Casterton Flood Investigations

Floodplain Management Report

RM2298 Final 1.0

Prepared for Glenelg Hopkins CMA and Glenelg Shire Council

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GLOSSARY

Annual Exceedence 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.
Average Recurrence Interval (ARI)	The average or expected value of the period between exceedances of a given discharge or event. A 100-year ARI event would occur, on average, once every 100 years.
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 events e.g. some roads may be designed to be overtopped in the 1 in 1 year or 100% AEP flood event.
Development	The erection of a building or the carrying out of work; or the use of land or of a building or work; or the subdivision of land.
Discharge	The rate of flow of water measured in terms of volume over time. It is to be distinguished from the speed or velocity of flow, which is a measure of how fast the water is moving rather than how much is moving.
Flood	Relatively high stream flow which overtops the natural or artificial banks in any part of a stream, river, estuary, lake or dam, and/or overland runoff before entering a watercourse and/or coastal inundation resulting from super elevated sea levels and/or waves overtopping coastline defences.
Floodplain	Area of land which is subject to inundation by floods up to the probable maximum flood event, i.e. flood prone land.
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.
Mathematical/computer models	The mathematical representation of the physical processes involved in runoff and stream flow. These models are often run on computers due to the complexity of the mathematical relationships. In this report, the models referred to are mainly involved with rainfall, runoff, pipe and overland stream flow.
Probability	A statistical measure of the expected frequency or occurrence of flooding. For a fuller explanation see Annual Exceedence Probability.
Risk	Chance of something happening that will have an impact. It is measured in terms of consequences 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.
Topography	A surface which defines the ground level of a chosen area.

1 INTRODUCTION

Cardno was engaged by Glenelg Shire Council (GSC) to investigate flooding in the Glenelg shire. The Shire is located within the Glenelg Catchment and the relevant catchment authority is the Glenelg Hopkins Catchment Management Authority (GHCMA). The Glenelg Shire is located in south west Victoria. The main urban centre is Portland. Other significant townships include Heywood and Casterton, located approximately 25km and 85km north of Portland, respectively.

This report outlines the process undertaken in developing and assessing the flooding at the town of Casterton on the Glenelg River. The study aimed to refine and confirm the existing hydrological assessments undertaken for Casterton as part of the previous report "Glenelg Flood Investigations" (Cardno, 2008), as well as confirm the Average Recurrence Intervals (ARIs) of the historic flood event data. This information would then form the basis for a revised hydraulic model of the township that would be calibrated and re-run to confirm or improve the existing 1% Annual Exceedence Probability (AEP) flood levels from the 2008 report.

In the Glenelg Shire Planning Scheme, Casterton has a Rural Floodway Overlay (RFO) and a Land Subject to Inundation Overlay (LSIO). Indicative 100 year ARI flood extents and floodway areas have been determined by the Department of Sustainability and Environment (DSE) as part of the Flood Data Transfer Project (FDTP) for Casterton. .These extents are based on the historical flood information from the 1946 and 1983 flood events. The 1946 flood was adopted as the 1% AEP event. The hydraulic modelling results are intended to be used as an accurate basis for declarations of flood levels and modifications to the current Glenelg Shire Planning Scheme Zoning and Overlay Maps.

1.1 Study Area

The Glenelg River flows from the Grampians in the north to Nelson on the southern coast of Victoria and the Glenelg River upstream of Casterton has an area of approximately 4,810 km^2. The Glenelg River system has one major storage, Rocklands Reservoir, which is located immediately downstream of the Grampians National Park and has a capacity of 116 GL (Southern Grampians Shire Council, 2009). The study area for the hydraulic model extends approximately 4 km upstream and 3 km downstream of Casterton. The hydrological assessment covers the full extent of the upstream catchment area. The study area is shown in Figure 1.1.

1.2 Scope of Works

The scope of services as defined in the tender documents includes the following:

- Revision of the design flood flow analysis using additional methods of estimating the peak design flows to verify and confirm existing design peak flow estimates.
- Recalibrating the hydraulic model to known historical events.
- Sensitivity analysis on the 1% AEP flood event to assess inflow changes +/- 20%, downstream boundary condition changes of +/- 0.5 m and an assessment of hydraulic roughness using a 'rough' and 'smooth' case.
- Develop the flood levels and extents for the 10%, 5%, 2% and 1% AEP flood events.

2 DATA

2.1 Summary of Data Sources

The following data was acquired for use in the study:

- Pluviograph data for Station 090135 (supplied by the Bureau of Meteorology via email, September 2009)
- Flow data for flow gauge 238212A (supplied by Thiess via email, September 2009)
- Existing Ground Survey of Casterton, in AutoCAD format (Supplied via CD and email by GHCMA, November and December 2009)
- Existing HEC-RAS model for the Glenelg River through Casterton (Supplied via email by GHCMA, December 2009)
- Aerial LiDAR survey, undertaken for DSE for the ISC project and supplied to GHCMA in xyz format (supplied via CD by GHCMA, October 2010).
- WSE points from the 1983 flood event, obtained from the plan “History of Flooding in Casterton” (Supplied by GHCMA, November 2010)

2.2 Site Inspections

A thorough site reconnaissance was undertaken in order to become familiar with local topography and physical features of the site. The field inspection was carried out on the 12 June 2008.

2.3 Survey Data and Digital Terrain Model

Aerial survey data derived from the 2010 ISC LiDAR dataset was supplied by Glenelg Hopkins CMA enabling the development of a fine scale DTM to define the existing floodplain. The data was in the form of thinned ground returns from Aerial Laser Scanning (ALS) survey and provides data points at a density of approximately 1 per square meter, with accuracies in the range of +/- 0.10 m at one sigma.

In order to verify the integrity of the dataset, previous data obtained from ground survey completed in the Casterton town centre was compared to the supplied data Figure 2.1 shows the locations of the survey points used to compare the topography. Figure 2.2 shows histogram results of the analysis, with average and median differences of +32 cm present in the LiDAR compared to the surveyed points.

By analysing the results it was found that the difference was relatively consistent across the surveyed area. Using this information it was considered that by lowering the entire topography layer by 32 cm an appropriate set of data may be obtained. Figure 2.3 shows the differences between the LiDAR and the ground survey in both the original and lowered topography cases.

Figure 2.4 shows the histogram obtained once this process was complete. The results obtained fall within the accuracy requirements of lidar of +/-0.10 m to one sigma, with 88% of the points analysed falling within +/-0.1 m. As such the initial topographic layer with a level shift of -32 cm was deemed suitable for this study. Figure 2.5 shows the DTM created after the topography shifts described above.

3 HYDROLOGY

The hydrology for Casterton was assessed using RORB and calibrated to known storm events for the purposes of determining appropriate rainfall and runoff model parameters. The RORB hydrological model version 6.0 (Laurenson, Mein and Nathan, 2007) was used for this study. RORB calculates flood hydrographs from storm rainfall hyetographs and can be used for modelling natural, part urban and fully urban catchments. RORB is an industry standard model that has been used widely in previous studies across Victoria.

The calibration process utilises known streamflow, rainfall and a definition of the catchment within RORB. The calibrated parameters are used to generate design storm events which will estimate flood peaks for the 5, 10, 20, 50 and 100 year average recurrence intervals (ARI) and will be compared to the flood frequency analysis (FFA) estimates, as well as the results generated in the regional analysis developed by Cardno (2008). The rating curve for this site allows for flows up to 26000 ML/day (301 m^3/s) to be accurately recorded

This section will present the data used within this process, the model calibration results and compare the FFA against the modelled hydrology from RORB and the regional analysis results.

3.1 Available Data

The closest daily rainfall gauge to Casterton is ‘Casterton at Casterton Showgrounds’ (090135) which recorded the daily rainfall total to 9am. This gauge had recorded rainfall data from Nov 1956 to current. The nearest pluviograph was located within Casterton (090135) and had 6 minute data available from Aug 1973 to Mar 2006. The pluviograph data was used to distribute the daily rainfall totals to better match the rainfall pattern for each of the design storm events. Figure 3.1 shows the locations of the rainfall and streamflow stations.

The streamflow gauge used for Casterton is ‘Glenelg River at Casterton’ (238212). The gauge had limited recorded instantaneous flow data recorded from Nov 1973 to Dec 1988 and Nov 2001 to Mar 2002. Within this period the three largest flow events were:

- 1983 – Peak flow 250.3 m^3/s – Estimated 15 year ARI
- 1975 – Peak flow 221.6 m^3/s – Estimated 10 year ARI
- 1978 – Peak flow 211.3 m^3/s – Estimated 9 year ARI

It is desirable to calibrate to the largest events on record in order to best understand the catchment flood characteristics. Unfortunately for Casterton, there were limited significant events in the available streamflow data. As stated the gauge was rated up to a maximum flow of 26,000 ML/day (301 m^3/s). The low flows at the site were stated to be unreliable due to the site stability around the gauge location.

3.2 Flood Frequency Analysis

The flood frequency analysis (FFA) was undertaken using the instantaneous flow data at Glenelg River at Casterton (238212) which had data available from 1974 to 1988. Due to the limited data available for the FFA, various methods were used to extend this time series including:

- Using the instantaneous flow data at Glenelg River at Casterton (238212) where available;
- Using the peak adjusted mean daily flows at Glenelg River at Casterton (238212) from 1960 to 1973;
- Using a regression relationship between Glenelg River at Sandford (238202) and Glenelg River at Casterton (238212) as a representative series at Casterton, 1989 to 2008;
- Using the difference between the instantaneous flows of Glenelg River at Sandford (238202) less Wannon River at Henty (238228) as a representative series at Casterton, 1989 to 2008.

These method use the available data as summarised in Table 3.1. It should be noted that while the 1946 event is the largest historic event for the region, there is currently no estimate of the peak flow rate during this event. The recurrence interval of this event has been anecdotally been prescribed as being between a 20 to 50 year ARI. Due to the uncertainty involved in the 1946 event this was not considered as part of this analysis.

Table 3.1: Available flow data for the Casterton catchment

Source	Data type	Data type	Availability
Glenelg River at Casterton	238212	Instantaneous flow	1974 to 1988
Glenelg River at Casterton	238212	Mean daily flow	1960 to 1988
Glenelg River at Sandford	238202	Instantaneous flow	1967 to 2008
Wannon River at Henty	238228	Instantaneous flow	1974 to 2008

It is important to adjust the mean daily flows recorded at Casterton as the mean daily flow is often significantly less than the daily instantaneous maximum flow. In order to adjust the mean daily flows the concurrent period of the instantaneous annual peaks and the annual maximum mean daily flows was used to develop a relationship between the mean daily flows and instantaneous peak flows. The peaks used in this analysis are shown in Table 3.2 with the percentage difference, and the regression relationship showing the relationship between the mean daily and instantaneous peaks is shown in Figure 3.2.

Ultimately the adjustment was based on the regression relationship and the annual mean daily peaks were increased by 17.1% from 1960 to 1973. The three events with the greatest difference were the 1976, 1978 and 1984 floods and this was caused by the events having a steep rising limb with the bulk of the flooding occurring during a 24 hour period. This leads to the largest differences in the mean daily flows and the instantaneous flows due to the daily average being calculated using the low flows as well as the peak flows. This lowers the average relative to the instantaneous peaks.

Table 3.2: instantaneous and mean daily peak flows for Casterton

Year	Mean Daily Flow Peak (m^3/s)	Instantaneous peak (m^3/s)	Difference (Inst. to mean)
1974	110.0	118.1	7%
1975	213.0	221.1	4%
1976	105.7	156.3	48%
1977	21.6	24.9	15%
1978	120.4	211.8	76%
1979	142.4	158.6	11%
1980	54.2	57.2	6%
1981	158.6	173.6	9%
1982	1.6	1.7	4%
1983	219.9	251.2	14%
1984	105.9	138.9	31%
1985	31.8	39.2	23%
1986	99.2	105.7	7%
1987	83.0	101.3	22%
1988	101.3	109.1	8%

For the period from 1989 to 2008 two methods were considered for estimating the annual peaks:

- Using the annual peak at Glenelg River at Sandford and removing the peak flow from the Wannon River at Henty (Option A).
- Developing a regression relationship between the peaks at the Glenelg River at Sandford and the Glenelg River at Casterton when they have a concurrent record (Option B).

Comparisons between the estimated peak flows from each method were compared to the recorded annual peak flows at Casterton from 1974 to 1988 and it was found that the regression relationship produced the more accurate results. The predicted peak flows are shown in Table 3.3. The greatest difficulty with using the difference method between the Wannon River gauge and the Glenelg River at Sandford was the distance between the gauges and the varying times between the peak flows.

Table 3.3: Methods A and B for predicting Casterton peak flows

		Option A		Option B	
Year	Recorded	Predicted (m^3/s)	Difference (%)	Predicted (m^3/s)	Difference (%)
1974	118.1	96.5	22%	113.7	4%
1975	221.1	315.1	-30%	247.3	-11%
1976	156.3	109.4	43%	140.8	11%
1977	24.9	15.8	57%	43.7	-43%
1978	211.8	164.1	29%	212.2	0%
1979	158.6	169.5	-6%	174.5	-9%
1980	57.2	50.8	13%	40.4	41%
1981	173.6	167.3	4%	172.1	1%
1982	1.7	1.9	-10%	1.6	5%
1983*	251.2	314.4	-20%		
1984	138.9	111.2	25%	116.4	19%
1985	39.2	26.2	50%	38.8	1%
1986	105.7	68.1	55%	97.8	8%
1987	101.3	92.3	10%	83.1	22%
1988	109.1	101.6	7%	101.2	8%

* This event was removed from the regression relationship for Option B.

Ultimately it was decided that the relationship, as shown in Figure 3.3, was the more accurate estimate of annual peak flow at Casterton from 1988 to 2008 based on the absolute error in the predicted peaks.

It should be noted that the 1983 event was removed from the regression relationship development between Casterton and Sandford as the flows at Sandford were mainly driven by the Wannon River flows (see Figure 3.4). Checks were made to ensure that the events during the 1989 to 2008 infill period were not predominantly driven by the Wannon River flows. The recorded annual peak flows are presented in Figure 3.4 for Casterton, Sandford and Wannon River.

Three sets of data were used to derive FFA for comparative purposes:

1. Recorded Casterton peak flows – 1974 to 1988.
2. Recorded Casterton peak flows extended with the regression with the mean annual peaks at Casterton – 1960 to 1988.
3. Recorded Casterton peak flows with regression with the mean annual peaks at Casterton and the transposed peaks from Sandford – 1960 to 2008.

The three time series of peak flows were fitted with a Log Pearson Type III (LPIII) distribution following the method outlined in AR&R Vol. 2, Book 4 (1987). The resulting FFA distributions are presented in Appendix A.1 and the statistics and peak flow in Table 3.4. Table 3.5 and Table 3.6 show the upper and lower confidence intervals of the FFA's undertaken.

Table 3.4: FFA results

Period	Outliers	Skew	ARI peak flows (m^3/s)				
			5	10	20	50	100
1974 – 1988	1977, 1980, 1982, 1985	0.22	197	229	260	301	333
1960 – 1988	1967, 1982	-0.49	165	221	276	348	402
1960 – 2008	1967, 1982, 1997, 1999, 2002, 2005, 2006, 2008	-0.37	164	220	277	355	415
2008 Glenelg Flood Study	N/A	-	200	244	273	297	307

Table 3.5: FFA results – Lower Confidence Intervals

Period	Confidence Limits 95% - Lower (m^3/s)				
	5	10	20	50	100
1974 – 1988	168	191	213	239	259
1960 – 1988	127	166	202	247	280
1960 – 2008	132	173	213	265	305

Table 3.6: FFA results – Upper Confidence Intervals

Period	Confidence Limits 95% - Upper (m^3/s)				
	5	10	20	50	100
1974 – 1988	251	312	376	470	548
1960 – 1988	231	326	427	568	678
1960 – 2008	213	299	392	525	633

The statistics show that with the outliers removed, all of the skews are within +/- 0.5 as recommended by AR&R. The results show that the 100 year ARI varies from 333 m^3/s to 415 m^3/s, although it should be noted that the 333 m^3/s was based on only 10 years of peak flows after the outliers were removed. The peak flows for the 20 year ARI to the 5 year ARI did not vary considerably using the 3 sets of peak flows. The predicted peak flows for Casterton using the 1960 to 2008 data set is presented in Figure 3.5.

Figure 3.5 shows that the 95% confidence limits for the FFA and indicates a range of peaks for the 100 year ARI event from 305 m^3/s to 633 m^3/s. This confidence range is consistent with many FFAs as there is often limited data, however in this instance it should be remembered that the periods from 1960 to 1973 and 1989 to 2008 have been estimated using the methods prescribed above and this introduces even more uncertainty to the peak prediction.

3.3 RORB Hydrological Model

The RORB model was developed and the Casterton catchment was divided into 25 sub-catchments. These catchments are shown in Figure 3.6. The RORB catchment vector is presented in Appendix A.2. RORB allows for the modification of a number of hydrological parameters for calibration purposes including:

- Coefficient of runoff/Continuing Loss;
- Initial rainfall loss;
- Variation of the stream lag parameter 'k_c' (affecting the routing time of flow through a sub-catchment);
- The non-linearity factor 'm'.

3.3.1 RORB Calibration

In order to calibrate RORB data is required for the concurrent pluviographic rainfall and instantaneous streamflow at a known gauge location near the outlet of the RORB model. The streamflow gauging station at Casterton provides this information.

The RORB parameters fitted for the calibration are shown in Table 3.7. The parameters were the same for the two largest events (1983 and 1975) which suggests that the rainfall runoff for the catchment is occurring consistently for the larger events. The model calibration plots are presented in Appendix A.3.

Table 3.7: RORB Calibration Parameters

RORB Event	k_c	m	Initial Loss (mm)	Continuing Loss (mm/h)
Casterton – 1983	115	0.96	10	0.9
Casterton – 1975*	115	0.96	10	0.9

* The pluviograph data at this location was cumulated for long periods, these periods were disaggregated to match similar patterns observed within the pluviograph time series.

The goodness of fit statistics are presented in Table 3.8 and show that for each event the peak was matched to within 10% error. This is by far the most important parameter for the calibration as the Casterton 2D hydraulic modelling was to be undertaken using a steady state peak flow (refer section 4.3). This implies that the time to peak and volume are of secondary importance but still provides guidance as to the accuracy of the RORB calibration.

For the 1983 event the total volume was matched very well to within 3%. The volume for the 1975 event was under-predicted in the modelled data by approximately 29% and this was thought to be due to the extended nature of the event which has multiple peaks and the possible influence of the Rockland Reservoir releases.

Table 3.8: Calibration Results

Event	Parameter	Modelled Value (m^3/s)	Recorded Value (m^3/s)	Absolute Difference (m^3/s)	Difference (%)
September 1983	Peak discharge,m^3/s	226.9	250.3	-23.3	-9.3
	Time to peak, h	87	117	-30	-25.6
	Volume,m^3	1.27E+08	1.31E+08	3.99E+06	-3.1
October 1975	Peak discharge,m^3/s	219.8	221.5	-1.7	-0.8
	Time to peak, h	86	121	-35	-28.9
	Volume,m^3	1.50E+08	1.85E+08	-3.50E+07	-19.0

3.3.2 RORB Design Events

The 'Intensity Frequency Duration' (IFD) coefficients listed in Table 3.9 were used for the generation of design storm events. The IFDs are taken from AR&R Vol. 2 (1987).

