creek catchment properties.	$5,000	Cost will depend on how much of chart preparation is out-sourced. Does not include allowance for floor level or further processing of hydraulic model results.
Install flood depth indicator boards at strategic locations along local roads where there is appreciable danger to human life due to flood depth and / or velocity (e.g. as indicated by the flood hazard maps delivered by the Bendigo Urban Flood Study).	~$500/board	Locations to be determined from hazard maps.

9 - SUGGESTED ACTIONS AIMED AT IMPROVING THE TFWS

The availability of "best possible" and timely information on rainfalls and the rapid and easy translation of that information to likely on-ground impacts and the good health of all TFWS elements are fundamental to delivery of an effective flash flood warning system.

A staged approach to the development of an effective flash flood warning system for the urbanised areas of the Bendigo Creek catchment is proposed. The stages have been ordered and the tasks within each stage grouped to facilitate incremental growth of the TFWS elements in a balanced manner and with full regard for matters discussed in this paper.

While it may be tempting to immediately move to install additional rain (and stream) gauges and to perhaps also develop a forecast capability, there are other more fundamental matters that experience tells us need to be addressed first. Thus early attention is directed at ensuring roles and responsibilities are agreed, understood and accepted and that there is a firm foundation for the development of an effective flash flood warning system: one that does not fail when it is needed most. Consideration is then given to establishing a robust framework for communicating and disseminating flood related information so that immediate and maximum use can be made of available information as the ability to detect and predict flooding within the Bendigo Creek catchment improves. Attention is then directed to sharing available flood intelligence with the at-risk communities. Next, attention is focussed on securing the funding needed to buy, install and operate field equipment as well as other services needed to build elements of the TFWS. The installation of data collection equipment follows. This could be staged or tiered in the event that funding is not available or is delayed. Development of other technical elements and the build and delivery of on-going flood awareness activities can then occur in the knowledge that required data is / will be available and that robust and sustainable arrangements are in place that will enable maximum benefit to be derived from any information or programs delivered to the community.

All activities associated with an earlier stage do not necessarily have to be fully completed before activities in subsequent stages are started. Commitment and community engagement are however key to each stage. A timetable and priorities have not, at this stage, been attached to any of the suggested actions.

Stage 1

1. Council, NCCMA, VICSES and other entities to determine the responsible entity in relation to "ownership" of each element of the flash flood warning system for Bendigo, where ownership is considered to denote overall responsibility for funding as well as the establishment and functioning of the system element and, in the event of failure, responsibility for either fault-fix or the organisation of appropriate fault-fix actions along with associated payments. VFWCC (2001) provides guidance on this matter although recommendations 1 and 5 from the Victorian Floods Review Report (Comrie, 2012) suggest that some clarifications may be required. DEPI have initiated a project to review the arrangements and deliver clarity where required.

Stage 2

1. Council and VICSES with input from others as required, to populate the "required actions" column of the Flood Intelligence Cards within the Bendigo MFEP.
2. VICSES, VicPol ad Council to complete the documentation / planning of evacuation arrangements for the Bendigo Creek catchment communities (Appendix E of the MFEP).
3. Council, VICSES and NCCMA (and community?) to determine how the indicative quick look "flood / no flood" tool is to be used and who by.

Stage 3

1. Following formal adoption of the MFEP, Council and / or VICSES to make the flood inundation and hazard maps, relevant Appendices of the MFEP and the indicative quick look "flood / no flood" tool publicly available in order to assist community members (and stakeholder agencies) determine the likely effects of a potential flood and inform their development of individual flood response plans.
2. VICSES and Council to encourage and assist residents and businesses to develop individual flood response plans.
3. Council to load and maintain flood related material (including the MFEP) to its website.

Stage 4

1. Council (probably in conjunction with VICSES and other agencies) to consider how flash flood alerts will be provided to the community, if at all. This will include consideration of:
   - Appropriate rainfall depth and rate trigger levels for the initiation of flash flood alerts;
   - Whether these alerts will be shared with the community (or retained within Council and / or VICSES); and
   - How these alerts will be communicated to the community (e.g. SMS, Xpedite, Melbourne Water approach, FM-88, Early Warning Network, web portal, etc).

Stage 5

1. Council with the support of VICSES, NCCMA and the Bendigo community to submit an application for funding under the Australian Government Natural Disaster Resilience Grants Scheme (or similar) for all outstanding elements (i.e. field and office equipment, floor level survey, rerun of the hydraulic model, awareness and other materials, etc) of the proposed FFWS for Bendigo.

