Wagga Wagga City Council

Gregadoo Road Hydrology and Hydraulic Study

Technical Report

April 2020

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Contents

Executive Summary

This report contains the hydrology and hydraulic investigation for culverts along the Gregadoo Road between the Plumpton Road and Main Street. This investigation studies the effects of flooding of four culverts located along this road that are subject to over topping during both frequent and rare flood events.

The catchment was analysis with the use of numerical models for both the hydrological (RAFTS/DRAINS) and hydraulic (QGIS/HEC-RAS 5) modeling. The RAFTS method based on the ARR 2019 guideline is utilized for hydrology modeling in the DRAINS software. The extracted hydrographs from DRAINS are imported to the 2D hydraulic model to analyze the over topped and overland flows. HEC-RAS 5 was used for hydraulic modeling.

Results show that the capacities of the existing culverts are undersized for conveying frequent flood event. This results in over topping of Gregadoo Road at all culvert locations.

It was determined that further investigation was needed to find mitigation measures to minimise road over topping. Results of this investigation indicate that protection of Gregadoo Road can be provided up to the 5% AEP flood event by upgrading the culvert capacities, road re-alignment and road raising. However, for protection from rarer flood events above the 5% AEP, major mitigation works would be preventative, based upon the size and number of the culverts required. Furthermore, protection of this size would have significant flood effects on downstream development with increases in flood levels and flood velocities.

1. Introduction

This report describes the data collection, Hydrology and Hydraulic modeling of flooding along the Gregadoo Road between the Plumpton Road and Main Street. The modeling is done in accordance with the Australian Rainfall and Runoff 2019 (ARR2019) guidlines. This progress report contains the following sections:

- Data gathering – GIS data, previous model build data, rainfall data;
- Hydrology modelling based on the ARR2019 approaches by using the DRAINS software; and
- 2D Hydraulic modelling with the HEC – RAS 5 software.

2. Study Area

Gregadoo Road is located at the southern side of Lake Albert. Study area covers the road from Plumpton Road junction all the way to the Main Street junction. Storm and flood waters over top the road during frequent and rare flood events at several locations. The study is highlighted in figure 1 including the google road map and satellite map.

3. Previous Studies

The following overland flow flood and risk management studies were undertaken for this area.

- Wagga Wagga Major Overland Flow Flood Study, WMAwater 2011
- Wagga Wagga Major Overland Flow Floodplain Risk Management Scoping Study, WMAwater 2012
- Wagga Wagga Major Overland Flow – Model Update Report, WMAwater 2015
- Draft Wagga Wagga Major Overland Flow Floodplain Risk Management Study and Plan, WMAwater 2020

In the latest study (2020), the 2D TUFLOW model results were updated based on the ARR2019 methodology in accordance with NSW DPIE Guidance. Figure 2 shows the draft maximum flood levels and extents for 100 yr, 20 yr and 5 yr events.

4. Data Gathering

The below items are essential for flood modeling along the road:

- Topographic data
- Hydraulic structures details

There are two types of topographic data used in this study. The first one is high resolution LiDAR data which was captured in 2009. It was delivered by Council asset management section and utilized to create the Digital Elevation Model (DEM) with 1 m cell size along the road by QGIS software package.

The second one is LiDAR data from http://elevation.fsdf.org.au/ (ELVIS), which is a Government website that provides free spatial data. The two data types are merged together with putting the high resolution one on top. Eventually, a single 5 m DEM is created for terrain analysis and catchment delineation as shown in Figure 3.

With using the aerial photo and terrain analysis, seven effective culverts have been figured out as shown in figure 4. Table 1 includes the culverts details with considering some assumptions. It should be noted that the accurate attributes need to be captured by surveying.

Table 1: Culverts attributes

ID Number	Type	Barrels Number	Upstream Invert Leve (AHD)	Downstream Invert Level (AHD)	Width or Diameter (m)	Height (m)
1	Box Culvert	1	205.35	205	1.5	0.6
2	Pipe Culvert	1	204.6	204.4	1.5	-
3	Box Culvert	1	204	204	1.5	0.6
4	Box Culvert	2	204.3	204.15	0.8	0.25
5	Box Culvert	2	208.5	208.5	2.45	1.5
6	Pipe Culvert	3	211.9	211.9	0.525	-
7	Box Culvert	1	211.35	211.35	1	0.25

5. Modeling

Modeling procedure including collection and manipulation of the raw data and hydrological and hydraulic modeling were undertaken in this part. Further discussion can be found in Appendices A and B respectively.

5.1 Raw Data

In this section, the procedures to reach the final outputs from the raw data are described and the final products are shown and discussed. More details can be found in the Appendix A.

5.2 Hydrology and Hydraulic

This section includes hydrology and hydraulic analysis for all culverts along the road. The results from the previous section are used as input data for hydrology and hydraulic modeling. The modeling results includ the maximum flood levels, depths and velocities for different flood events. More details are provided in Appendix B

6. Possible Mitigation Works

Some further analysis is done to find some measures to minimize the road being overtopped as below.

- Culvert 1:

Investigation results indicate that this culvert can accommodate a maximum flow of 1.5 cumecs under existing conditions. This is equivalent to a 5%AEP flood flow. However, interaction between this culvert (culvert 1) and culvert 2 with backwater effects needs to be further investigated and is detailed under Culvert 2 analysis.

- Culvert 2:

There is a low point area along the Gregadoo road between the Plumton Rd and culvert 2. The lowest elevation is around 206.1 m AHD. If culvert 1 and culvert 2 are upgraded to 8m* 0.65m and 12m*1.5m box culverts respectively and the road level is raised to 206.7 m AHD along the low point area, this measure can prevent road be overtopped up to 5% AEP flood event. Figure 5 shows the long section along the Gregadoo road from Plumton Rd to the station 380 m. Figure 6 shows the maximum flood depths for 5% AEP event after upgrading the culverts and road level.

To analyze the upgrading effects on flood level at downstream and upstream of the road, a separate map is prepared as figure 7. This map shows the wet and dry area for 5% AEP flood event between pre and post upgrading the road and the culverts. Figure 8 also shows the flood levels differences for 5% AEP flood event between pre and post upgrading the road and the culverts. As can be found there are not significant maximum water levels differences between the pre and post upgrading for 5% AEP flood event.

- Culvert 3:

The existing culvert can carry flow up to 1 in 1 year flood event. By upgrading this culvert from 1.5m*0.6m to 5m*0.6m, the floods up to 5% AEP can pass through the culvert without flood overtopping. Figure 9 shows the maximum flood depths for 5% AEP event after upgrading culvert 3. To analyze the upgrading effects on flood levels at downstream and upstream of the road, a separate map is prepared as figure 10. This map shows the wet and dry area for 5% AEP flood event between pre and post upgrading of culvert 3. Figure 11 also shows the flood levels differences for 5% AEP flood event between pre and post upgrading culvert3.

- Culvert 4:

Model results indicate that this culvert is significantly undersized and causes overland flooding at nuisance flood events (i.e. less than the 1 in 1 year event). Further comprehensive investigation is required at this location due to downstream effects on existing development.

7. Conclusion

The results from the hydrology and hydraulic analysis of culverts along the Gregadoo road are summarized in below table.

Table 2: Summery of the modeling results

Culvert No	Flood Events	Maximum Overtopping Length (m)	Maximum Overtopping Depth (m)	Maximum Velocity (m/s)	Maximum Hazard Category
Culvert 1 & 2	20% AEP	193	0.3	1	H2
	5% AEP	209	0.38	1.1	H2
	1% AEP	223	0.5	1.2	H2
Culvert 3	20% AEP	56	0.12	0.42	H1
	5% AEP	72.5	0.15	0.46	H1
	1% AEP	78	0.2	0.5	H1
Culvert 4	20% AEP	519	0.4	0.6	H2
	5% AEP	561	0.55	0.65	H2
	1% AEP	575	0.65	0.7	H3

Based on the modeling results, the existing culverts capacities for passing the discharges are very low and the road is overtopped even in frequent flood events.

With respect to upgrading the culverts this can have an adverse effect on downstream areas as flooding characteristics may be increased (e.g. flood area, flood depths and flood velocities). In additions to creating adverse flood effects downstream, the cost of replacing the existing culverts with larger culverts or augmentation of the existing culverts would be preventative due to the significant cost and low benefit/cost ratio.

An alternative cost effective solution would be the placement of flood hazard signs at the culvert locations showing depth of flood inundation.

With respect to the flood risk associated with each culvert shown in the Table above, culvert 4 has the highest risk category.

Main Report Figures

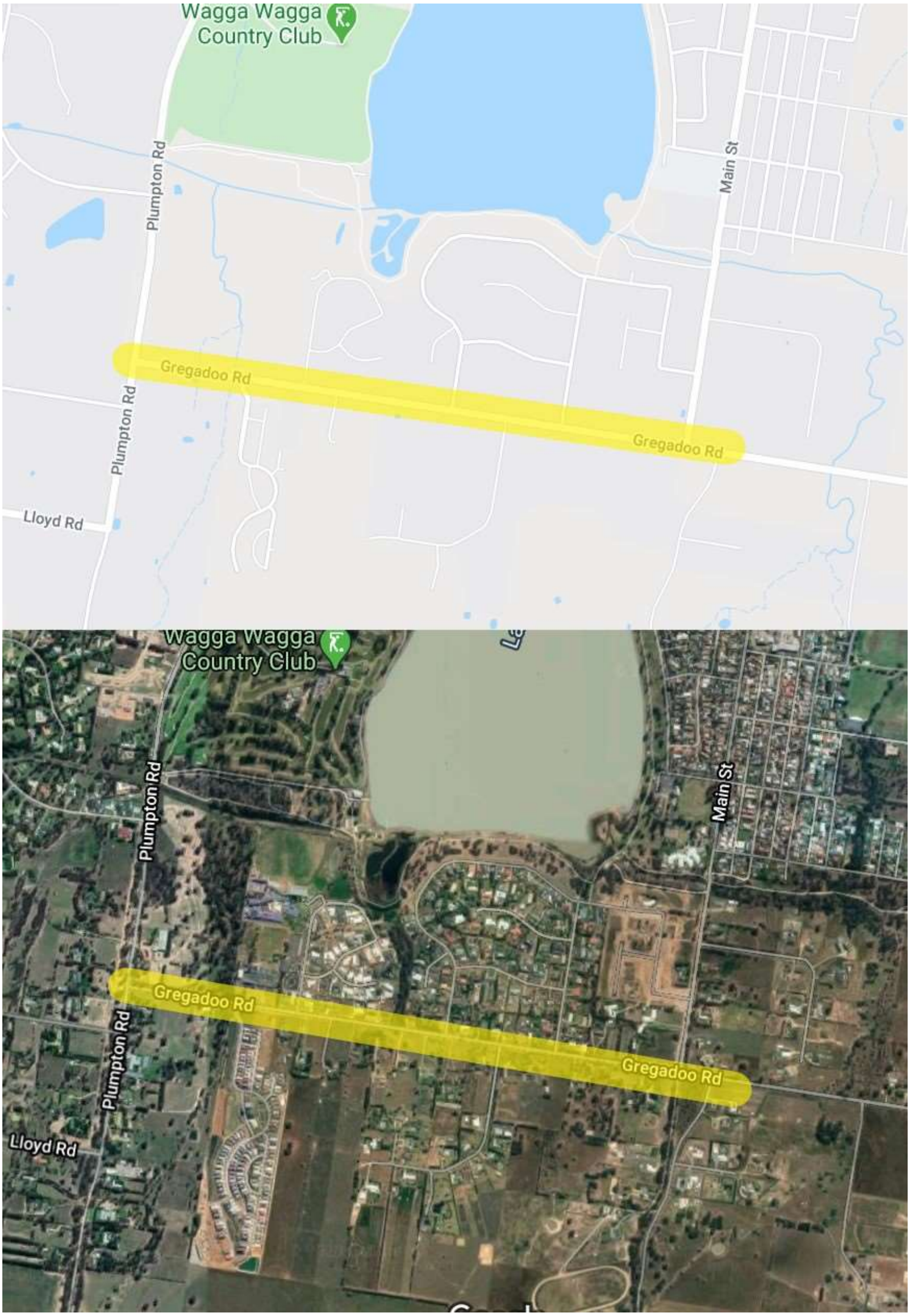


Figure 1: Study area (Gregadoo Rd highlighted in yellow)

Figure 2-a: Maximum flood levels and extent for 100 yr events

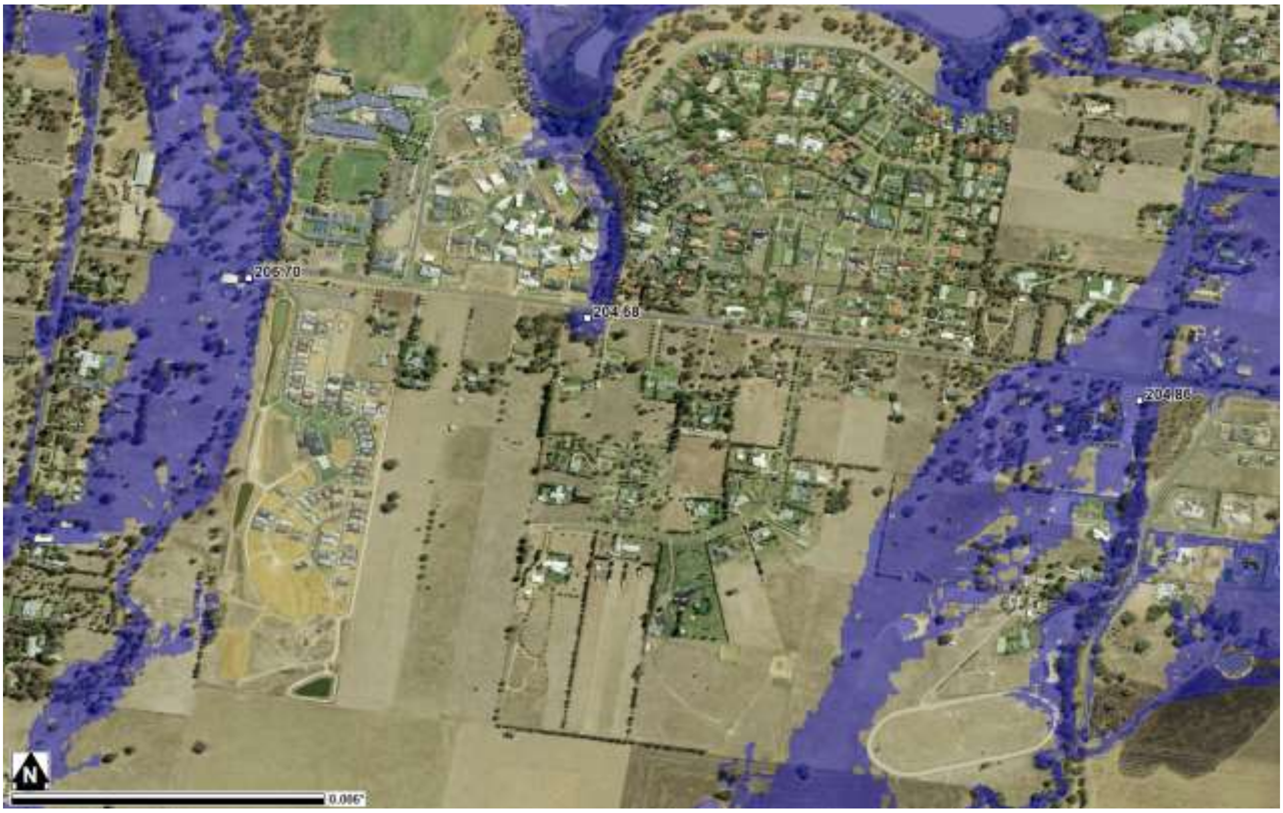


Figure 2-b: Maximum flood levels and extent for 20 yr events

Figure 2-a: Maximum flood levels and extent for 5 yr events

Figure 2: Maximum flood levels and extents for 100 yr, 20 yr and 5 yr events (Draft Wagga Wagga Major Overland Flow Floodplain Risk Management Study and Plan, WMAwater 2020) – Flood levels are based on AHD.