Table 3.9: IFD Coefficients (after AR&R 1987)

Parameter	Casterton Value
$^{2}I_{1}$	17.75
$^{2}I_{12}$	3.35
$^{2}I_{72}$	0.87
$^{50}I_{1}$	34.13
$^{50}I_{12}$	6.31
$^{50}I_{72}$	1.64
G	0.47
F2	4.38
F50	14.76

For the design events the k_c and m values were maintained from the calibration at 115 and 0.96 respectively. As a comparison, the estimated k_c for a catchment in this area using ARR (eqn 3.22) is 114.48. Using the default RORB equation would provide a k_c of 146.01. An m value of 0.96 was used as it gave the best fit to the two calibration events selected. The initial loss and continuing loss were set at the recommended rates specified in AR&R Vol. 2 Table 3.4 (1987) at 20 mm initial loss and 2.0 mm/hr continuing loss. These parameters are used because there is a lack of information regarding suitable regional parameters. The resulting design rainfall totals and peak flow rates are presented in Table 3.8 and Table 3.8 respectively.

Table 3.10: **IFD Total Rainfall Depths and Aerial Reduction Factors**

		Total Rainfall Depth (mm)				
Duration (hours)	Aerial Reduction Factor	5y ARI	10y ARI	20y ARI	50y ARI	100y ARI
6	0.86	40.2	46.3	54.6	66.5	76.3
9	0.87	45.9	52.7	62.2	75.6	86.7
12	0.89	50.3	57.8	68.1	82.8	94.9
18	0.90	56.7	65.1	76.7	93.3	106.9
24	0.92	61.5	70.7	83.3	101.2	116.0
30	0.92	65.3	75.1	88.5	107.5	123.2
36	0.92	68.4	78.6	92.7	112.7	129.1
48	0.93	73.1	84.0	99.0	120.3	137.9
72	0.94	78.4	90.1	106.2	129.1	148.0

Table 3.11: RORB Peak Flow Casterton

	Loss Rates		Peak Flow at Casterton (m^3/s)				
Duration (hours)	IL (mm)	CL (mm/hr)	5y ARI	10 y ARI	20y ARI	50y ARI	100y ARI
6	20	2	62.5	97.7	160.4	242.6	319.8
9	20	2	68.1	116.7	186.3	267.8	352.4
12	20	2	80.6	133.1	205.9	295.5	389.7
18	20	2	93.6	148.1	208.6	319.0	419.1
24	20	2	111.6	156.2	245.8	370.1	480.7
30	20	2	102.9	166.9	260.1	389.7	506.3
36	20	2	97.2	160.0	251.8	378.7	494.1
48	20	2	87.5	149.4	241.4	367.5	477.0
72	20	2	102.2	166.8	258.0	370.0	455.4

The peak flows occur during the 24hr rainfall event for the 5 year ARI and for the 30hr event for 10, 20, 50 and 100 year ARIs. The peak flows were from the longer duration events due to the large size of the catchment and the long travel times to Casterton. The 100 year ARI peak flow was estimated at 506 m^3/s.

3.3.3 Design Sensitivity Analysis

In order to assess the sensitivity of the RORB design runs to the loss rates used, a range of values were analysed for the 100 year ARI. The k_c and 'm' parameters were not part of this sensitivity analysis as these are catchment specific parameters and represented the system well in the two largest calibration events. The sensitivity analysis examined the initial and continuing losses used for the design runs and the results of the three runs are presented in Table 3.12. The percentage difference in the 100 year ARI peak flows is presented in Table 3.13.

Table 3.12: Sensitivity analysis runs showing the 100 year ARI peak flows (k_c = 115, m = 0.96)

100 year ARI Peak Flows (m^3/s)		Continuing Loss		
		1.5 mm/h	2.0 mm/h	2.5 mm/h
Initial Loss	15 mm	605.4	552.1	501.4
	20 mm	559.4	506.3*	455.7
	25 mm	513.0	460.1	409.7

* Recommended Victorian parameters

Table 3.13: Sensitivity analysis runs (k_c = 115, m = 0.96)

100 year ARI Peak Flows (% difference from mean)		Continuing Loss		
		1.5 mm/h	2.0 mm/h	2.5 mm/h
Initial Loss	15 mm	19.6%	9.0%	-1.0%
	20 mm	10.5%	0.0%	-10.0%
	25 mm	1.3%	-9.1%	-19.1%

The variation in the initial and continuing losses showed a range of peak flows varying by +/- 20%. This range was from 410 m^3/s to 605 m^3/s which was consistent with the findings from the FFA (see Section 3.2) and from the previous studies undertaken for Casterton.

When the initial loss is fixed at the 20 mm recommended rate for Victoria, the variation in the continuing loss over the full range of recommended rates was +/- 10% which was a range from 456 m^3/s to 559 m^3/s. This range was comparable with previous flow rate studies and the estimated 100 year ARI peak flow using an IL of 20 mm and CL of 2.0 mm/h was adopted. This was chosen as without more accurate regional parameters, using the median values from the acceptable range is most appropriate.

The full set of sensitivity results are shown in Table 3.14

Table 3.14: Full sensitivity results for 5, 10, 20, 50 and 100 year ARIs at Casterton

kc, m	Initial Loss	Continuing Loss	ARI Peak Flow (m^3/s)				
			5	10	20	50	100
115, 0.96	15	1.5	186	255	353	488	605
115, 0.96	15	2.0	147	212	305	436	552
115, 0.96	15	2.5	117	176	266	390	501
115, 0.96	20	1.5	144	209	307	442	559
115, 0.96	20	2.0	112	167	260	390	506
115, 0.96	20	2.5	89	131	220	343	456
115, 0.96	25	1.5	113	165	261	399	517
115, 0.96	25	2.0	85	129	215	344	460
115, 0.96	25	2.5	66	100	175	298	410

3.4 Recommendations

This section has assessed various methods of determining the peak flow rates for Casterton. The method employed in the previous study by Cardno (2008) utilised a regional assessment and the purpose of this analysis was to explore the validity of this method and to confirm the steady state flood peak flow rates used in the hydraulic flood modelling. The 100 year ARI predicted values and the upper and lower limits are shown for the regional method, FFA method and the RORB model in Table 3.15.

Table 3.15: Comparison of 100 year ARI estimates for Casterton

Method	100 year ARI peak (m^3/s)		
	Predicted	Lower Limit	Upper Limit
Regional method – 2008 Study	520	-	-
Regional method – 2010 FFA	425		
FFA method (1960 to 2008)	415	305	633
RORB (k_c = 115, m = 0.96)	506	410	605

The predictions range from as low as 305 m^3/s up to 633 m^3/s and the RORB and regional methods estimate the 100 year ARI peak flow at just above 500 m^3/s. The 2010 regional method uses the same multiplier as the 2008 regional method with the revised 5yr FFA flow rate. The extended FFA method predicted value was lower with a peak at 415 m^3/s, however the 520 m^3/s value is well within the 95 percentile confidence limits of the analysis.

The 5, 10, 20, 50 and 100 year ARI estimated peak flows are as shown in Table 3.16.

Table 3.16: Comparison of peak flows for Casterton

Method	ARI Peak Flow (m^3/s)				
	5	10	20	50	100
Regional method – 2008 Study	200	272	344	442	520
Regional method – 2010 FFA	164	223	282	362	425
FFA method (1960 to 2008)	164	220	277	355	415
RORB (k_c = 115, m = 0.96)	112	167	260	390	506

The comparison shows that there is significant variance present between the methodologies, however all flows are still within the FFA 95% confidence interval. It is recommended that the flows derived using the flood frequency analysis is used in the creation of the design ARI flood events. These flows represent values well within the confidence boundaries presented without producing overly conservative flows.

4 HYDRAULIC MODELLING

4.1 Introduction

The WL|Delft 1D2D modelling system, SOBEK, was used to compute the channel (1D) and overland flow (2D) components of the study. SOBEK is a professional software package developed by WL|Delft Hydraulics Laboratory, which is one of the largest independent hydraulic institutes in Europe (situated in The Netherlands) and is world-renowned in the fields of hydraulic research and consulting (WL|Delft, 2005).

This combined package allows for the computation of channel and pipe flow (including structures such as culverts, weirs, gates and pumps, and pipe details such as inverts, obverts, pipe sizes and pipe material) by the 1D module, which is then dynamically linked to the 2D overland flow module. The 1D and 2D domains are automatically coupled at 1D-calculation points (such as manholes) whenever they overlap each other. The model commences with the 1D component operating as the inflow increases until such time as the pipe or channel is full and overflows, with the flow then moving to the 2D domain. The 1D network and the 2D grid hydrodynamics are solved simultaneously using the robust Delft scheme that handles steep fronts, wetting and drying processes and subcritical and supercritical flows (Stelling, 1999).

The advantages of this system are that the channel/pipe system is explicitly modelled as a sub-system within the two-dimensional overland flow computation. This means that generalised assumptions regarding the capacity of the channel/pipe system are not required. This system employs a unique implicit coupling between the one and two-dimensional hydraulic components that provides high accuracy and stability within the computation.

4.2 Hydraulic Model Establishment

The hydraulic model consists of two main hydraulic components:

- The channel network (1D); and
- 2D grid of the surface topography.

The establishment of these two components of the model is described in the following section.

4.2.1 Channel System (1D)

Using data obtained during the site visit, previous 1D models and from survey along the Glenelg River, a 1D network containing all relevant hydraulic structures in the model was created. The location of these structures is shown in Figure 4.1.

4.2.2 Topography

The major component of the two-dimensional model is the grid that describes the topography of the area. In order to accurately represent the topography within the Casterton floodplain, a detailed DTM was compiled from the aerial survey data supplied by GHCMA. The DTM consisted of points that were used to define the major terrain features (i.e. overland drainage paths) within the catchment area.

The digital elevation model (DEM) was constructed as a square grid of elevations that were sampled from the DTM. The DEM extent used in the study is shown in Figure 4.1 and this extent defined the topography of the catchment. A 5 m grid size was adopted as this resolution was determined to be fine enough to appropriately define topographical features such as open drains and buildings. The grid was aligned in a north-south orientation consistent with the MGA94 coordinate projection. The grid parameters used in the Sobek model are listed in Table 4.1.

Table 4.1: Two-Dimensional Grid Parameters

Grid Parameter	Dimension
Grid Size	5 * 5 metres
X-dimension	795 columns
Y-dimension	998 rows

4.2.3 Hydraulic Roughness

The hydraulic roughness for the overland flow model was described using a two-dimensional roughness map of Manning's "n" values. This was developed by digitising different land-use zones from the digital aerial photographs captured from the aerial survey within a GIS environment (MapInfo). The catchment is generally rural with areas of residential development within the Casterton township present. The land-use zones, as defined in the model, are shown in Figure 4.2 and their appropriate roughness values are summarised in Table 4.2. The roughness used within the model was calibrated using a known flood event as described in Section 4.3.

Table 4.2: Two-Dimensional Grid Roughness Classification

Land Use	Calibrated Hydraulic Roughness (Manning's "n")
Residential	0.15
Road	0.018
Farmland and Rivers	0.05

4.3 Hydraulic Model Calibration – 1983 Storm Event

In order to ensure that the digitised model acts in a manner consistent with known storm events for the catchment, calibration to the 1983 storm event was undertaken. As the catchment was significantly different in the 1983 (such as the railway which is no longer present) minor alterations were undertaken the model to ensure that the flood event could be replicated. This alteration was to add the railway bridge only. The railway bridge was added into the model by blocking the 2d topography and using existing survey data to define the rail bridge width in the 1D component of the model. Figure 4.3 shows the calibration model setup. Figure 4.4 shows the locations and ID numbers of the recorded flood levels for the 1983 event.

As the Glenelg River is historically an avulsive and changing river, it is likely that the channel depths and shape defined in the model may be different to the channel that was present in 1983 and aerial photography cannot capture the changes in the depths and shape of the river cross section. However, as no cross sections are known from the 1983 period it was considered that the channel present in the DTM would suffice for the calibration.

A stream flow gauge was active during the time of this event and a peak flow of 250.3 m^3/s was recorded. This flow was considered accurate. The flow of 250.3 m^3/s was applied to the upstream boundary of the model as a steady state flow. Steady state was deemed appropriate as the peaks flows entering the area tend to remain at peak for long periods of time. As such using a hydrograph to steadily increase and decrease the flow rates entering the system will not impact the maximum level achieved.

This calibration was undertaken to ensure that the roughness grid and the downstream boundary are appropriate for the design. A total of 43 water levels were obtained during the 1983 flood event and as such a good calibration could be achieved. Some surveyed levels seemed to be inconsistent with the other levels obtained and as such were omitted from the calibration. Table 4.3 shows the calibration results obtained. The levels that were considered inappropriate have been highlighted and have not been included in analysis of calibration.

Table 4.3: Calibration Levels – Modelled and Observed WSEs

ID	Recorded WSE (m AHD)	Modelled WSE(m AHD)	Difference (m)	Comments
1	43.66	43.85	0.19	U/S of Rail Line - Area not important in design model
2	43.94	43.71	-0.23	D/S of Rail Line - Area not important in design model
3	45.03	45.02	-0.01	
4	45.01	45.03	0.02	
5	45.69	44.67	-1.02	Level not consistent with nearby level
6	44.39	44.53	0.14	
7	44.23	44.17	-0.06	
8	45.08	45.07	-0.01	
9	45.04	45.02	-0.02	
10	44.95	44.99	0.04	
11	44.88	44.91	0.03	
12	45.10	45.10	0.00	
13	45.49	45.03	-0.46	Level higher than upstream flood levels
14	46.03	45.87	-0.16	
15	42.86	43.00	0.14	
16	44.90	45.01	0.11	
17	44.97	45.01	0.04	
18	45.04	45.01	-0.03	
19	45.15	45.03	-0.12	Level not consistent with nearby level
20	45.06	45.05	-0.01	
21	44.93	44.98	0.05	
22	44.98	44.98	0.00	
23	45.21	45.01	-0.20	
24	45.02	45.02	0.00	
25	44.99	45.01	0.02	
26	44.99	45.01	0.02	
27	44.98	45.01	0.03	
28	44.99	45.01	0.02	
29	45.33	45.02	-0.31	Level not consistent with nearby level
30	44.99	45.02	0.03	
31	44.94	45.00	0.06	
32	44.92	44.94	0.02	
33	44.78	44.88	0.10	
34	44.49	44.50	0.01	
35	44.49	44.50	0.01	

36	44.02	43.99	-0.03	
37	43.40	43.33	-0.07	
38	43.37	43.18	-0.19	
39	44.59	44.49	-0.10	Level higher than upstream flood levels
40	44.30	44.37	0.07	
41	44.93	44.95	0.02	
42	44.87	44.93	0.06	
43	44.95	44.84	-0.11	
		Average	**0.00**	
		Standard Deviation	**0.09**	

From the results, it is shown that the parameters selected for the downstream boundary and the roughness of the catchment are appropriate for use in determining the design flood extents for the Casterton township. Figure 4.5 shows the depth extent for the 1983 calibration.

5 RESULTS

5.1 Hydraulic Model Results

The hydraulic model has been run for the 10, 20, 50 and 100 year ARI events for the existing conditions scenario. The two-dimensional, overland flow results are reported as depths and levels (m and m AHD) and flow velocities (m/s) for every grid cell at regular time intervals.

It should be noted that the flood shapes shown are a representation only of the actual flooding conditions in the catchment. The flood shapes are based on the DEM developed for use in the project (Section 2) and do not include consideration of features such as localised flow obstructions (such as parked cars and telephone poles) or other topographical features that are smaller than the grid cell definition.

Figures 5.1 to 5.4 show the maximum flood depths in the existing scenario across the modelled flood events. Note that all figures have been filtered to remove depths less than 0.01 m. Figures 5.5 – 5.8 shows the flood extent developed for each of the modelled storm events.

5.2 Flood Behaviour

It can be seen that the flood shape for the existing condition is relatively well defined with significant flooding experienced within the town of Casterton in all modelled events.

During the 10 year ARI flood event, well defined flow paths can be seen within the main channel and within a remnant channel that runs east-west just north of Casterton-Naracoorte Road. Within the township of Casterton, north of the Glenelg Highway Bridge, flooding is contained between Casterton-Naracoorte Road to the north and Miller Street to the east. The Glenelg Highway is overtopped in the 10 year event, however the road is still trafficable with levels of less than .20 m and velocities less than 0.25 m/s present. To the south of the bridge, significant flooding is present between the Glenelg River and the Glenelg Highway. Minor flooding is present on the eastern banks of the river.

During the 100 year ARI event, significantly more flooding is experienced within the Casterton township. The 100 year ARI event inundates the Casterton-Naracoorte Rd and extends to the corner of McEvoy and Mitchell St in the west of Casterton. The Glenelg Highway becomes un-trafficable in the 100 year event with depths of over 1 m present. To the south of the bridge, the flood shape is generally similar to the 10 year event with increases in depth present but only minor increases in extent. Increased flooding is noticed between the Glenelg Highway and Jackson St where the highway has been overtopped.

6 SENSITIVITY ANALYSIS

The sensitivity analysis aims to examine the impact that changes to the roughness parameters, the flow rate and downstream water level have on the hydraulic model. The sensitivity was undertaken on the 1% AEP design event.

6.1 Sensitivity to Inflow Changes

The flows being applied can significantly influence the flood extents by increasing or decreasing the flows present in the system. In order to evaluate the model sensitivity to this parameter, the 100 year ARI flow was varied by +/- 20%. An increase of flow by 20% results in a flow rate of 498 m^3/s, which is approximately the flow rate present in the 1% AEP if the RORB approach was selected.

Table 6.1 shows the differences in depth present in each of the sensitivity models compared to the 100 Year ARI design event. A 20% increase tends to result in a 13% or 17 cm depth difference on average. This level change is well within the 600 mm freeboard that is generally used in river flood plains.

The 20% increased flow also represents the levels and extents that would be present in the upper bounds of the hydrology in the 100 year ARI event. As the difference is well within the freeboard requirements, the chosen design flow for this scenario is deemed applicable without being over conservative.

The 20% reduced flow results in extents very similar to the 50 year, however there is very little difference between the 50 and 100 year design event extents. As such it is considered that the selected flow is appropriate for the 100 year ARI event.

6.2 Sensitivity to Downstream Conditions

The depth of the downstream boundary can influence the flood extents by reducing the available storage downstream of the area of interest. In order to evaluate the models sensitivity to this parameter, the downstream water level was varied +/- 0.5 m from its initial level of 37 m AHD.

This analysis found that neither raising nor lowering the downstream boundary significantly altered the flood shape, with the majority of the differences occurring within 20 m of the downstream boundary. No changes in flood extent or depth were present within the Casterton township area.