Stage 6

1. If considered appropriate, Council to champion and in conjunction with VICSES oversee the establishment of a flash flood action group(s) for Bendigo. Clearly establish the role for the group(s) along with its authority and structure (i.e. terms of reference) with due regard for possible liability issues.

Stage 7

1. Council in conjunction with BoM to identify and verify appropriate locations for all proposed ERTS rain gauges in the upper parts of the Bendigo Creek catchment. Preliminary work will need to include radio path testing. Long term maintenance, data archival and other responsibilities will need to be agreed before equipment is ordered. A priority has not been attached to any of the gauges: they are all important to the FFWS.
2. Council to establish, if and as necessary, appropriate permissions for the:
   - Addition of ERTS telemetry and a rain gauge at the Bendigo Creek at Bendigo stream gauge site; and
   - Installation of stream gauge equipment at additional sites (e.g. immediately upstream of the CBD).
3. Council to contract for the supply, installation, commissioning and warranty / maintenance (and other deliverables) of:
   - The proposed up to 9 x ERTS rain gauges;
   - ERTS telemetry and rain gauge at the Bendigo Creek at Bendigo stream gauge site;
   - Staff gauges;
   - Additional stream gauge site(s).

4. Council to establish on-going maintenance arrangements for data collection network sites, ideally through the Surface Water Monitoring Partnership.
5. As soon as possible after the equipment is fully operational, Council to approach BoM to ingest data from these new telemetered gauges so that all data is available to the community from the BoM website via bulletins, data tables and other related products. Requires telemetry systems used to be fully compatible with BoM systems.
6. VICSES to initiate a community engagement program at Bendigo in order to communicate how the flash flood warning system will work along with evacuation arrangements. This will need to be repeated as the FFWS matures.
7. VICSES to develop and distribute a Local Flood Guide for Bendigo.

Stage 8

1. After additional rain gauges have been installed, Council to review the quick look tool to ensure that the tool is making best use of available data.
2. Council to determine the extent to which is will engage in flash flood forecasting activities:
   - Status quo – no action;
   - Maintenance of the shared indicative quick look "flood / no flood" tool";
   - Investment in the development of a GIS based prediction too (see above); or
   - Some other approach.

Stage 9

1. Council to develop, review and update protocols in conjunction with VICSES and with input from NCCMA and other stakeholders as required => who does what when and the process to be followed to update material consistently across all parts of the flood warning and response system, including the MFEP, quick look tool and personal / business flood action plans. This should include the capture of information contained in Rapid Impact Assessment reports.
2. VICSES in consultation with Council to establish protocols for routinely reviewing, updating and repeating distribution of flood awareness material, particularly the Local Flood Guide.

Stage 10

1. Council to decide whether to alert residents and visitors to the risk of flooding in more direct ways. This could include the installation of flood depth indicator boards at strategic locations along local roads where there is appreciable danger to human life due to flood depth and / or velocity (e.g. as indicated by the flood hazard maps delivered by the Bendigo Urban Flood Study).
2. Council to consider the preparation and distribution of property specific flood depth charts and / or meter box flood level stickers for each property within the Bendigo Creek catchment subject to over-floor flooding up to and including the 200-year ARI event. The data to inform the charts will need to be prepared following floor level survey and rerun of the hydraulic model developed as part of the Bendigo Urban Flood Study.
3. Council to consider including flood related information in (say) Council welcome packages for new residents and business owners and also perhaps with annual rate notices.
4. Council to consider loading and maintaining other flood related material on their websites with appropriate links to relevant useful sites (e.g. the Flood Victoria website http://www.floodvictoria.vic.gov.au/centric/home.jsp).
5. Council in conjunction with VICSES, to consider periodically providing feature articles to local media on previous flood events and their effects on the community. This could extend to establishing photo displays of past flood events in local venues (these could be permanent).
6. When appropriate, VICSES to formally request BoM to establish flood class levels for stream gauge sites in the Bendigo Creek catchment. Flood class levels will need to be proposed by Council consistent with BoM definitions and local impacts / consequences.

10 – KEY QUESTIONS

There are a number of fundamental questions that need to be answered before a firm direction can be developed aimed at establishing a sustainable flash flood warning system for Bendigo.

