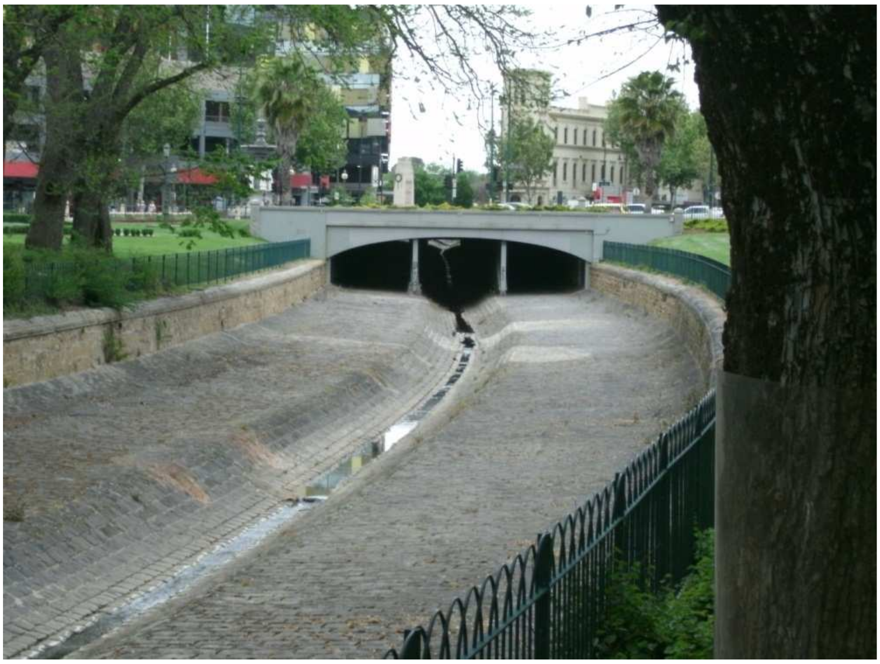
WATER TECHNOLOGY
WATER, COASTAL & ENVIRONMENTAL CONSULTANTS

Bendigo Urban Flood Study

Interim Technical Report



November 2013

NORTH CENTRAL Catchment Management Authority
Connecting Rivers, Landscapes, People

CITY OF GREATER BENDIGO

State Government Victoria

Australian Government

DOCUMENT STATUS

Version	Doc type	Reviewed by	Approved by	Distributed to	Date issued
v01	Draft	BAT	BAT	NCCMA/CoGB	04/10/2013
v02	Draft	BAT	BAT	NCCMA/CoGB	12/11/2013
v03	Interim Report	NCCMA	NCCMA	NCCMA / CoGB / Water Technology	18/11/2013

PROJECT DETAILS

Project Name	Bendigo Urban Flood Study
Client	North Central CMA & City of Greater Bendigo
Client Project Manager	Shaun Morgan
Water Technology Project Manager	Chris Beardshaw and Ben Tate
Report Authors	Chris Beardshaw, Julian Skipworth, Ky Tran
Job Number	1957
Report Number	R01
Document Name	Interim Technical Report

In association with:

Michael Cawood & Associates Pty Ltd

Cover Photo: Bendigo Creek looking towards town centre

15 Business Park Drive
Notting Hill VIC 3168

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

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

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.

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, 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.

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.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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)
- Conclusions and Recommendations

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

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).

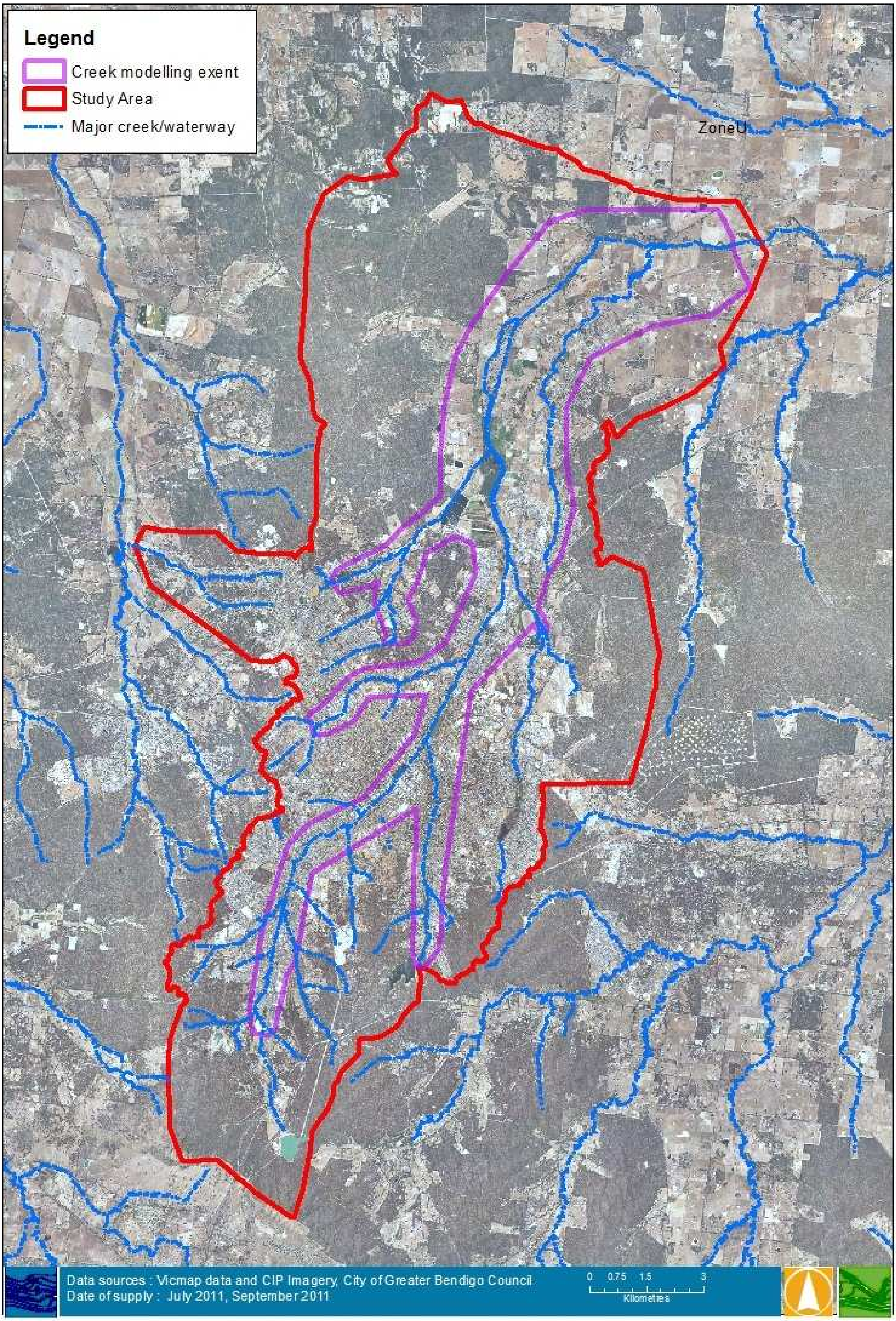


Figure 1-1 Study Area and Catchments

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

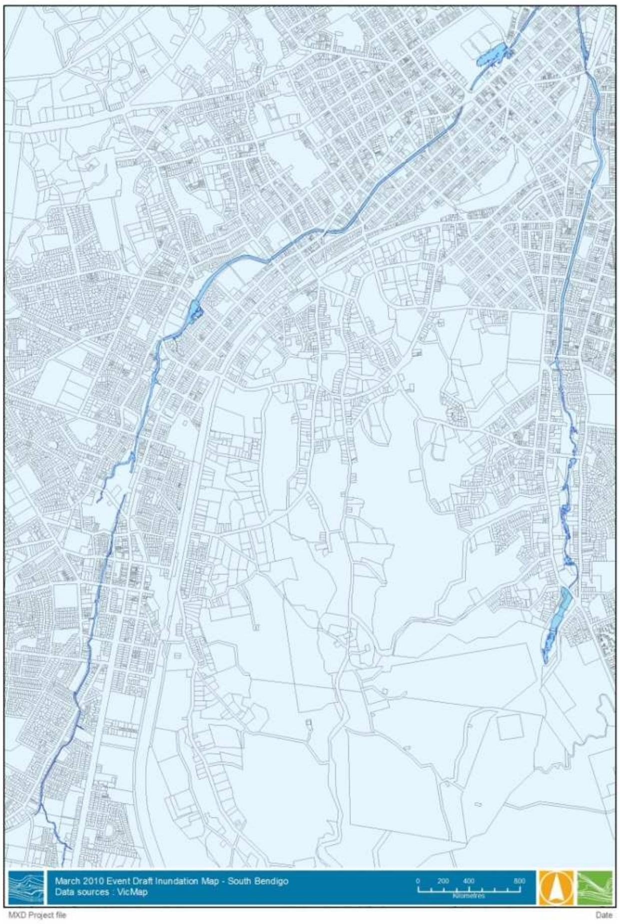
Date	Area Affected	Rainfall		*Event*	Properties Affected
		Depth (mm)	Duration (hours)		
26 December 1999	Bendigo East to Epsom ~1 in 100 year ARI	75	45	Thunderstorm	Extensive flooding 10+ houses flooded.
27 December 1999	Strathdale, Bendigo East ~1 in 35 year ARI	21	15	Thunderstorm	Moderate property 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.



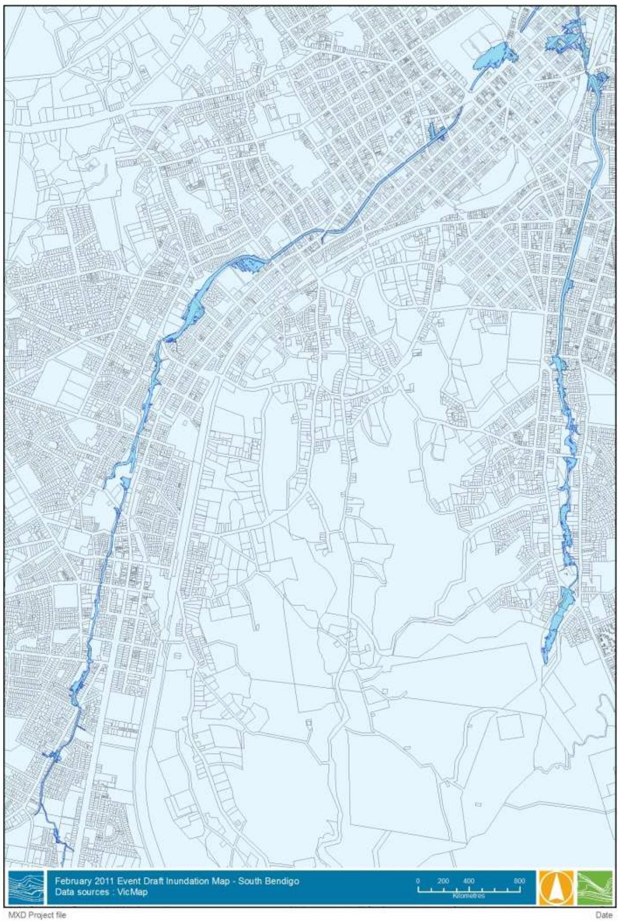


Figure 1-3 Calibration Events Preliminary Model (March 2010 left, February 2011 right)

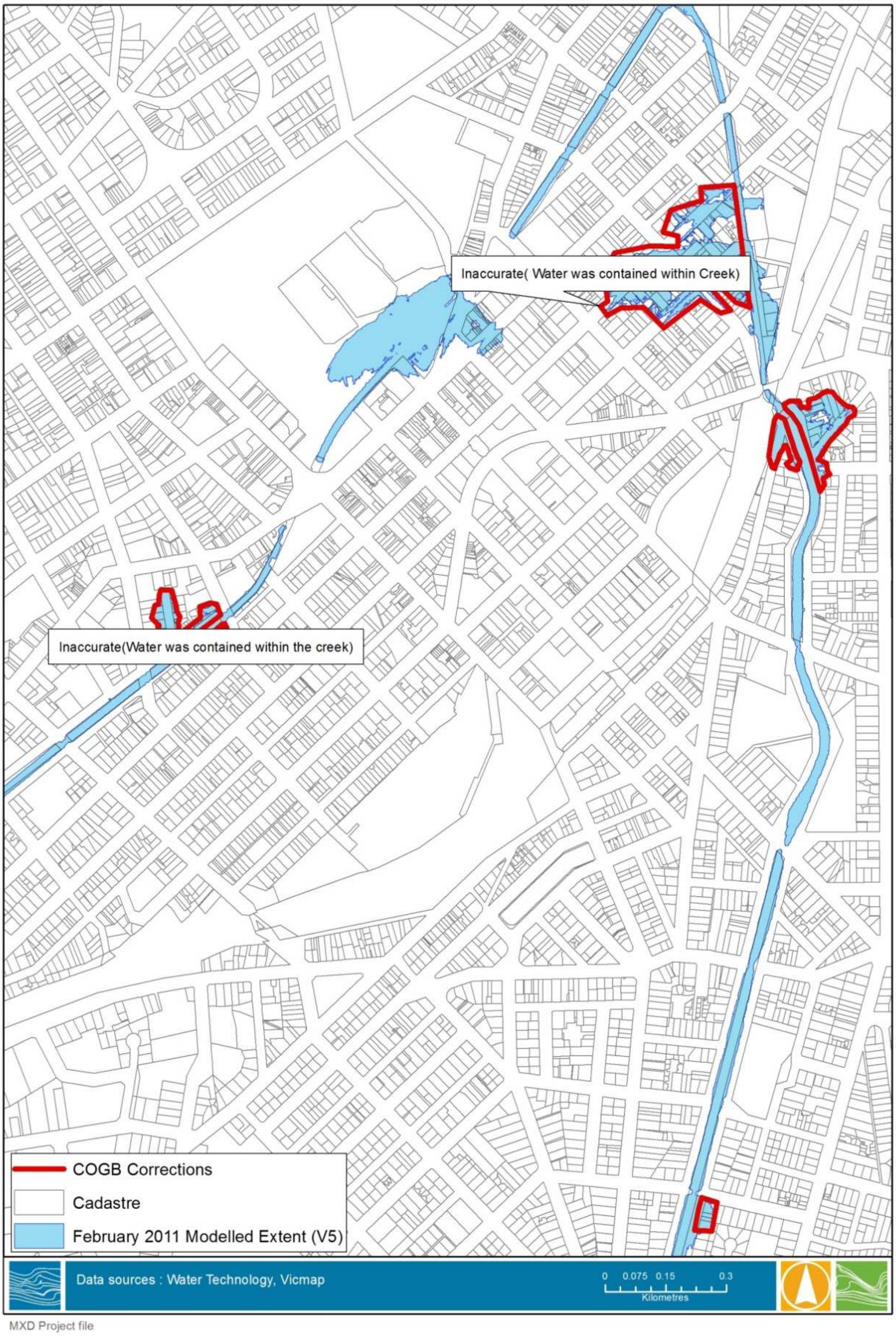


Figure 1-4 Rough flood extent prepared for the February 2011 event with review

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.