6.3 Sensitivity to Roughness Parameters

The selected roughness parameters can have a marked effect on the flow behaviour and flooding depths present within the model. As the model has been calibrated to a known event by varying the roughness parameters, this sensitivity analysis was undertaken to identify the maximum and minimum flood depths achievable in the model using accepted parameters for each land use zone. It must be noted that while the roughness parameters used are within acceptable boundaries for each zone, they may represent the land use zone in a far different state than its current conditions (ie the flood plain may be assumed to be well maintained low cut grass).

Both the decreased and increased roughness sensitivity runs resulted in mean changes to depth of 0.33 m (decrease in the lower roughness, increase in the higher roughness). As these cases represented the absolute extremes of the acceptable roughness parameters of each land use zone, and resulted in reductions of approximately only half the recommended freeboard, it was considered that the model was not highly sensitive to alterations of the roughness grid.

Table 6.1: Sensitivity Results, Average change in depth

Sensitivity Run	Average Depth (m)	Difference (m)	Comments
Design 100 Year ARI	1.25	0	Design ARI event
100 Year flow +20%	1.42	0.17	Minor extent changes, increased flood depths due to increased flow
100 Year flow -20%	1.12	-0.13	Minor extent changes, decreased flood depths due to decreased flow
100 Year ARI, Lowered Downstream (-0.5 m)	1.25	0	No noticeable difference to the results except minor changes close to the downstream boundary
100 Year ARI, Raised DS (+0.5 m)	1.25	0	No noticeable difference to the results except minor changes close to the downstream boundary
100 Year ARI. Lowered Roughness	0.92	-0.33	Reasonably large changes in the depth representing the extremes of the acceptable roughness values
100 Year ARI, Increased roughness	1.58	0.33	Reasonably large changes in the depth representing the extremes of the acceptable roughness values

7 RECOMMENDATIONS

This project has provided base flooding information for the Casterton township. The following actions are recommended:

- Incorporate the results of the study into the Glenelg Planning Scheme and create appropriate Land Subject to Inundation and Floodway Overlays
- Utilise the data set to inform the flood planning provisions of the Municipal Emergency Response Flood Sub Plan for Casterton
- Undertake analysis of the lag times and behaviour of the Glenelg River upstream of Casterton to provide flood warnings for the township.

8 REFERENCES

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WL|Delft Hydraulics Laboratory, (2005) *Sobek Advanced Version 2.10.000.RC01*, WL|Delft Hydraulics Laboratory.

Figures

Figure 1.1 - Study location

Figure 2.1 - Survey Point Locations

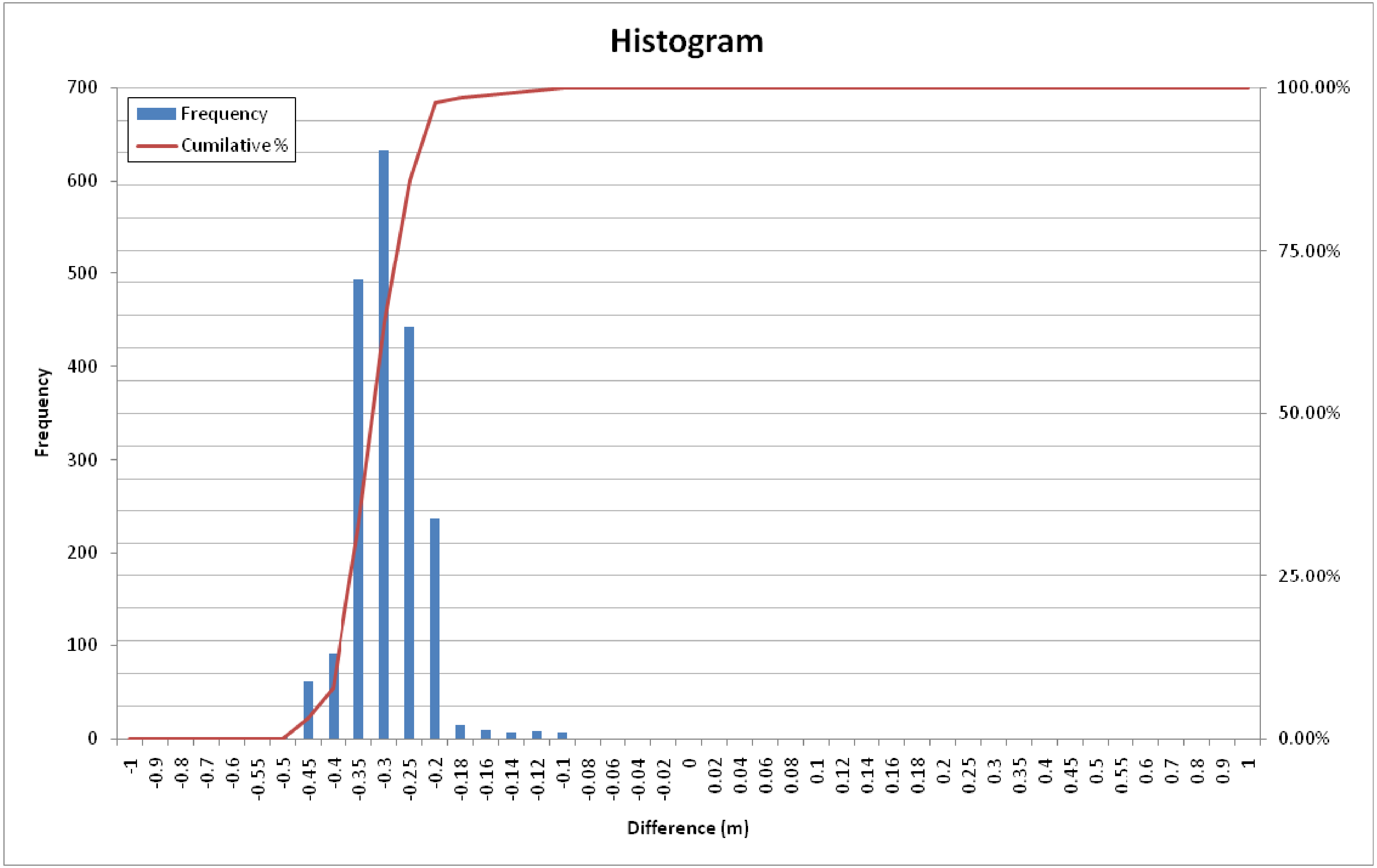


Figure 2.2 – Histogram plot – Supplied topography layer versus survey points

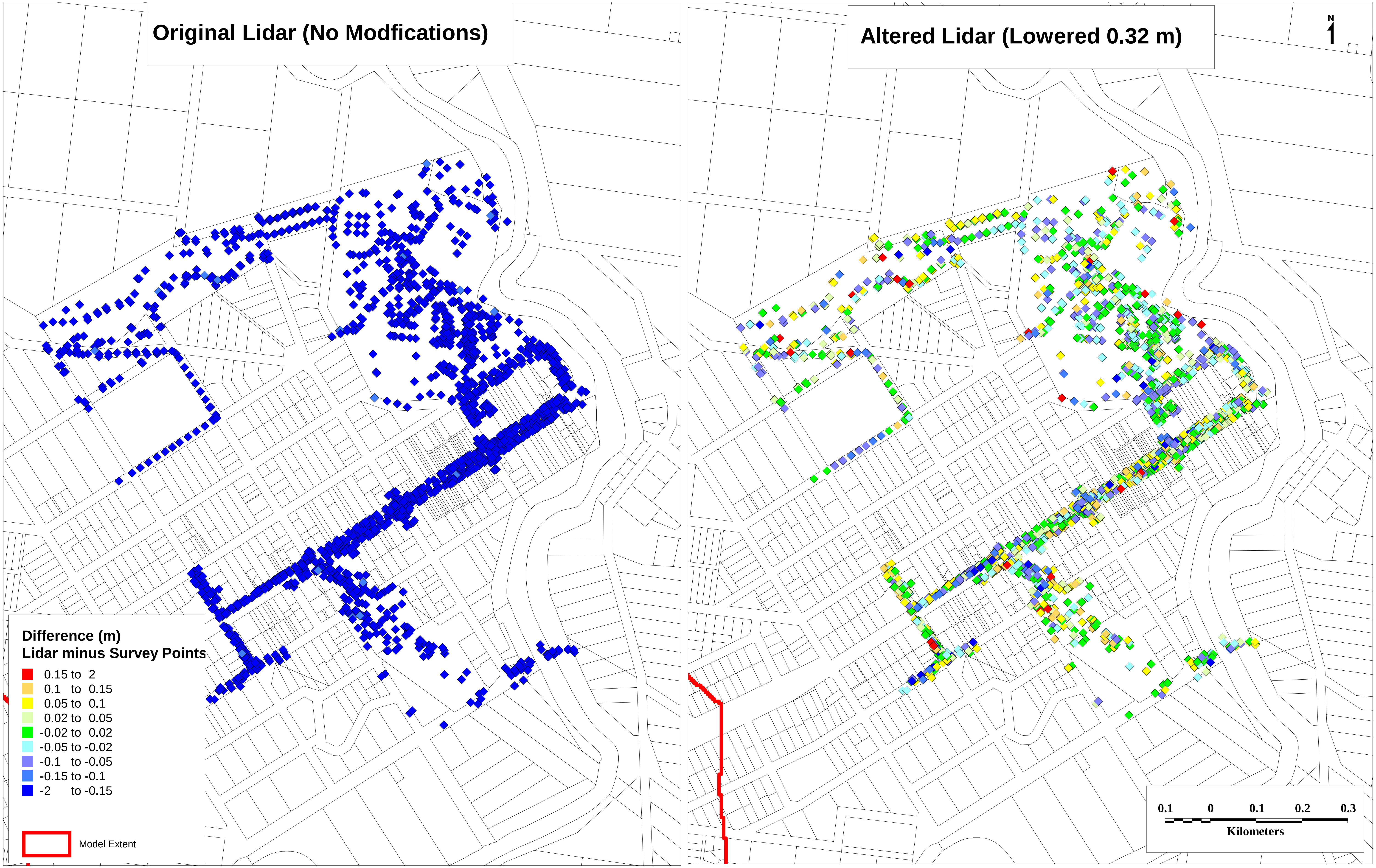


Figure 2.3 - Lidar Comparison to Survey - Original Data and Lowered Grid (used in hydraulic model)

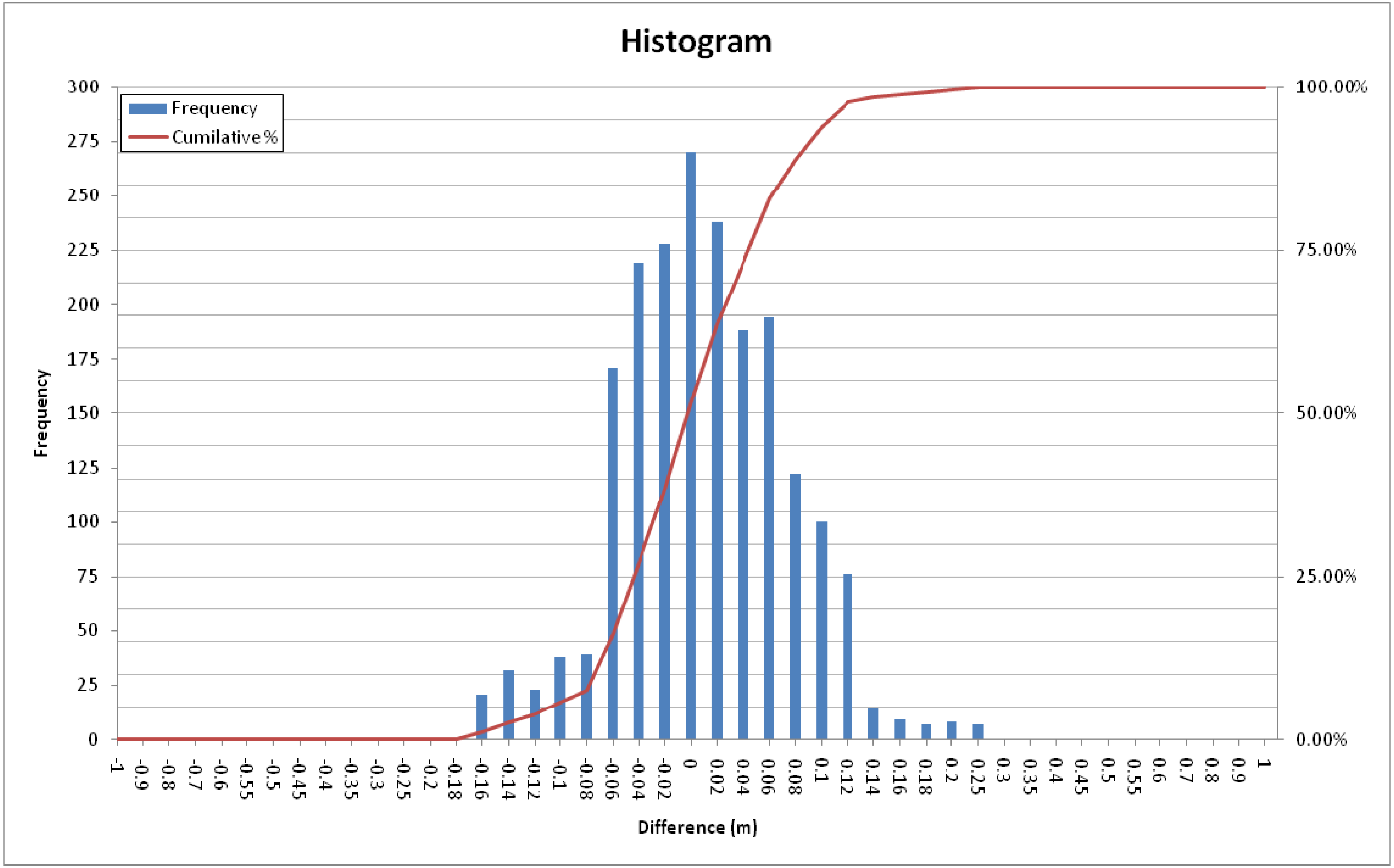


Figure 2.4: Histogram plot – Shifted topography layer compared to the survey points

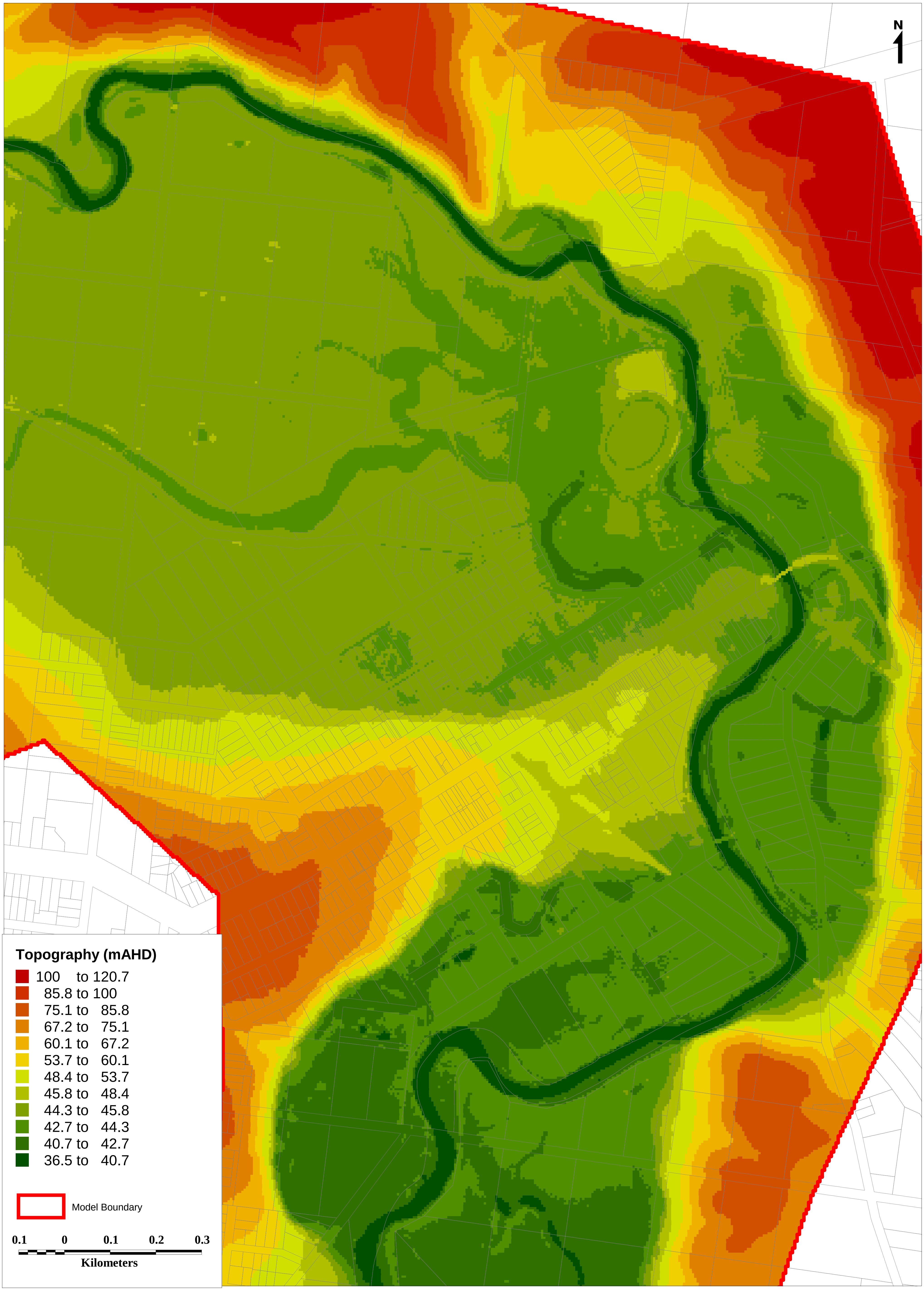


Figure 2.5 - Hydraulic Model Topography

Figure 3.1 - Rainfall and Streamflow Locations

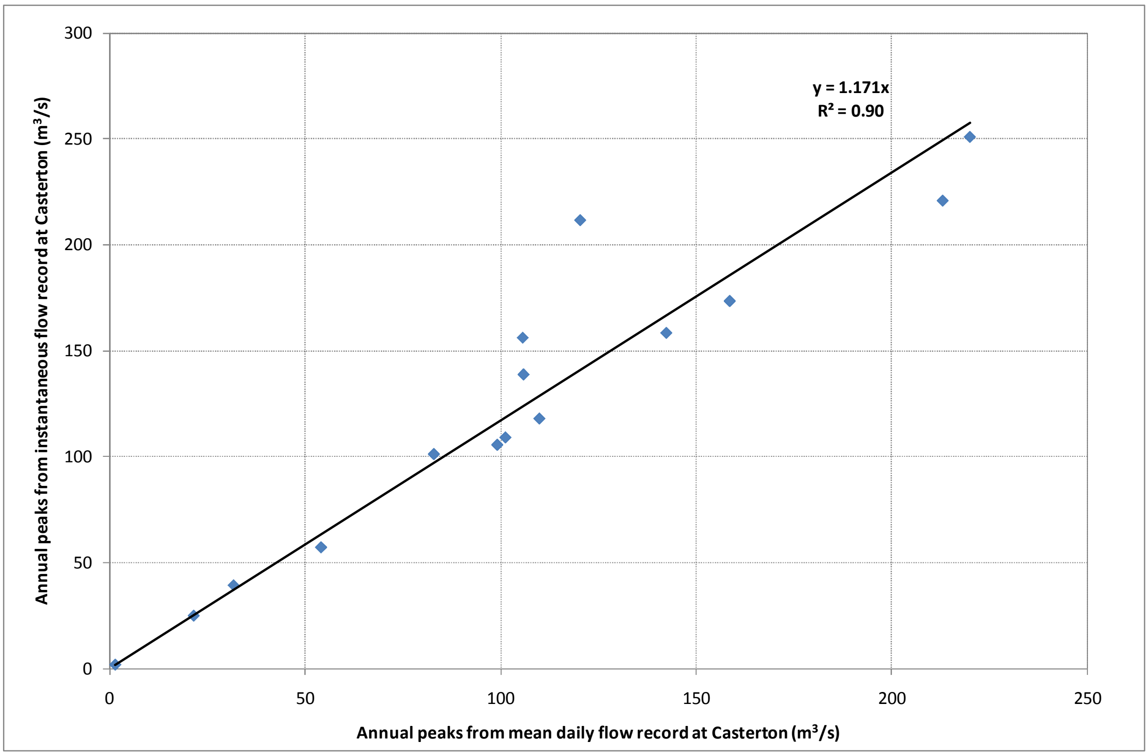


Figure 3.2: Regression relationship between instantaneous and mean daily peak flows for Casterton