- Is the City of Greater Bendigo willing (and in a position) to take on the role of establishing, operating and maintaining the FFWS?
- For Bendigo, and in the context of Council's response to the first question, how sophisticated (or developed) will each of the TFWS elements of the FFWS be for Bendigo Creek?
- Is a staged approach to development supported in principle?
- Who will be the responsible entity?
  - In terms of:
    - System establishment
    - On-going maintenance of equipment; and
    - Associated maintenance and operational costs;
  - For receipt of alerts when threshold triggers have been exceeded;
  - For initiating local alerting and response;
  - Championing a local flash flood action group(s), if established;
  - Establishing and maintaining community awareness of flood risk and system alerts; and
  - Routine system testing (monthly, annually?) to confirm system integrity.
- Will the community accept responsibility for individual flood damage reducing actions?
  - Recipients must understand the message they receive and be able to interpret it for the alerting and warning system to be effective. This extends to appreciating that responsibility for non-receipt of alerting messages rests with the individual and using all available information – environmental indicators, information on individual risk, BoM warnings, etc.
- Is it agreed that ERTS equipment is considered most appropriate for the data collection and collation element of the flash flood warning system for Bendigo? Considerations include the existence of local service provider experience with ERTS equipment, limited need for capture of additional skills, that the equipment is simple and that office systems and experience with their use already exist, that establishment and on-going costs per station are relatively low and that reliance on outside service providers will be minimised.
- Should a local ERTS base station be established?
- Does the ERTS base station need to be duplicated? And if so, where should the duplicate reside?
- From the BoM's point of view, how practical is it to use Enviromon to initiate an alerting system?
- Would a community based web portal that displays flood hazard (i.e. areas likely to experience hazardous flood conditions) in real-time using local rainfall data be useful and be supported?
- Experience suggests that there will be some false alerts. Will this be a problem?
  - While Enviromon tests filtered data against the alarm criteria some erroneous data is not flagged as such until after receipt of new data. This may occur after alerts had been sent out. There needs to be an understanding of and process for handling false alerts, within Council, VICSES and the community.
- How involved does the Council wish to become in the flash flood forecasting and / or alerting task?
- Will VICSES provide funding for a Local Flood Guide and update and reprint it from time to time?
- Is any element in the "possible solution" column of Table 7-1 likely to cause problems, not work effectively or be unpalatable to stakeholders?
- Are proposed arrangements consistent with State policy on FFWS development, maintenance and operation?
- With due regard for matters raised in this Discussion Paper and arising from consideration of the above matters, what is the process, budget and timeline for designing a flash flood warning system for Bendigo?

11 - ACRONYMS

AEMI	Australian Emergency Management Institute
AHD	Australian Height Datum

AWS	Automatic Weather Station
BoM	Bureau of Meteorology
DEPI	Department of Environment and Primary Industries
DoTARS	Department of Transport and Regional Services
CMA	Catchment Management Authority
EA	Emergency Alert
EMA	Emergency Management Australia
EMMV	Emergency Management Manual Victoria
ERTS	Event Report Radio Telemetry System
FFWS	Flash Flood Warning System
IC	Incident Controller
ICC	Incident Control Centre
MEMPC	Municipal Emergency Management Planning Committee
MERO	Municipal Emergency Resource Officer
MFEP	Municipal Flood Emergency Plan
NCCMA	North Central Catchment Management Authority
OESC	Office of the Emergency Services Commissioner
QA	Quality Assure
RDO	Regional Duty Officer
TFWS	Total Flood Warning System
VicPol	Victoria Police
VICSES	Victoria State Emergency Service

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Appendix A Flood Warning Services Provided by BOM

OVERVIEW OF FLOOD WARNING SERVICES PROVIDED BY BoM

Flood Warning Products

Flood Warning products and Flood Class Levels can be found on the BoM website. Flood Warning products include Severe Thunderstorm Warnings, Severe Weather Warnings, Flood Watches and Flood Warnings.

Severe Thunderstorm and Severe Weather Warnings

The BoM can forecast the environment in which severe thunderstorms or small scale weather systems that are locally intense and slow moving may occur and provides a generalised service to that effect. However, it is not yet scientifically possible to predict individual flash flooding events except on time scales of tens of minutes at the very best.

The BoM issues warnings of flash flooding when it becomes apparent that an event has commenced which may lead to flash flooding or when flash flooding has commenced.

Flood Watches

Flood watches are issued by the BoM to notify communities and other stakeholders within broad areas (rather than specific catchments) of the potential flood threat from a developing weather situation. They provide a “heads up” of likely flooding.