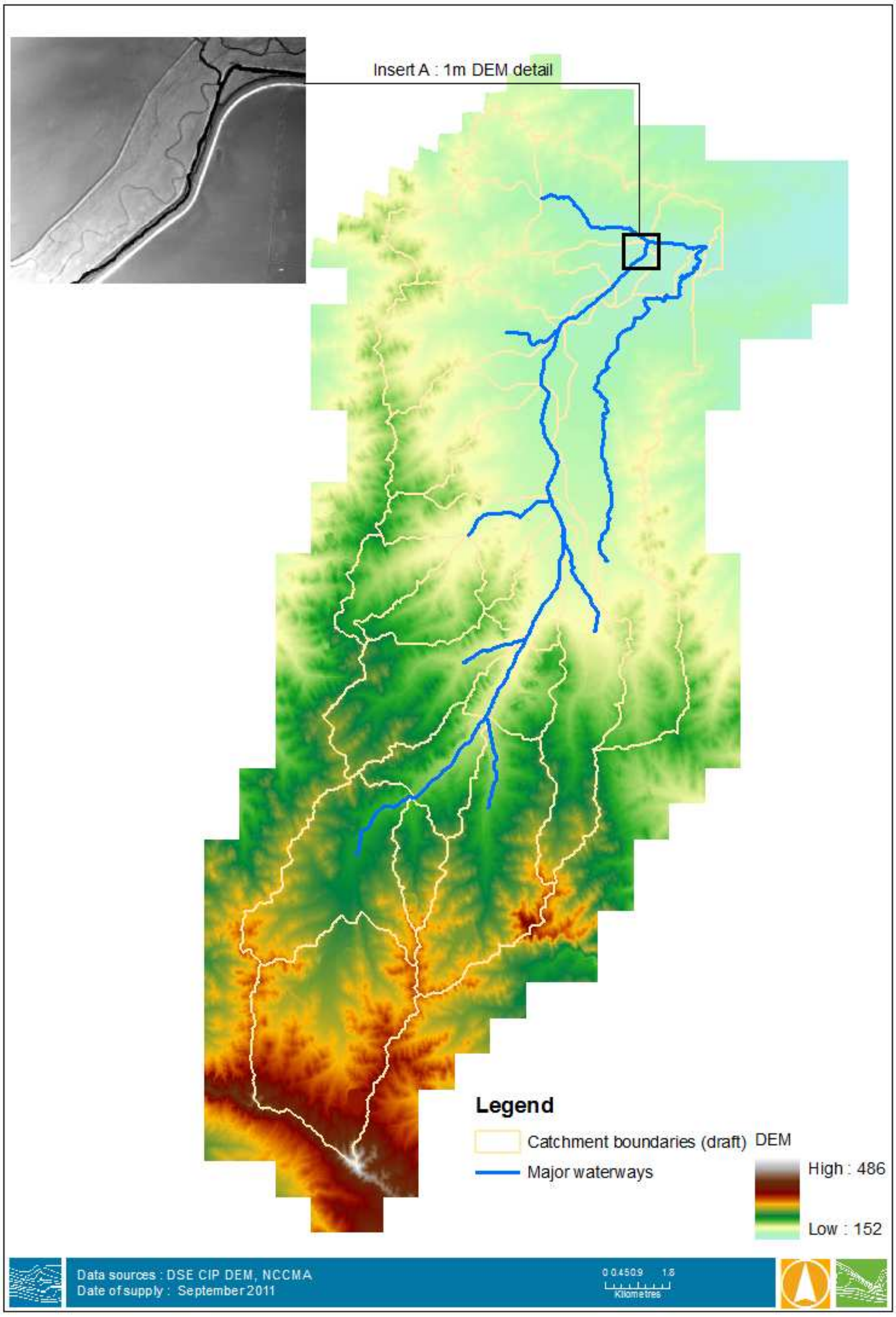


Figure 2-1 1 m resolution LiDAR coverage for Bendigo (source: DEPI)

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.

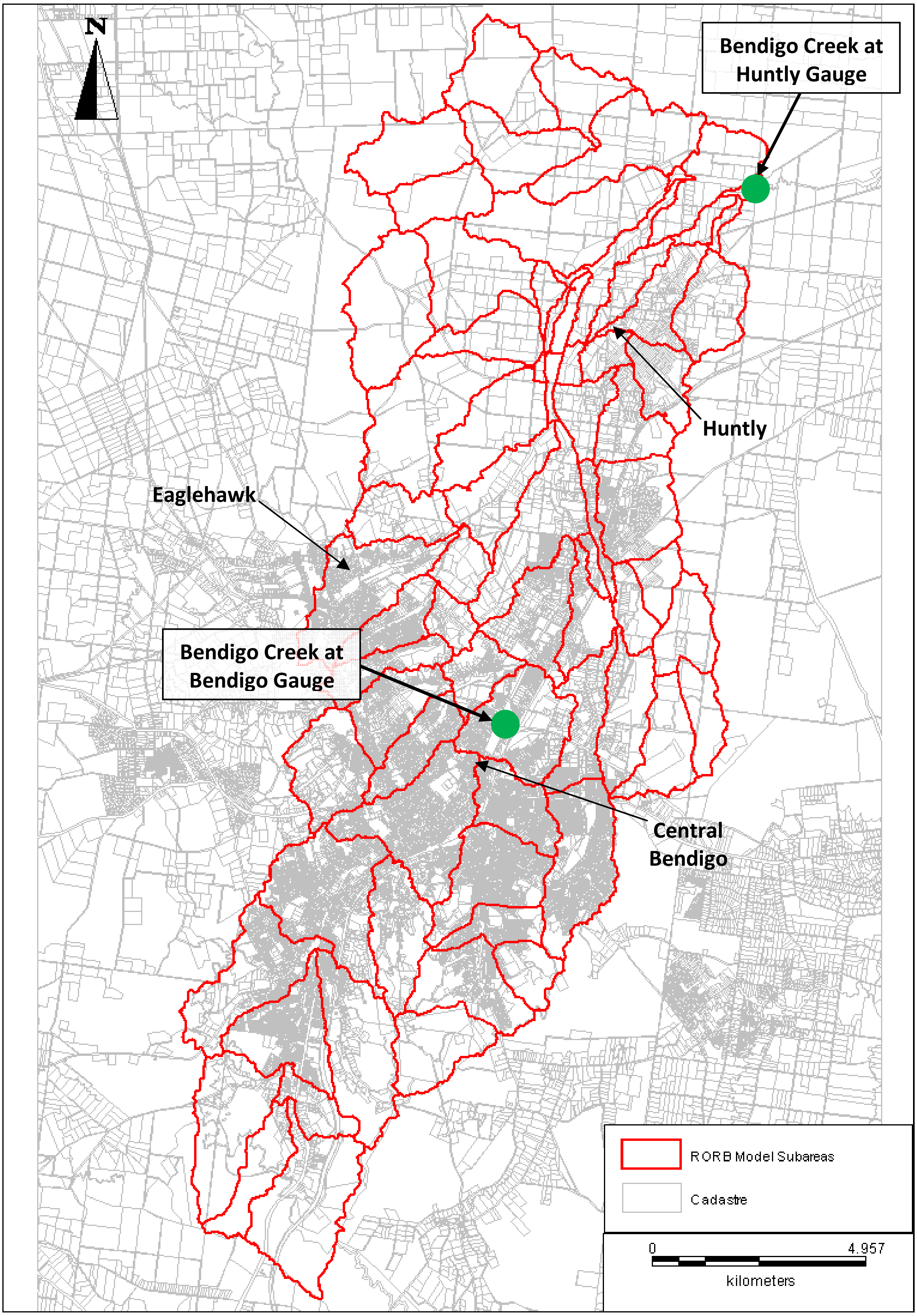


Figure 3-1 RORB Model Subcatchment Breakup and Stream Gauge Location

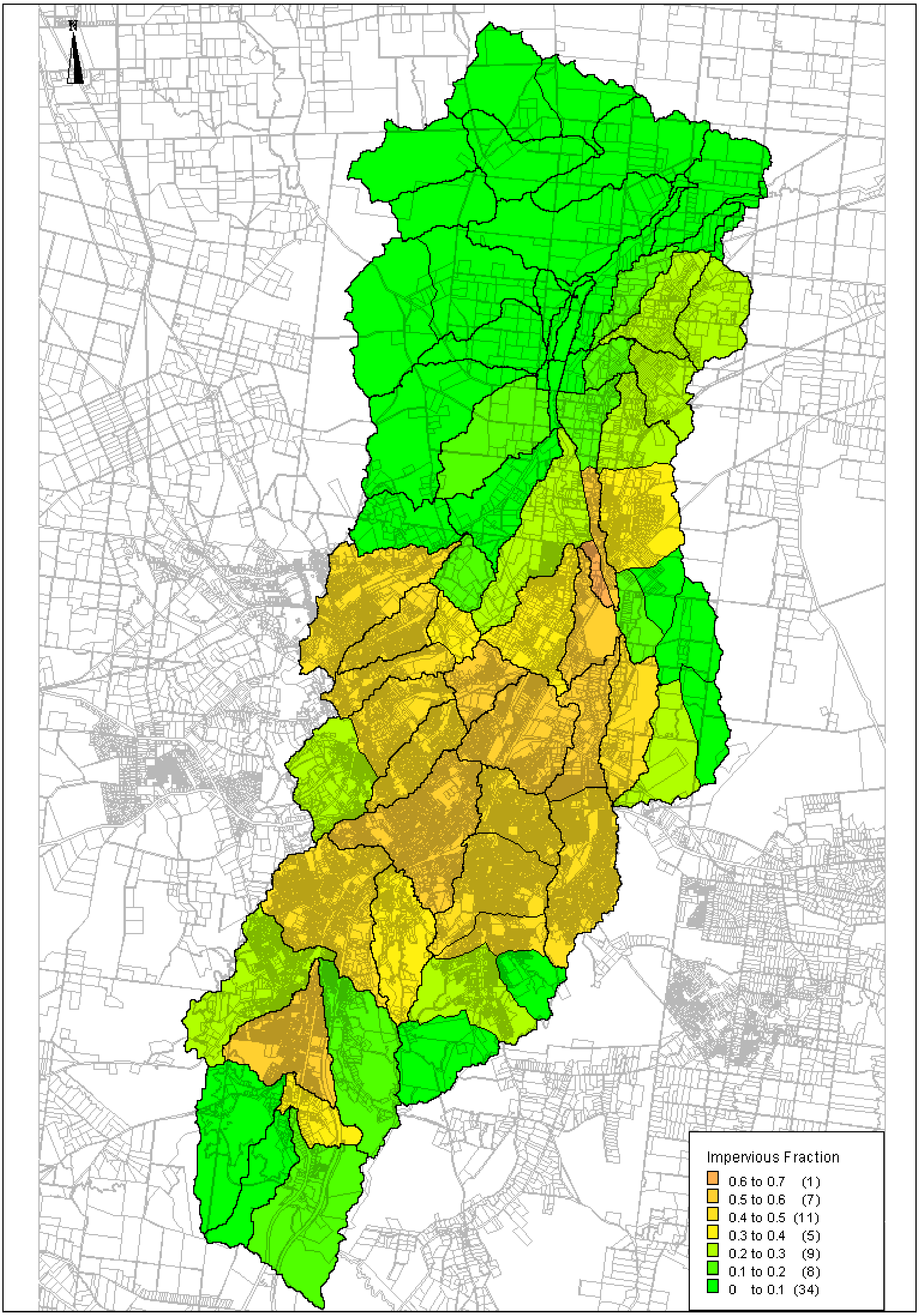


Figure 3-2 RORB Model Fraction Impervious Values

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.