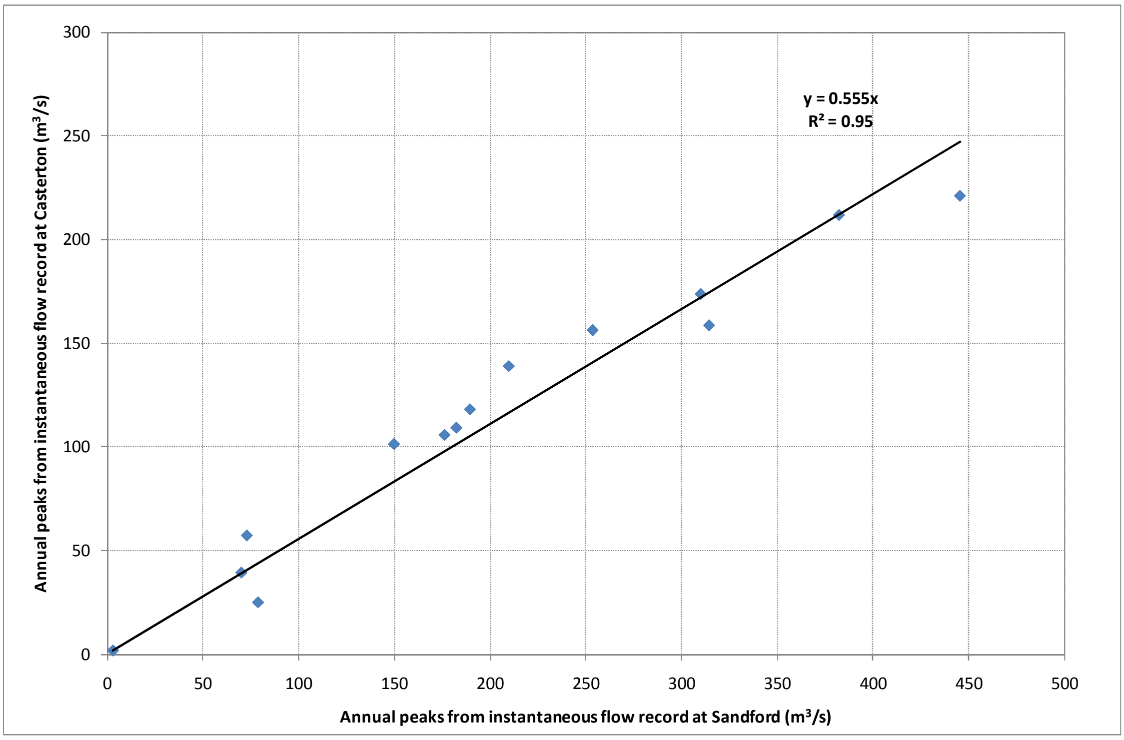


Figure 3.3: Regression relationship between instantaneous daily peak flows for Casterton and Sandford

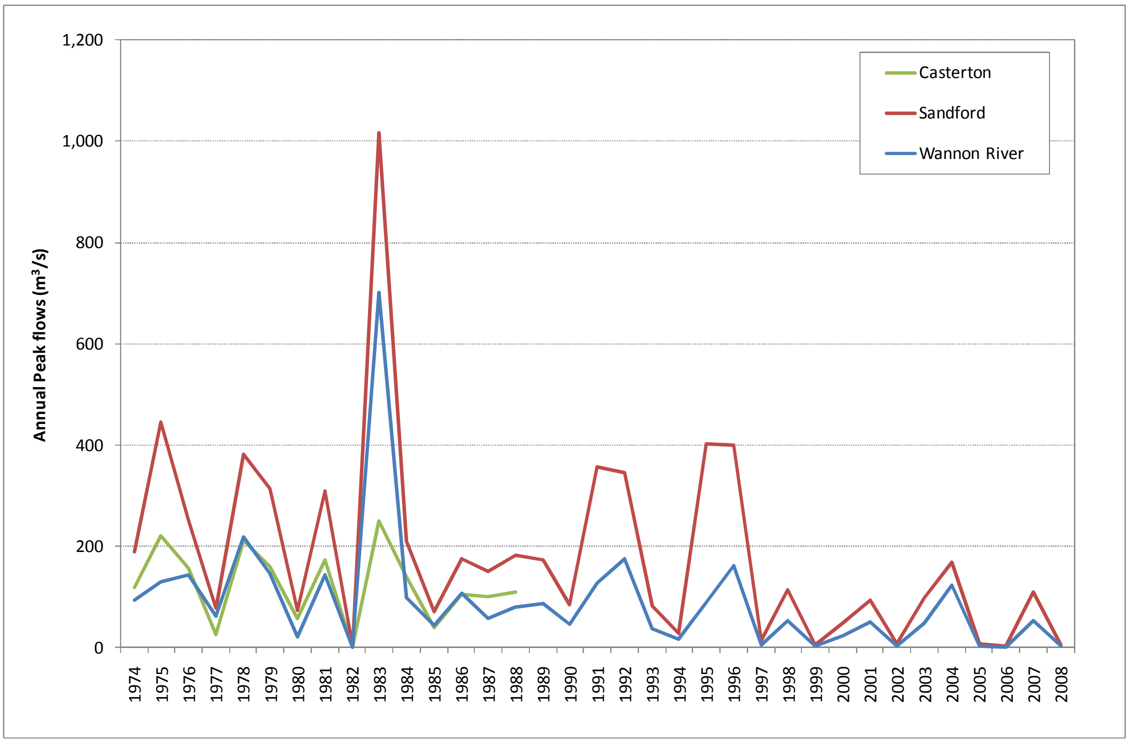


Figure 3.4: Peak annual flows for Wannon River, Glenelg River at Sandford and Casterton