Flood watches are based on an assessment of the developing weather situation and indicators of current catchment wetness. They provide generalised statements about expected forecast rainfall totals, the current state of the catchments within the target area and the streams at risk from flooding. Instructions for obtaining rain and stream level observations and access to updated Watches and Warnings are also included.

Normally, the BoM would issue a Flood Watch 24 to 36 hours in advance of any likely flooding and issue updates as required. If at any time during that period there was an imminent threat of floods occurring within an area covered by the formal flood forecast and warning service, the Flood Watch would be upgraded to a Flood Warning.

Flood Warnings

Flood Warnings are firm predictions of flooding based on actual rainfall and river height information as well as the results of stream flow based models of catchment behaviour that take account of antecedent conditions (i.e. the “wetness” of the catchment, storage levels within dams, etc) and likely future rainfall. Releases from dams are an essential input to such models.

Flood warnings are categorised as “minor”, “moderate” or “major” (see BoM website for an explanation of these terms and current flood class levels) and indicate the expected severity of the flood for agreed key locations along the watercourse.

Generally flood warnings are issued by the BoM to the media, VICSES, Council and other stakeholder agencies and organisations. VICSES promptly alerts and disseminates such warnings to other agencies and organisations. Stakeholder agencies and organisations, including Council, are responsible for onward dissemination of the warning details.

Flood warnings usually include:

- Rainfall amounts for selected locations within and adjacent to the subject catchment;
- River heights and trends (rising, steady, falling) at key locations within the subject catchment;
- Outflows (in ML/d) from any major storages within the catchment;
- Forecasts of the height and time of flood peaks at key locations;
- A weather outlook and the likely impact of expected rainfall on flooding; and
- A warning re-issue date and time.

Note 1: The term “local flooding” and “flash flooding” may be used for localised flooding resulting from intense rainfall over a small area.

Note 2: The term “significant rises” may be used in the early stages of an event when it is clear that river levels will rise but it is too early to say whether they will reach flood level.

Additional information (e.g. weather radar and satellite images as well as updated rain and river level information) can also be obtained from the BoM website (www.bom.gov.au/hydro/flood/vic) or for the cost of a local call on ☎ 1300 659 217.

Flood Class Levels

The occurrence of a certain class of flooding at one point in a catchment will not necessarily lead to the same class of flooding at other points – for example along the main river and its tributary creeks or along a drainage network’s overland flow paths. This is because the floodplain physiography and use (and thus flood impact) varies along the river or flow path and also because antecedent conditions combined with where and how rainfall occurs (both in time and space) will drive how a flood develops and progresses.

It is emphasised that the flood class levels refer to that part of the watercourse where the flood effects can be related to the gauge reading.

It is important to remember that flood impact is dependent on more than the peak height or flow. The rate of rise, duration, extent and season of flooding are also important. For this reason, flood class levels can only be considered as a guide to flood severity.

Note that in the future it is likely that not all sites for which flood class levels exist will automatically be provided with a quantitative flood forecast by the BoM. It is understood that sites will be classified on the basis of flood risk and consequence. The lower rated sites will receive a quantitative warning service only. For these sites, BoM will issue warnings that advise only of the exceedance (or likely exceedance) of flood class levels along with the class of flooding expected: a detailed flood forecast will not be provided.

APPENDIX B ADDITIONAL CATCHMENTS MODELLING DATA (STRATHFIELDSAYE, JUNORTOUN, MAIDEN GULLY)

During the study an additional three urban catchments were included, Strathfieldsaye, Junortoun and Maiden Gully. The same modelling and mapping approach as used for the urban areas of Bendigo and as discussed in the main body of the report was utilised for these additional areas.

Strathfieldsaye is located to the southeast of Greater Bendigo. The study area, approximately 3,100 ha, stretches from the western end of Strathfieldsaye Road in the west to Axe Creek in the east. Northern and southern limits of the study area generally follow the administrative boundaries of Strathfieldsaye.

Junortoun is to the east of Greater Bendigo and shares its southern border with Strathfieldsaye. The study extent covers some 2,670 ha and generally follows the administrative boundaries.

Maiden Gully is situated to the West of Greater Bendigo and about 7 km away from Bendigo's Central Business District. The study area of Maiden Gully is about 4,590 ha and generally aligns with the administrative boundaries.