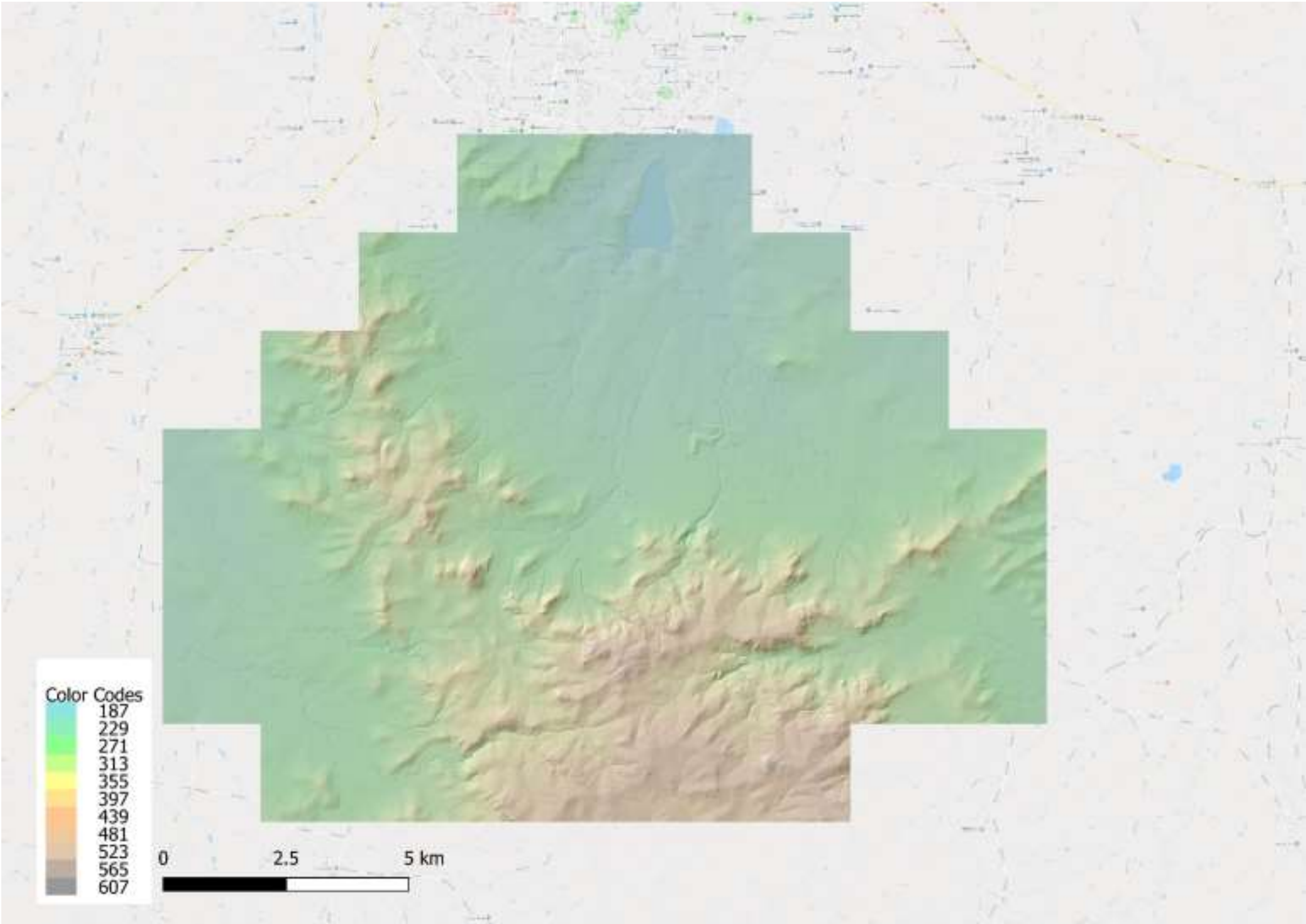


Figure 3: Prepared DEM for the study area

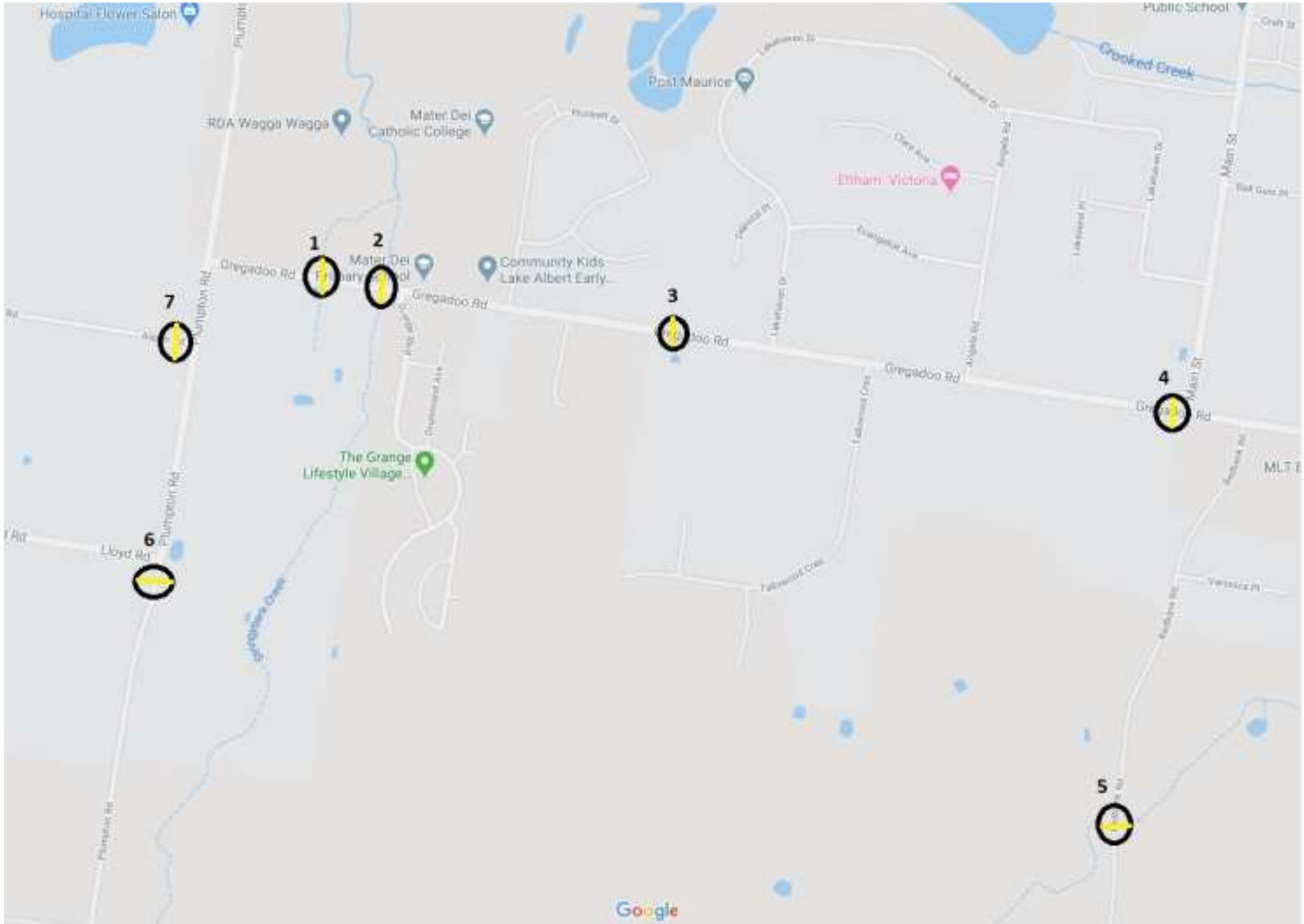


Figure 4: Culverts along the roads

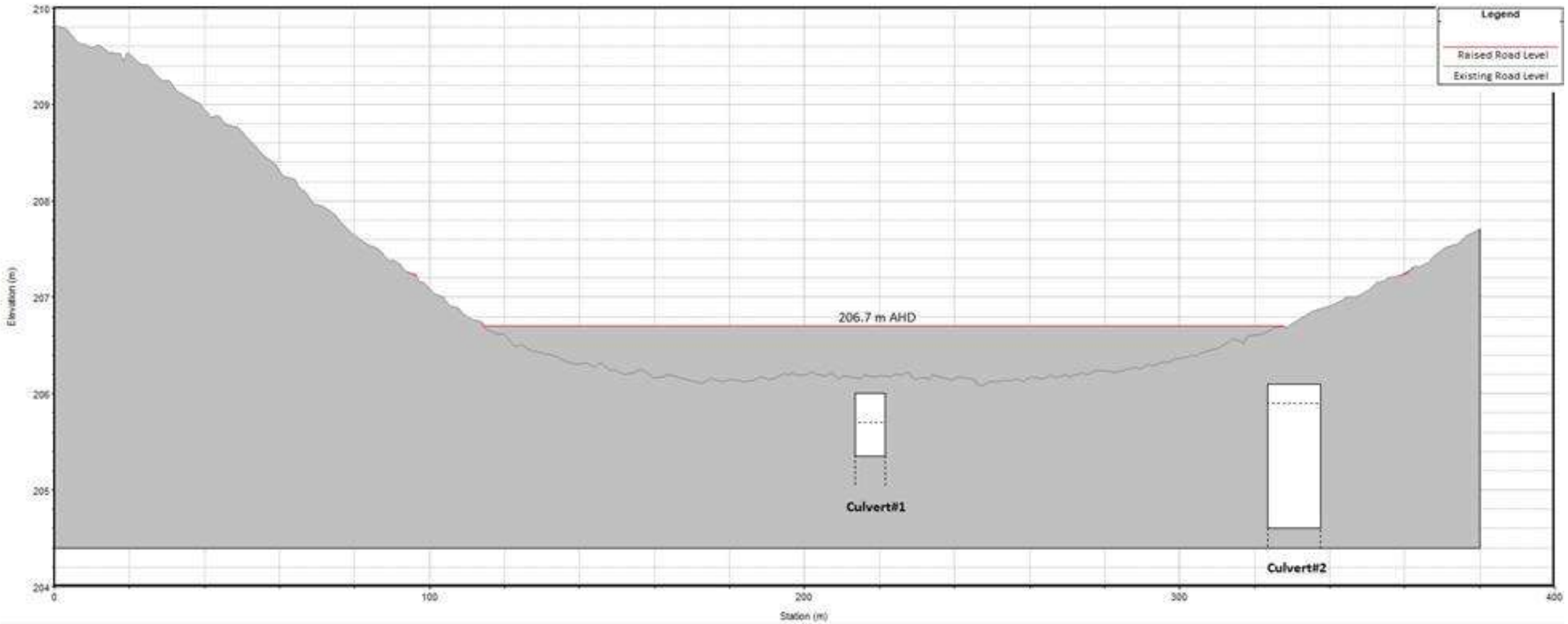


Figure 5: Long section along the Gregadoo road from Plumton Rd to station 380 m.

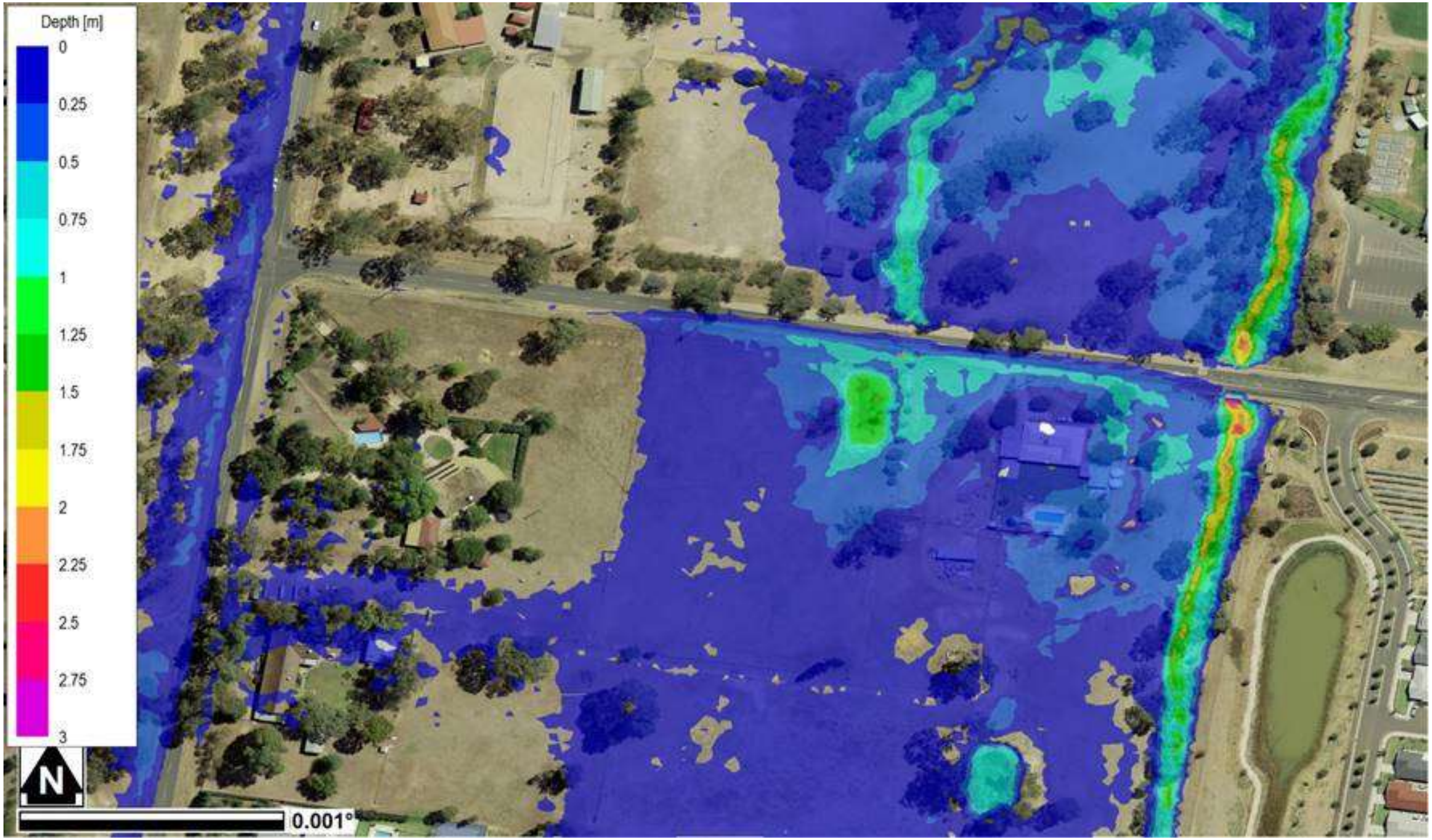


Figure 6: Maximum flood depths for 5% AEP event after upgrading the culverts 1, 2 and road level

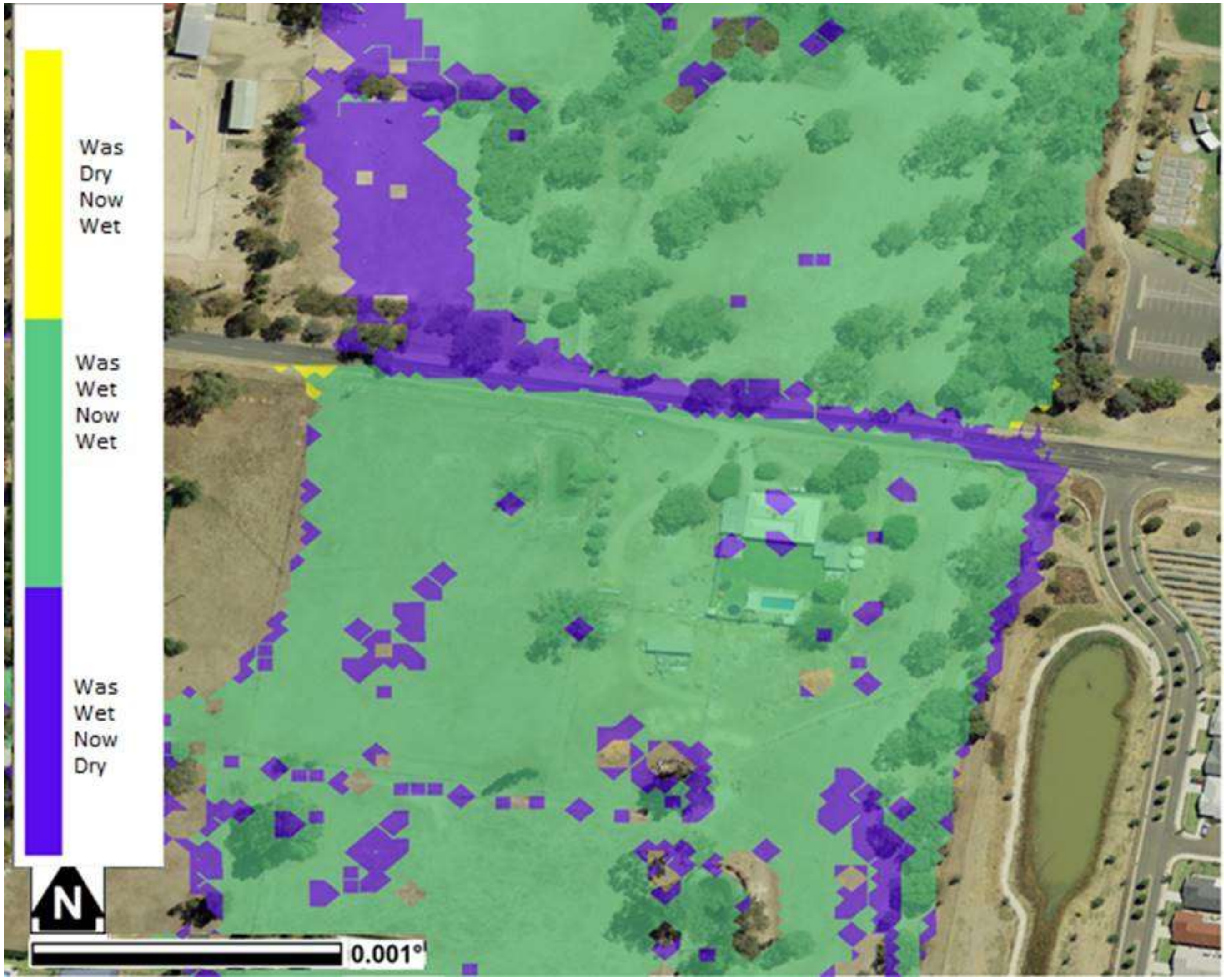


Figure 7: Wet and dry area for 5% AEP flood event between pre and post upgrading the road and the culverts 1, 2