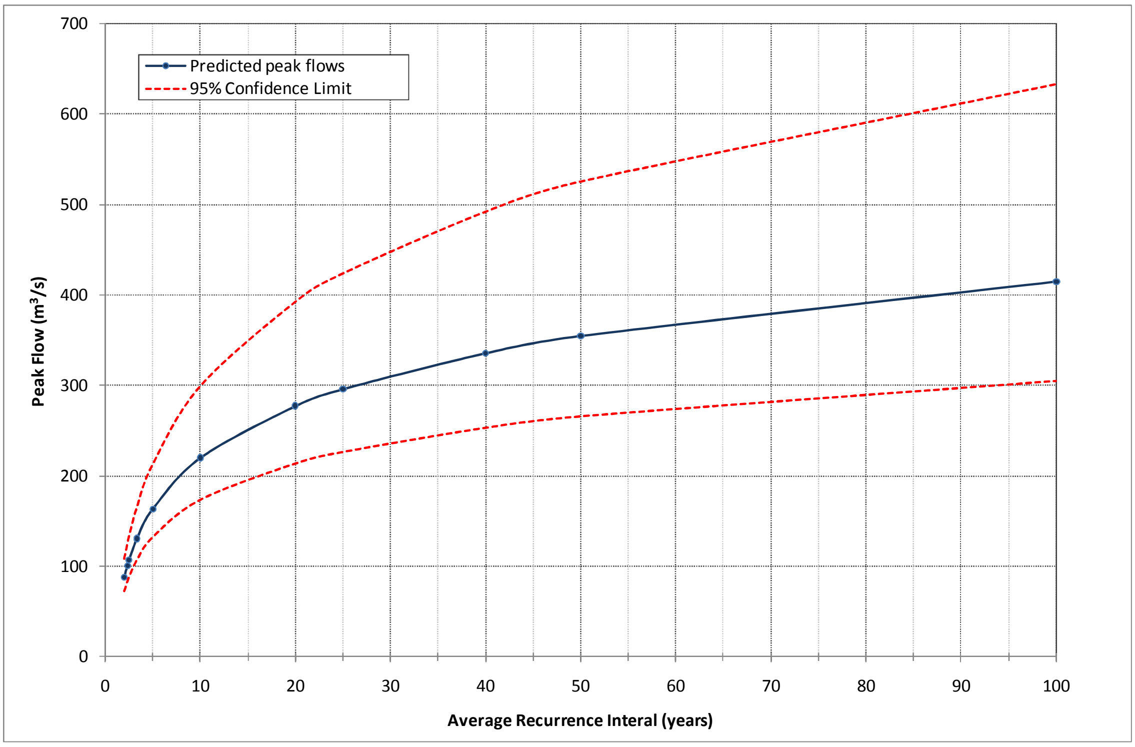


Figure 3.5: Predicted peak flows for Casterton using the 1960 to 2008 data set

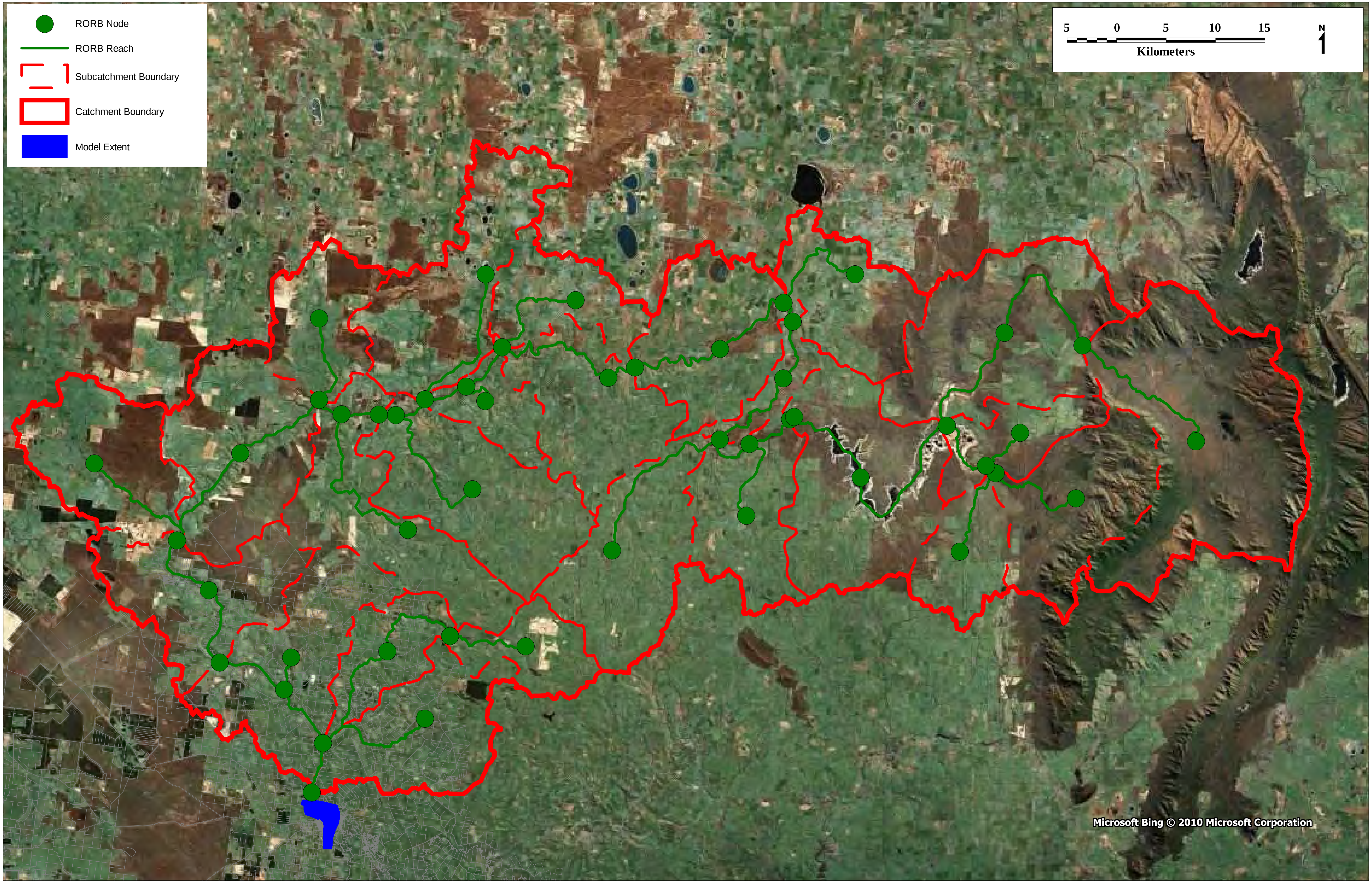


Figure 3.6 - RORB Model Layout

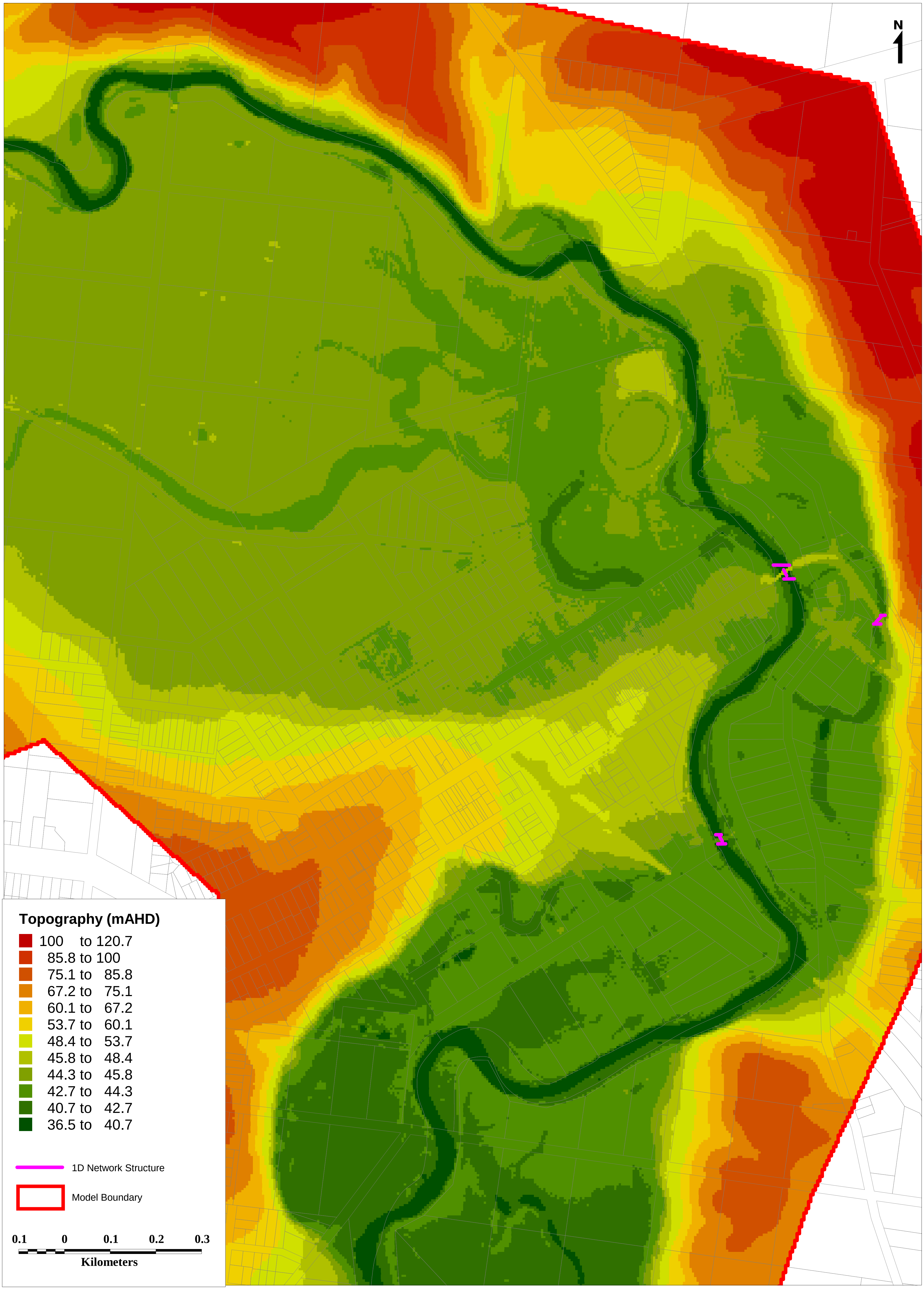


Figure 4.1 - Casterton Network Structures

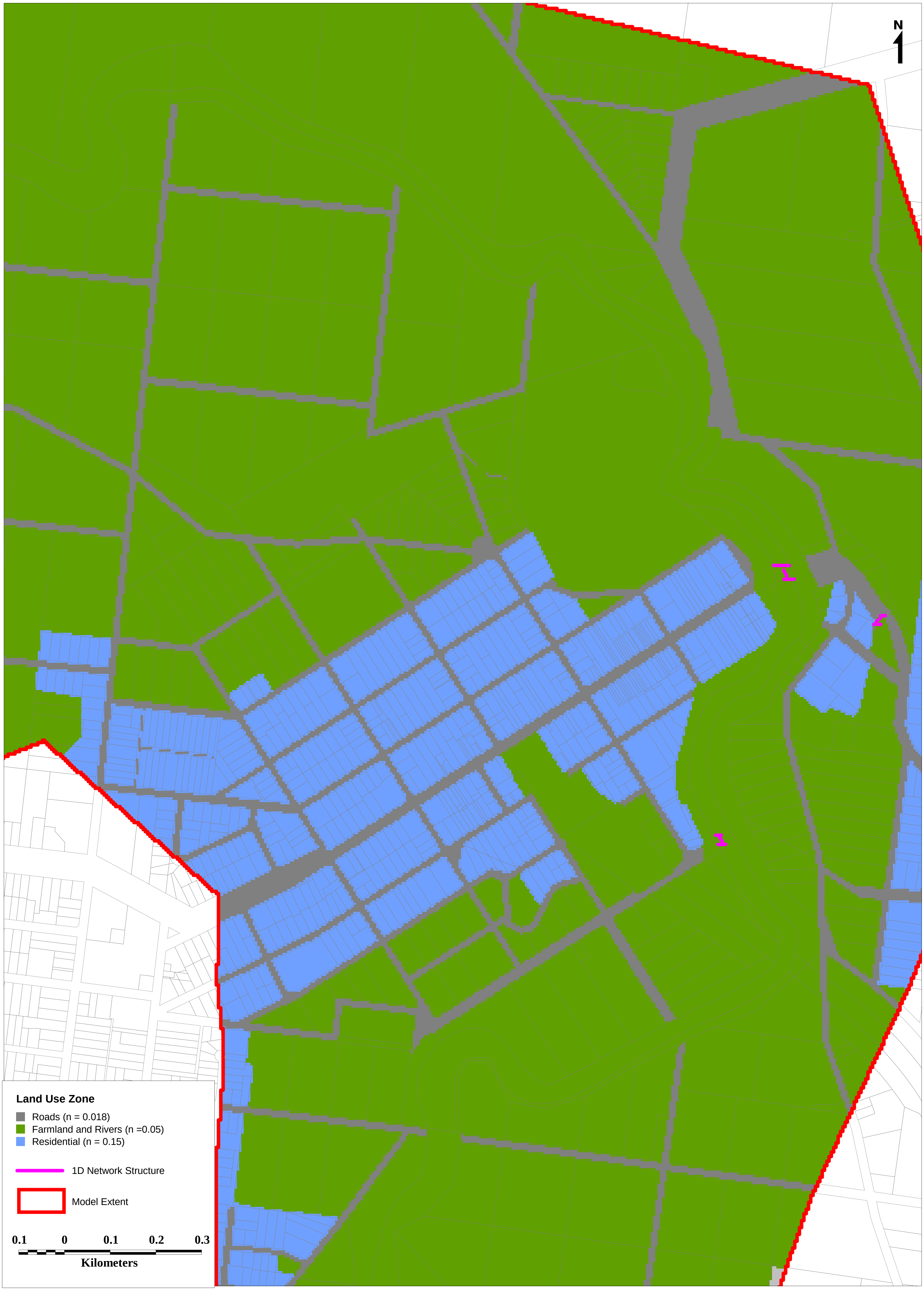


Figure 4.2 - Land Use Zones

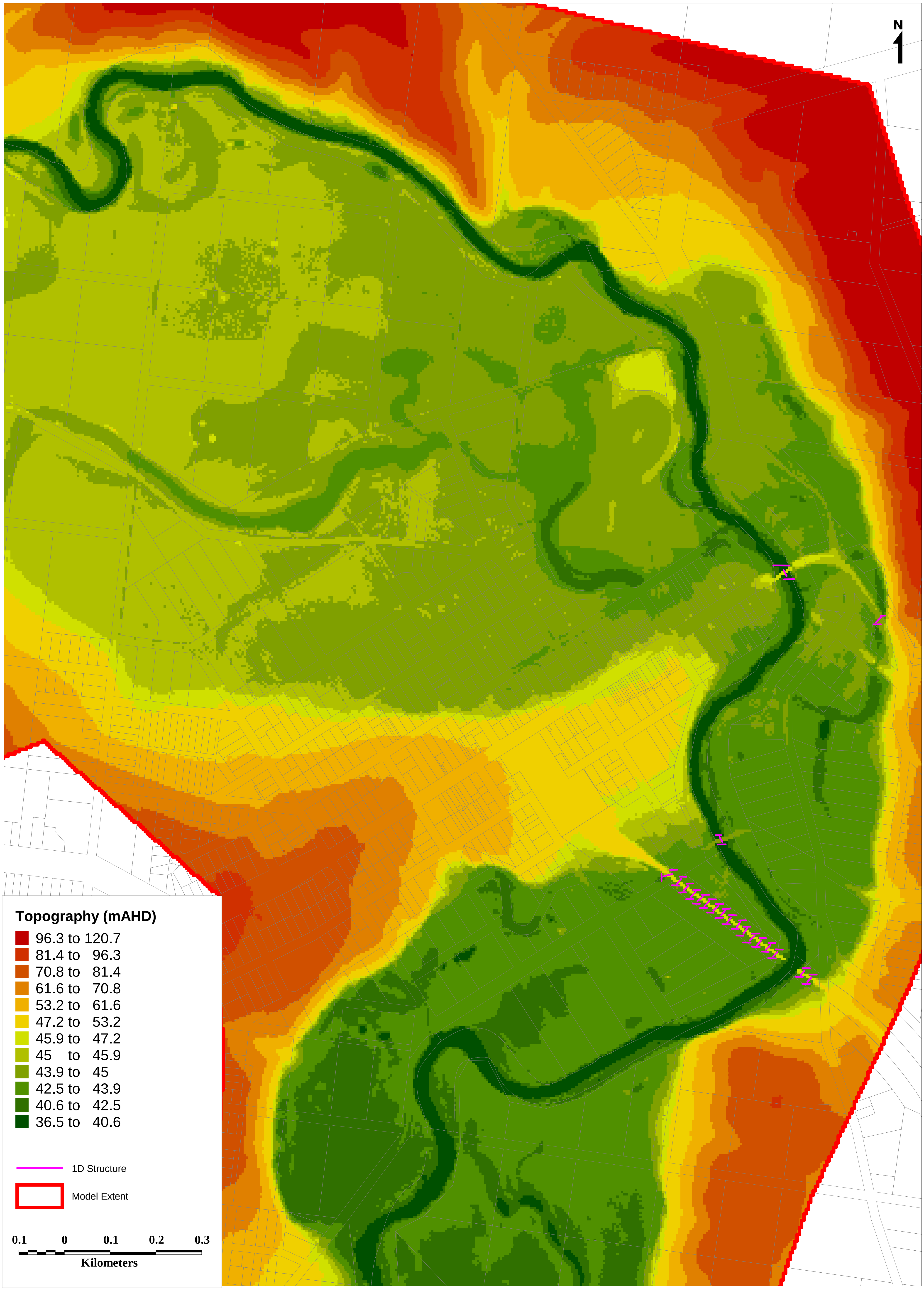


Figure 4.3 - Calibration Model Setup

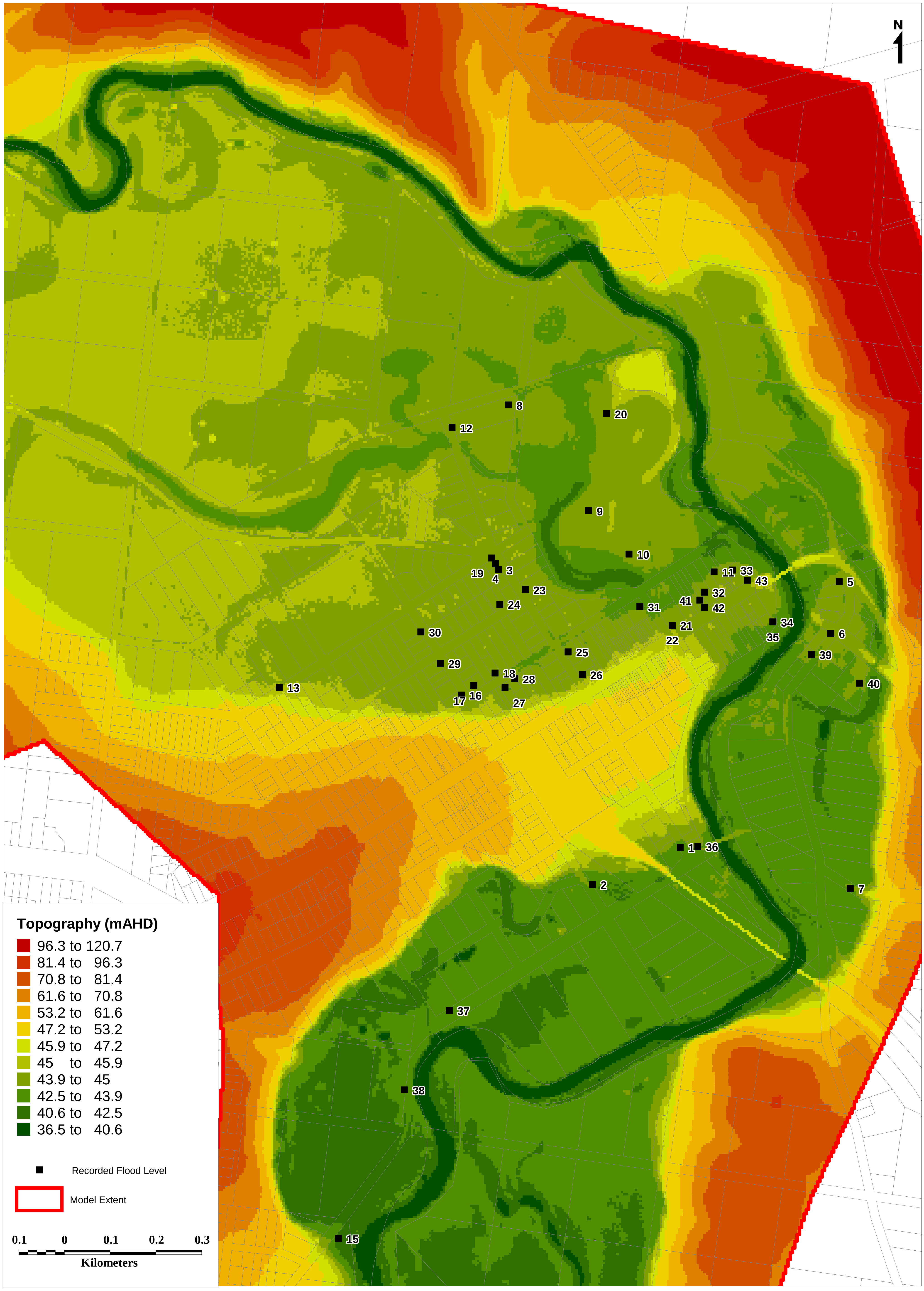


Figure 4.4 - Calibration Levels and Locations

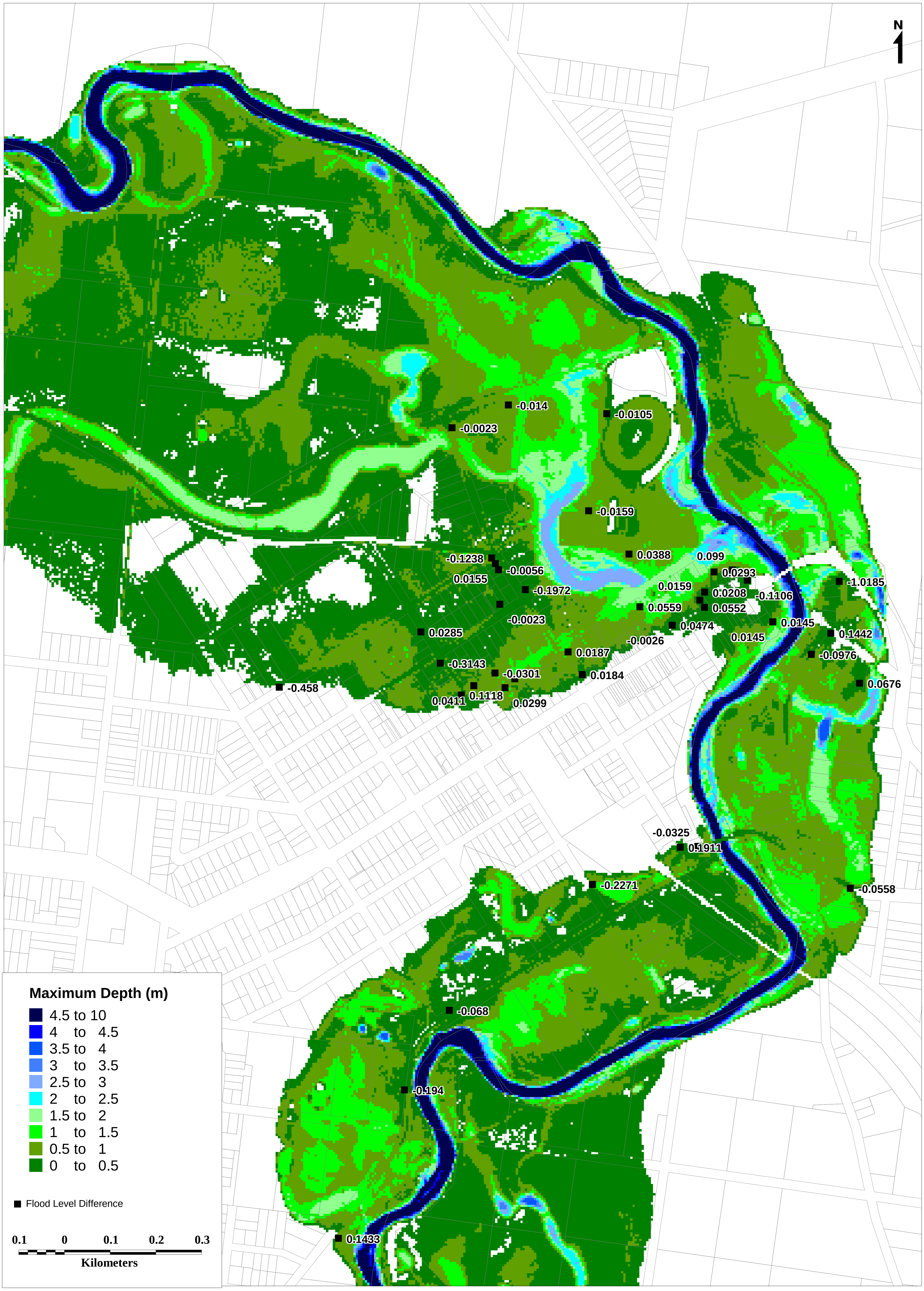


Figure 4.5 - Depth Extents - 1983 Flood Event

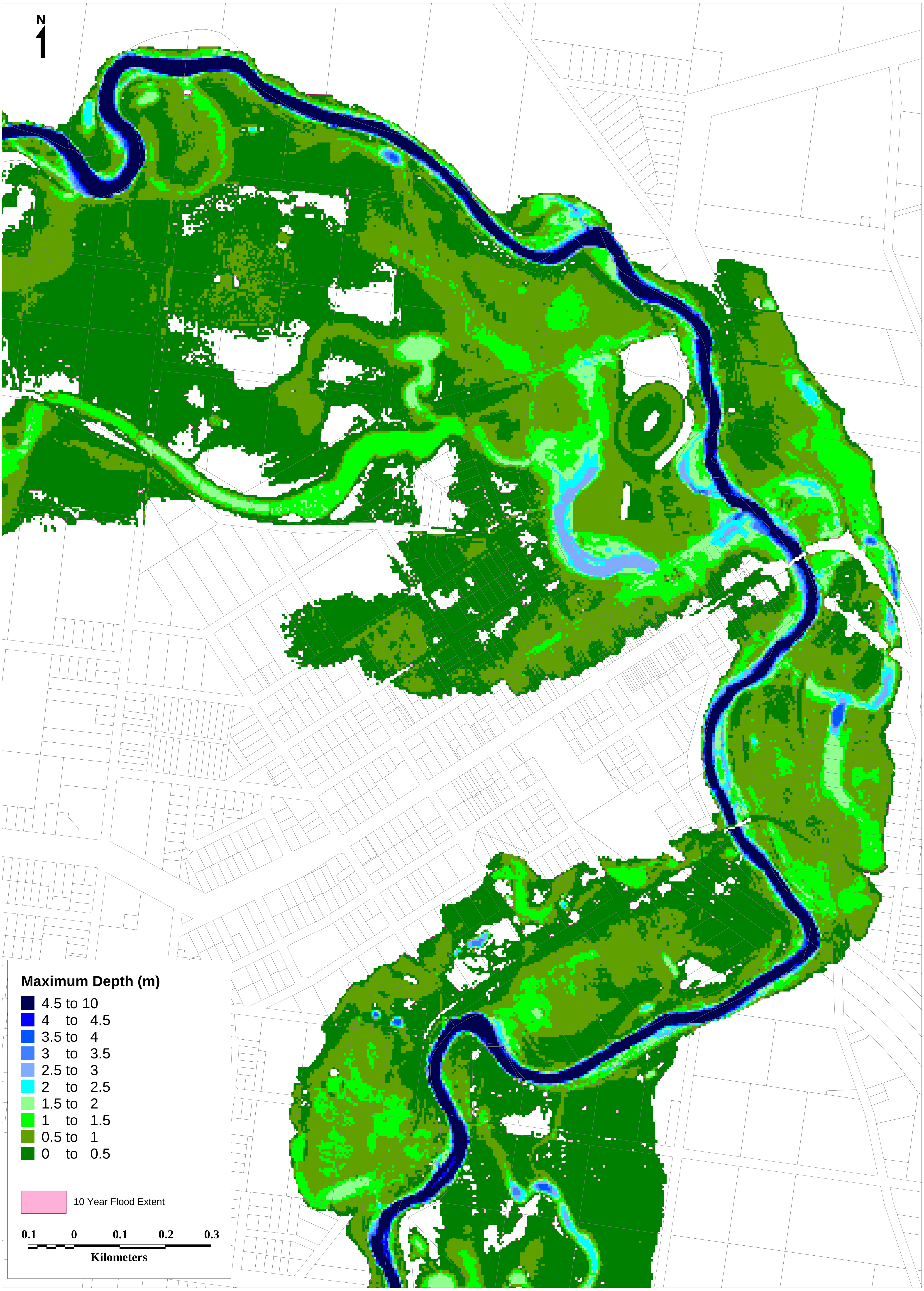