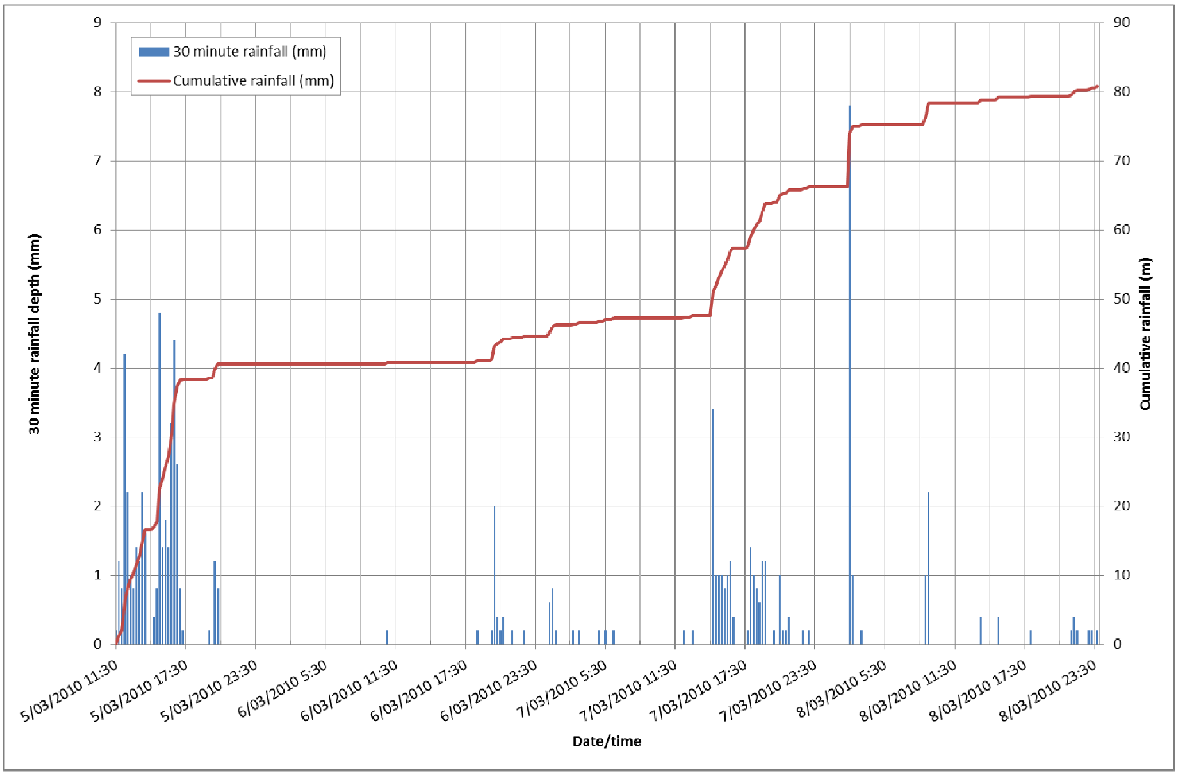


Figure 3-3 Pluviograph records (15 minute rainfall) - March 2010 Event

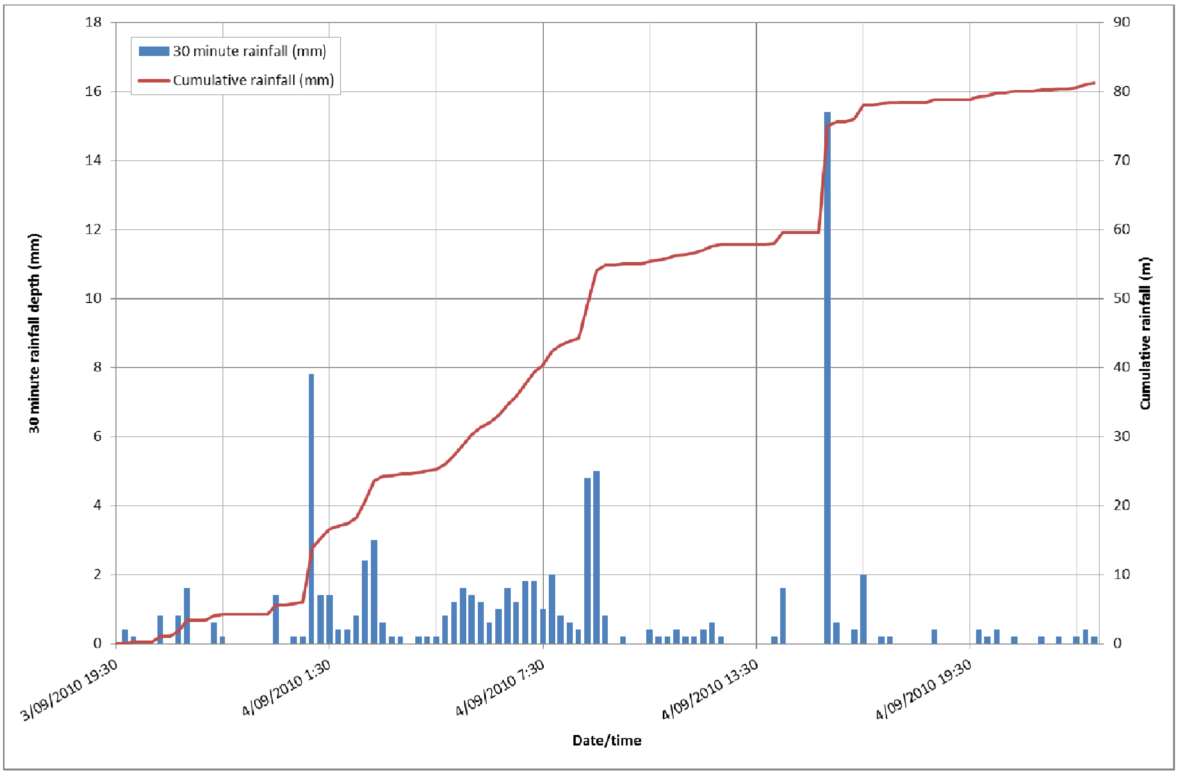


Figure 3-4 Pluviograph records (15 minute rainfall) - September 2010 Event

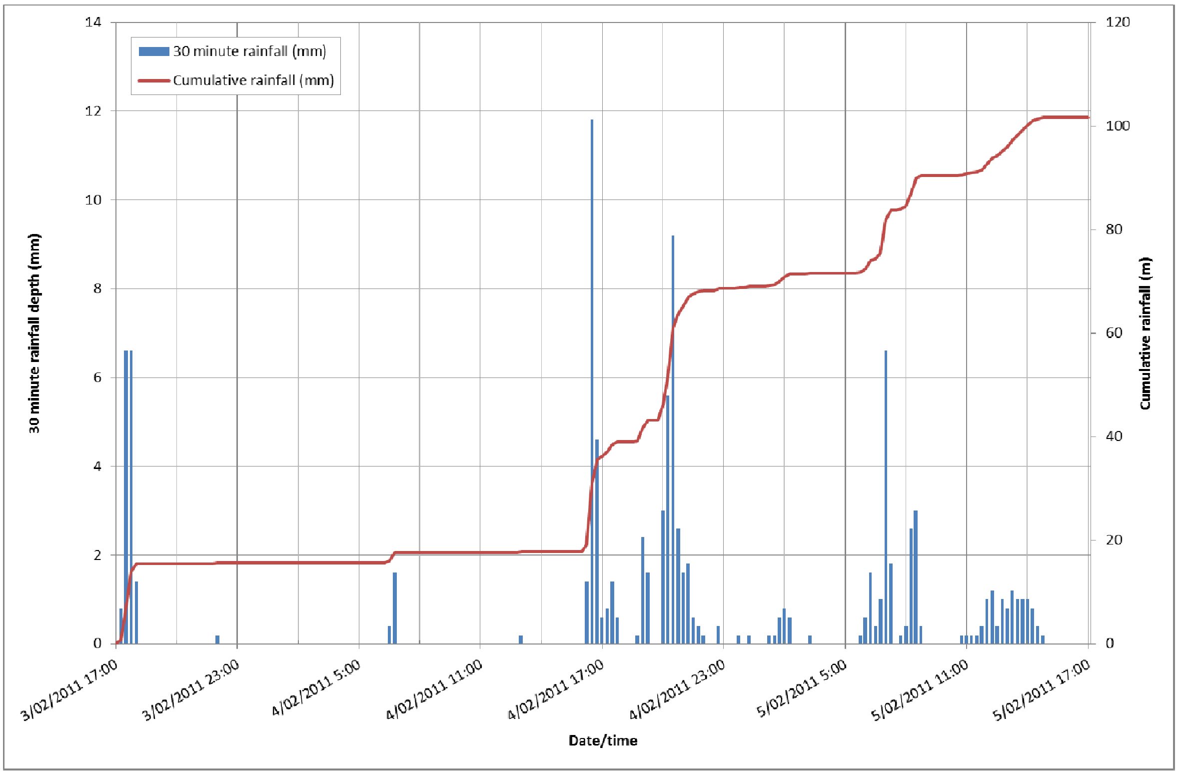


Figure 3-5 Pluviograph records (15 minute rainfall) - February 2011 Event

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.

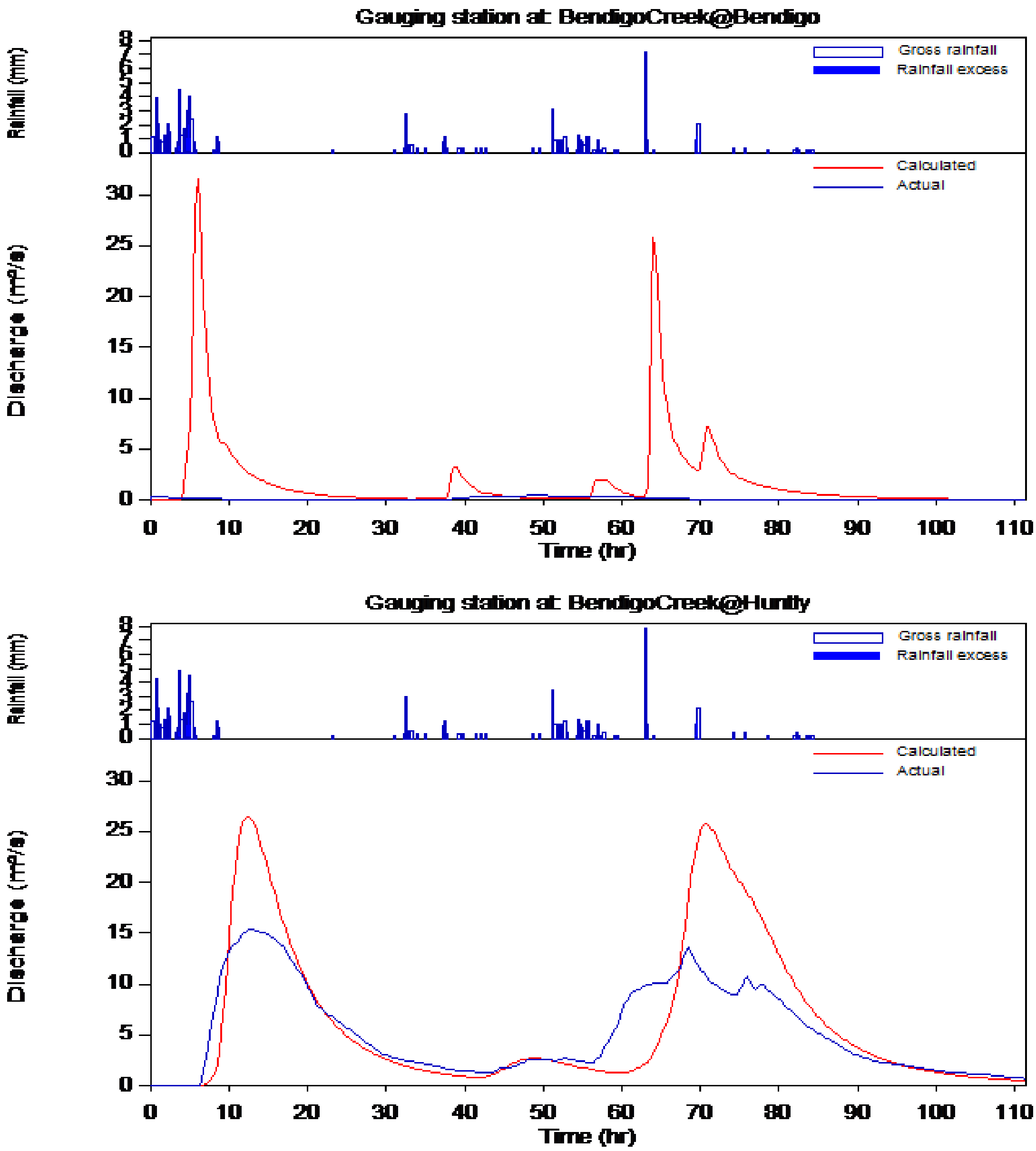


Figure 3-6 **RORB Calibration – Comparison of modelled and observed surface runoff hydrographs at Bendigo (407254) and Huntly (407255) for the March 2010 Event**

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

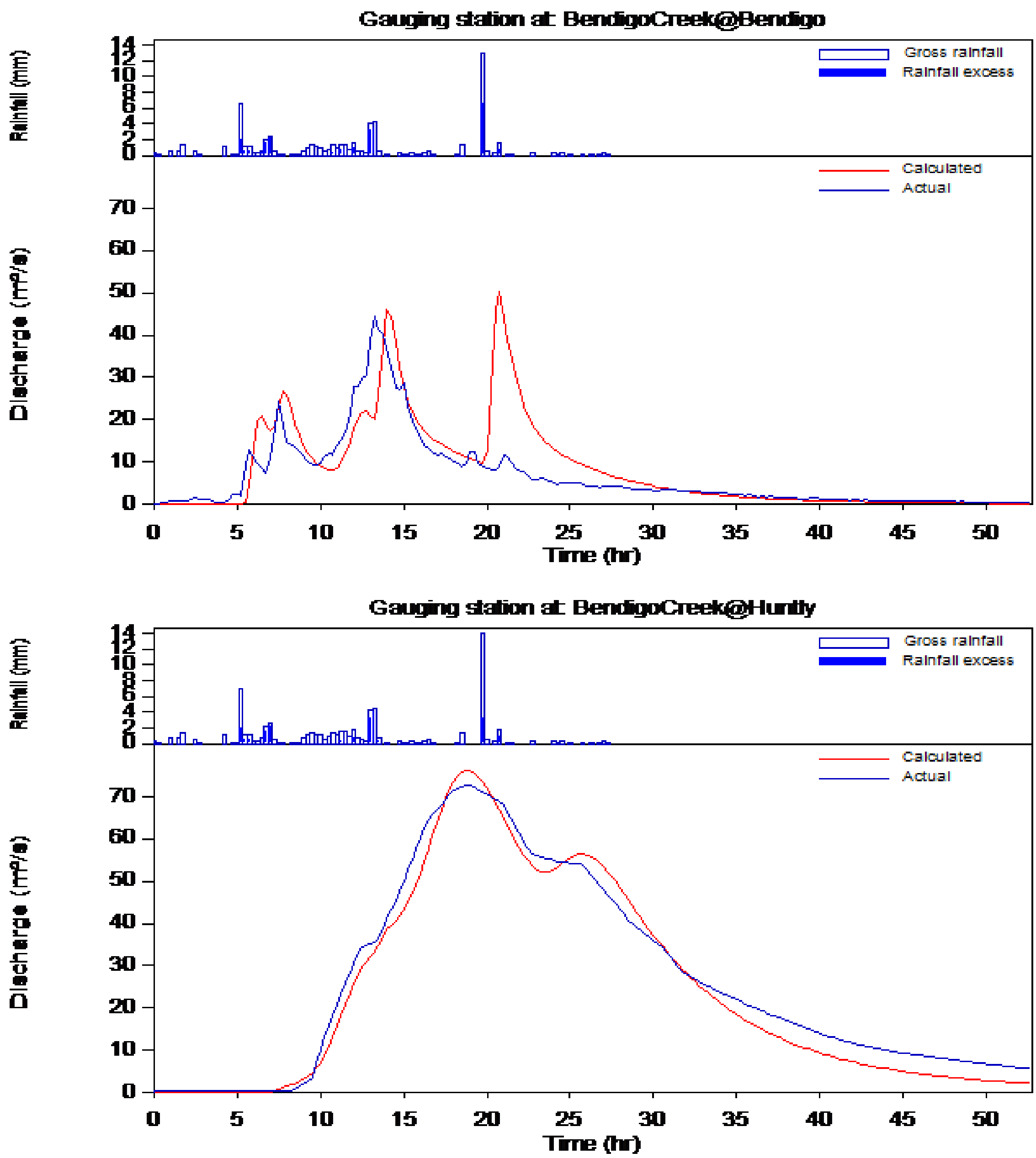


Figure 3-7 RORB Calibration – Comparison of modelled and observed surface runoff hydrographs at Bendigo (407254) and Huntly (407255) for the September 2010 Event

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.

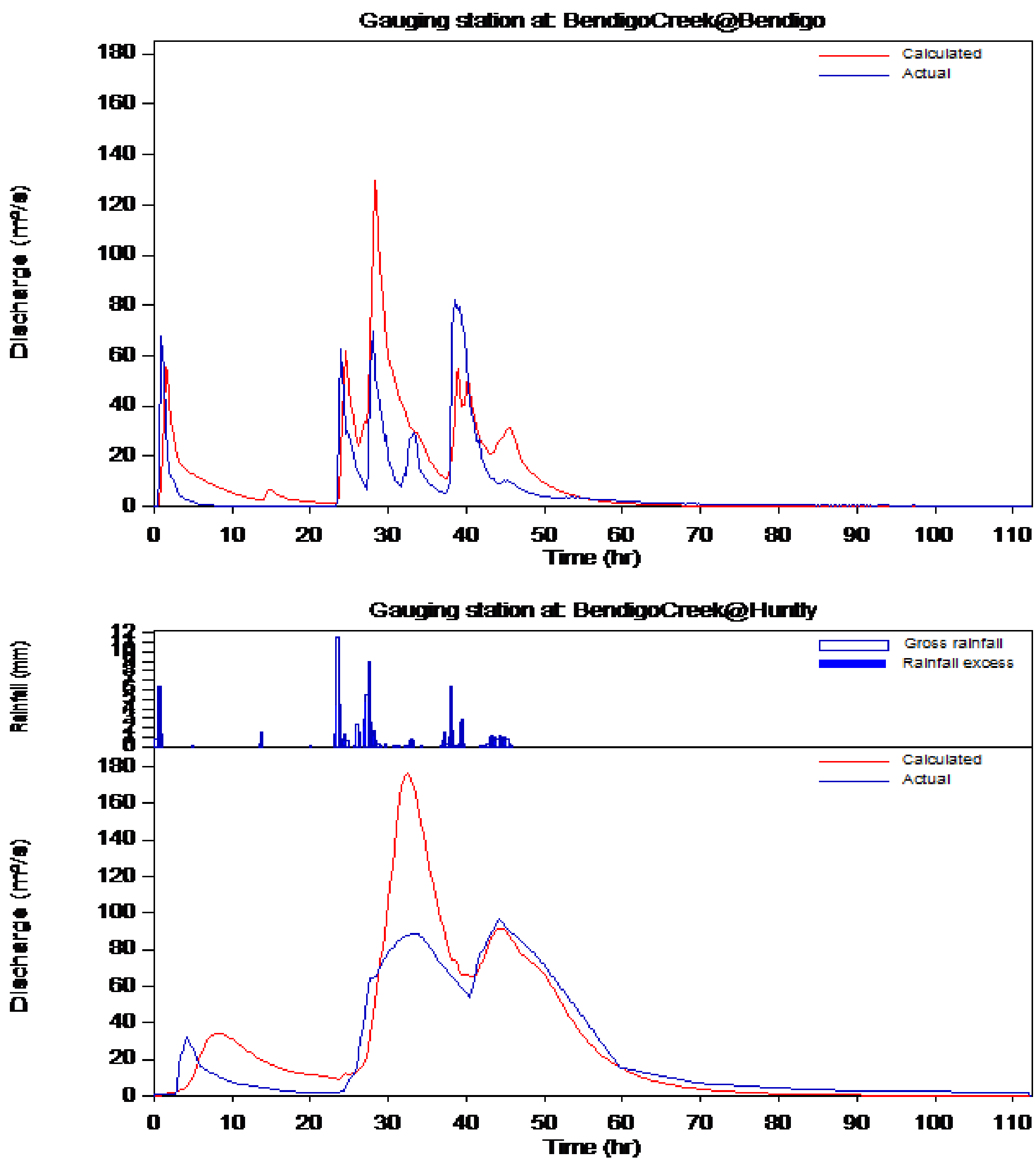


Figure 3-8 RORB Calibration – Comparison of modelled and observed surface runoff hydrographs at Bendigo (407254) and Huntly (407255) for the February 2011 Event

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	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	$k_c = 1.14 \text{ x } d_{av}$	8.9	12.72
Pearse et al. (2002) after Yu (1989)	Australia wide	$k_c = 0.96 \text{ x } d_{av}$	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.