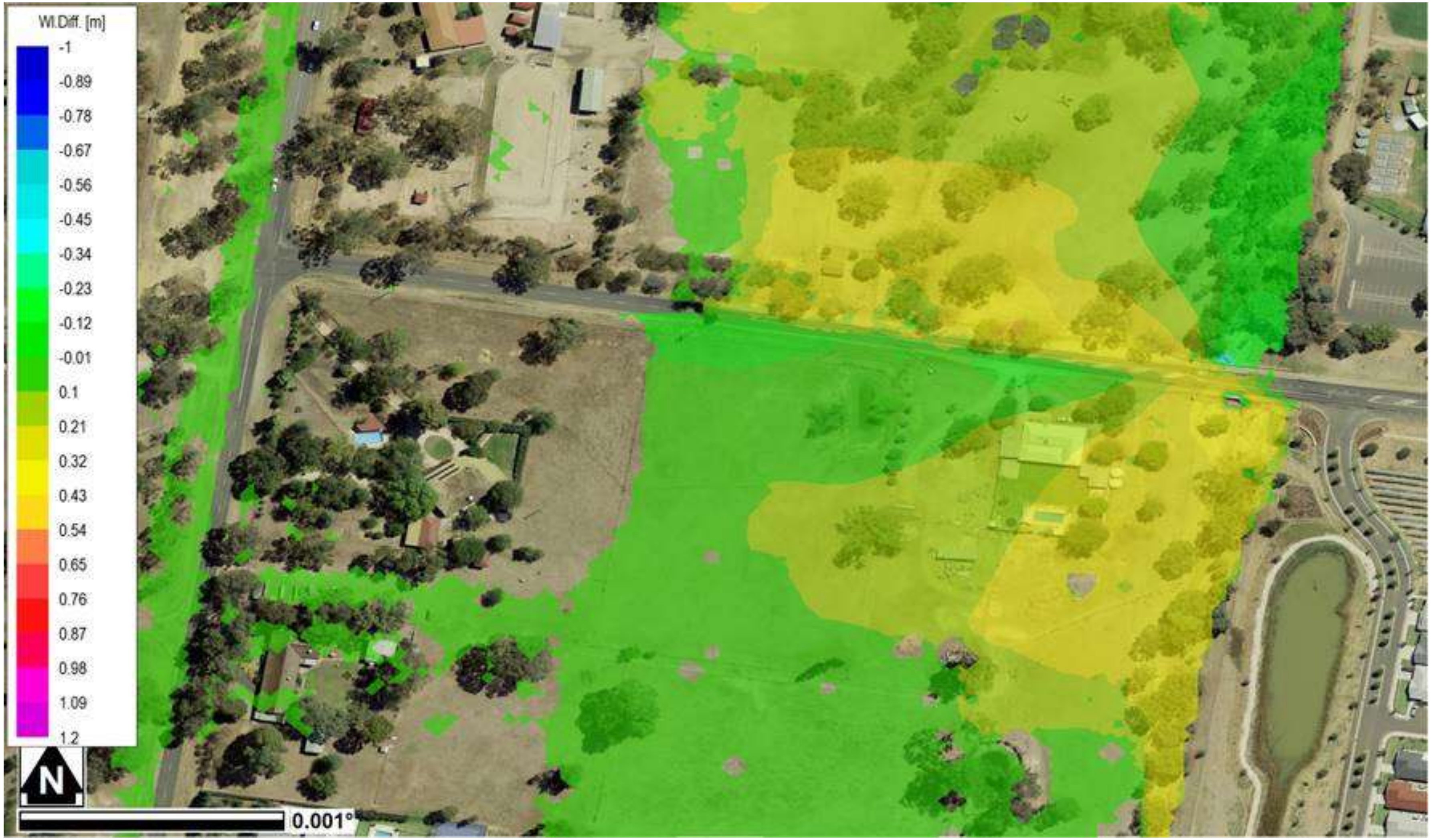


Figure 8: Flood levels differences for 5% AEP flood event between pre and post upgrading the road and the culverts 1, 2.

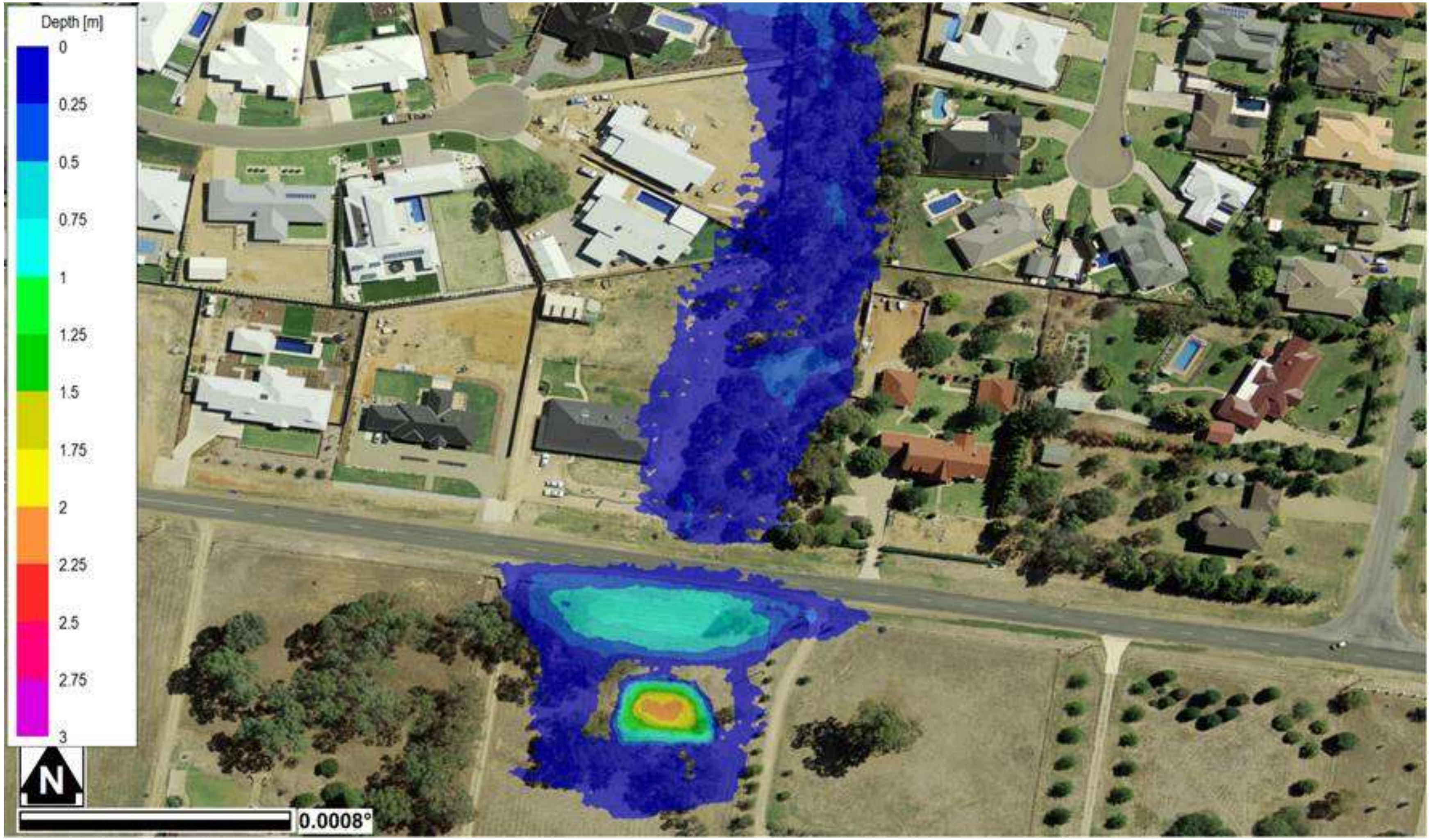


Figure 9: Maximum flood depths for 5% AEP event after upgrading culvert 3

Figure 10: Wet and dry area for 5% AEP flood event between pre and post upgrading of culvert 3

Figure 11: Flood levels differences for 5% AEP flood event between pre and post upgrading culvert 3

Appendix A: Processing the raw data for modelling

A.1 Creating the DEM layer

As it was described in the section 4, two DEMs have been created for the flood study. A high resolution 1 m DEM covering the Gregadoo road area and a broad scale 5 m DEM covering the whole upstream catchment area. The low resolution and high resolution DEMs are used for hydrology and hydraulic modeling, respectively.

A.2 Burning stream network into DEM

Stream burning is a common flow enforcement technique used to correct surface drainage patterns derived from digital elevation models (DEM). The technique involves adjusting the elevations of grid cells that are coincident with the features of a vector stream network hydrography layer. It also helps to justify the effect of culverts and bridges on the created DEM.

The stream network layer is extracted from the Open Street Map (OSM) website. OSM is a collaborative project to create a free editable map of the world. The stream network layer is clipped to the DEM extended and the culverts are also included to the layer by adding the extra lines. Burning procedure is done by QGIS software.

A.3 Filling the sinks on the DEM layer

For catchment delineation procedure, sinks on the DEM layer need to be filled artificially. During the overland streams creating, software (QGIS) compares each cell elevation with the surrounding cells and finds the streams direction. If there was a sink point which cell elevation was lower than surrounding cells, software cannot proceed further and crashed. Filling the sinks, helps software to find the overland streams correctly which is described in the next part. With comparing the artificially filled sinks DEM and the real one it can be found that the most differences between two DEM layers are related to the water bodies like lake and pools.

A.4 Preparing the flow direction layer

Based on the filled DEM layer, a flow direction map has been prepared. It is a raster layer which every grid contains a code. Each code shows the flow direction as below:

0 — to the North
1 — to the North East
2 — to the East
3 — to the South East
4 — to the South
5 — to the South West
6 — to the West
7 — to the North West

A.5 Creating the Strahler order map

'Stream order' is used to describe the hierarchy of streams from the top to the bottom of a catchment. The Strahler system is based on the confluence (joining) of streams of the same order, as shown in Figure A1.

Numbering begins at the top of a catchment with headwater flow paths being assigned the number 1. Where two flow paths of order 1 join, the section downstream of the junction is referred to as a second order stream. Where two second order streams join, the waterway downstream of the junction is referred to as a third order stream, and so on. Where a lower order stream (e.g. first order) joins a higher order stream (e.g. third order), the area downstream of the junction will retain the higher number (i.e. it will remain a third order stream).

Based on the filled DEM a Strahler order map is prepared for the study area by using QGIS software as shown in figure A2. For better clarity only the Strahler order greater than 1 are shown on the map.

A.6 Creating the channel network map

For channel detection, Strahler order equal or greater than 5 considered as channel. Figure A3 shows the final channel network map. The map is based on the raster file but for next steps it is converted to the vector file.

A.7 Delineation catchment for the outlets

According to the prepared channel map (Figure A3) and culverts map (Figure 4) the outlet locations are specified. Catchment delineation can be done based on the outlet locations.

There are four culverts are along the Gregadoo Road between Plumpton Rd and Main St. So, the main outlets are fixed at the upstream of the culverts. Delineated catchments for culverts are as below:

- Culvert No 1.

Figure A4 shows the upstream catchment for culvert 1. The catchment area is about 8.3 ha. As shown in Figure 4, if the flood at the culvert 7 exceeds the culvert capacity, it will overtop the road and flow to the culvert 1 catchment. Therefore, the effect of culvert 7 should be considered for culvert 1 analysis.

- Culvert No 2.

The upstream catchment area of culvert 2 is shown in Figure A5. It is a big catchment area (about 1238 ha) and consists the Rowan area.

Culvert 6 is upstream of the culvert 2, which is located along the Plumpton Rd. If the flood at the culvert 6 exceeds the culvert capacity, it will overtop the roads (Plumpton Rd and Lloyd Rd). By overtopping along the Lloyd Rd, flood flows toward culvert 7. So, the effect of overtopping of the culvert 6 should be considered in hydraulic analysis.

- Culvert No 3.

Figure A6 shows the upstream catchment for culvert 3. The catchment area is about 33 ha.

- Culvert No 4.

The upstream catchment area of culvert 4 is shown in Figure A7. The catchment area is about 417 ha and consists Valleyfield.

Culvert 5 located along the Redbank Rd conveys flood flow from east to west. If the flood exceeds the culvert capacity, the back water flows toward the culvert 4. Therefore, the effect of the backwater from culvert 5 should be considered in hydraulic analysis.

Appendix A Figures

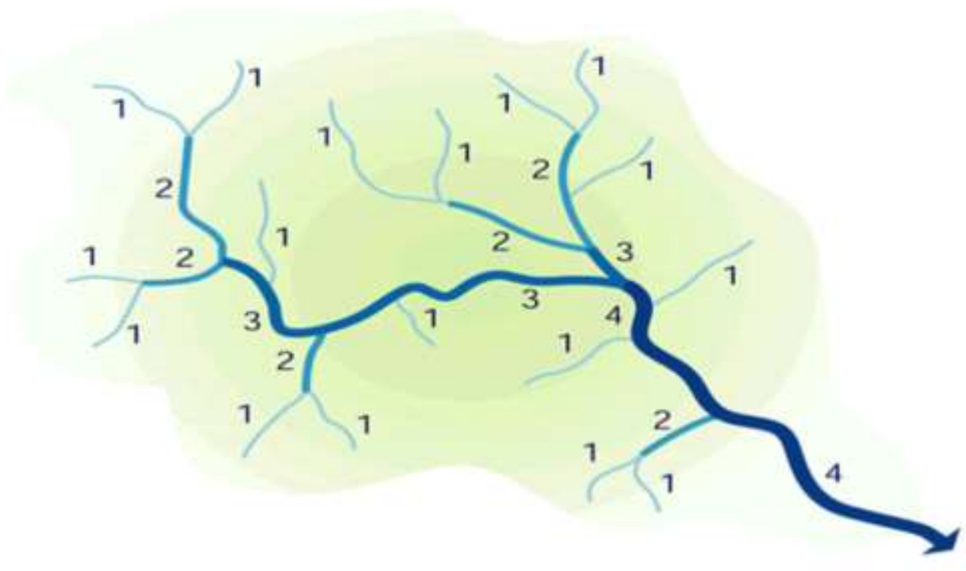


Figure A1: Schematic diagram of the Strahler system

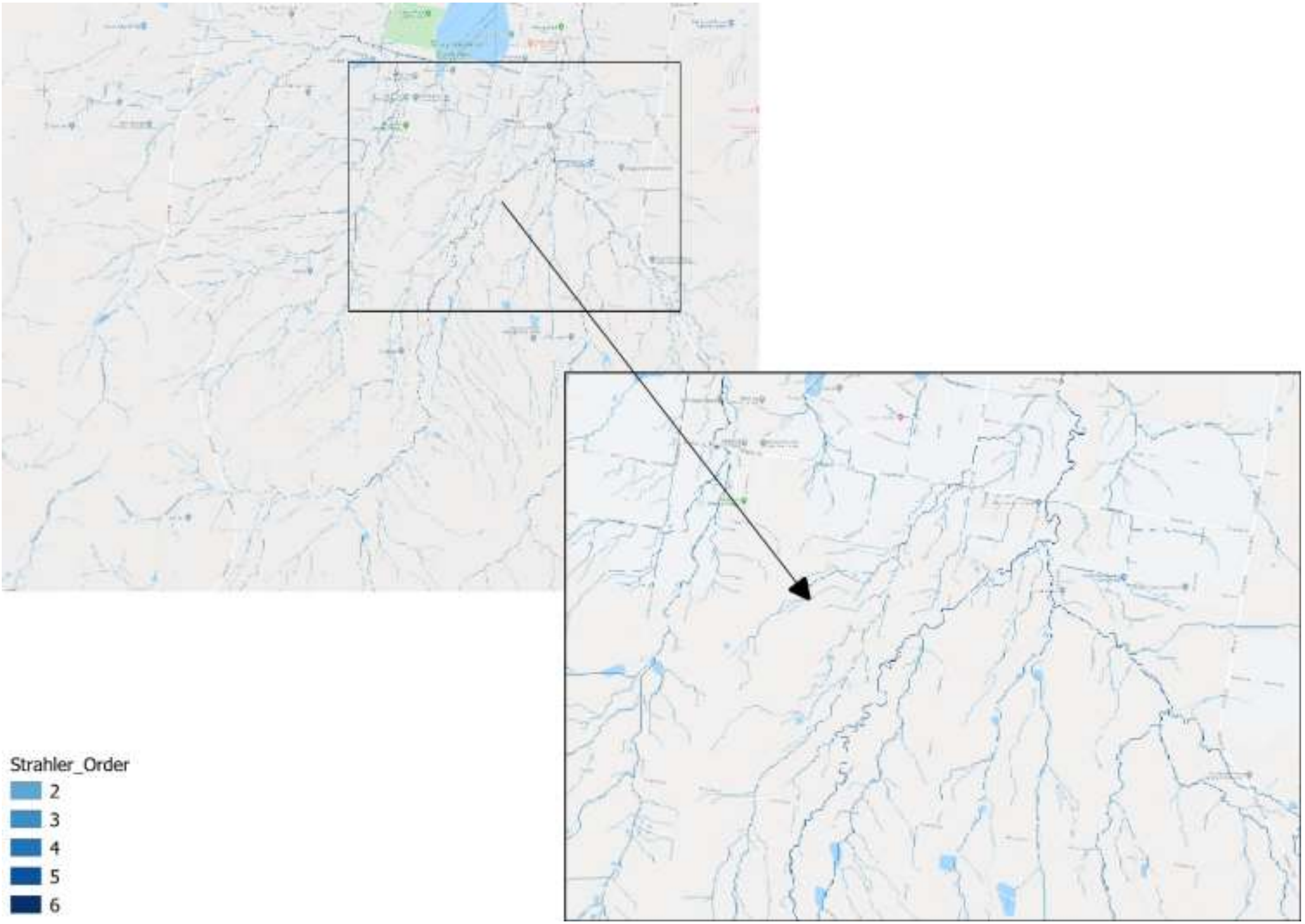


Figure A2: Strahler order map for the study area (greater than 1)