Figure 5.1 - Depth Extent - 10 Year ARI

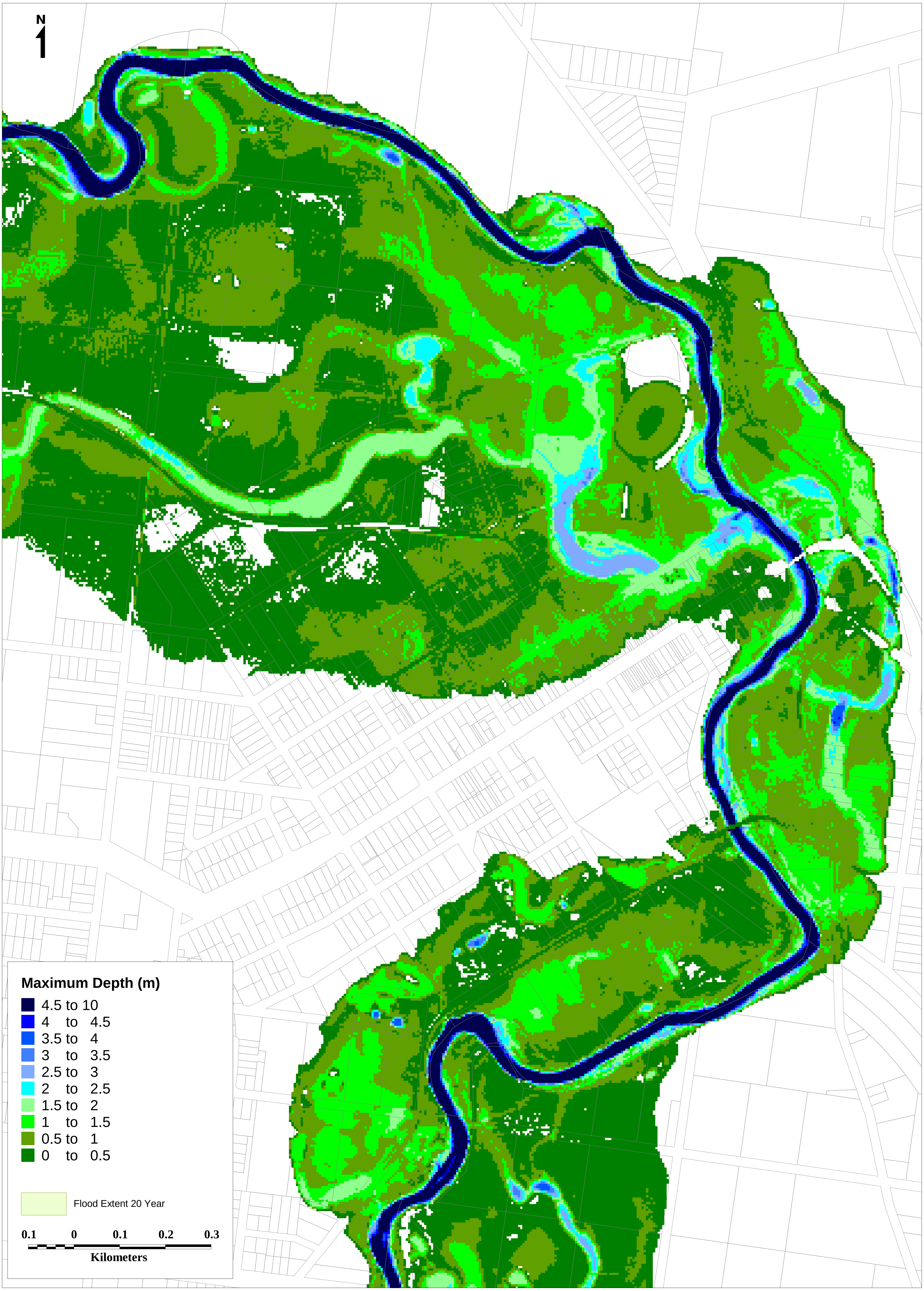


Figure 5.2 - Depth Extent - 20 Year ARI

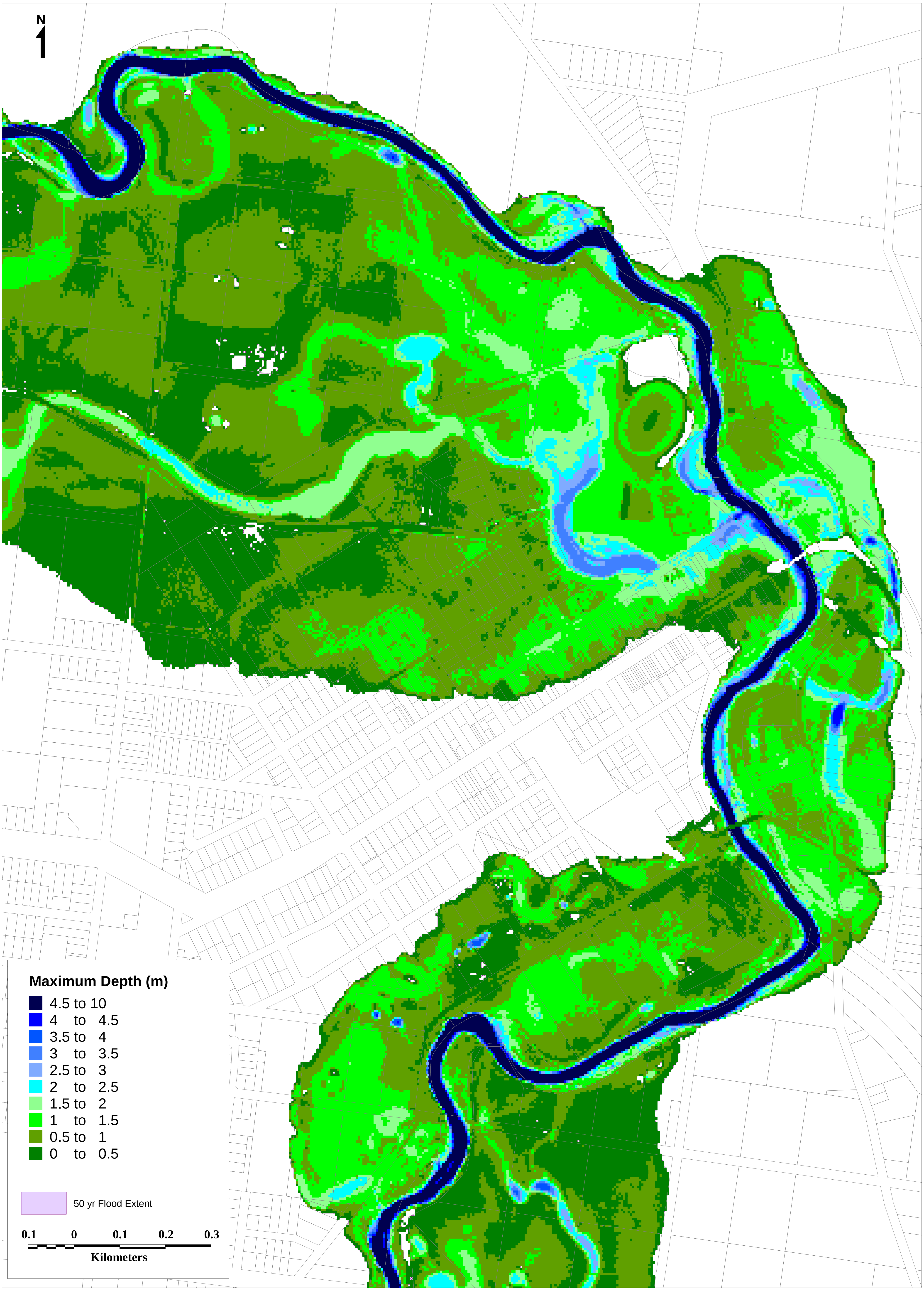


Figure 5.3 - Depth Extent - 50 Year ARI

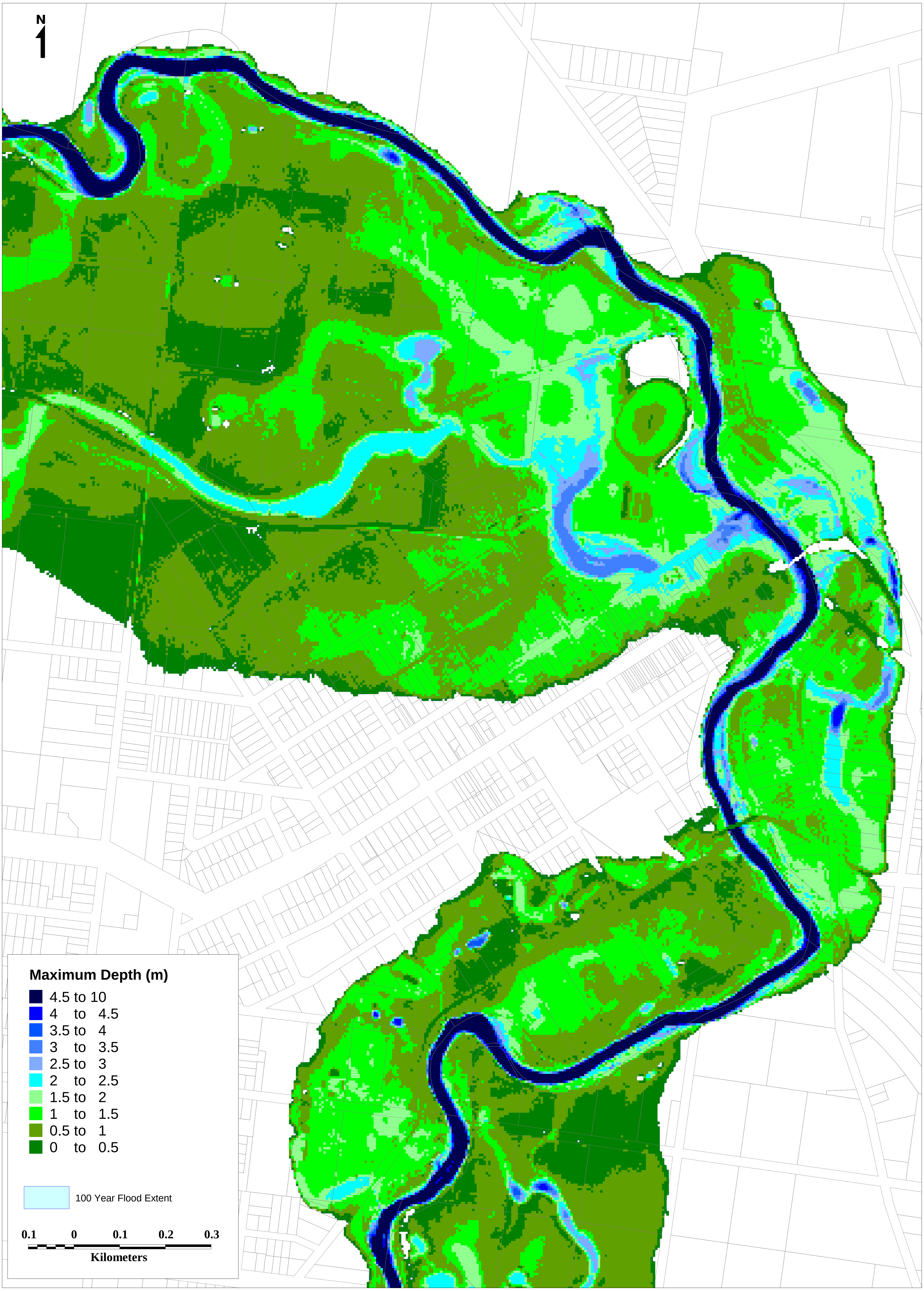


Figure 5.4 - Depth Extent - 100 Year ARI

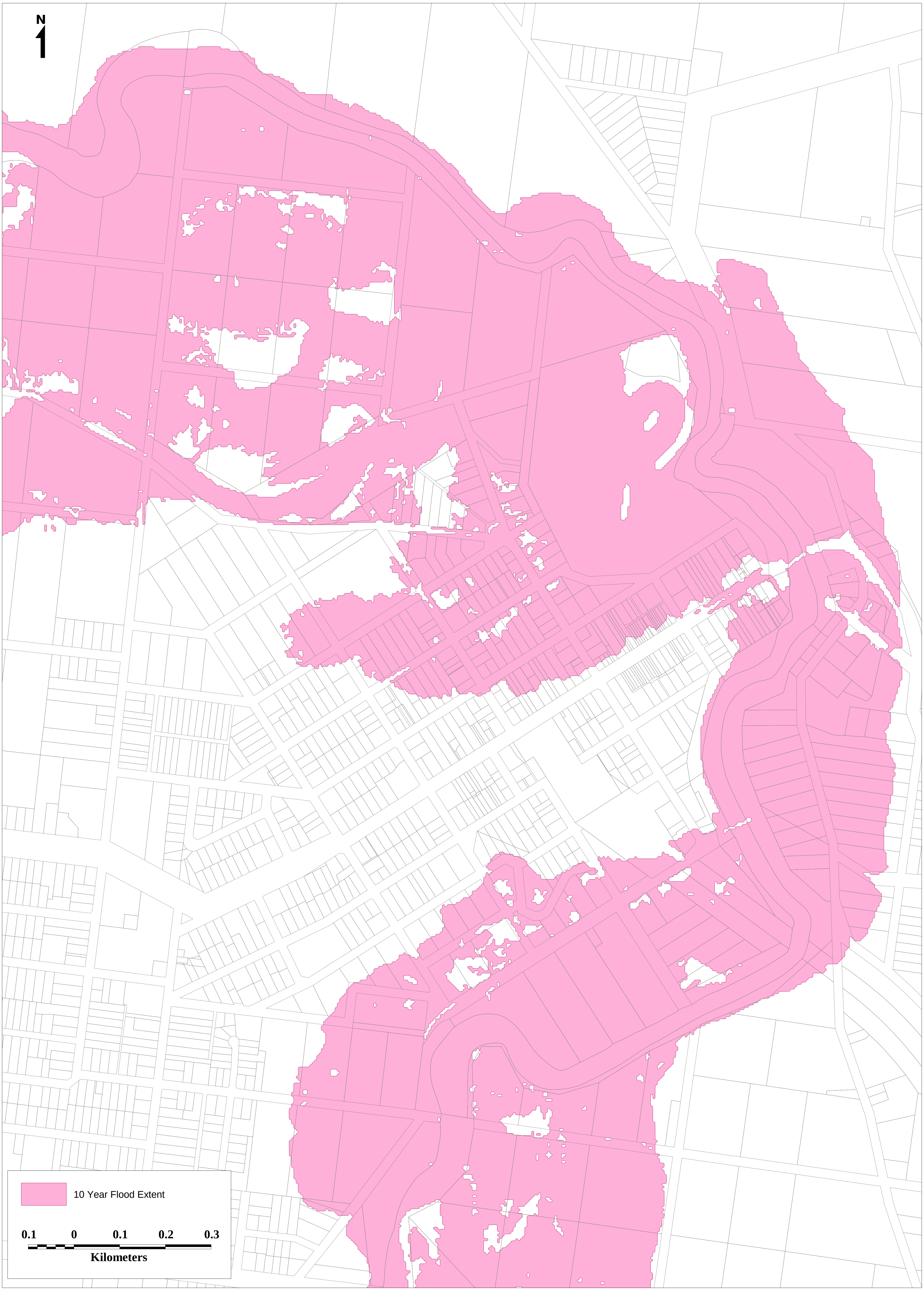


Figure 5.5 - Flood Extent - 10 Year ARI

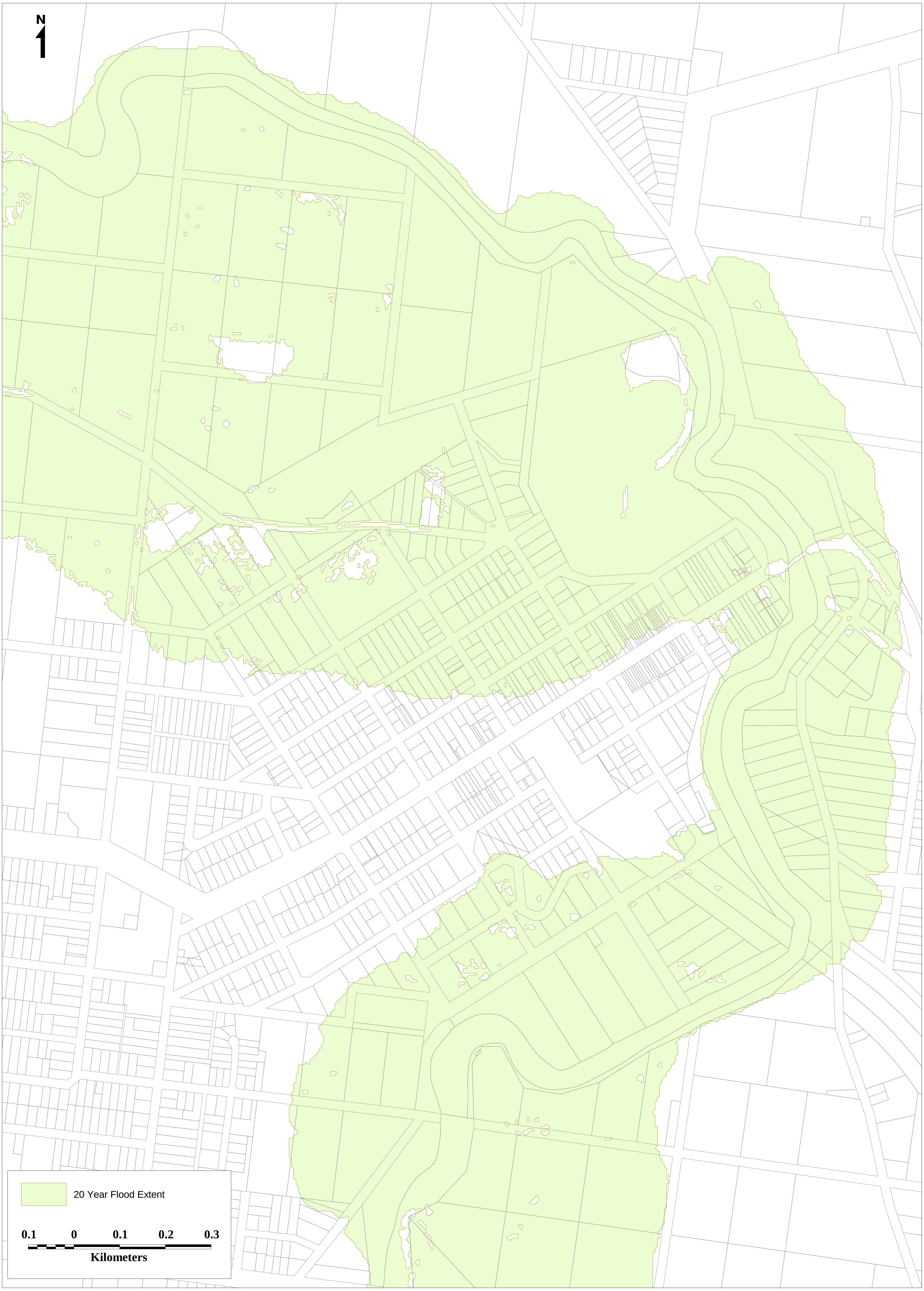


Figure 5.6 - Flood Extent - 20 Year ARI

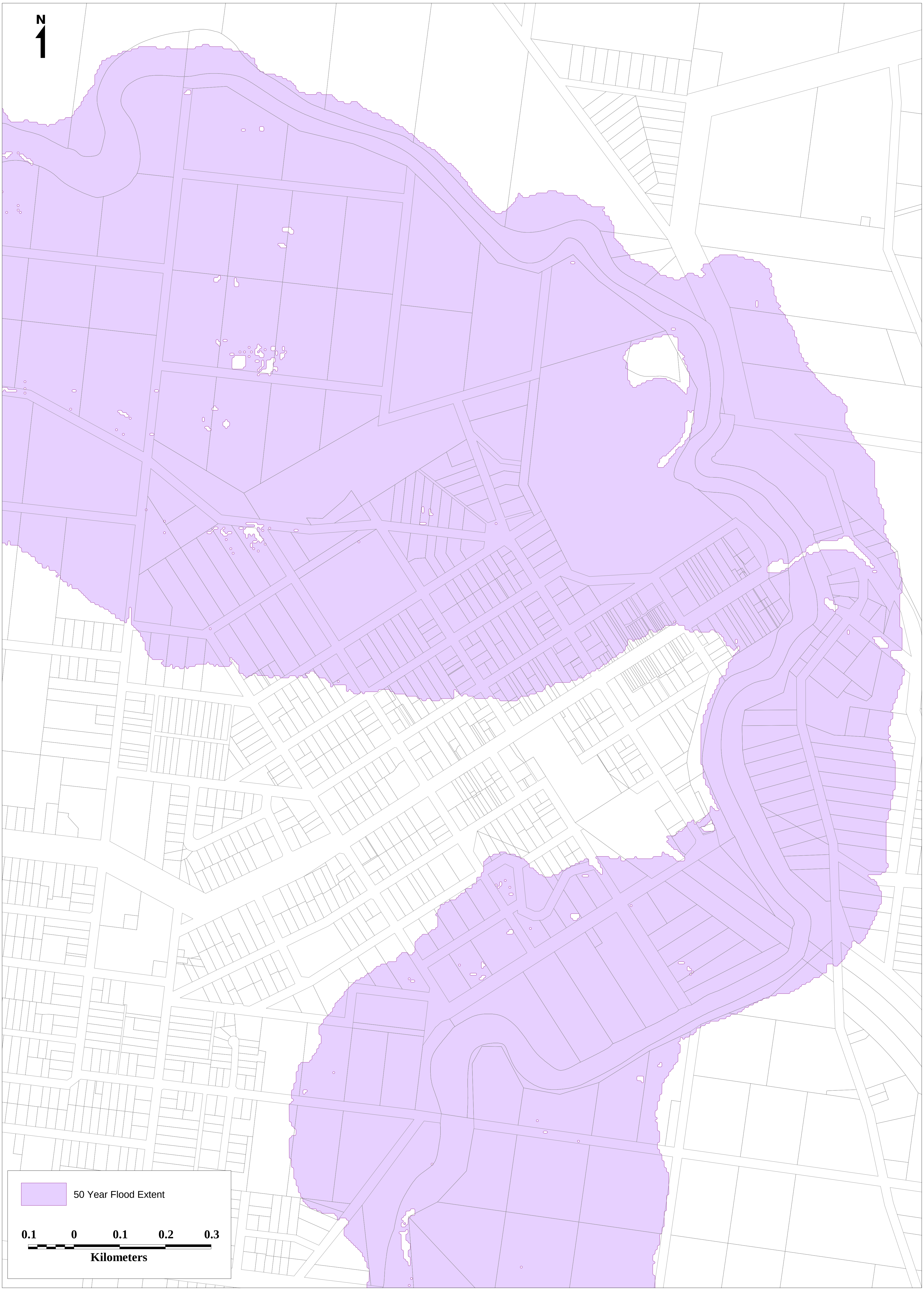


Figure 5.7 - Flood Extent - 50 Year ARI

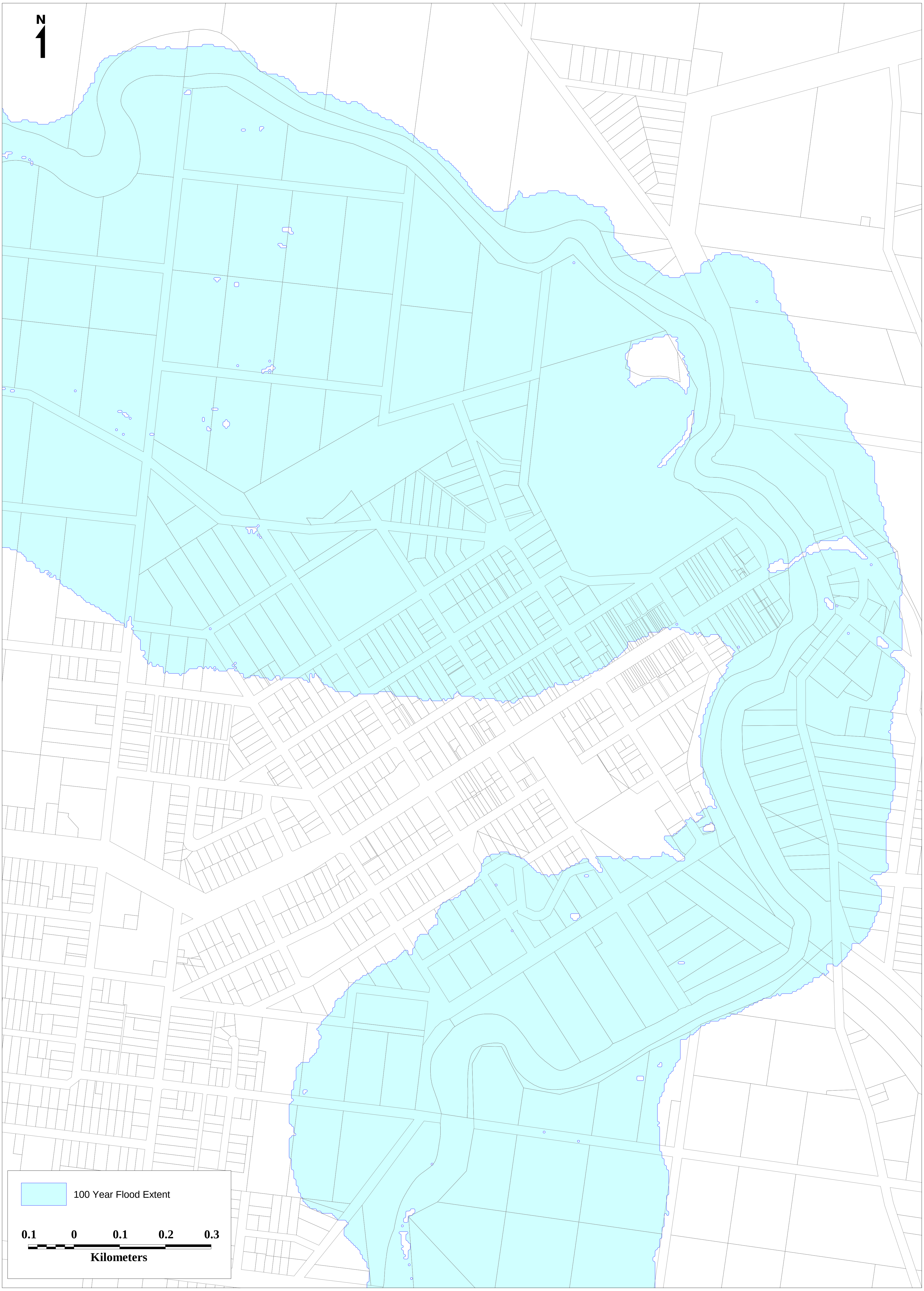


Figure 5.8 - Flood Extent - 100 Year ARI

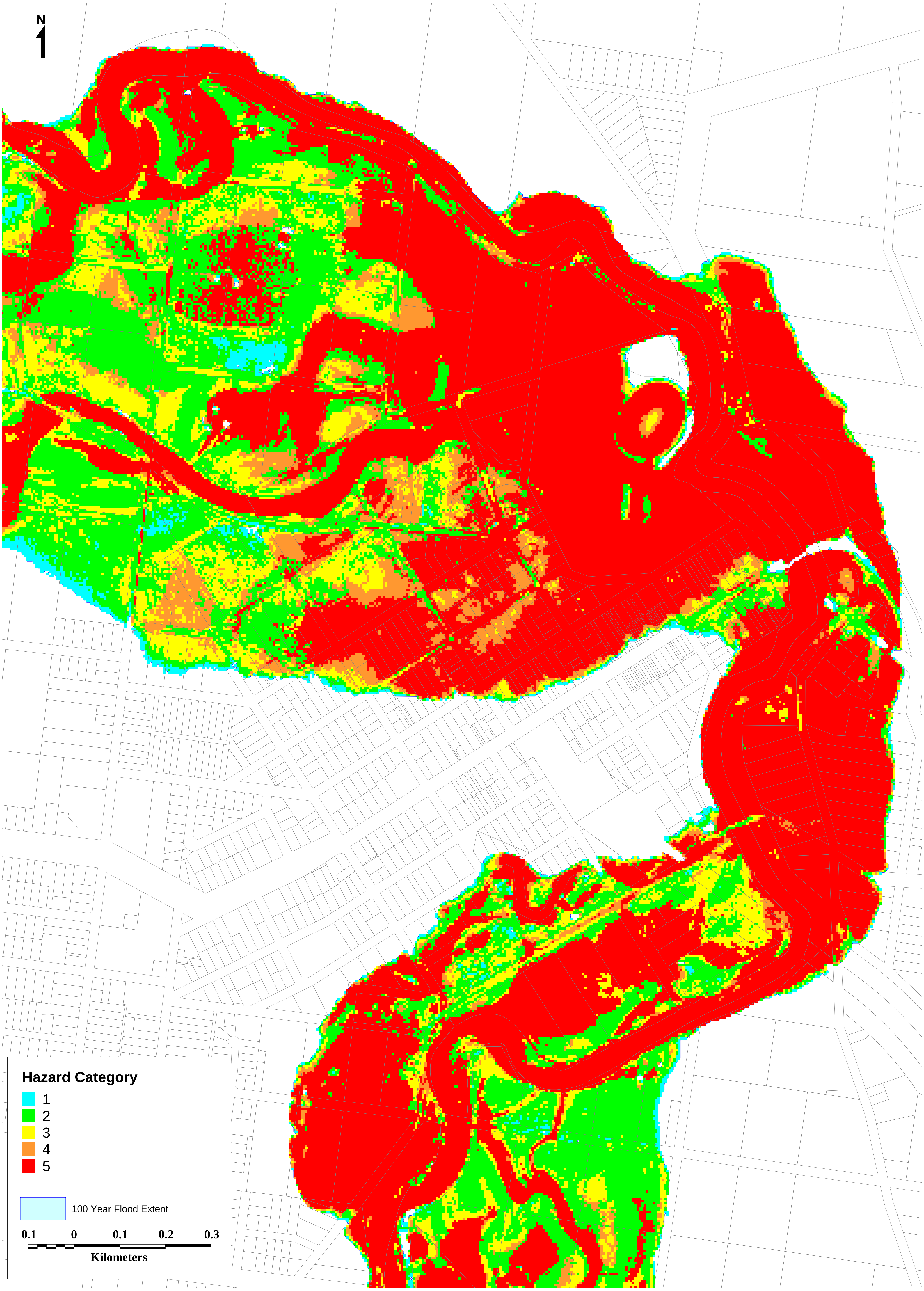