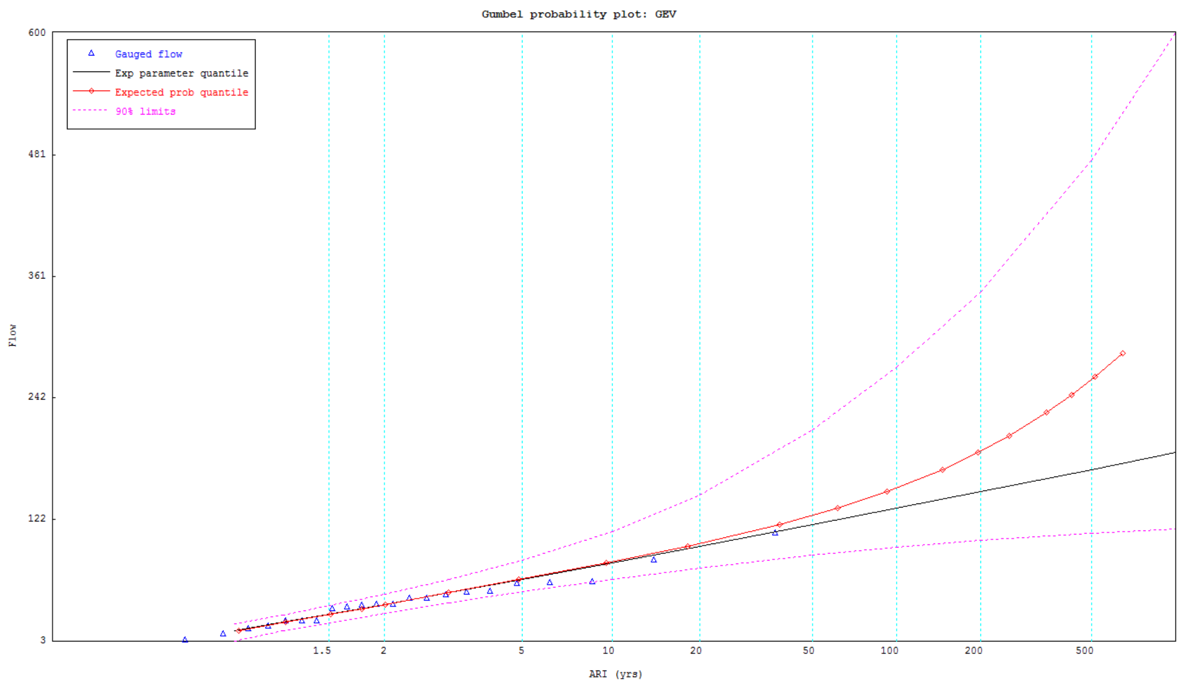


Figure 3-9 Generalised Extreme Value Flood Frequency Analysis – Bendigo Creek at Bendigo

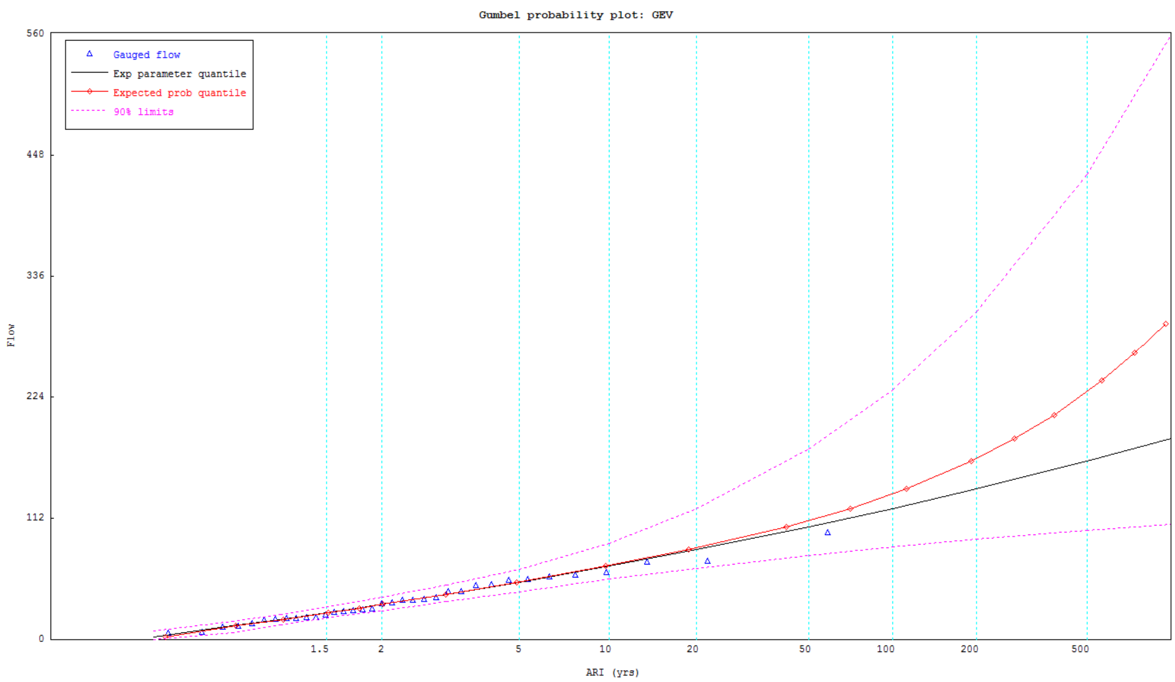


Figure 3-10 Generalised Extreme Value Flood Frequency Analysis – Bendigo Creek at Huntly

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.

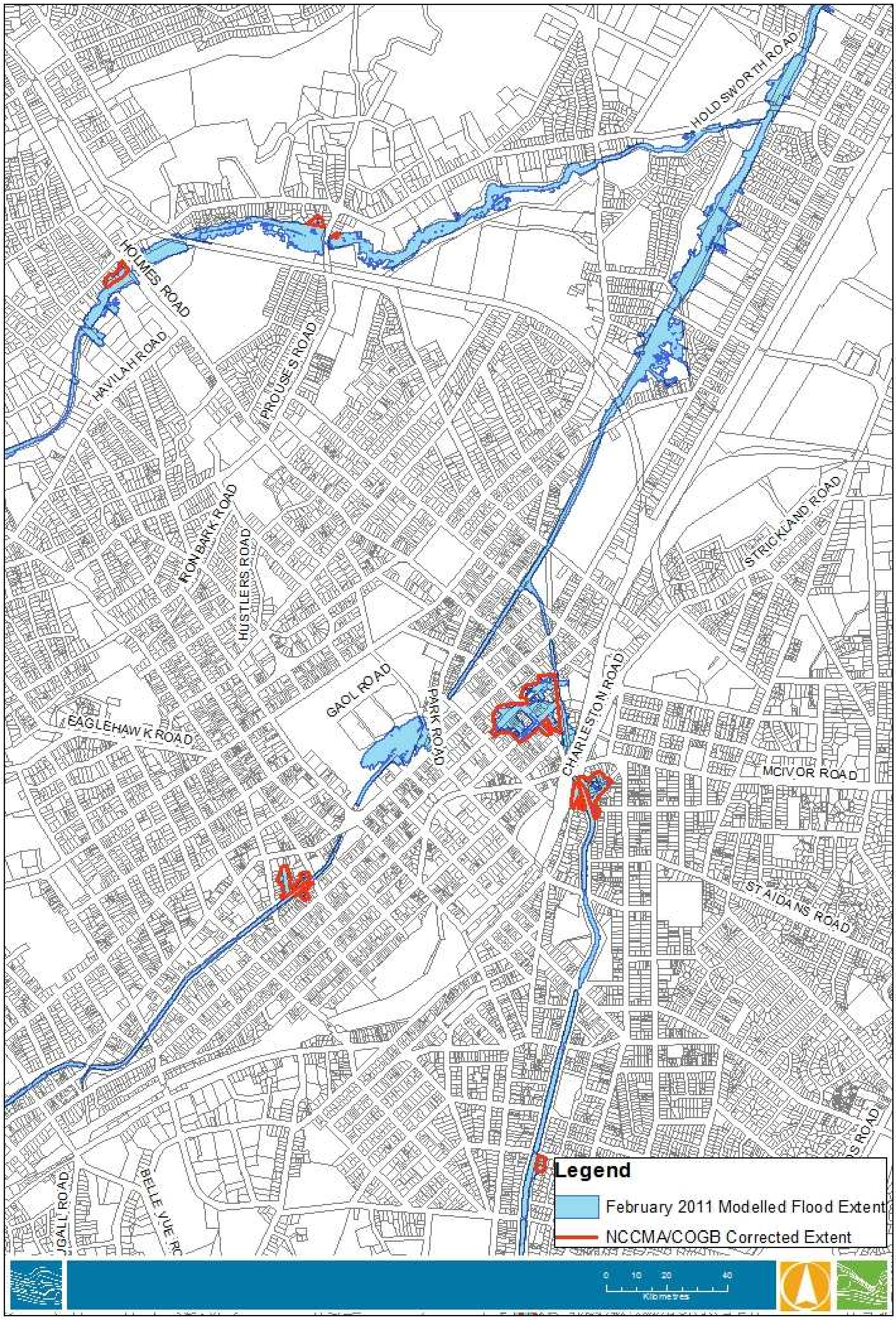


Figure 3-11 Example of the NCCMA/COGB review of the modelled flood extent for the February event around Central Bendigo.

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.

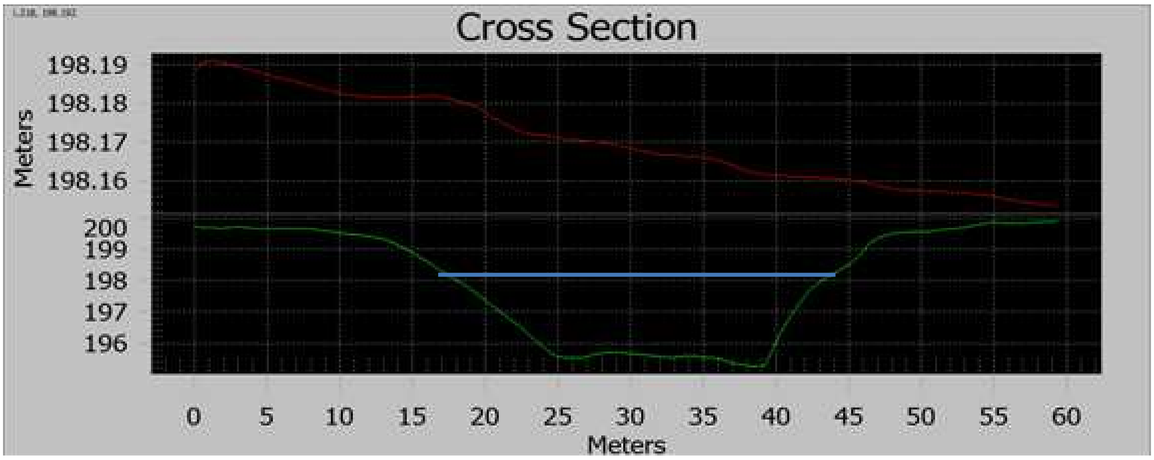


Figure 3-12 Cross-section at the location of the Holdsworth Road bridge with the peak modelled flood level marked with the blue line.

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

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

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.

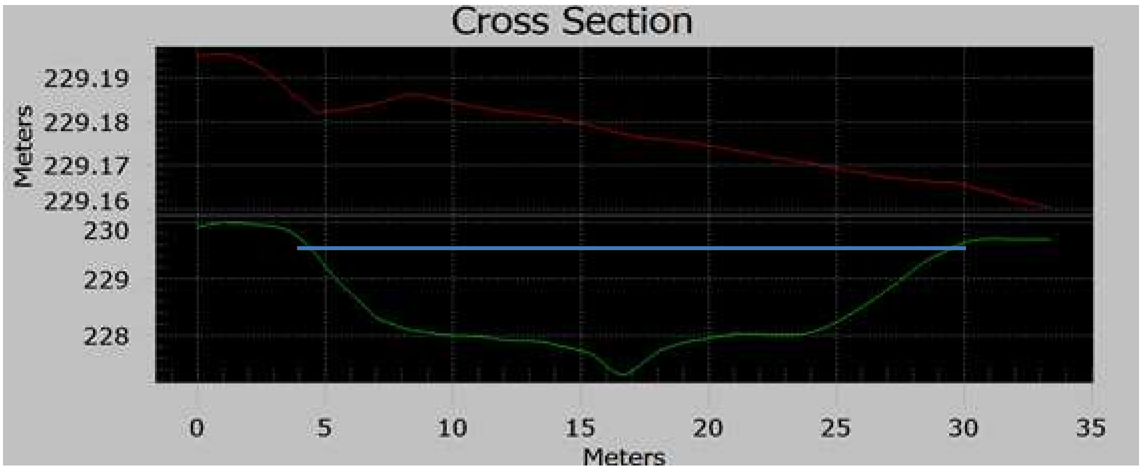


Figure 3-14 Cross-section at the location of the Central City Caravan Park bridge with the peak modelled flood level marked with the blue line.