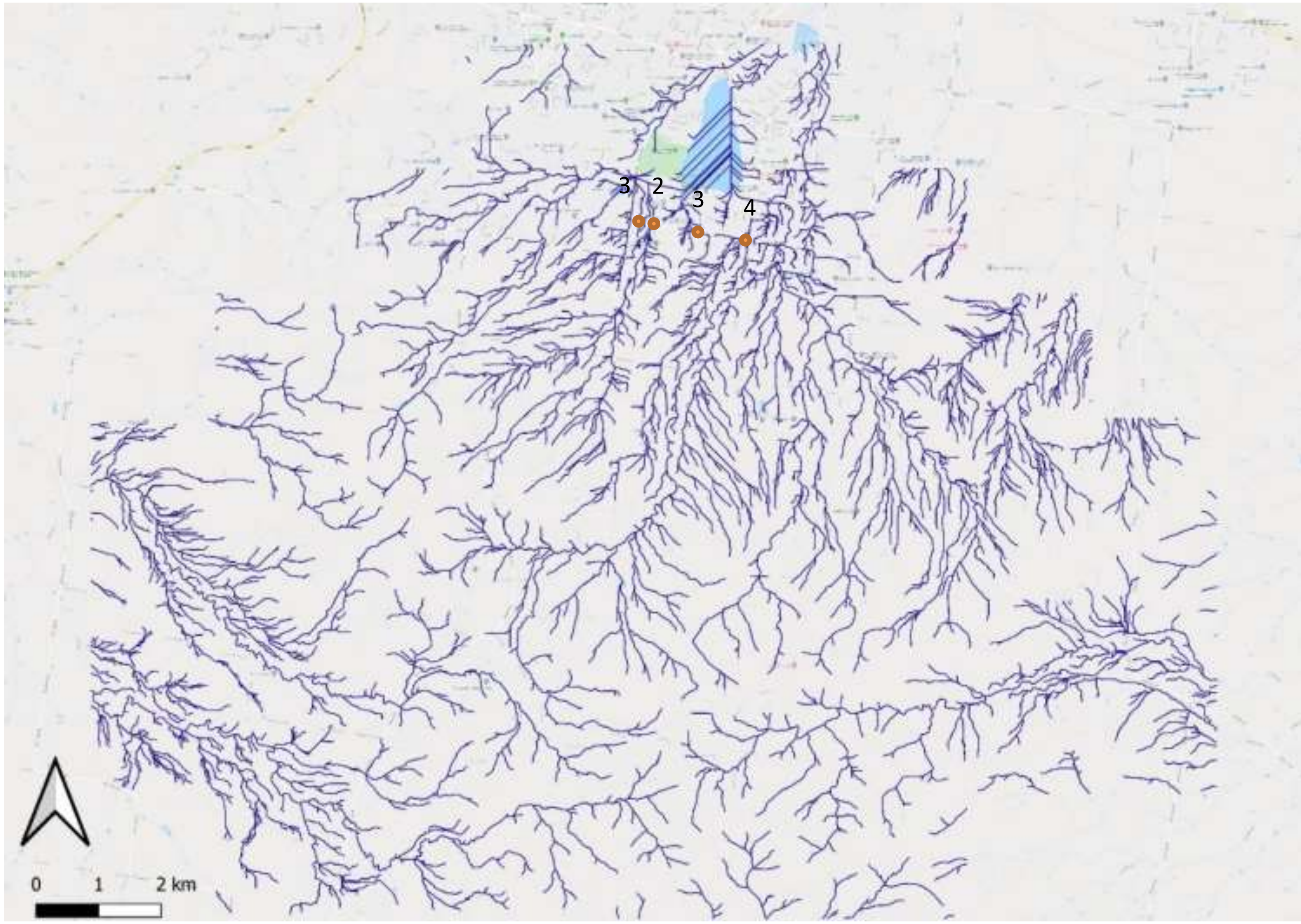


Figure A3: Generated channel map for the study area (Culverts location are shown with orange circles)

Figure A4: Culvert 1 catchment

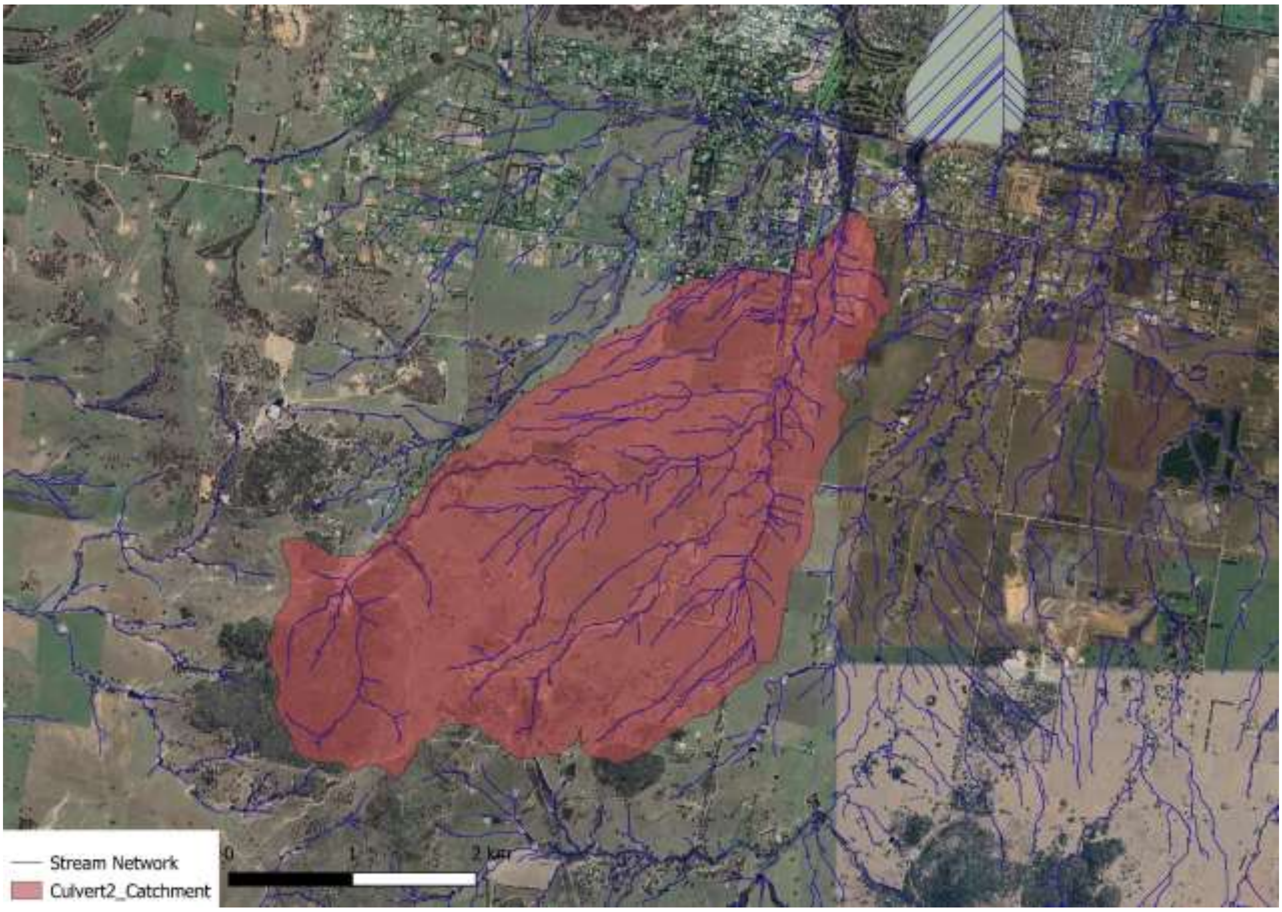


Figure A5: Culvert 2 catchment

Figure A6: Culvert 3 catchment

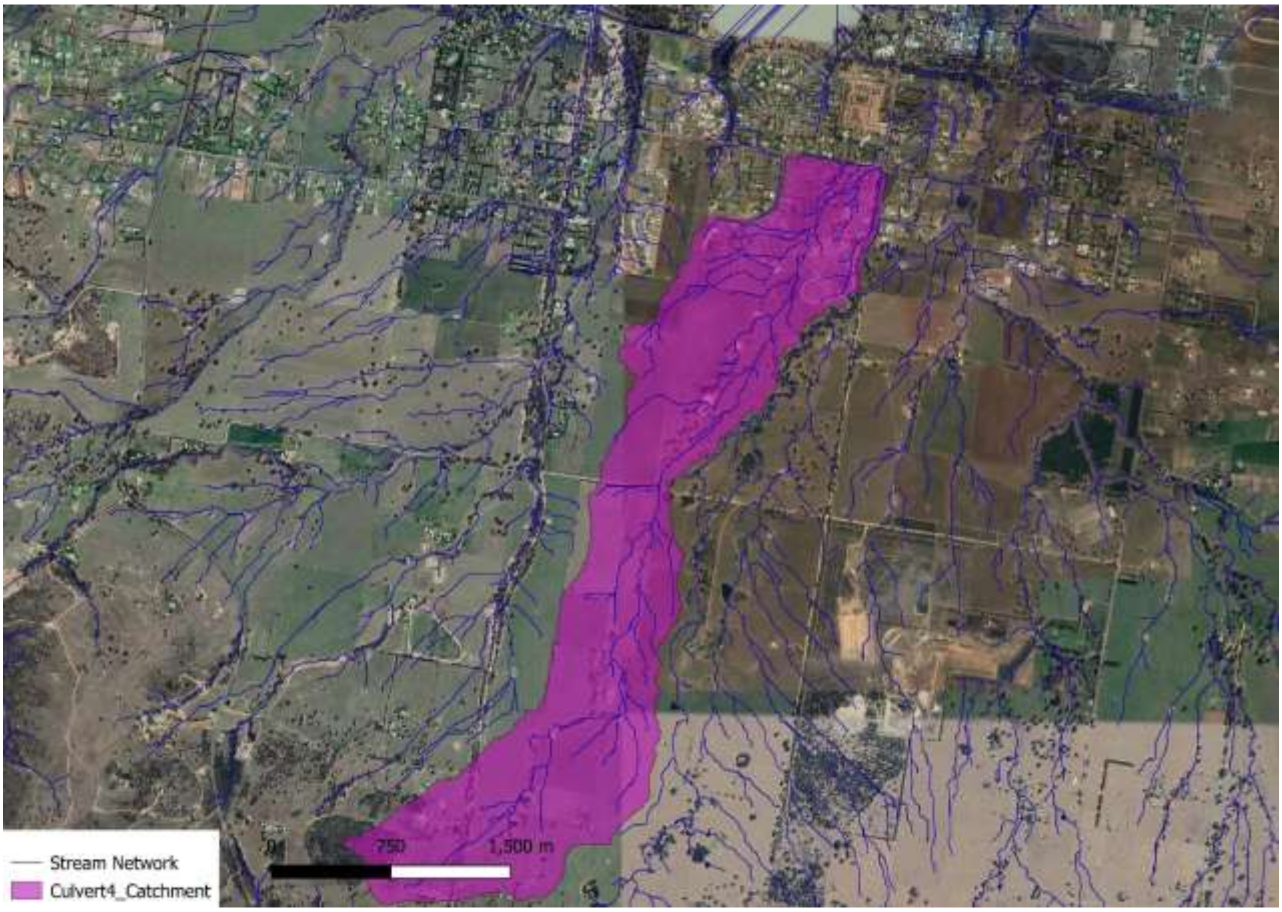


Figure 13: Culvert 4 catchment

Appendix B: Hydrology and Hydraulic Modelling

In this section, hydrology and hydraulic analyzing for the culverts are investigated. Figure B1 shows all upstream catchments of the culverts.

During the flood events and when the culverts capacities are not enough to convey all flood, roads are overtopping, and backwater is flowing from on catchment to the other one. It obviously occurs for culverts 4 which can be affected by backwater from culvert 5. Th same issue occurs for culvert2 which is affected by culverts 6 and 7.

Because of the above reasons, a hydrology and 1D hydraulic modelling is not suitable for this study and the results are not considering the all effective parameters. So, a separate hydrology analysis is done for each sub catchments and the extracted hydrographs are imported to a 2D hydraulic model to consider the overland flows, backwater, overtopped flows.

B.1 Rainfall data

Point design rainfall depths were downloaded from the Bureau of Meteorology's IFD webpage as Table B1. Temporal patterns for different rainfall durations are also downloaded from ARR data hub website. All rainfall data imported to DRAINS for further hydrology modelling.