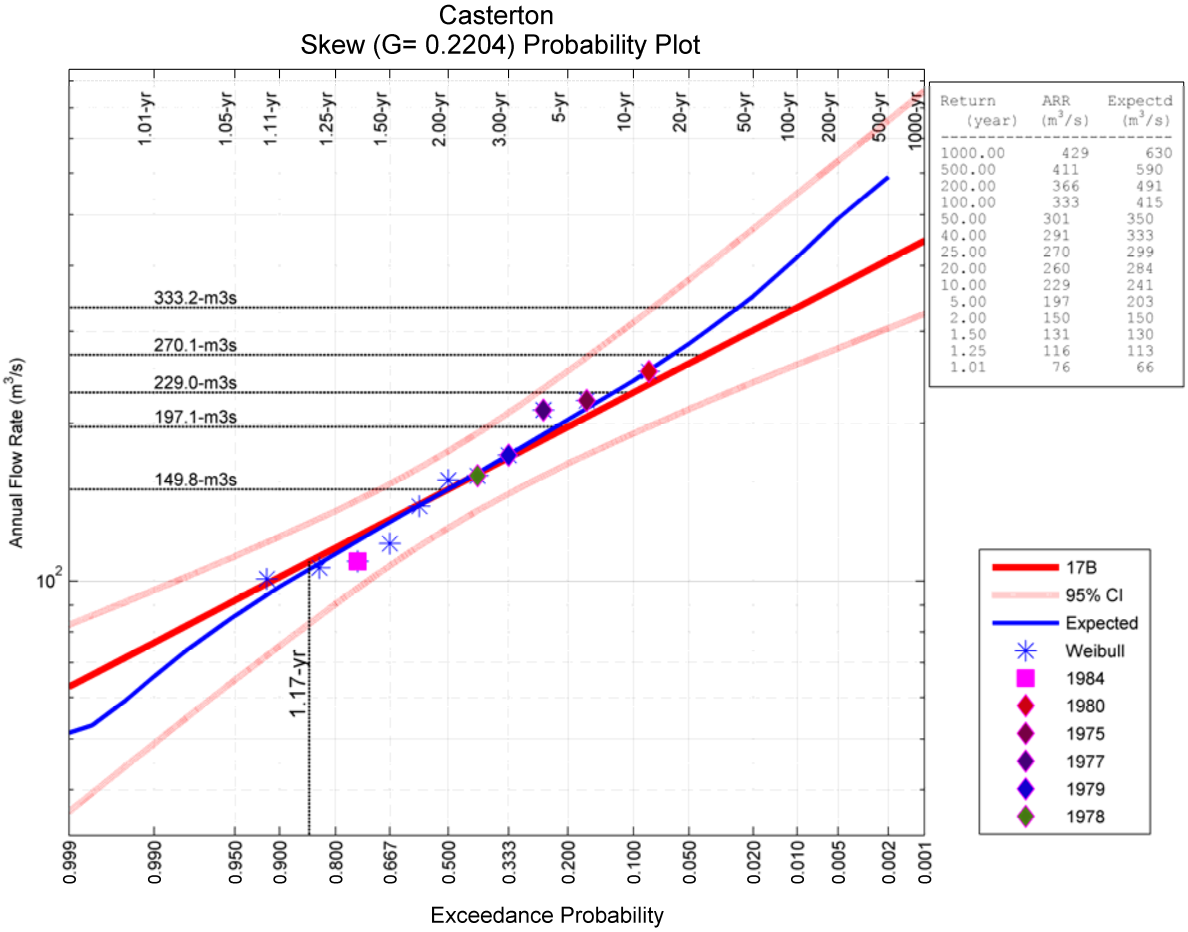


Figure 5.8 - Hazard Map - 100 Year ARI

Appendix A

Hydrology

A.1 FFA Calibration Plots



Return (year)	ARR (m^3/s)	Expectd (m^3/s)
1000.00	429	630
500.00	411	590
200.00	366	491
100.00	333	415
50.00	301	350
40.00	291	333
25.00	270	299
20.00	260	284
10.00	229	241
5.00	197	203
2.00	150	150
1.50	131	130
1.25	116	113
1.01	76	66

Figure A.3 FFA results for Glenelg River at Casterton (1974 to 1988) – Years 1977, 1980, 1982 and 1985 were removed as low outliers

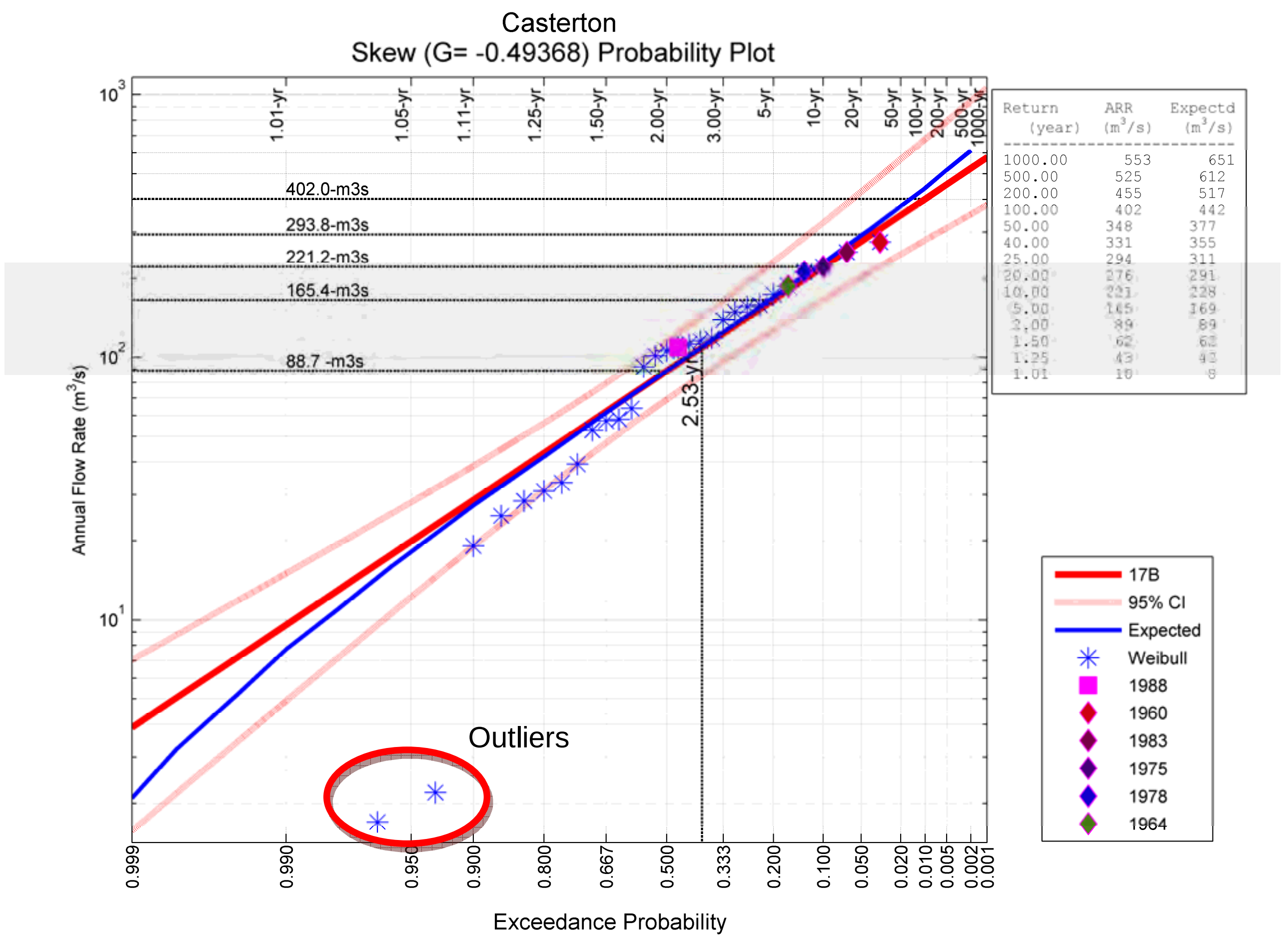


Figure A.4 FFA results for Glenelg River at Casterton (1960 to 1988) – Years 1967 and 1982 were removed as low outliers