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

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

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

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

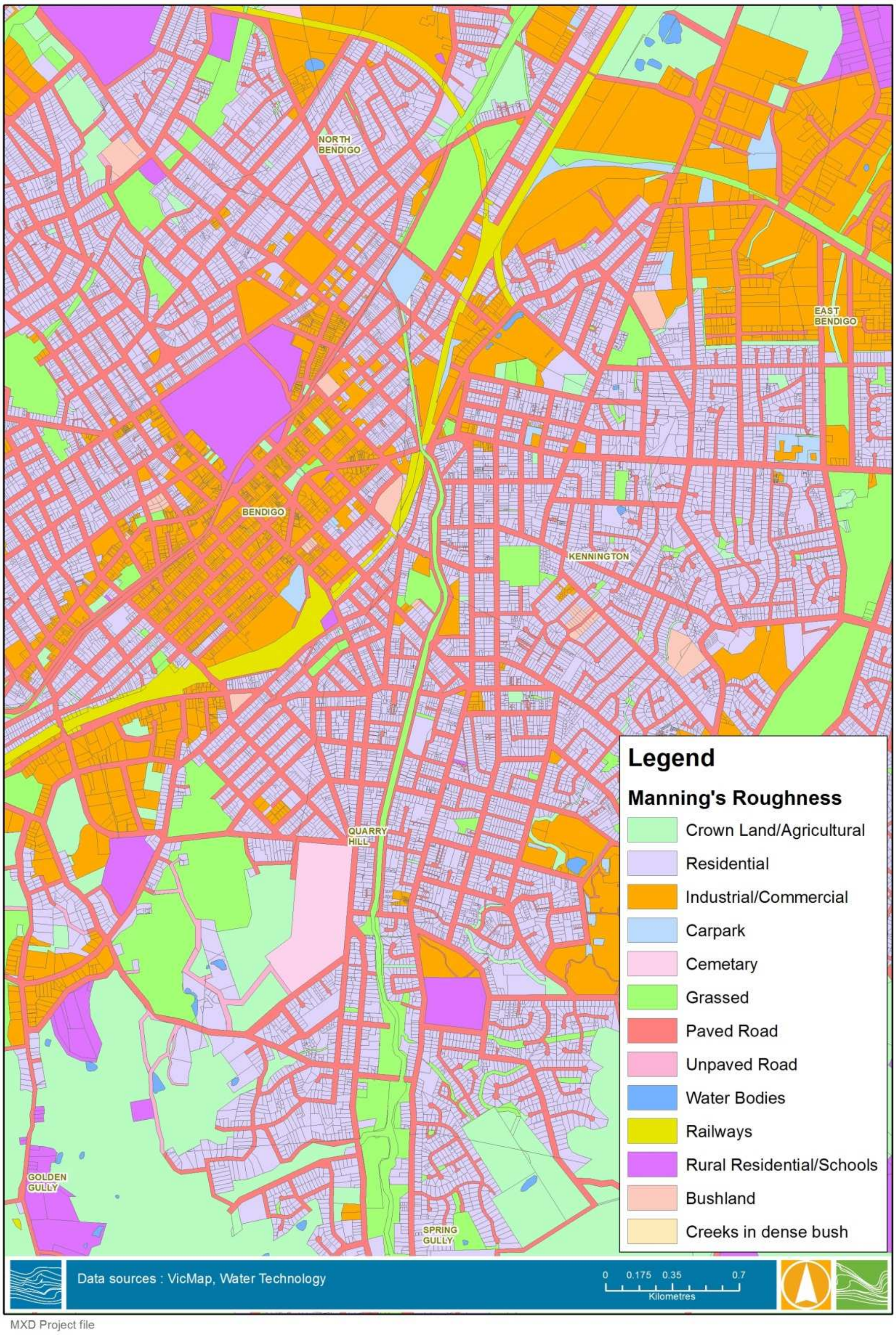


Figure 4-1 Roughness map of central Bendigo

4.2.5 Boundary Conditions

Upstream inflow boundary

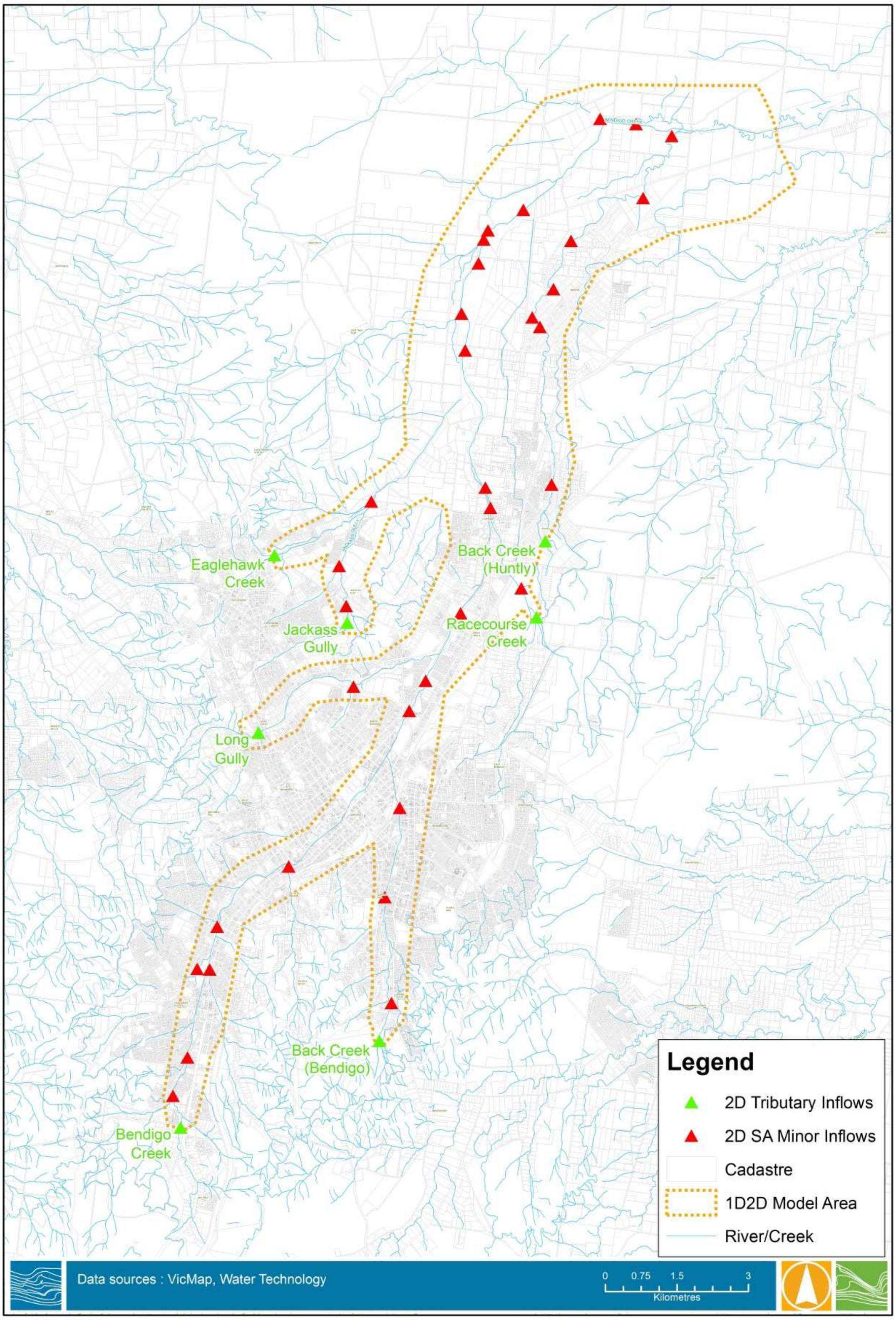
The spine model has 17 major inflow locations throughout the catchment. 7 of these boundaries are at the upstream ends of the major tributaries while the remainder are located at the outlets of smaller tributaries located throughout the catchment. The major tributary inflows were modelled using 2D_BC 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.