Table B1: Design rainfall depths from the Bureau of Meteorology's IFD

Copyright Commonwealth of Australia 2016 Bureau of Meteorology (ABN 92 637 533 532)																			
All Design Rainfall Depth (mm)																			
Issued:	3-Apr-20																		
Location Label:																			
Requeste	Latitude	-35.203	Longitude	147.365															
Nearest g	Latitude	35.2125 (S	Longitude	147.3625 (E)															
		Exceedan	Annual Exceedance Probability (AEP)																
Duration	Duration i	12EY	6EY	4EY	3EY	2EY	63.20%	50%	0.5EY	20%	0.2EY	10%	5%	2%	1%	1 in 200	1 in 500	1 in 1000	1 in 2000
1 min	1	0.61	0.717	0.915	1.06	1.29	1.72	1.96	2.18	2.74	2.8	3.29	3.84	4.59	5.17	5.79	6.59	7.23	7.88
2 min	2	1.08	1.27	1.61	1.87	2.25	2.94	3.35	3.72	4.66	4.76	5.58	6.49	7.72	8.69	9.71	11	12	13.1
3 min	3	1.45	1.71	2.18	2.53	3.05	4	4.56	5.06	6.35	6.48	7.59	8.84	10.5	11.9	13.2	15	16.5	17.9
4 min	4	1.77	2.09	2.67	3.1	3.74	4.92	5.61	6.22	7.82	7.97	9.36	10.9	13	14.6	16.4	18.6	20.4	22.2
5 min	5	2.04	2.41	3.09	3.59	4.33	5.72	6.52	7.24	9.1	9.29	10.9	12.7	15.2	17.1	19.1	21.8	23.8	26
10 min	10	3.07	3.62	4.62	5.38	6.51	8.65	9.88	11	13.8	14.1	16.6	19.4	23.2	26.1	29.3	33.4	36.6	39.9
15 min	15	3.8	4.46	5.67	6.59	7.97	10.6	12.1	13.4	17	17.3	20.4	23.8	28.5	32.1	36	41	44.9	49
20 min	20	4.38	5.12	6.48	7.52	9.08	12	13.8	15.3	19.3	19.7	23.2	27.1	32.3	36.5	40.9	46.5	51	55.7
25 min	25	4.86	5.66	7.15	8.27	9.97	13.2	15.1	16.7	21.1	21.6	25.4	29.6	35.4	39.9	44.7	50.9	55.8	60.8
30 min	30	5.27	6.13	7.71	8.91	10.7	14.2	16.2	18	22.6	23.1	27.2	31.7	37.9	42.7	47.8	54.4	59.6	65
45 min	45	6.25	7.24	9.04	10.4	12.5	16.4	18.7	20.7	26.1	26.6	31.2	36.4	43.4	48.9	54.7	62.3	68.2	74.4
1 hour	60	7.01	8.09	10.1	11.5	13.8	18	20.5	22.7	28.5	29.1	34.1	39.7	47.3	53.3	59.6	67.8	74.3	81
1.5 hour	90	8.16	9.38	11.6	13.3	15.7	20.3	23.1	25.7	32.1	32.7	38.3	44.5	52.9	59.5	66.6	75.8	83	90.5
2 hour	120	9.03	10.4	12.8	14.6	17.2	22.1	25.1	27.9	34.7	35.4	41.4	48	57	64.1	71.7	81.6	89.4	97.5
3 hour	180	10.4	11.9	14.6	16.6	19.5	24.8	28.1	31.2	38.6	39.4	45.9	53.2	63.1	70.8	79.3	90.3	98.9	108
4.5 hour	270	11.8	13.5	16.6	18.8	22	27.9	31.5	34.9	43	43.8	51	58.9	69.7	78.1	87.6	99.8	109	120
6 hour	360	12.9	14.8	18.1	20.5	24	30.2	34.1	37.8	46.3	47.3	54.9	63.3	74.8	83.8	94.1	107	118	129
9 hour	540	14.5	16.7	20.4	23.1	27	33.9	38.1	42.3	51.6	52.6	60.9	70.2	82.8	92.7	104	119	130	142
12 hour	720	15.8	18.1	22.2	25.2	29.4	36.8	41.3	45.8	55.6	56.8	65.6	75.5	89.1	99.6	112	128	140	153
18 hour	1080	17.6	20.2	24.9	28.2	32.9	41.2	46.2	51.2	61.9	63.1	72.8	83.7	98.6	110	124	141	154	169
24 hour	1440	19	21.8	26.8	30.4	35.5	44.6	49.8	55.3	66.7	68	78.3	90	106	118	133	151	165	180
30 hour	1800	20	23.1	28.3	32.2	37.6	47.2	52.8	58.6	70.5	71.9	82.8	95	112	125	138	156	170	185
36 hour	2160	20.9	24.1	29.6	33.6	39.3	49.5	55.2	61.3	73.7	75.2	86.5	99.2	117	130	143	161	176	191
48 hour	2880	22.3	25.6	31.6	35.9	42	53	59.1	65.6	78.8	80.4	92.3	106	124	139	152	171	187	202
72 hour	4320	24	27.7	34.2	38.9	45.7	57.8	64.5	71.6	85.8	87.6	100	115	135	150	166	187	203	220
96 hour	5760	25	29	36	41	48.2	61	68.1	75.6	90.6	92.4	106	121	142	157	174	197	214	232
120 hour	7200	25.6	29.8	37.2	42.5	50.1	63.3	70.8	78.6	94.1	95.9	110	125	146	162	180	203	220	239
144 hour	8640	25.9	30.4	38.1	43.7	51.5	65.1	72.8	80.8	96.7	98.6	113	129	150	166	183	206	224	243
168 hour	10080	26.1	30.8	38.9	44.6	52.7	66.6	74.4	82.6	98.8	101	115	131	152	168	184	206	225	243

B.2 Catchment analyzing

The RAFTS method based on the ARR 2019 guideline is utilized for hydrology modelling. It is carried out by DRAINS software package. A benefit of using RAFTS method is that it can be integrated well with other hydrological models in DRAINS (IL-CL, Horton ILSAX, ERM) within the same model resulting in the ability of modelling integrated rural and urban models.

For using RAFTS method, some hydrological data is prepared for catchments as below table:

Table B2: Catchment hydrology parameter

Catchment ID	Area (ha)	Impervious Area (%)	Slope (%)	Manning's n
1	8.3	10	0.76	0.02
2	1238.6	2	1.86	0.02
3	33.2	2	2.17	0.02
4	417.15	1	0.94	0.02
5	1808.8	1	1.53	0.02
6	110.2	1	1.19	0.02
7	27.25	10	1.02	0.02

Based on the ARR 2019 recommendation, 1 mm initial loss and 0 mm/hr continuing loss are considered for impervious area. For pervious areas 10 mm initial loss and 1.88 mm/hr continuing loss imported to the model. Below are results of separate hydrology analysis for each culvert.

B.3 Hydrology and hydraulic analyzing

- Culvert No 1.

For the upstream catchment of culvert 1 without any other catchments interfering, the critical output hydrographs for 1%, 5% and 20% AEPs are shown in figure B2.

With checking the topography at upstream and downstream of the culvert 1, it can be assumed that the culvert hydraulic situation is inlet control. In the inlet control, the flow through the culvert mainly depends upon the inlet conditions, e.g., area, shape and configuration at the inlet. The flow in the culvert is supercritical and thus it is independent of the conditions in the culvert or in the tailwater area. The rate of discharge through a box culvert may be computed from the following equations [Henderson, 1966].

Unsubmerged entrance (H < 1.2D)

$$Q = \frac{2}{3} C B H \sqrt{\frac{2}{3} g H}$$

in which D is the height of the culvert at the entrance, H = the upstream water level − the culvert invert level, B = culvert width and the coefficient C accounts for the contraction on the sides. For square-edged sides, C = 0.9; and for slightly rounded sides, C = 1.

Submerged entrance (H > 1.2D)

In this case, the discharge may be computed from the orifice equation.

$$Q = CBD\sqrt{2g(H - CD)}$$

in which C accounts for the contractions at the sides and the top. For a square-edge entrance, C = 0.6; for rounded edges, C = 0.8.

The low point of the road close to the culvert location is about 206.1 m. The culvert invert level is 205.35 m and the height of the box culvert is 0.6 m.

H=(206.1-205.35=0.75 m), D=0.6 and H>1.2D, so it is a submerged entrance. By using the above equation, the maximum discharge through the culvert is about 1.66 m3/s with considering C=0.8.

Furthermore, a separate analysis is done by HY-8 software to calculate the culvert hydraulic parameters in different incoming discharges. The results are as below table:

Table B3: HY-8 Analysis results for Culvert1

Total Discharge (cms)	Culvert Discharge (cms)	Roadway Discharge (cms)	Headwater Elevation (m)	Inlet Control Depth(m)	Outlet Control Depth(m)	Flow Type	Normal Depth (m)	Critical Depth (m)	Outlet Depth (m)	Tailwater Depth (m)	Outlet Velocity (m/s)	Tailwater Velocity (m/s)
0.99	0.99	0.00	205.94	0.59	0.11	1-S2n	0.18	0.35	0.21	0.44	3.19	0.41
1.09	1.09	0.00	205.99	0.64	0.16	5-S2n	0.19	0.38	0.22	0.46	3.27	0.42
1.20	1.20	0.00	206.03	0.68	0.21	5-S2n	0.20	0.40	0.24	0.48	3.34	0.43
1.31	1.31	0.00	206.08	0.73	0.27	5-S2n	0.21	0.43	0.26	0.50	3.41	0.44
1.44	1.43	0.00	206.14	0.79	0.41	5-S2n	0.22	0.45	0.27	0.53	3.48	0.45
1.52	1.49	0.02	206.17	0.82	0.43	5-S2n	0.23	0.47	0.28	0.54	3.52	0.46
1.63	1.53	0.10	206.19	0.84	0.45	5-S2n	0.23	0.47	0.29	0.56	3.53	0.47
1.74	1.54	0.19	206.20	0.85	0.46	5-S2n	0.24	0.48	0.29	0.58	3.54	0.47
1.85	1.56	0.28	206.20	0.85	0.46	5-S2n	0.24	0.48	0.29	0.59	3.55	0.48
1.95	1.57	0.38	206.21	0.86	0.47	5-S2n	0.24	0.48	0.29	0.61	3.55	0.49
2.06	1.58	0.48	206.21	0.86	0.47	5-S2n	0.24	0.48	0.30	0.62	3.56	0.49

The results show that the culvert 1 capacity is almost enough to convey its upstream catchment flood. A small amount of overtopping flow occurs for discharges higher than 1.44 cms. However, it should be noted that in real flood events, backwater from the culvert 2 is diverted to the culvert 1 and its effect should also be considered. The 1D models are not able to model this back water effects, so a 2D hydraulic model is needed to be utilized. The next part is considering this scenario.

- Culvert No 2.

To find the critical rainfall durations and median temporal patterns for culvert 2, catchments 1 and 2 are merged together and run through different rainfall duration (from 5 min to 166 hr) and 10 temporal patterns. Figure B3 shows the peak outflow of different rainfall durations and temporal patterns for 1% AEP event at the culvert 2 location.

With the same methodology, ctritical durations and median temporal patterns are extracted for 5% and 20% AEPs. The ctritical storm for different events are as below:

- 1% AEP: 1.5 hr burst, storm 1 – 97.4 m^3/s
- 5% AEP: 1.5 hr burst, storm 6 – 65.5 m^3/s
- 20% AEP: 2 hr burst, storm 6 – 41.2 m^3/s
- 1 Exceedances per Year (EY): 2 hr, storm 8 – 20.4 m^3/s
- 2 EY: 2 hr, storm 7 – 13.4 m^3/s

These rainfall hytographs are applied to the upstream subcatchments of culverts 1, 2, 6 and 7 which are participating in total flow discharching at upstream of culvert 2. Because of overtopping of flood along the roads and flow interfiering between the catchments, the 1D models can not be used. So, hydrograghs are imported to 2D hydraulic model to find the flood extent, levels, depths, velocities and hazard. HEC-RAS 5 is used for 2D hydraulic modeling with 5 m mesh grid size. Figures B4, B5, B6 and B7 show the maximum flood depth, level, velocity and hazard for 1 % AEP flood event. Figures B8, B9, B10 and B11 shows the maximum flood depth, level, velocity and hazard for 5 % AEP flood event. Figures B12, B13, B14 and B15 shows the maximum flood depth, level, velocity and hazard for 20 % AEP flood event.

As can be seen, the output results are well matched with the Draft Wagga Wagga Major Overland Flow Floodplain Risk Management Study and Plan, WMAwater 2020 results. However, in some areas the flood levels from this study are around 15 cm higher than the Draft MOFFS 2020 results. It may be because of different methods for finding the critical storms event. The other thing can cause differences between the results, is using filtration (showing the depths >= certain amount) for MOFFS study.

Flood hazard is defined as the threat that a particular type of flooding will pose to human activity. It is initially calculated based on the flood's depth and velocity in each model grid cell, as part of the flood study stage. It is finalized during the floodplain risk management stage by considering other factors not covered by the depth-velocity calculation. The calculation is based on the Australian Emergency Management Handbook 7 guideline, which considers the threat to types of people (children, adult) and activity (pedestrian, vehicle and within a building). The calculation is presented in figure B16 chart.

The chart divides a particular flood event into six categories of hazard, specifically:
• H1 – Generally safe for people, vehicles and buildings (corresponding to very shallow and slow flow)
• H2 – Unsafe for small vehicles
• H3 – Unsafe for vehicles, children and the elderly
• H4 – Unsafe for people and vehicles
• H5 – Unsafe for vehicles and people. All buildings vulnerable to structural damage. Some less robust building types vulnerable to failure.
• H6 – Unsafe for vehicles and people. All building types considered vulnerable to failure (corresponding to very deep and fast flow)

As can be seen on the hazard maps, the hazard category along the road for 1% and 5% AEPs are H2, which is unsafe for small vehicles.

- Culvert No 3.

For the upstream catchment of culvert 3 without any other catchments interfering, the critical output hydrographs for 1%, 5% and 20% AEPs are shown in figure B17.

Since the culvert capacity in below the upstream catchment outflow, a road overtopping is inevitable. Same as previous culverts, 2D hydraulic model with 2.5 m mesh grid size is used for overtopping modelling.

Figures B18, B19, B20 and B21 shows the maximum flood depth, level, velocity and hazard for 1 % AEP flood event. Figures B22, B23, B24 and B25 shows the maximum flood depth, level, velocity and hazard for 5 % AEP flood event. Figures B26, B27, B28 and B29 shows the maximum flood depth, level, velocity and hazard for 20 % AEP flood event.

As can be seen, the maximum depth for 1% AEP flood event is about 15 cm and hazed category along the road is H1 which means generally safe for people, vehicles and buildings (corresponding to very shallow and slow flow)

- Culvert 4

With the same methodology of other culvers, ctritical storm are extracted for 1%, 5% and 20% AEPs for on the upstream catchment of culvert 4. The output hydrographs are shown in figure B30.

Culvert 5 backwater can flow through the culver 3 catchment. So, it should be considered in hydraulic analysis of culvert 4 by using 2D hydraulic modelling. Figures B31, B32, B33 and B34 shows the maximum flood depth, level, velocity and hazard for 1% AEP flood event. Figures B35, B36, B37 and B38 shows the maximum flood depth, level, velocity and hazard for 5% AEP flood event. Figures B39, B40, B41 and B42 shows the maximum flood depth, level, velocity and hazard for 20% AEP flood event.

Appendix B Figures

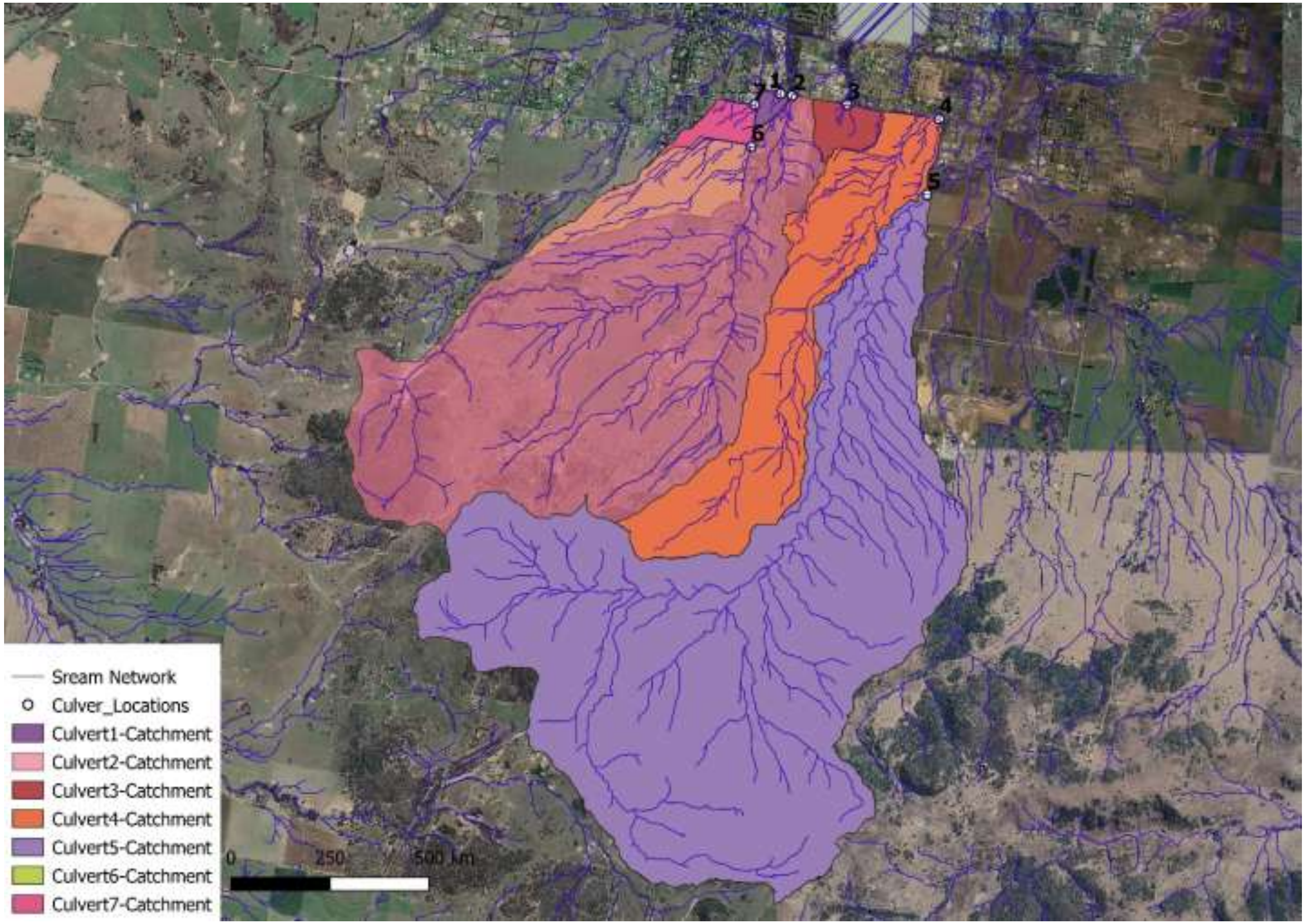
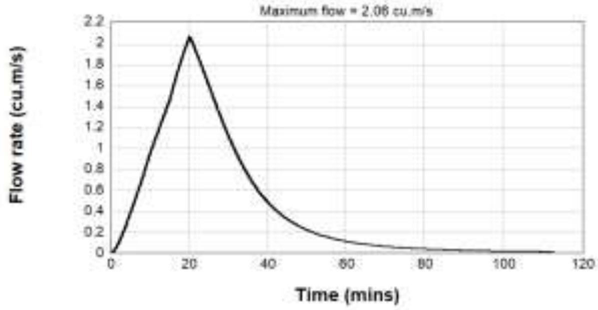
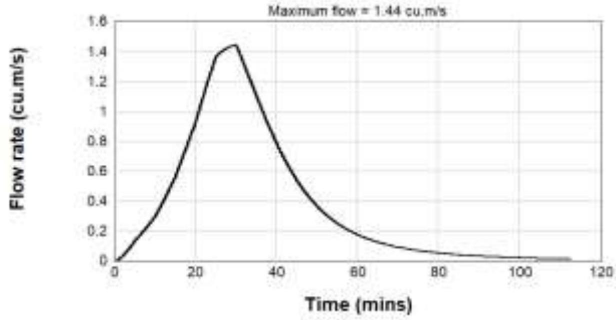