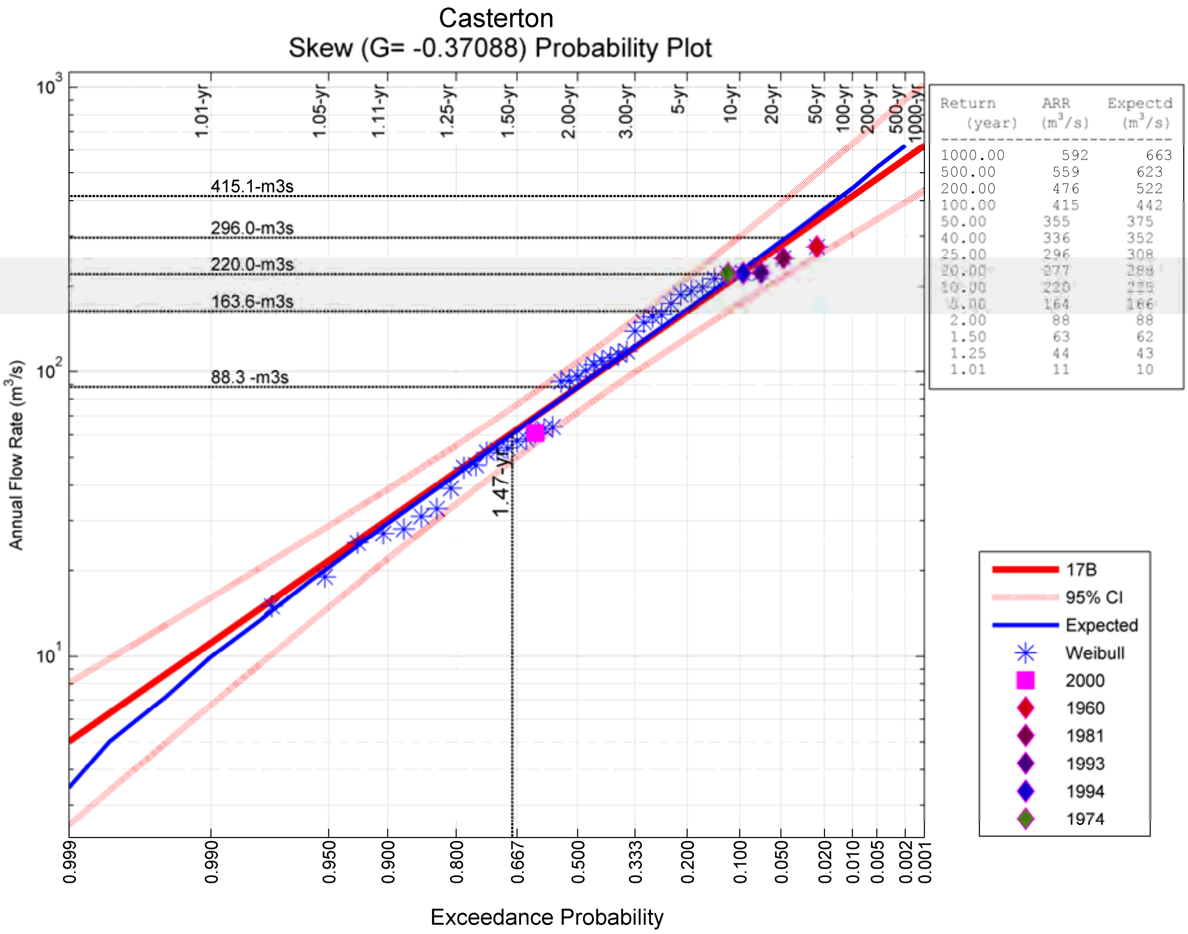


Figure A.5 FFA results for Glenelg River at Casterton (1960 to 2008) – Years 1967, 1982, 1997, 1999, 2002, 2005, 2006 and 2008 were removed as low outliers

A.2 RORB Vector

```
C File created using RORB Tools for MapInfo (MiRORB) version 1
C Original CATG file created on 21/09/2009 at 10:27:53
1
1, 18.598,  -99     ,Reach 1 node 1    Sub-area A, Reach A-A2 - Generate rainfall excess h'graph
and route downstream
5, 16.919,  -99     ,Reach 2           Reach A2-B - Route running h'graph downstream
2, 13.807,  -99     ,Reach 3 node 2    Sub-area B, Reach B-BE2 - Generate rainfall excess h'graph,
add to running h'graph, and route downstream
3                   ,                  Store running hydrograph
1, 11.637,  -99     ,Reach 4 node 3    Sub-area C, Reach C-CD2 - Generate rainfall excess h'graph
and route downstream
3                   ,                  Store running hydrograph
1, 10.032,  -99     ,Reach 5 node 4    Sub-area D, Reach D-CD2 - Generate rainfall excess h'graph
and route downstream
4                   ,                  Add running h'graph to last stored h'graph
5, 1.240,  -99      ,Reach 6           Reach CD2-E1 - Route running h'graph downstream
3                   ,                  Store running hydrograph
1, 5.771,  -99      ,Reach 7 node 5    Sub-area E, Reach E-E1 - Generate rainfall excess h'graph
and route downstream
4                   ,                  Add running h'graph to last stored h'graph
5, 7.674,  -99      ,Reach 8           Reach E1-BE2 - Route running h'graph downstream
4                   ,                  Add running h'graph to last stored h'graph
5, 17.515,  -99     ,Reach 9           Reach BE2-F - Route running h'graph downstream
2, 10.742,  -99     ,Reach 10 node 6   Sub-area F, Reach F-F2 - Generate rainfall excess h'graph,
add to running h'graph, and route downstream
16                  ,                  Storage
Rocklands
3, .000, 1, Spillway data (2 values x 1 spillways)
 195.470,  154.530,2.15,-99
C Elevation-storage relationship
1, 51, Elevation-storage table (2 values x 51 lines)
182.000,              0.000,
182.100,        2570000.000,
182.200,        2800000.000,
182.300,        3050000.000,
182.400,        3310000.000,
182.500,        3600000.000,
182.600,        3890000.000,
182.700,        4210000.000,
182.800,        4540000.000,
182.900,        4890000.000,
183.100,        5640000.000,
184.100,       10320000.000,
185.100,       17000000.000,
186.100,       26260000.000,
187.100,       37790000.000,
188.100,       52500000.000,
189.100,       70330000.000,
190.100,       94180000.000,
191.020,      121730000.000,
191.300,      131160000.000,
191.700,      145630000.000,
191.900,      153350000.000,
192.100,      161410000.000,
192.400,      174200000.000,
192.600,      183200000.000,
192.920,      198340000.000,
193.200,      212300000.000,
193.400,      222670000.000,
193.600,      233360000.000,
193.800,      244380000.000,
194.000,      255720000.000,
194.200,      267370000.000,
194.400,      279329984.000,
194.630,      293449984.000,
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195.230,      332120000.000,
195.500,      350360000.000,
195.520,      351729984.000,
195.540,      353100000.000,
195.560,      354480000.000,
195.580,      355860000.000,
195.600,      357249984.000,
195.620,      367551296.000,
195.640,      379227680.000,
195.660,      392279072.000,
195.680,      406705568.000,
195.700,      422507104.000,
196.000,      458934496.000,
197.000,      564114752.000,
198.000,      738047872.000,
199.000,      980733824.000,
200.000,     1292172670.000, -99
5, 5.472,   -99        ,Reach 11         Reach F2-G1 - Route running h'graph downstream
3                      ,                 Store running hydrograph
1, 9.731,   -99        ,Reach 12 node 7  Sub-area G, Reach G-G1 - Generate rainfall excess h'graph
and route downstream
4                      ,                 Add running h'graph to last stored h'graph
5, 5.547,   -99        ,Reach 13         Reach G1-GH2 - Route running h'graph downstream
3                      ,                 Store running hydrograph
1, 19.184,  -99        ,Reach 14 node 8  Sub-area H, Reach H-GH2 - Generate rainfall excess h'graph
and route downstream
4                      ,                 Add running h'graph to last stored h'graph
5, 12.015,  -99        ,Reach 15         Reach GH2-I - Route running h'graph downstream
2, 6.875,   -99        ,Reach 16 node 9  Sub-area I, Reach I-IJ2 - Generate rainfall excess h'graph,
add to running h'graph, and route downstream
5, 2.660,   -99        ,Reach 18         Reach IJ2-K1 - Route running h'graph downstream
3                      ,                 Store running hydrograph
1, 13.366,  -99        ,Reach 17 node 10 Sub-area J, Reach J-K1 - Generate rainfall excess h'graph
and route downstream
4                      ,                 Add running h'graph to last stored h'graph
5, 9.698,   -99        ,Reach 19         Reach K1-K - Route running h'graph downstream
2, 12.298,  -99        ,Reach 20 node 11 Sub-area K, Reach K-K2 - Generate rainfall excess h'graph,
add to running h'graph, and route downstream
5, 5.091,   -99        ,Reach 21         Reach K2-L - Route running h'graph downstream
2, 16.465,  -99        ,Reach 22 node 12 Sub-area L, Reach L-ML2 - Generate rainfall excess h'graph,
add to running h'graph, and route downstream
3                      ,                 Store running hydrograph
1, 12.525,  -99        ,Reach 23 node 13 Sub-area M, Reach M-ML2 - Generate rainfall excess h'graph
and route downstream
4                      ,                 Add running h'graph to last stored h'graph
5, 5.884,   -99        ,Reach 24         Reach ML2-N1 - Route running h'graph downstream
3                      ,                 Store running hydrograph
1, 4.169,   -99        ,Reach 25 node 14 Sub-area N, Reach N-N1 - Generate rainfall excess h'graph
and route downstream
4                      ,                 Add running h'graph to last stored h'graph
5, 4.502,   -99        ,Reach 47         Reach N1-N2 - Route running h'graph downstream
3                      ,                 Store running hydrograph
1, 16.526,  -99        ,Reach 26 node 15 Sub-area O, Reach O-NO2 - Generate rainfall excess h'graph
and route downstream
4                      ,                 Add running h'graph to last stored h'graph
5, 3.868,   -99        ,Reach 27         Reach NO2-P1 - Route running h'graph downstream
3                      ,                 Store running hydrograph
1, 16.016,  -99        ,Reach 28 node 16 Sub-area P, Reach P-P1 - Generate rainfall excess h'graph
and route downstream
4                      ,                 Add running h'graph to last stored h'graph
5, 1.720,   -99        ,Reach 29         Reach P1-P2 - Route running h'graph downstream
5, 3.870,   -99        ,Reach 30         Reach P2-Q1 - Route running h'graph downstream
3                      ,                 Store running hydrograph
1, 20.066,  -99        ,Reach 31 node 17 Sub-area Q, Reach Q-Q1 - Generate rainfall excess h'graph
and route downstream
4                      ,                 Add running h'graph to last stored h'graph
5, 3.024,   -99        ,Reach 32         Reach Q1-QR2 - Route running h'graph downstream
```

```
3                     ,                 Store running hydrograph

1, 9.711,   -99       ,Reach 33 node 18 Sub-area R, Reach R-QR2 - Generate rainfall excess h'graph
and route downstream
4                     ,                 Add running h'graph to last stored h'graph
5, 10.934,   -99      ,Reach 34         Reach QR2-S - Route running h'graph downstream
2, 12.118,   -99      ,Reach 35 node 19 Sub-area S, Reach S-ST2 - Generate rainfall excess h'graph,
add to running h'graph, and route downstream
3                     ,                 Store running hydrograph
1, 13.951,   -99      ,Reach 36 node 20 Sub-area T, Reach T-ST2 - Generate rainfall excess h'graph
and route downstream
4                     ,                 Add running h'graph to last stored h'graph
5, 8.181,   -99       ,Reach 37         Reach ST2-U - Route running h'graph downstream
2, 8.939,   -99       ,Reach 38 node 21 Sub-area U, Reach U-U2 - Generate rainfall excess h'graph,
add to running h'graph, and route downstream
5, 7.751,   -99       ,Reach 39         Reach U2-V1 - Route running h'graph downstream
3                     ,                 Store running hydrograph
1, 3.823,   -99       ,Reach 40 node 22 Sub-area V, Reach V-V1 - Generate rainfall excess h'graph
and route downstream
4                     ,                 Add running h'graph to last stored h'graph
5, 7.473,   -99       ,Reach 41         Reach V1-VXY2 - Route running h'graph downstream
3                     ,                 Store running hydrograph
1, 9.675,   -99       ,Reach 42 node 23 Sub-area W, Reach W-W2 - Generate rainfall excess h'graph
and route downstream
5, 10.993,   -99      ,Reach 43         Reach W2-X - Route running h'graph downstream
2, 14.172,   -99      ,Reach 44 node 24 Sub-area X, Reach X-VXY2 - Generate rainfall excess
h'graph, add to running h'graph, and route downstream
4                     ,                 Add running h'graph to last stored h'graph
3                     ,                 Store running hydrograph
1, 15.687,   -99      ,Reach 45 node 25 Sub-area Y, Reach Y-VXY2 - Generate rainfall excess h'graph
and route downstream
4                     ,                 Add running h'graph to last stored h'graph
5, 5.378,   -99       ,Reach 46         Reach VXY2-END - Route running h'graph downstream
7.1                   ,                 PRINT
0
C Sub-area areas in km2
 448.200,  302.955,  198.434,   98.636,   93.063,
 100.000,  158.707,  213.254,   45.343,  152.628,
 201.524,  187.692,  114.682,   69.891,  233.851,
 245.520,  217.096,  126.203,  237.007,  186.640,
 191.089,  225.904,   84.173,   93.943,  178.278,
 -99
C Impervious Fraction Data
0,  -99              ,No impervious areas in system
```

A.3 RORB Calibration Plots

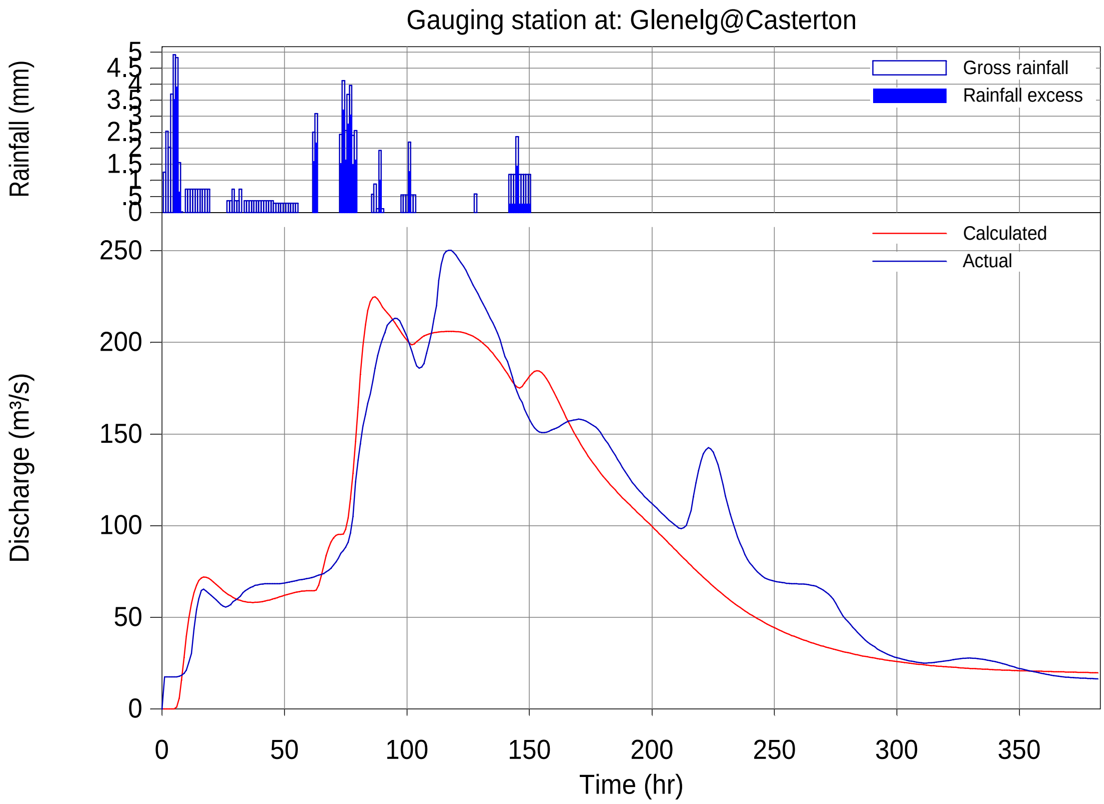

Figure A.1 Calibration for the 1983 flood event at Glenelg River at Casterton (k_c = 115, m = 0.96, IL = 11 mm, CL = 0.8 mm/h)

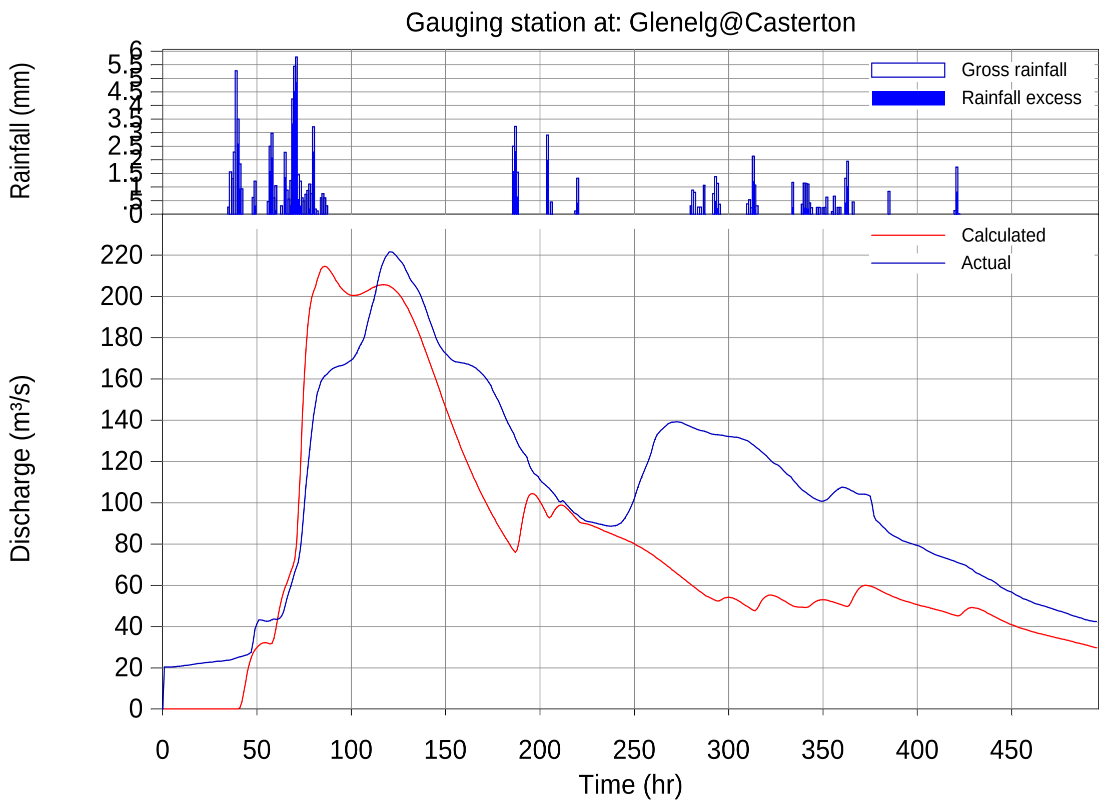

Figure A.2 Calibration for the 1975 flood event at Glenelg River at Casterton (k_c = 115, m = 0.96, IL = 11 mm, CL = 0.8 mm/h)