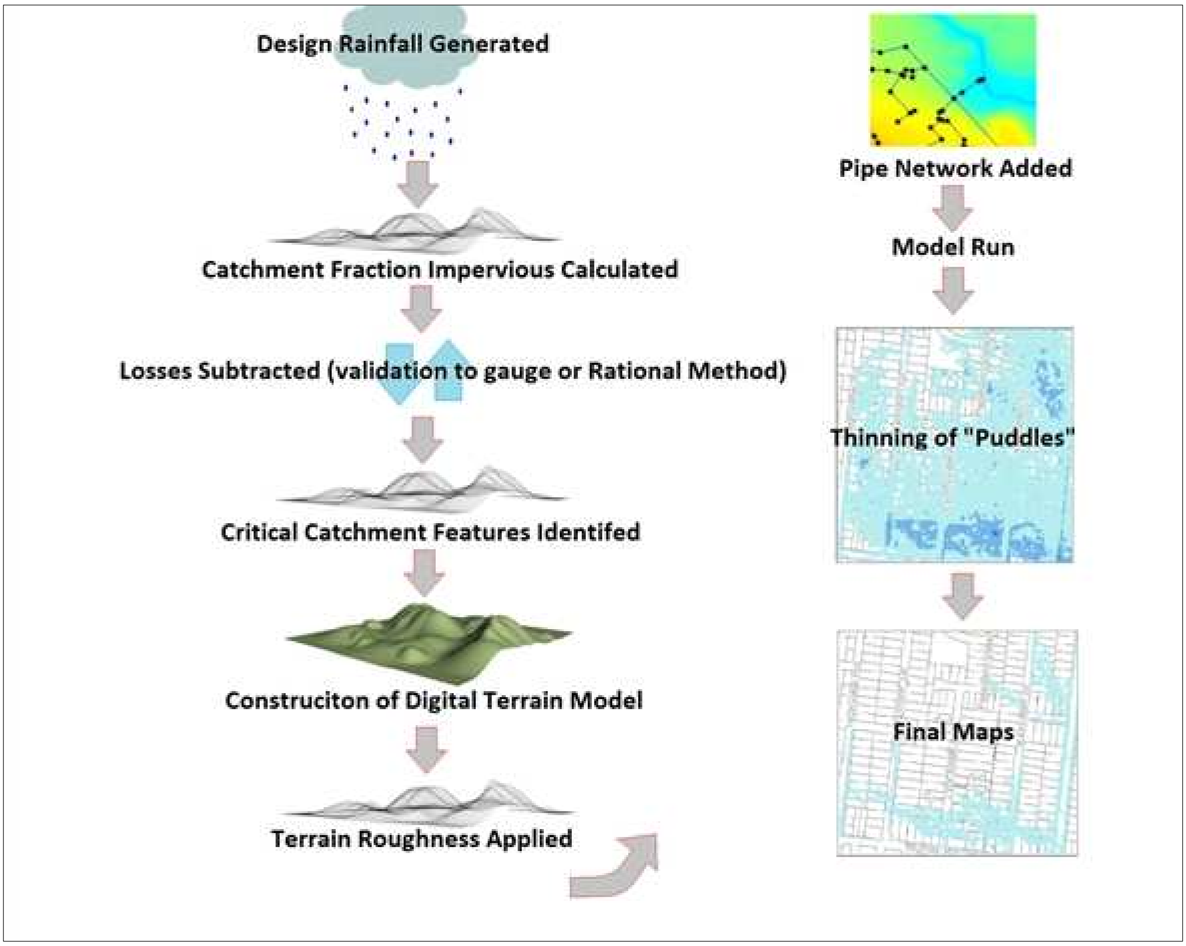


Figure 5-1 ROG modelling process

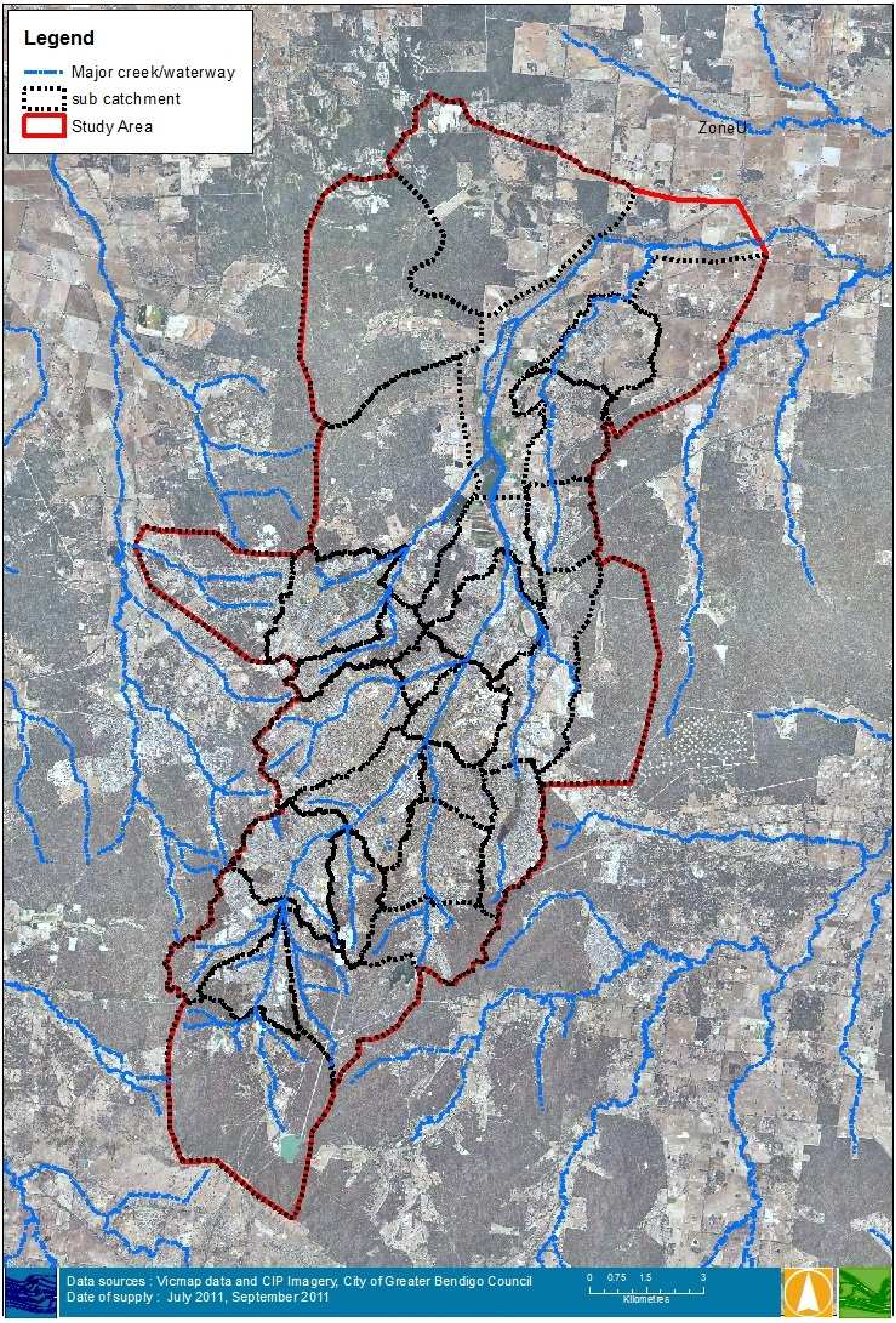


Figure 5-2 Catchment delineation

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

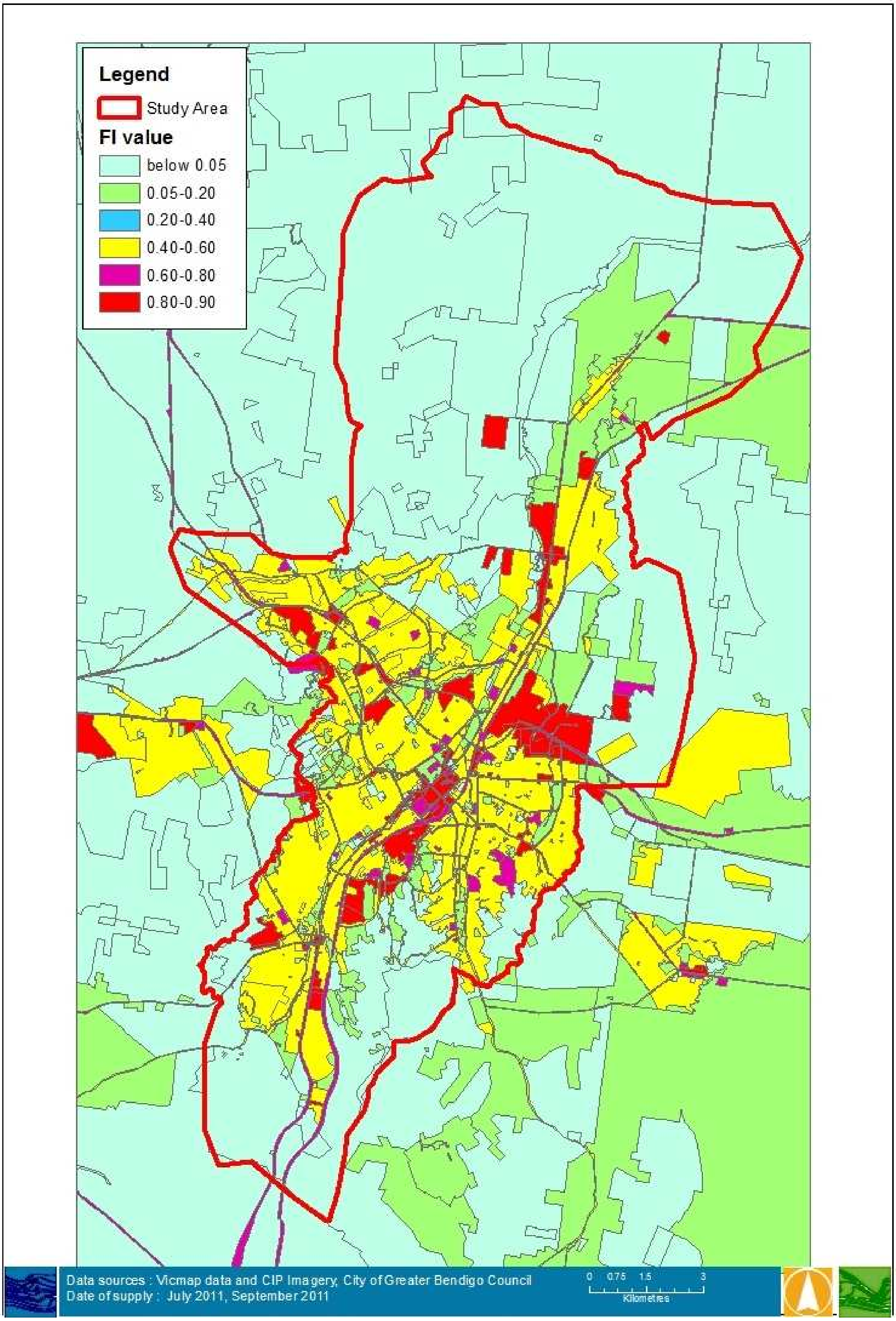


Figure 5-3 Catchment Impervious Fraction

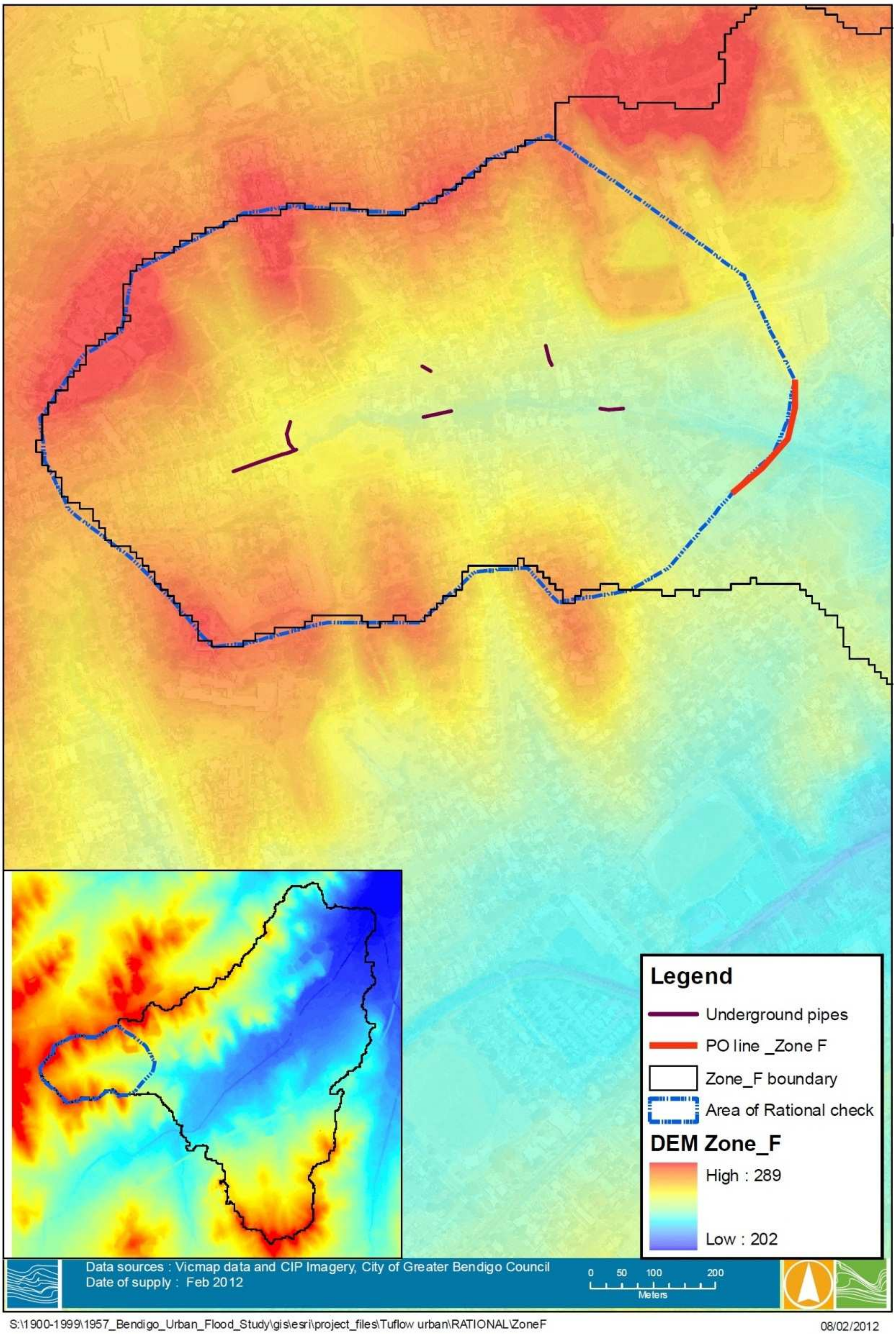


Figure 5-4 Zone F Reconciliation Location

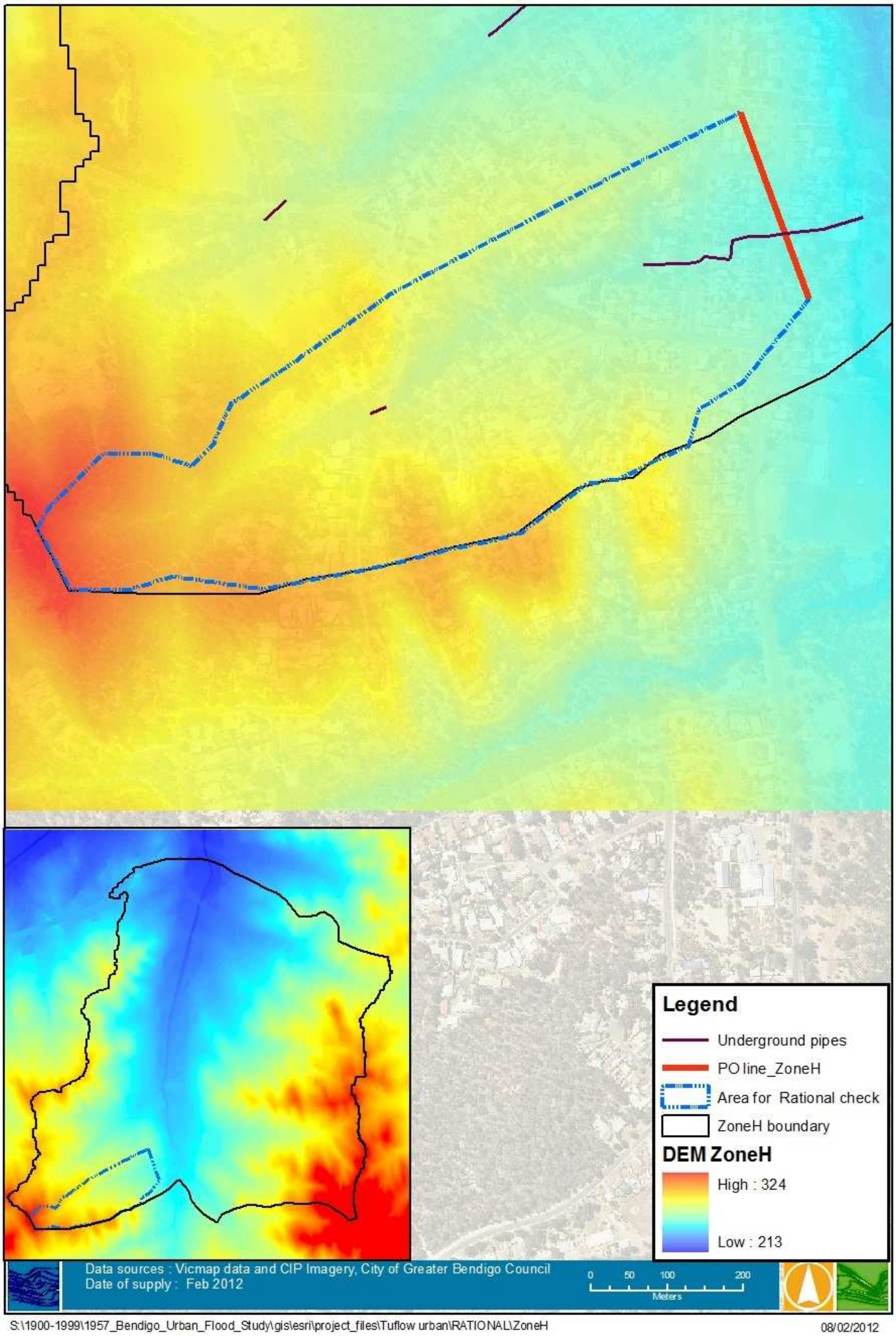


Figure 5-5 Zone H Reconciliation Location

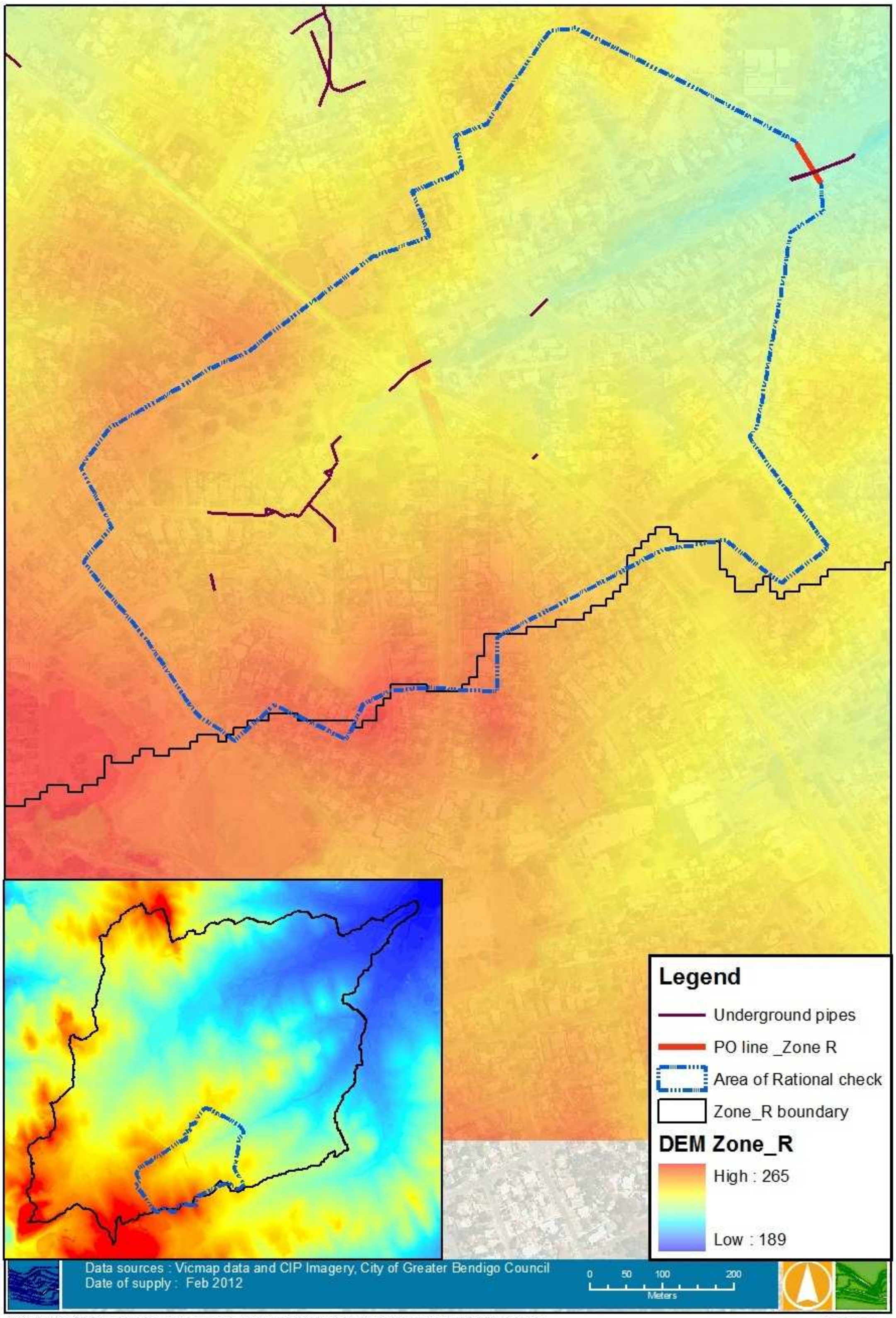


Figure 5-6 Zone R Reconciliation Location

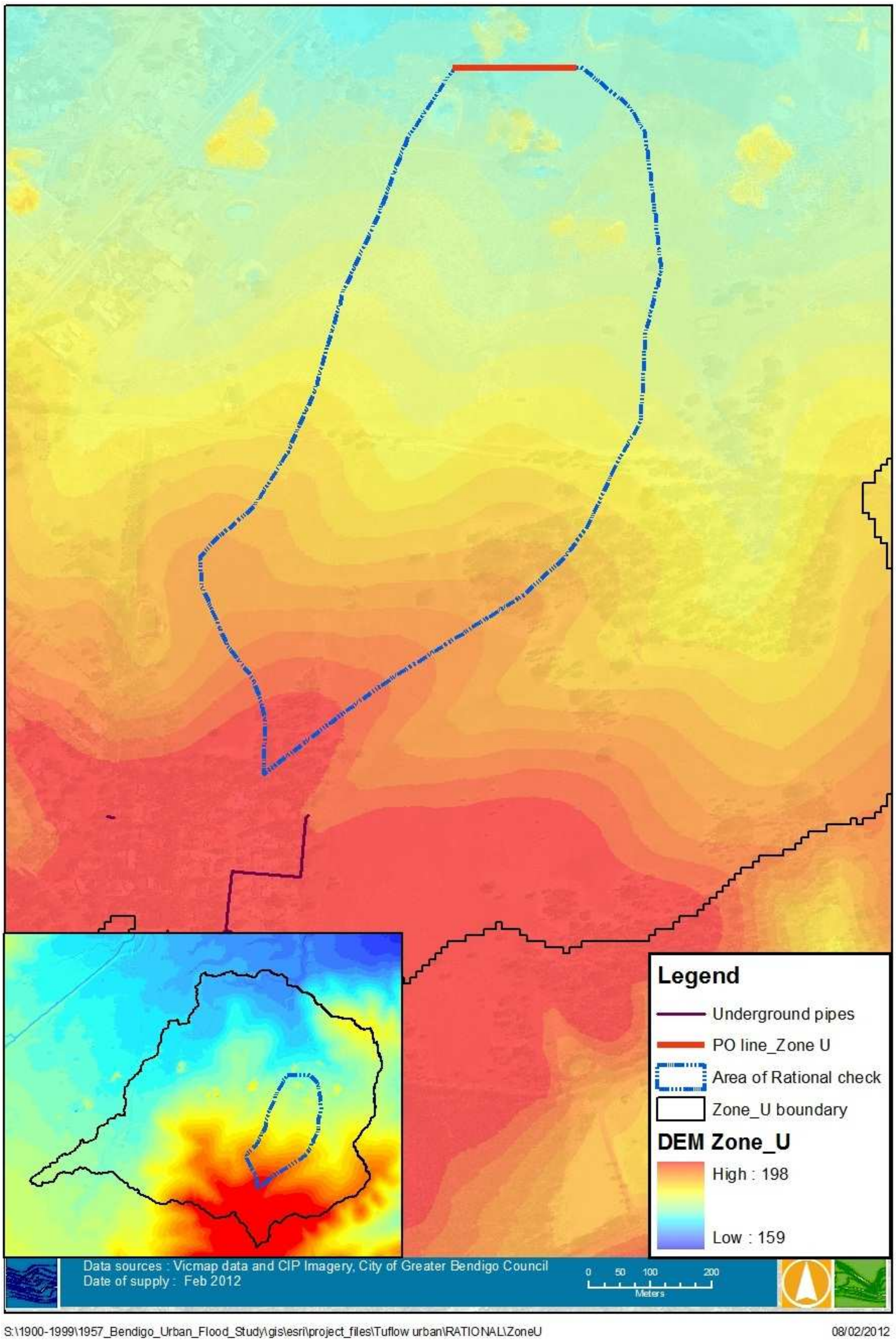