Figure B1: Catchments at upstream of the culverts

1% AEP (20 min, storm 2)



5% AEP (30 min, storm 7)



20% AEP (30 min, storm 6)

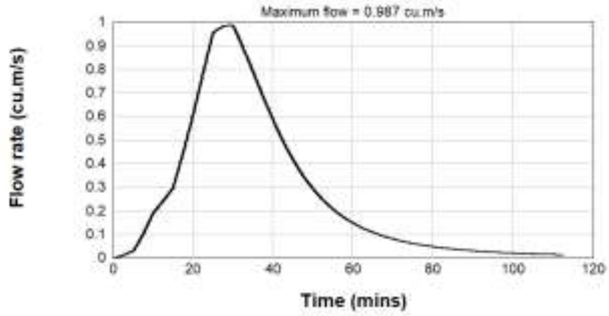


Figure B2: The 1%, 5% and 20% AEPs output hydrographs for catchment 1.

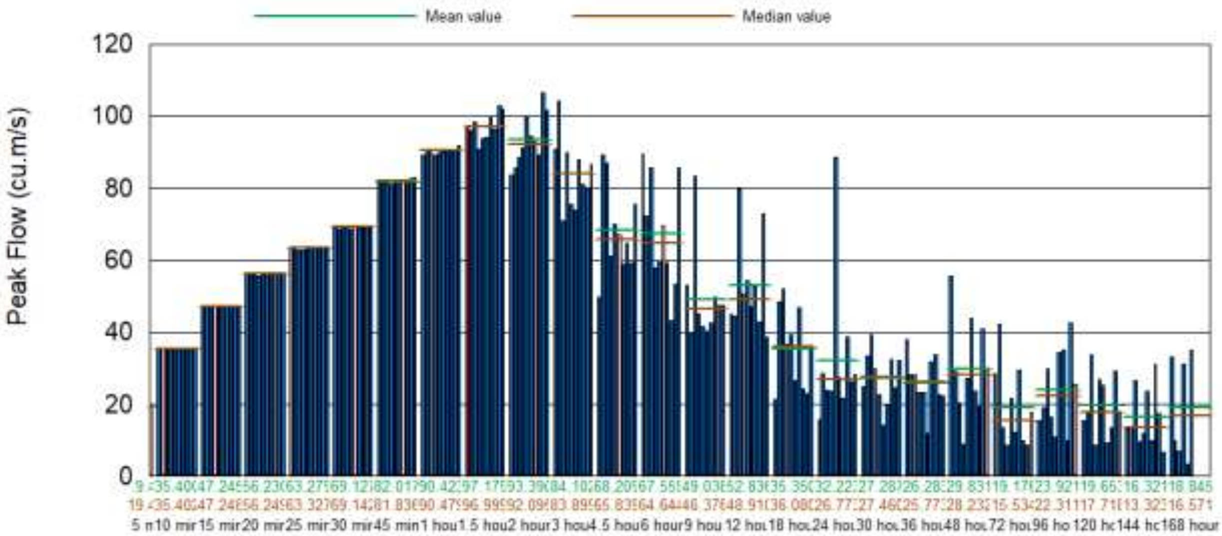


Figure B3: Peak outflow for different rainfall durations and temporal patterns of 1% AEP event at culvert 2 location.

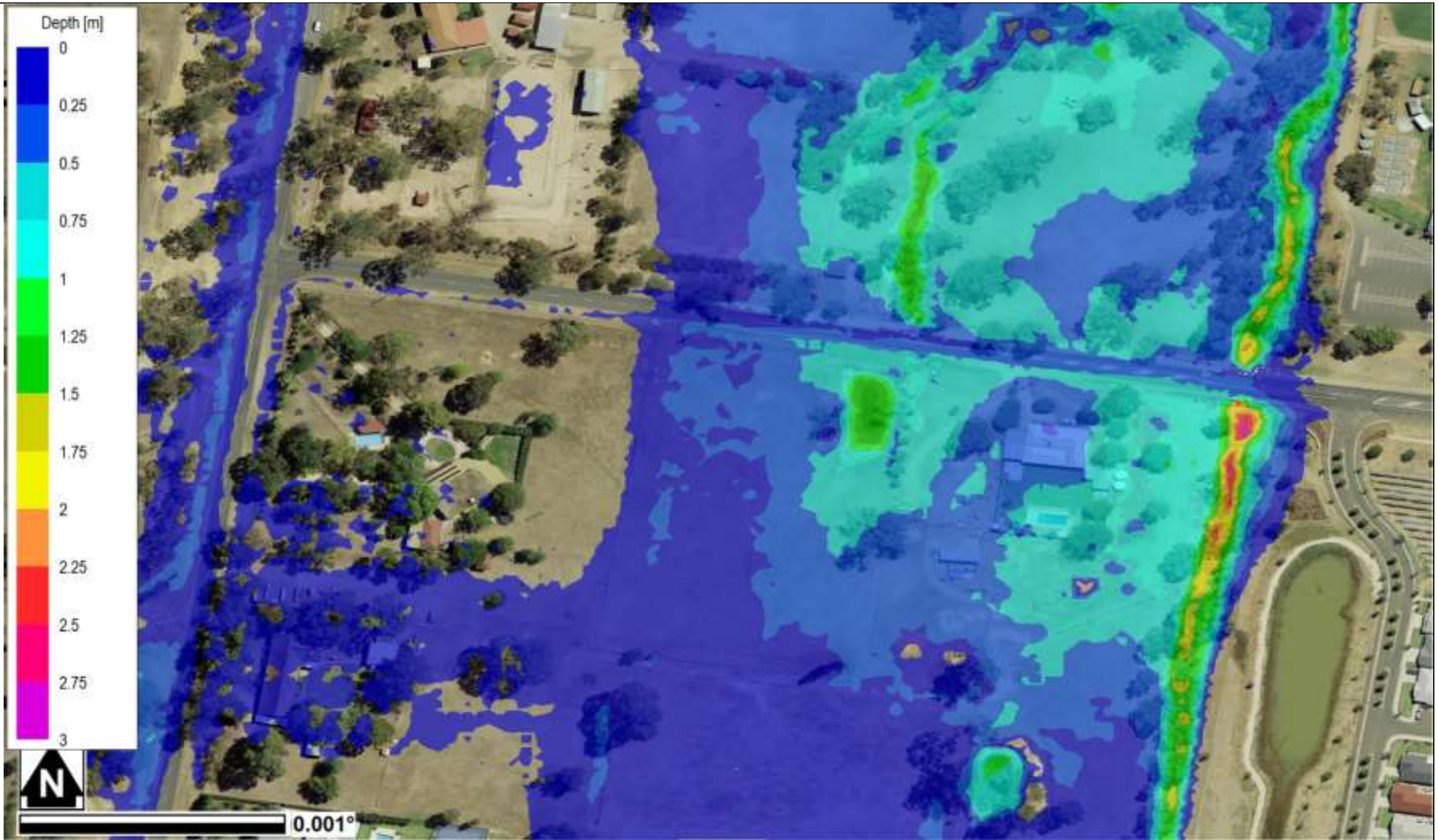


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Figure B4: Culvert 1-1% AEP-Depth
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Figure B5: Culvert 1-1% AEP-Level
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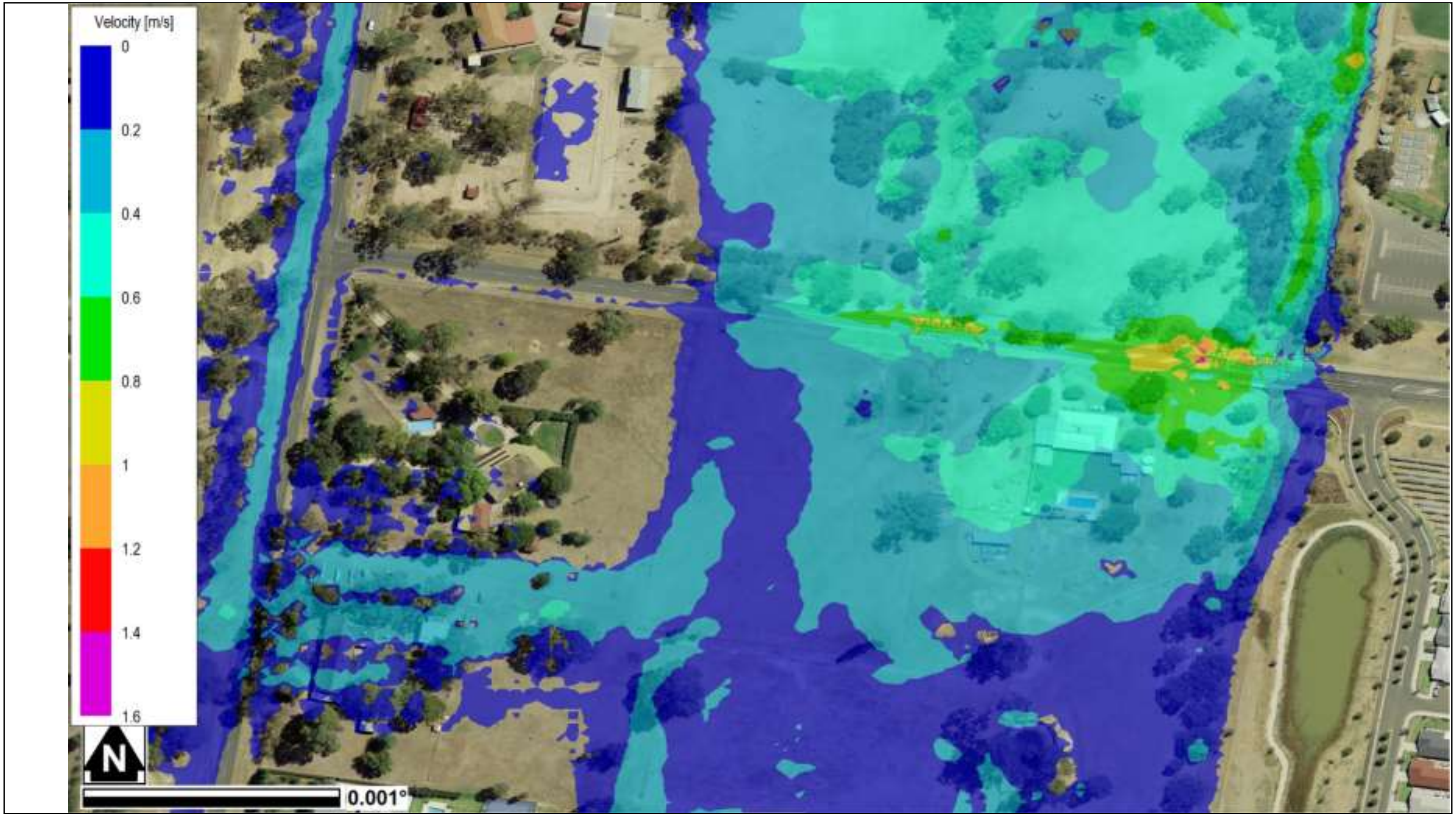

Wagga Wagga City Council	Figure B6: Culvert 1-1% AEP-Velocity All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 08:27 **Printed By:** Amir Abbasnia **Document Version:** 1.0A