Strathfieldsaye, Junortoun and Maiden Gully have similar topography, land use and drainage infrastructure as the urban area covered by the study. Unlike Maiden Gully and Junortoun, the Strathfieldsaye study area receives external flows from SheepWash Creek, Emu Creek, and Axe Creek. The external flow from Axe Creek was not included as it is at the model's downstream end. The external flows were computed by RORB modelling software and input into the ROG model in the form of hydrographs.

The modelling extent of Strathfieldsaye, Mainden Gully, and Junortoun are presented in Figure B 1

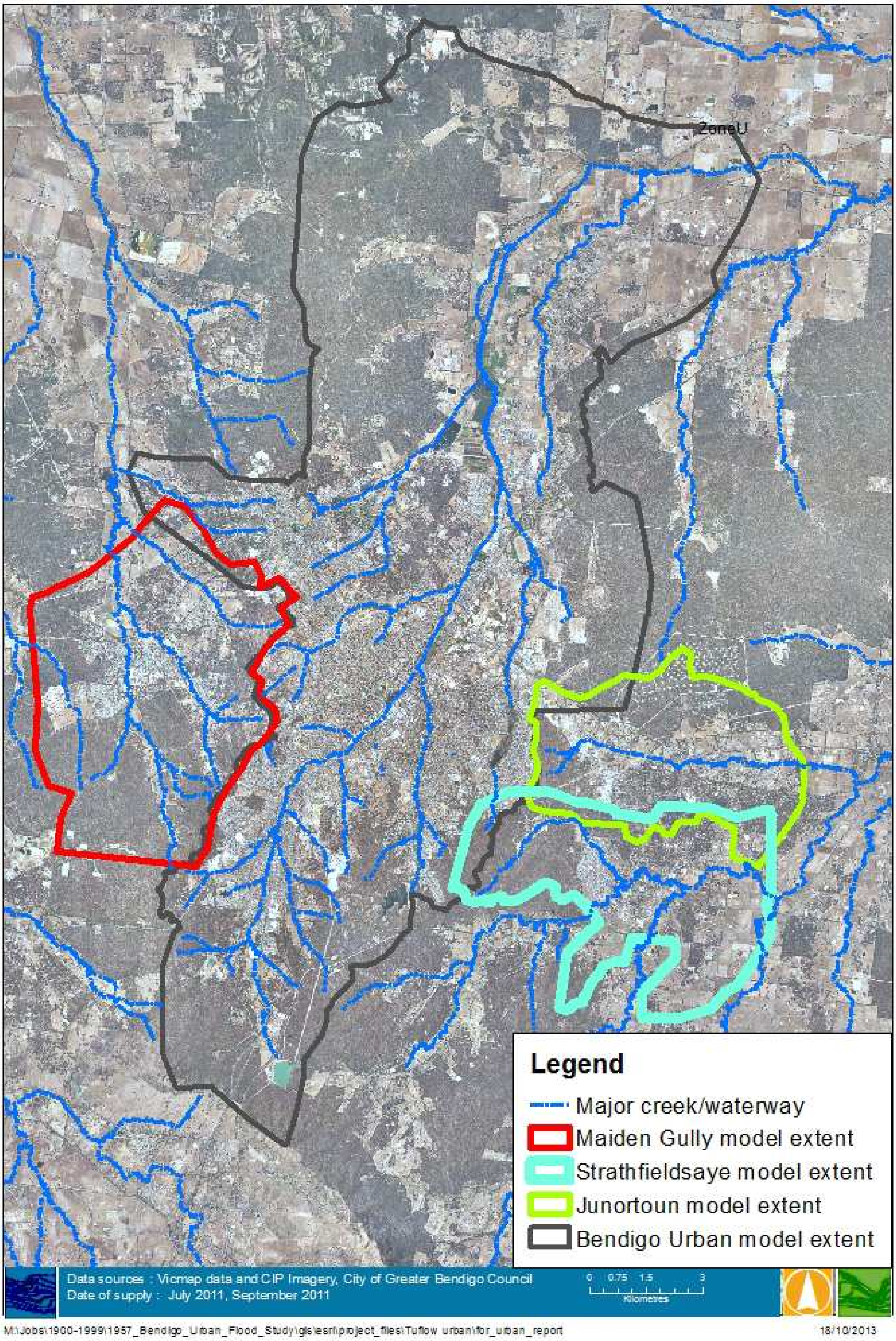

Figure B 1 **Maiden Gully, Strathfieldsaye, Junortoun model extents**