Figure 5-7 Zone U Reconciliation Location

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.

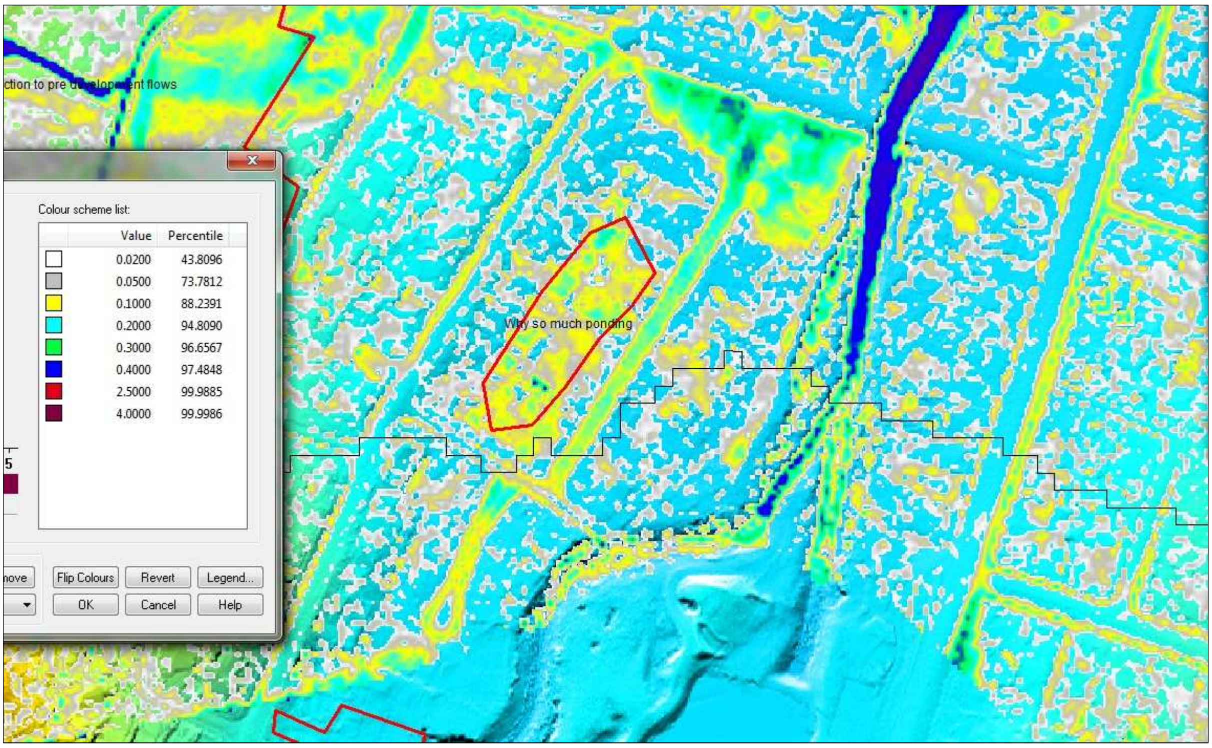


Figure 5-8 Example interrogation of modelling results

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 2Dl 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.

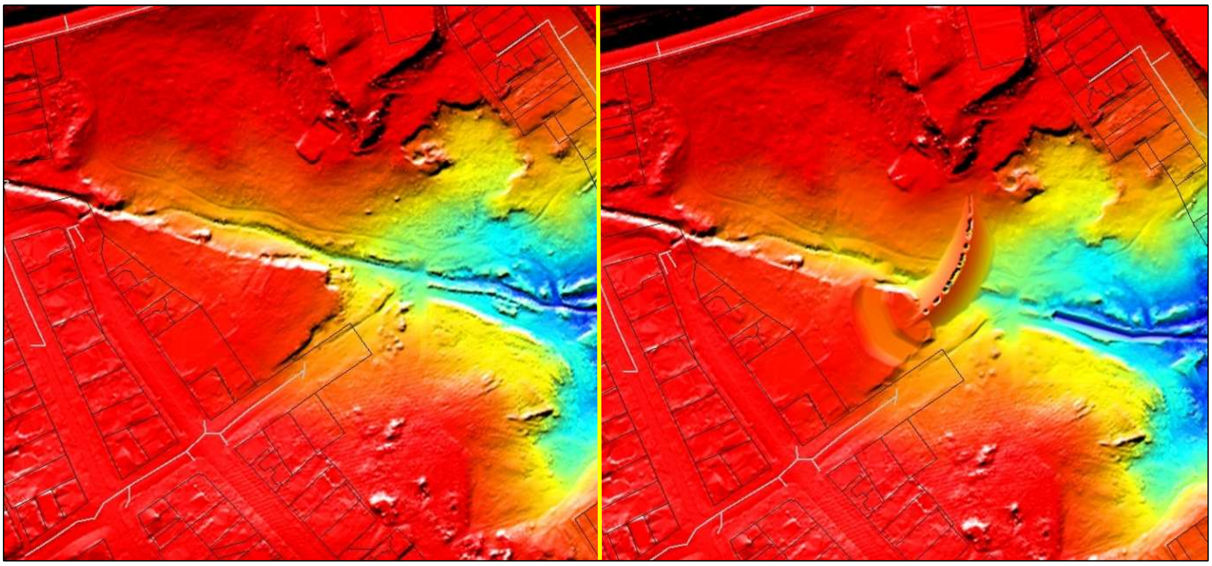


Figure 5-10 DEM before and after a Retardation Basin

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.

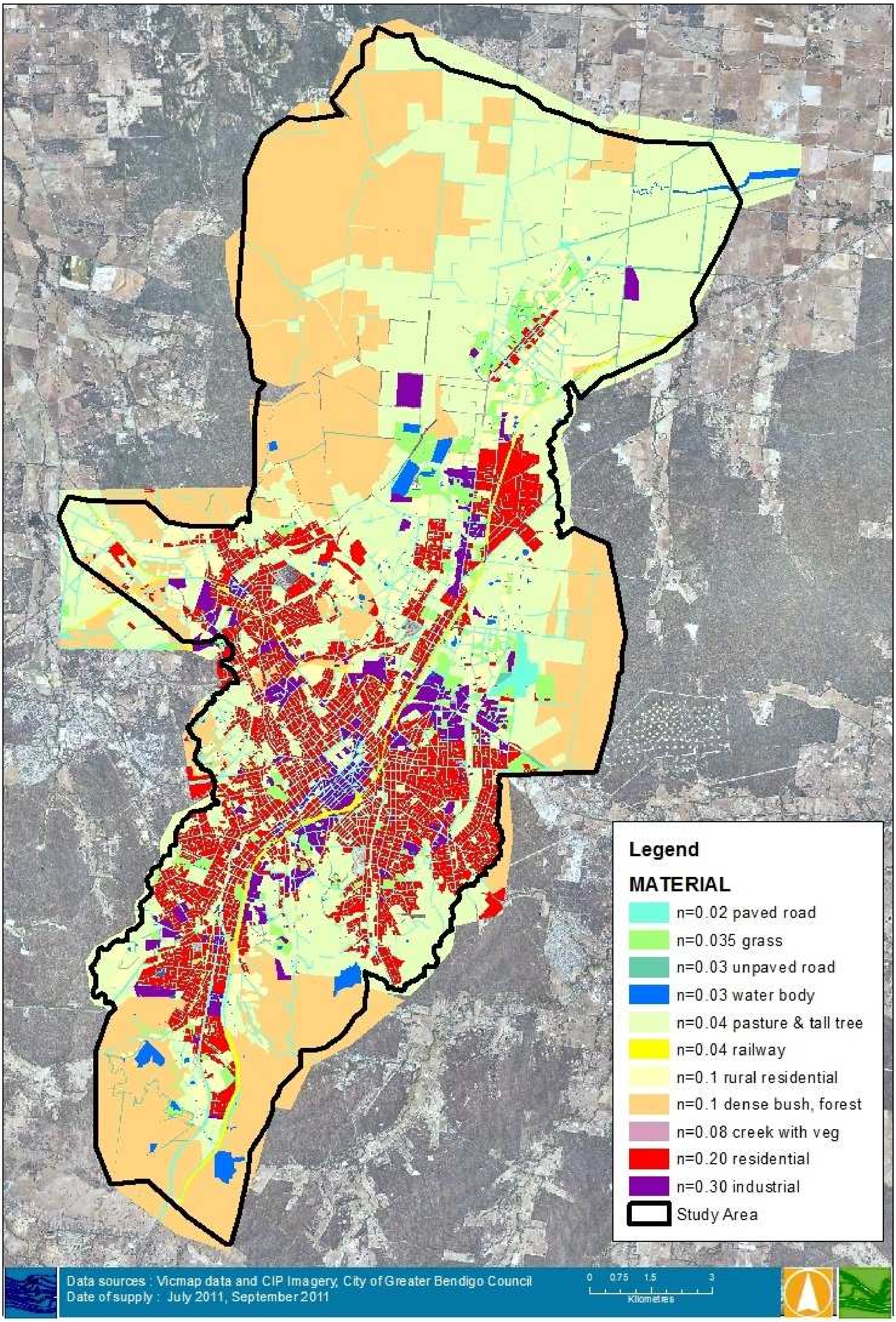


Figure 5-11 Model roughness map

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.