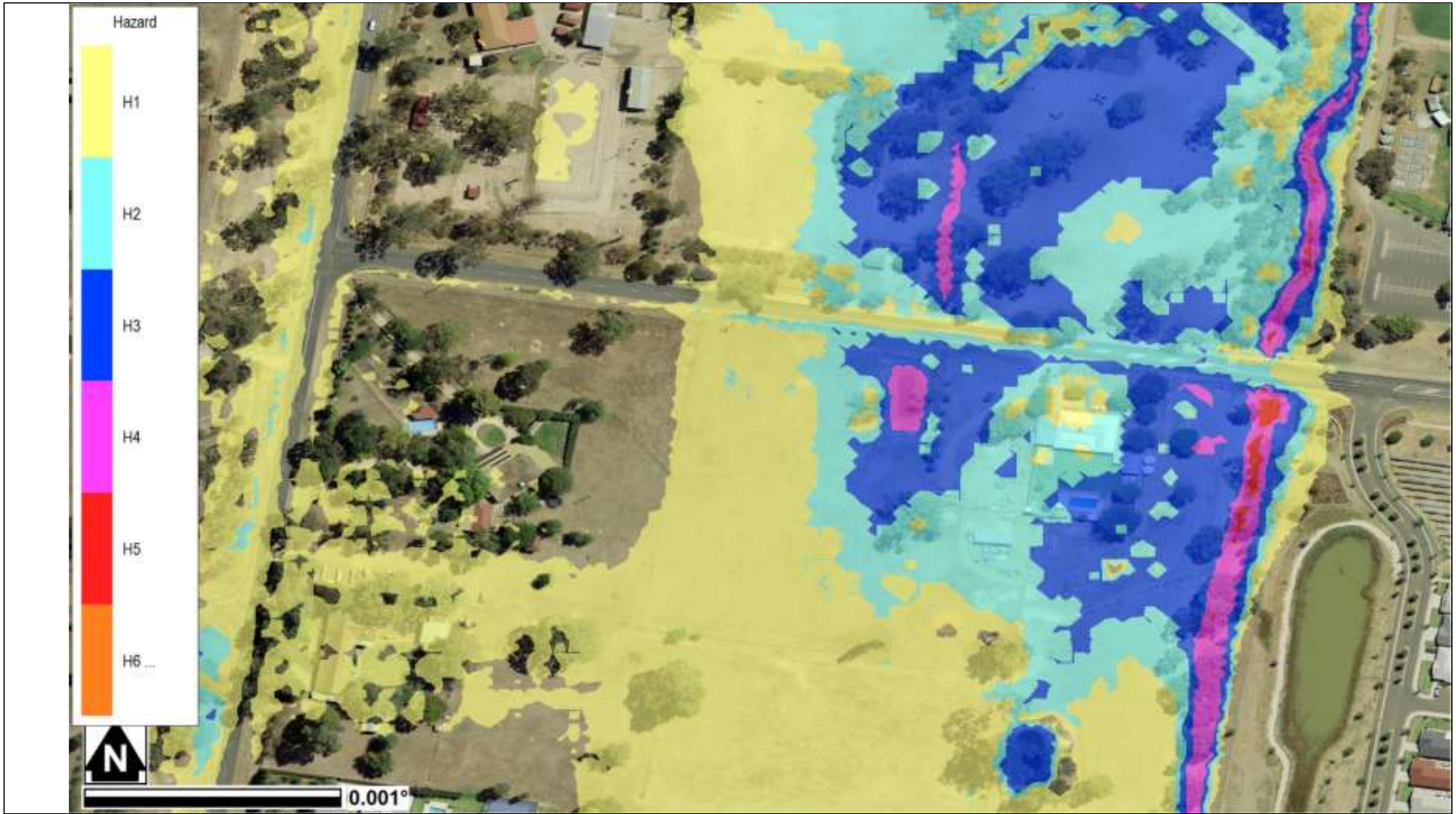

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Figure B7: Culvert 1-1% AEP-Hazard-ARR 2016
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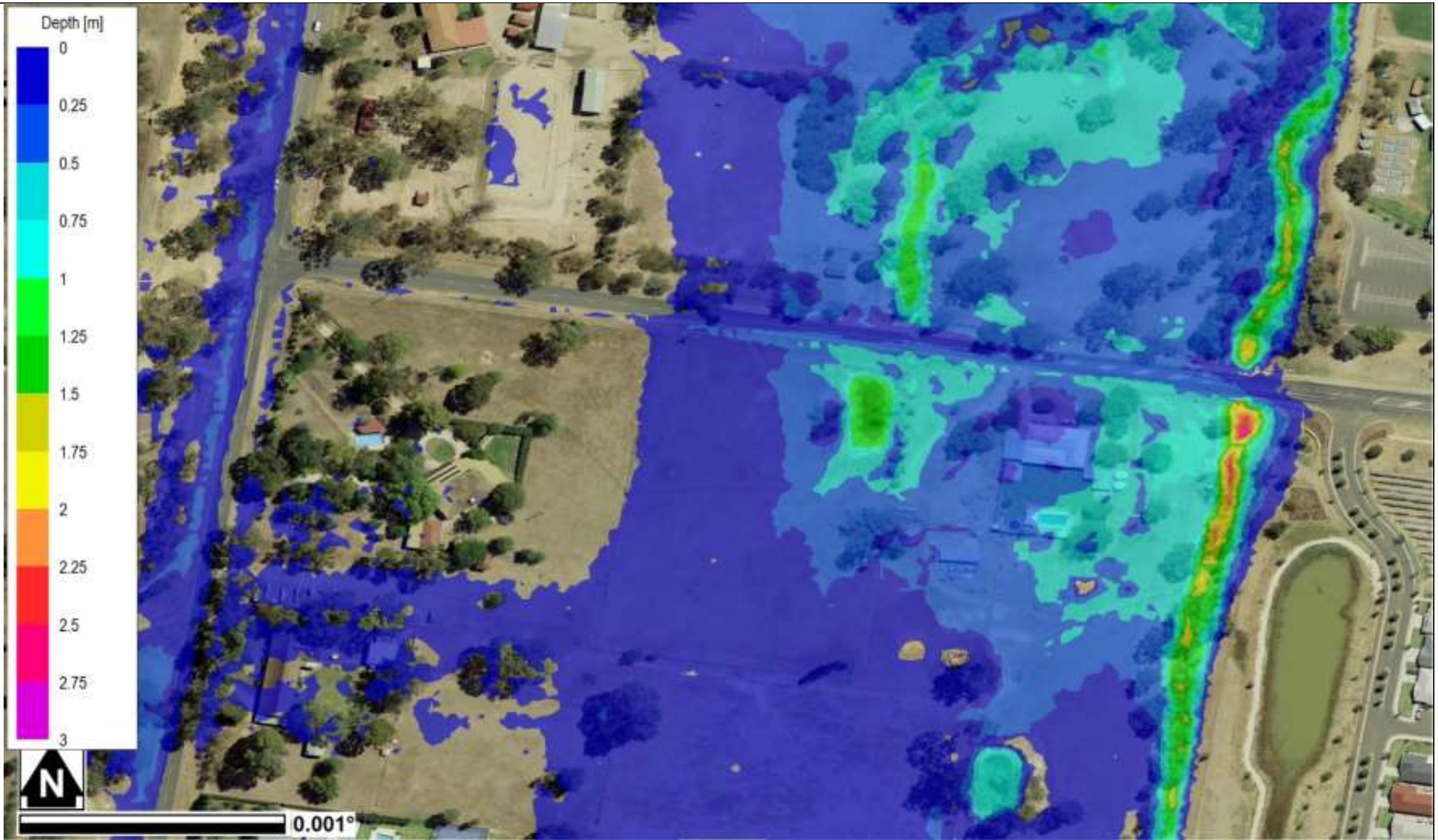

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Figure B8: Culvert 1-5% AEP-Depth

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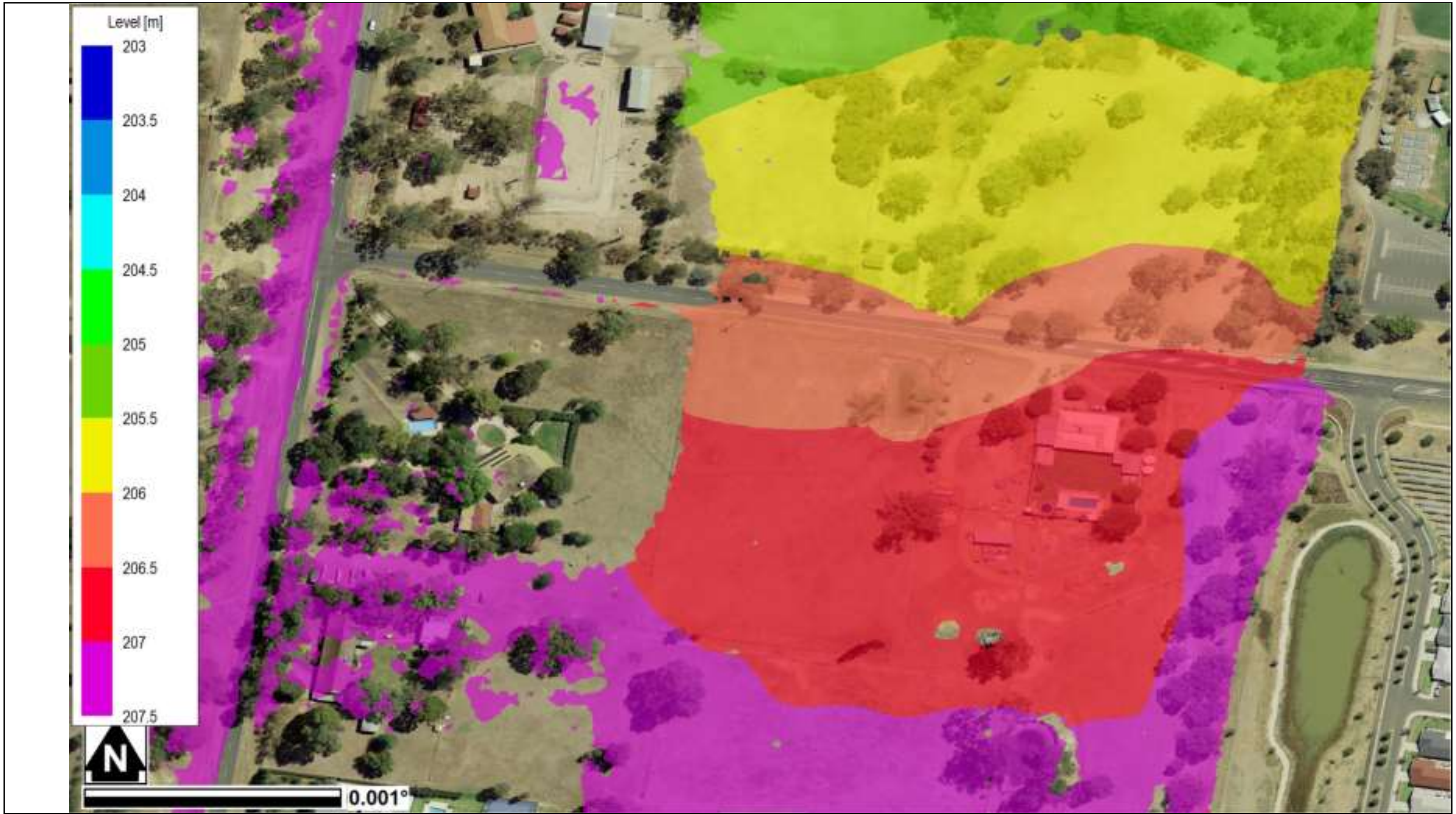
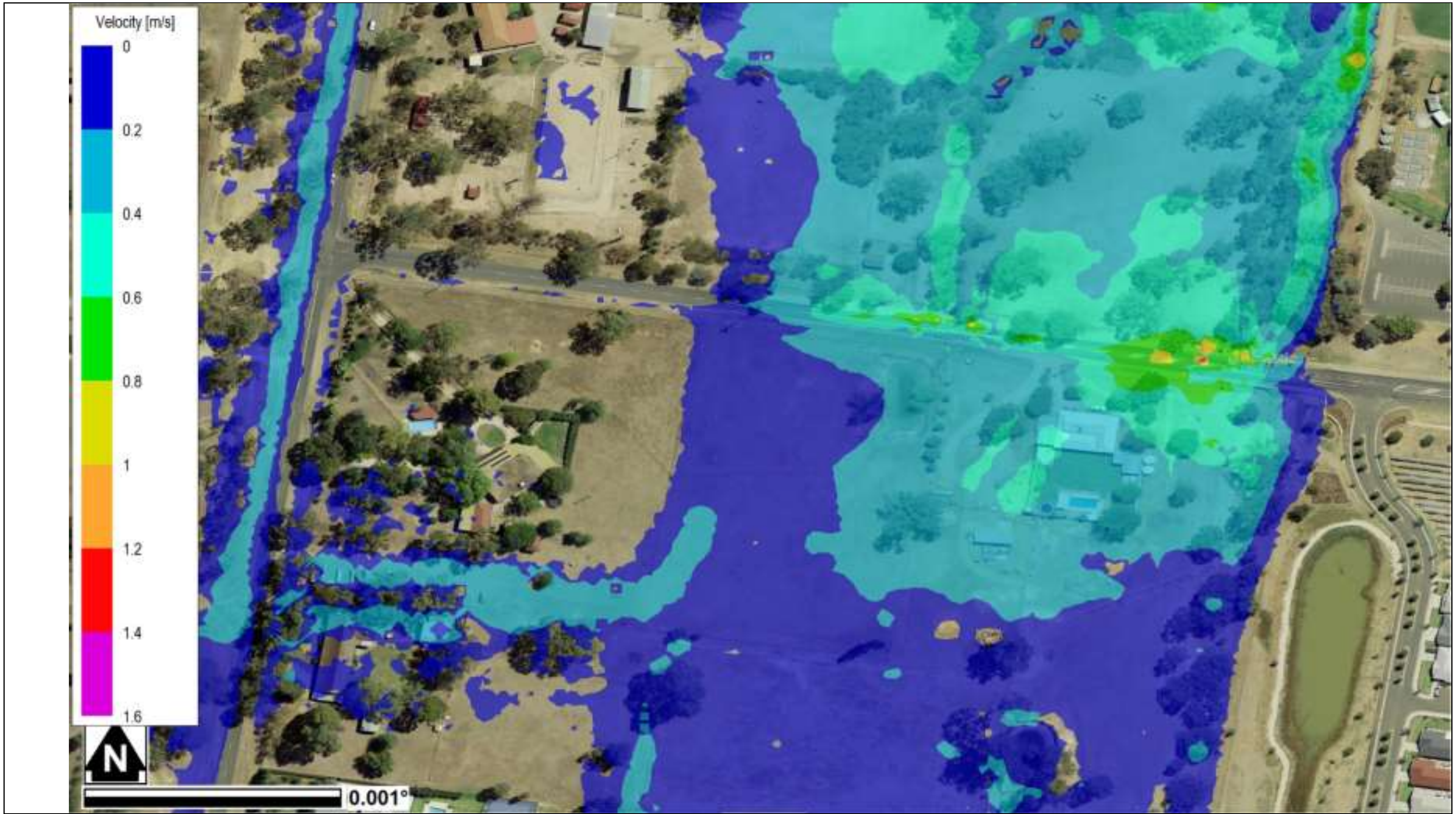


Wagga Wagga City Council	Figure B9: Culvert 1-5% AEP-Level All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 09:09 **Printed By:** Amir Abbasnia **Document Version:** 1.0A



Wagga Wagga City Council	Figure B10: Culvert 1-5% AEP-Velocity All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 09:09 **Printed By:** Amir Abbasnia **Document Version:** 1.0A

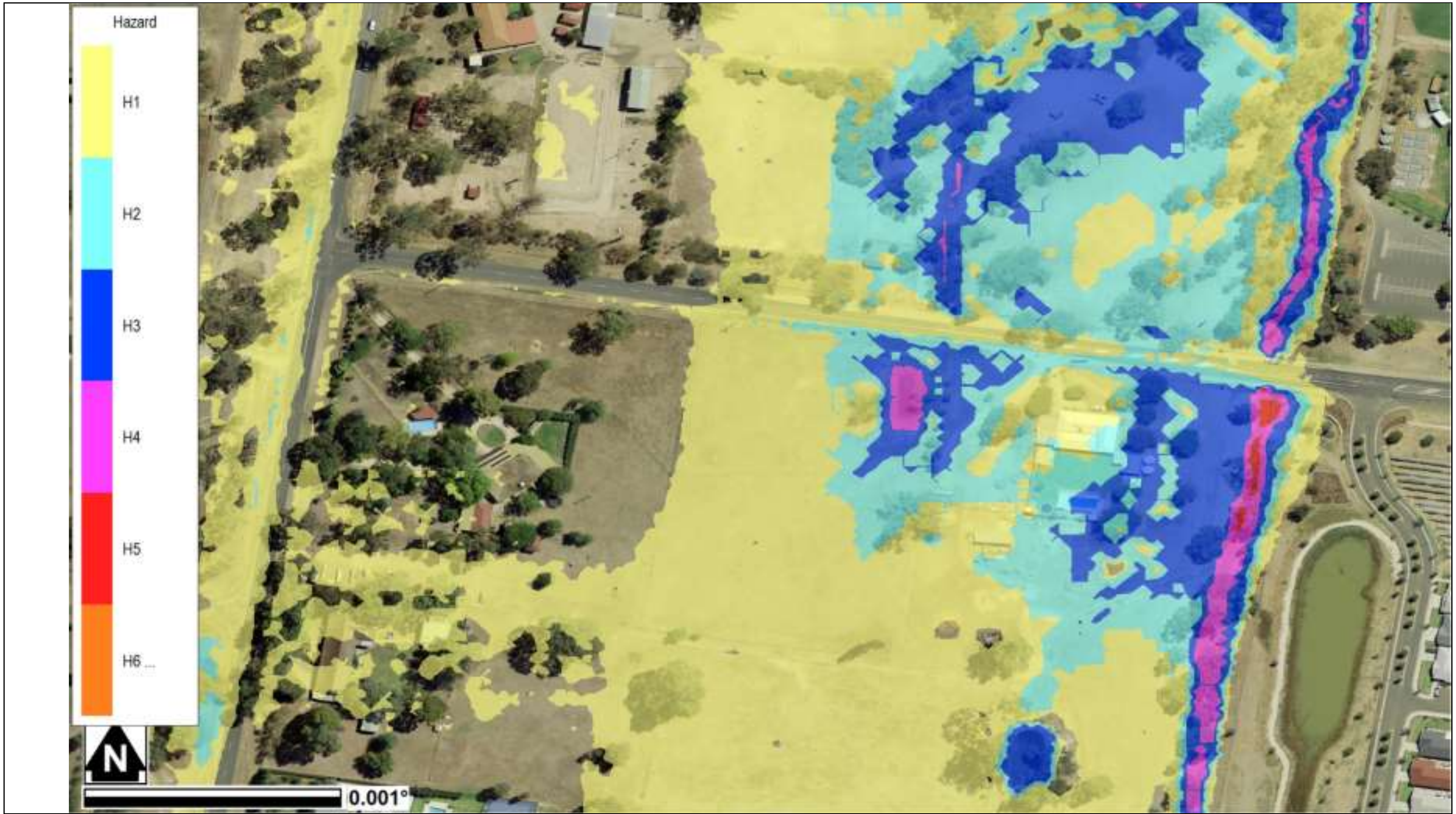


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Figure B11: Culvert 1-5% AEP-Hazard-ARR 2016