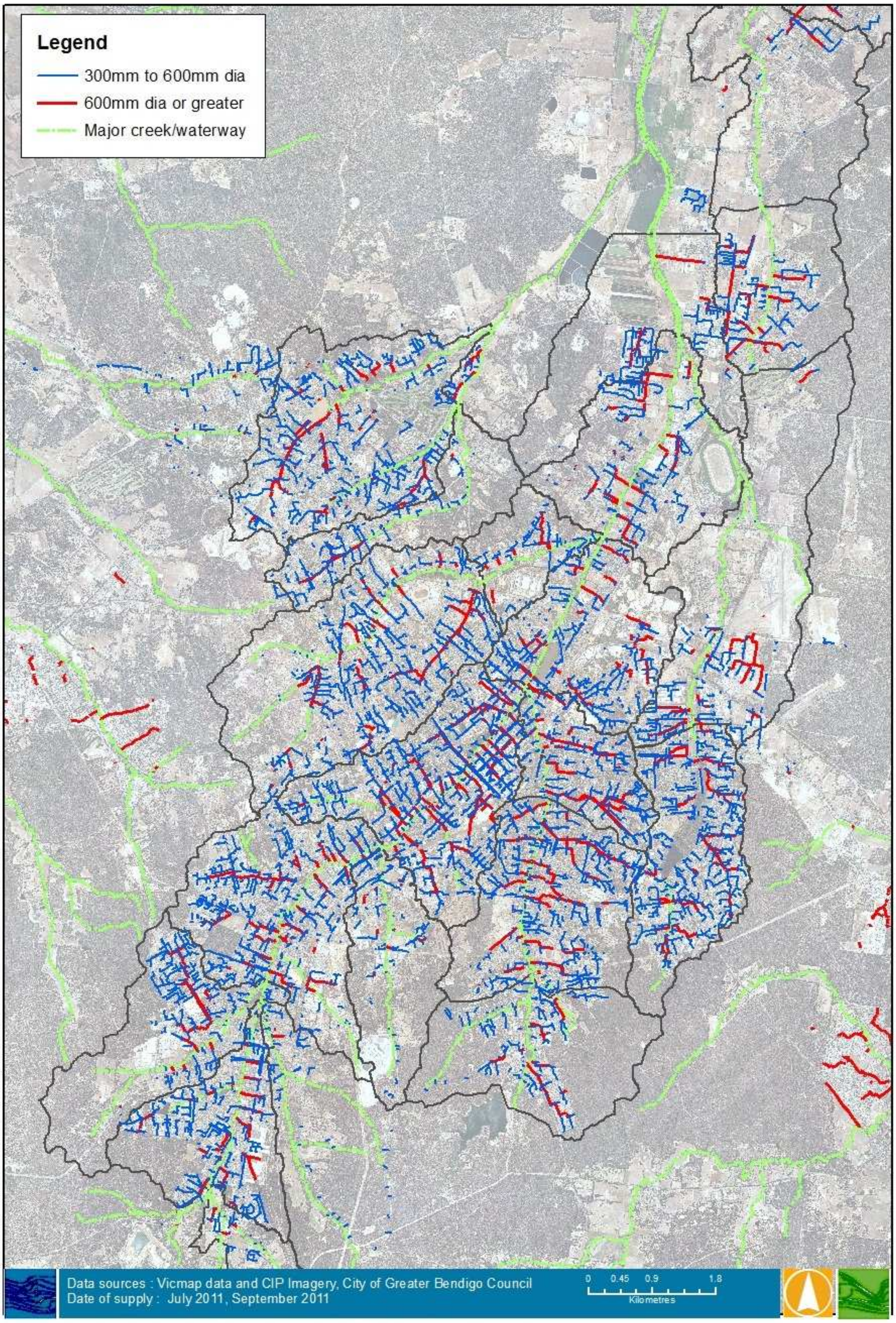


Figure 5-12 1d Pipe network

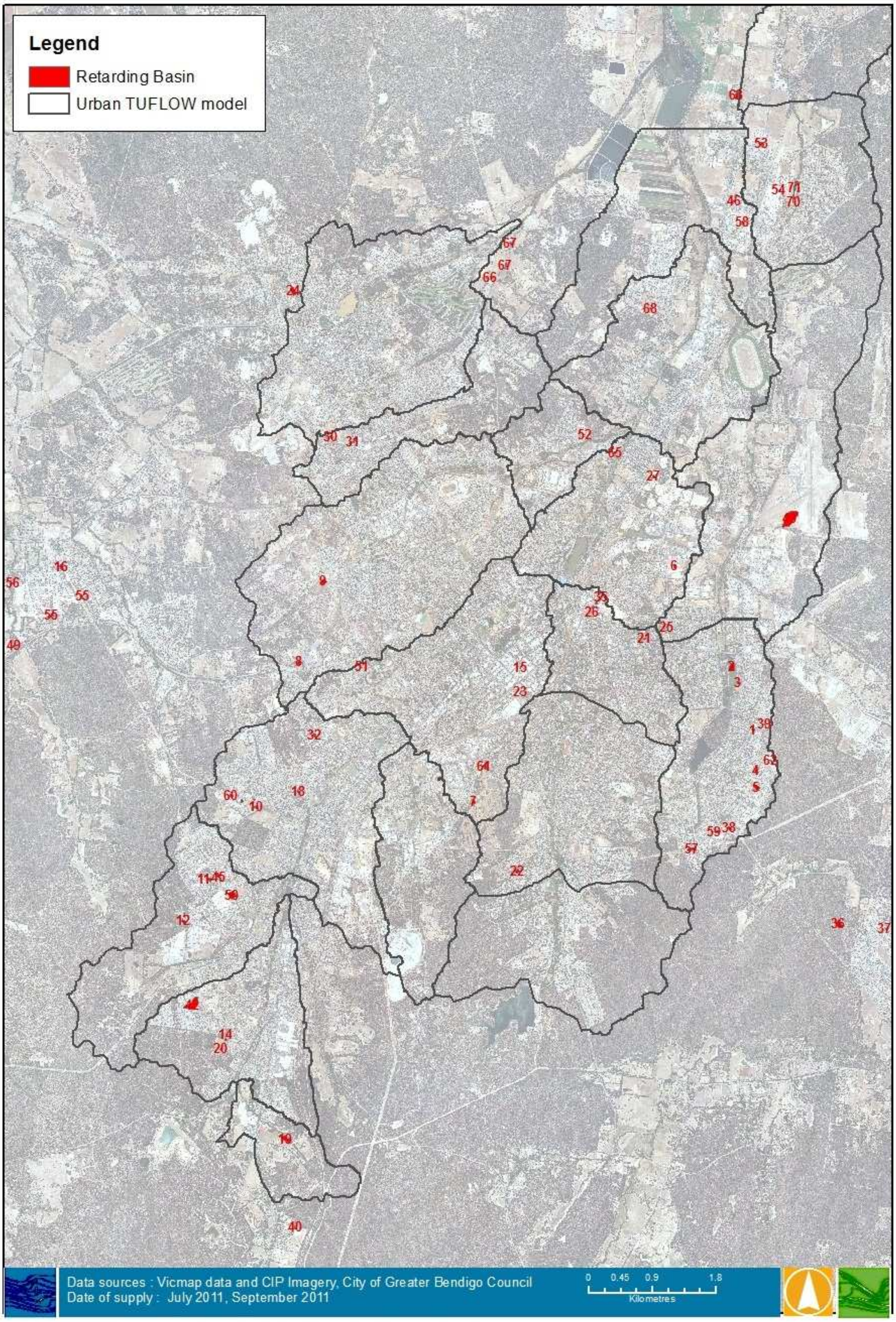


Figure 5-13 Retardation Basin (RB) locations

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

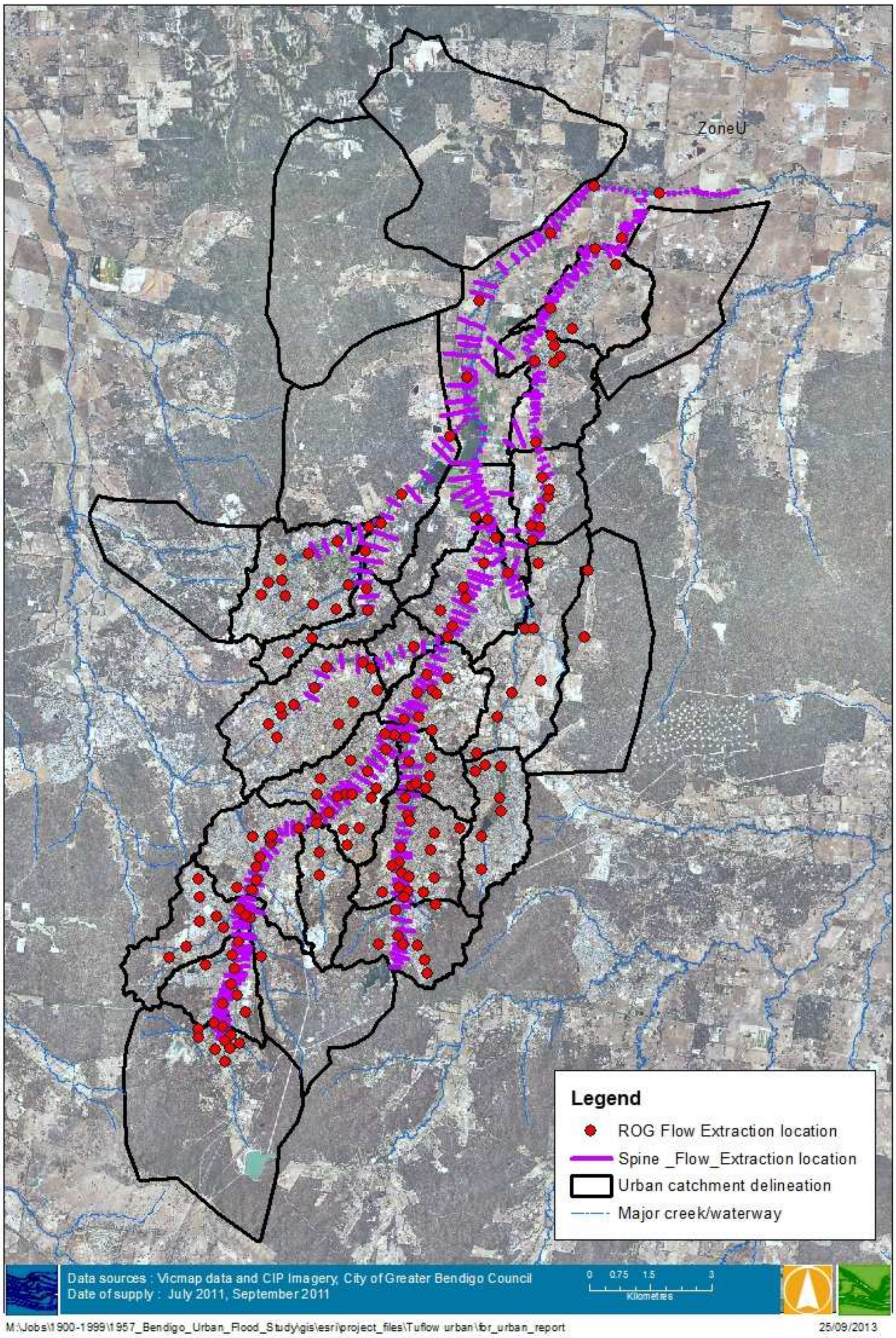


Figure 5-14 Flow output locations

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.

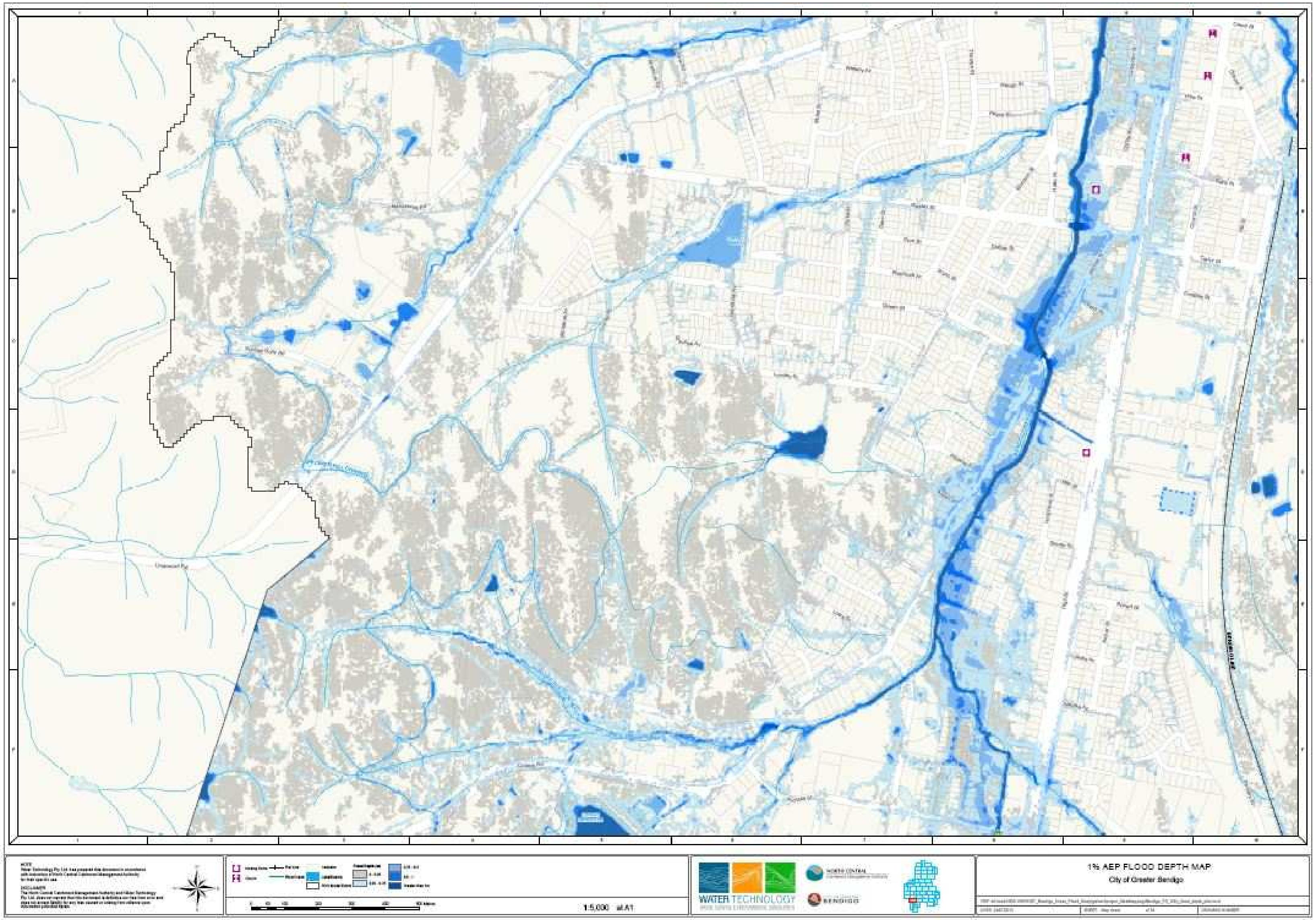


Figure 5-15 Typical depth map

This page intentionally blank

6. 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.

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.

7. REFERENCES

To include prior to finalisation.

APPENDIX A FLOOD WARNING DISCUSSION PAPER AND RECCOMENDATIONS

To be included on finalisation of report.

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, Maiden Gully, and Junortoun are presented in Figure B 1

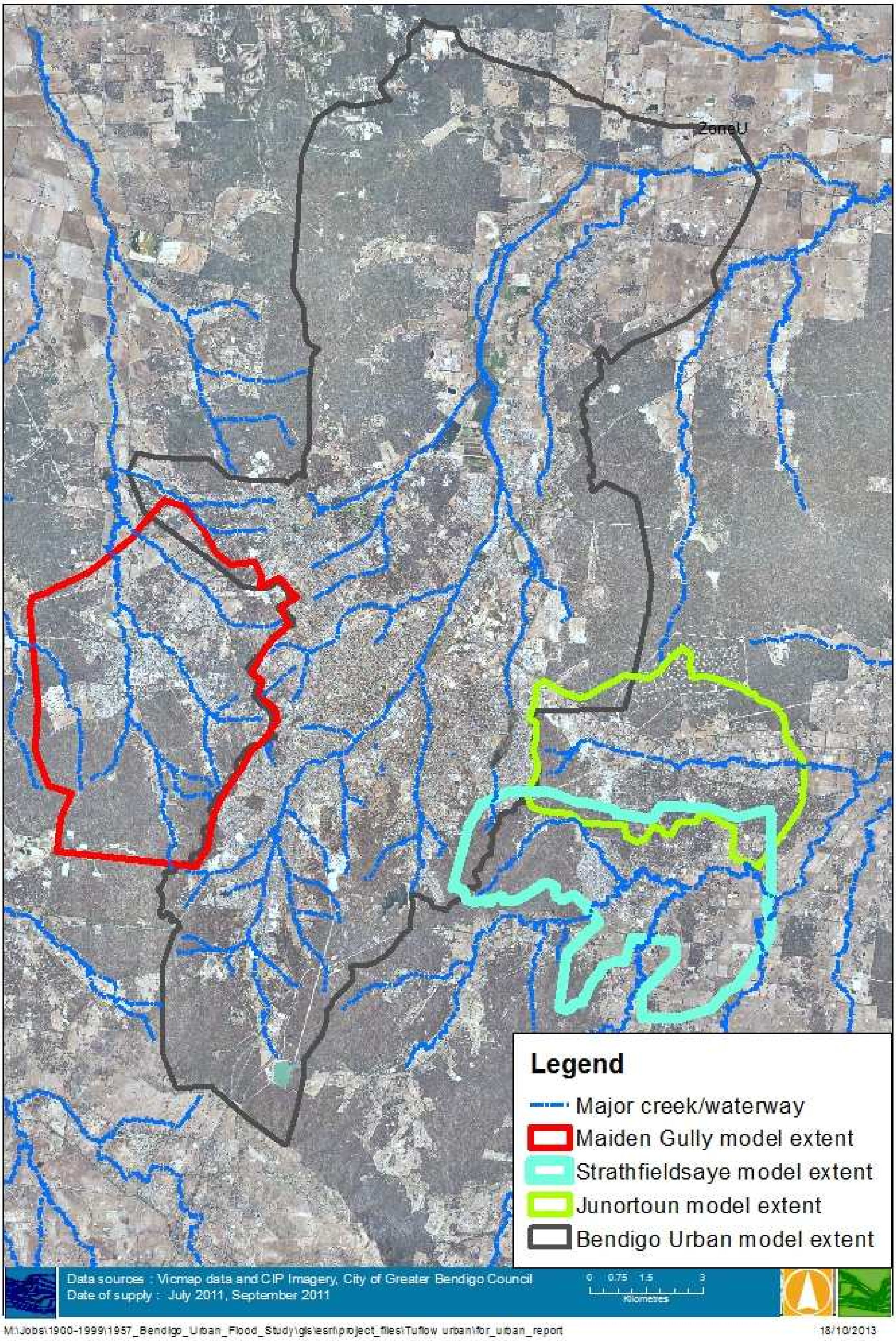


Figure B 1 Maiden Gully, Strathfieldsaye, Junortoun model extents