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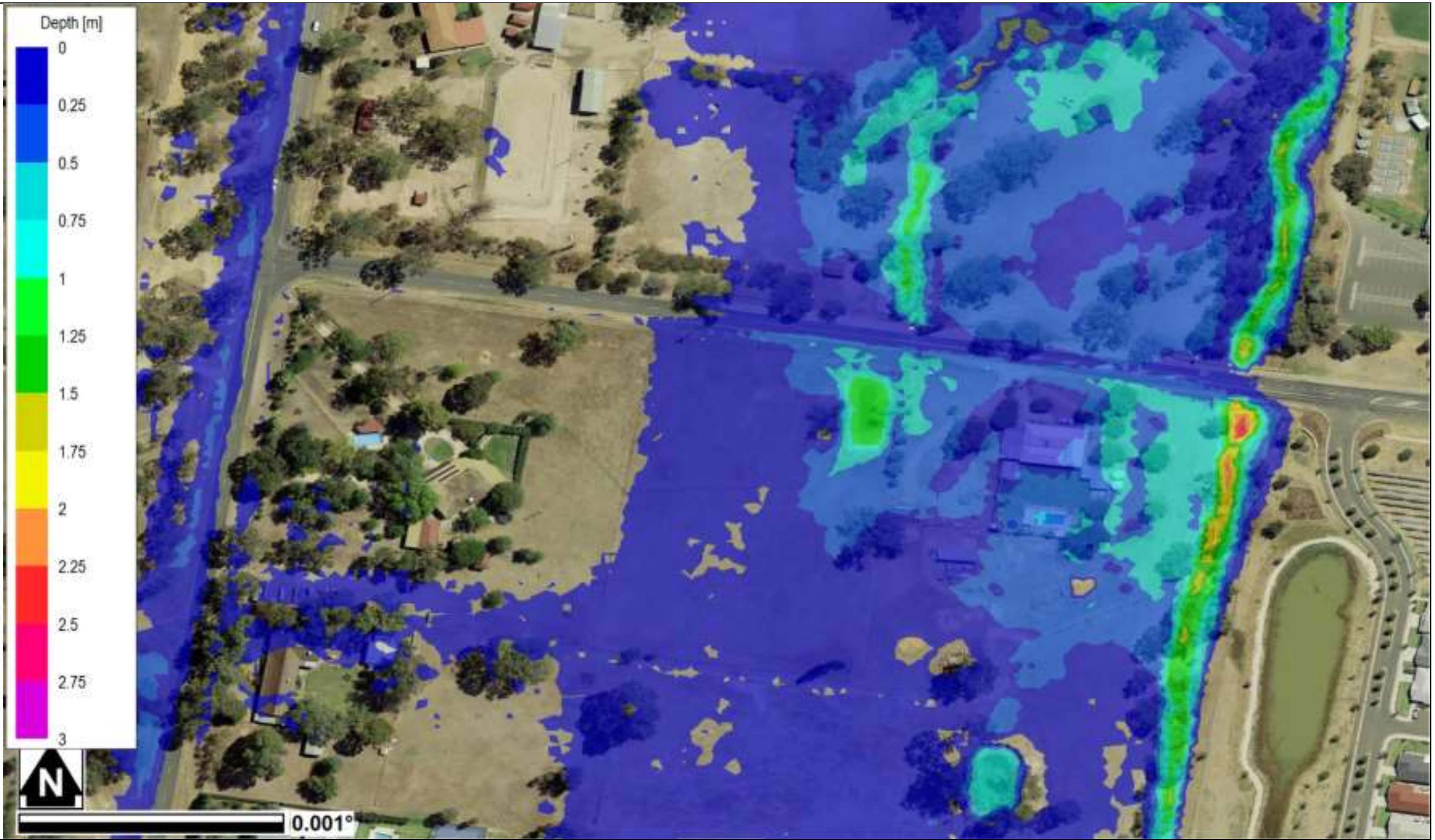
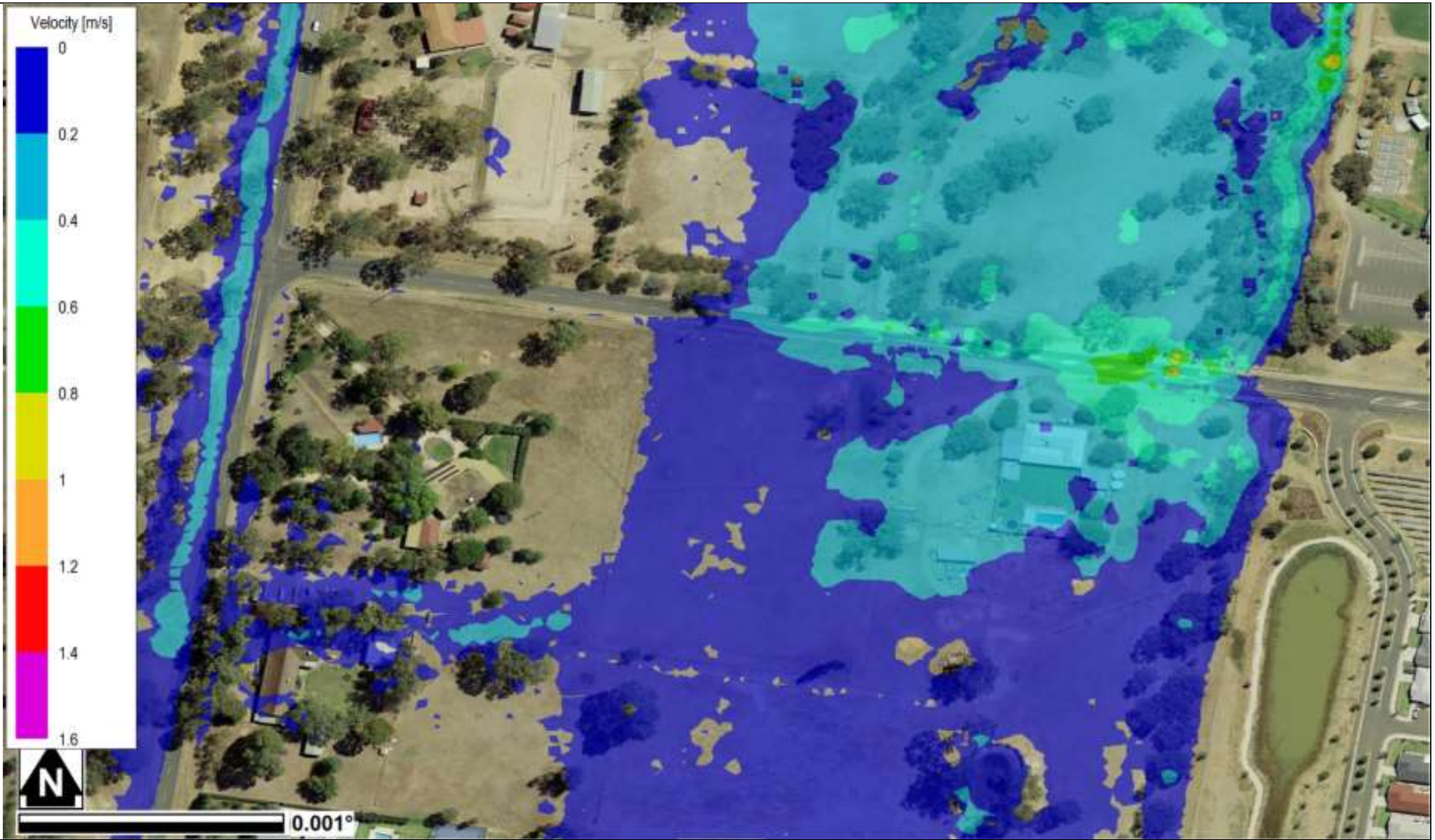


Wagga Wagga City Council	Figure B12: Culvert 1-20% AEP-Depth All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 08:28 **Printed By:** Amir Abbasnia **Document Version:** 1.0A

Wagga Wagga City Council	Figure B13: Culvert 1-20% AEP-Level All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 08:29 **Printed By:** Amir Abbasnia **Document Version:** 1.0A



Wagga Wagga City Council	Figure B14: Culvert 1-20% AEP-Velocity All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 08:29 **Printed By:** Amir Abbasnia **Document Version:** 1.0A

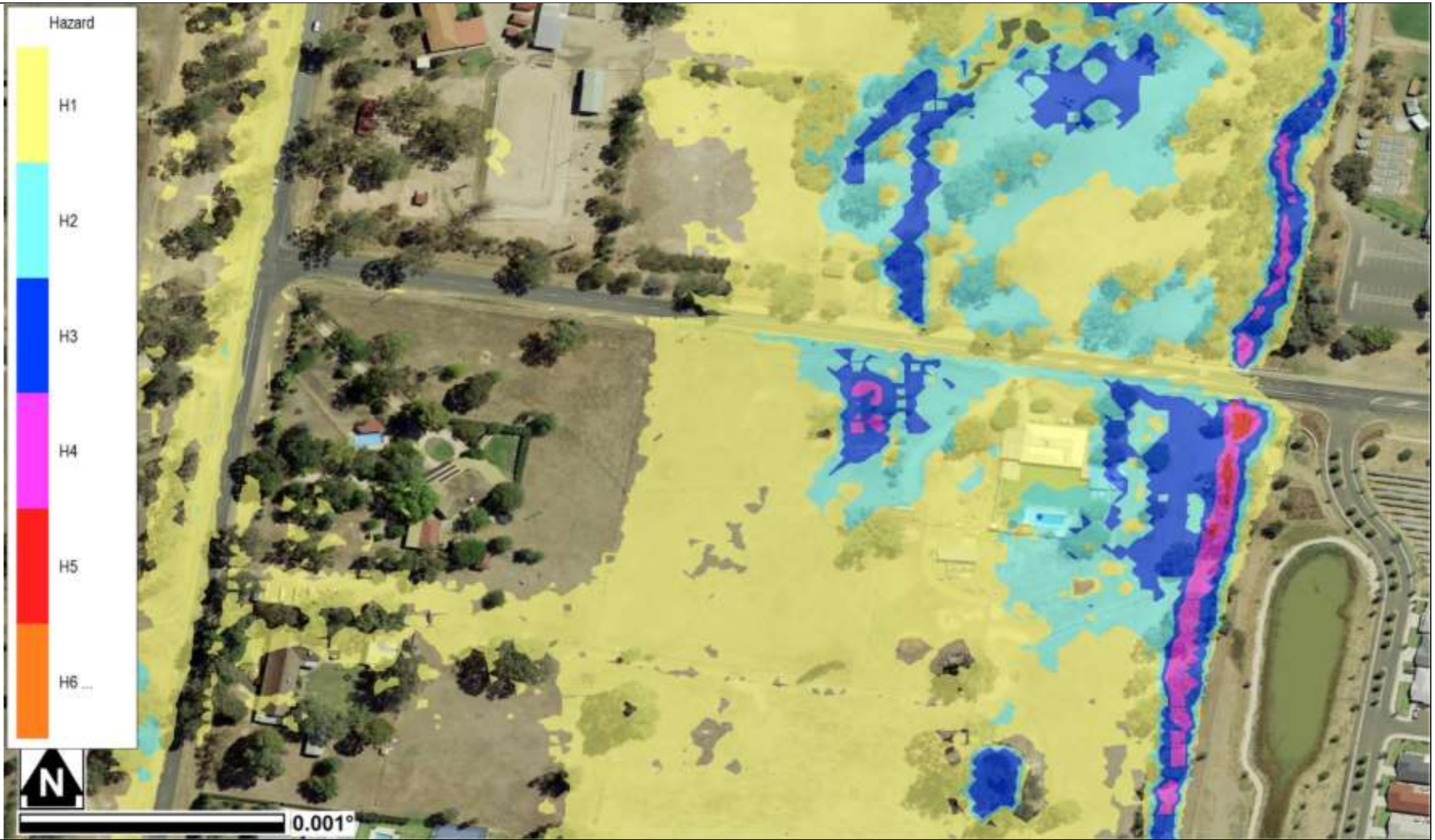


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Figure B15: Culvert 1-20% AEP-Hazard-ARR 2016
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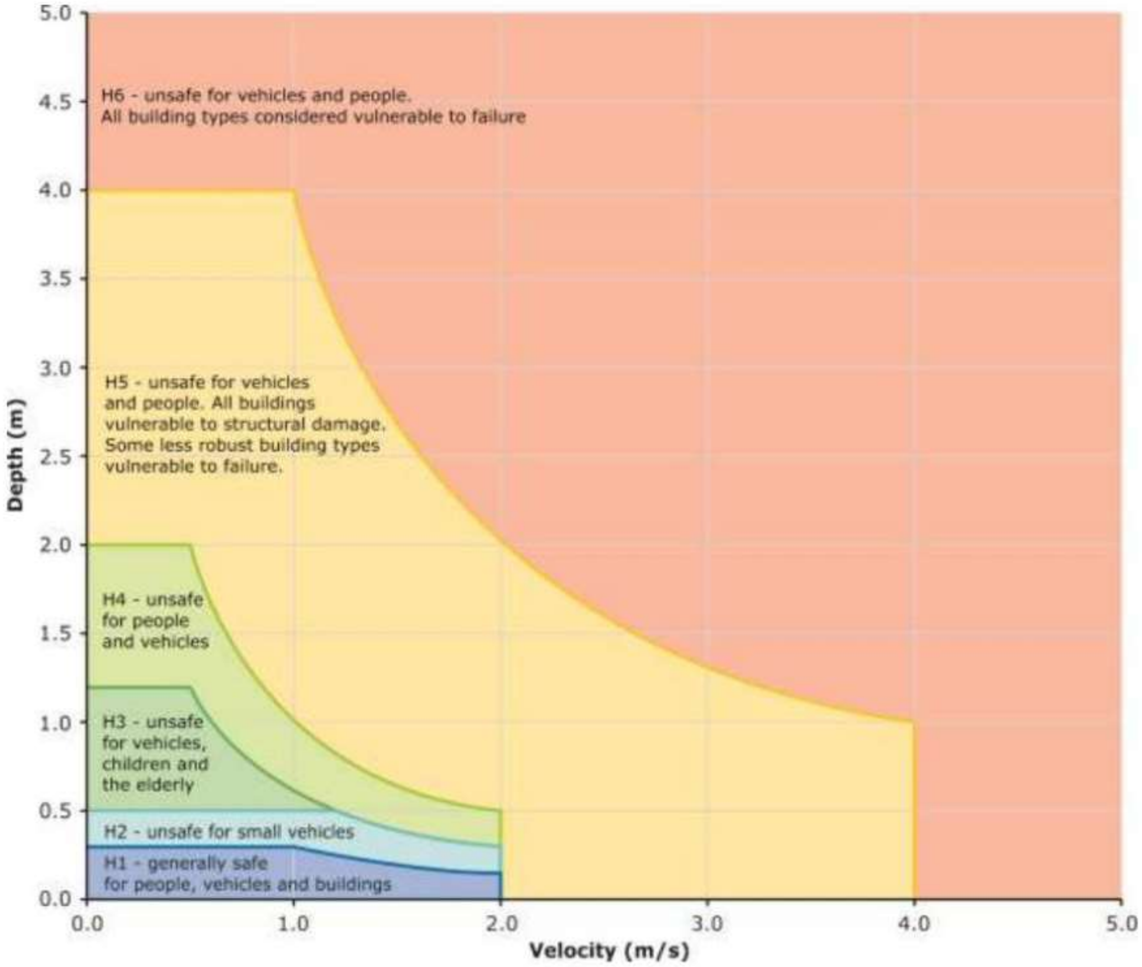
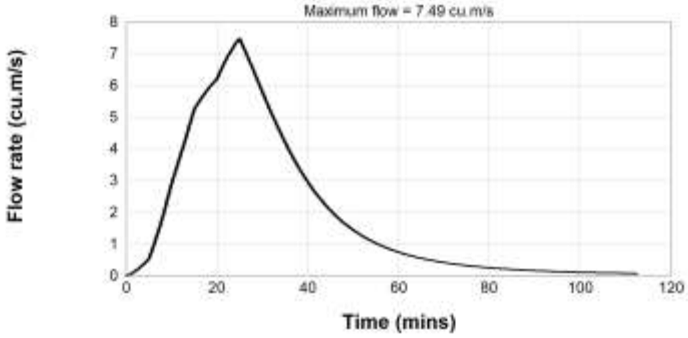
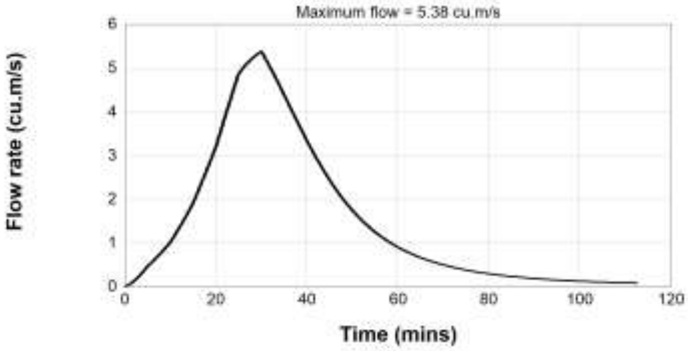


Figure B16: Flood hazard Chart based on the Australian Emergency Management Handbook 7 guideline

1% AEP (25min, storm 8)



5% AEP (30 min, storm 7)



20% AEP (30 min, storm 10)

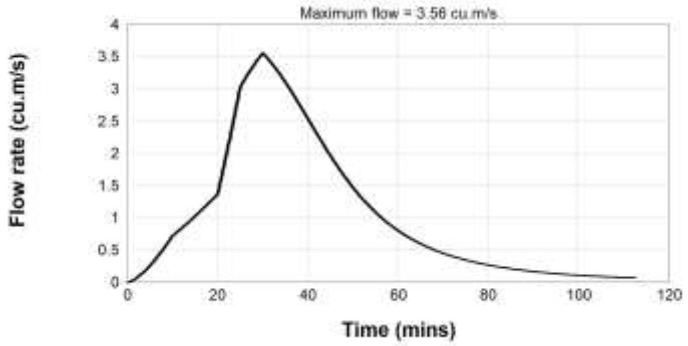
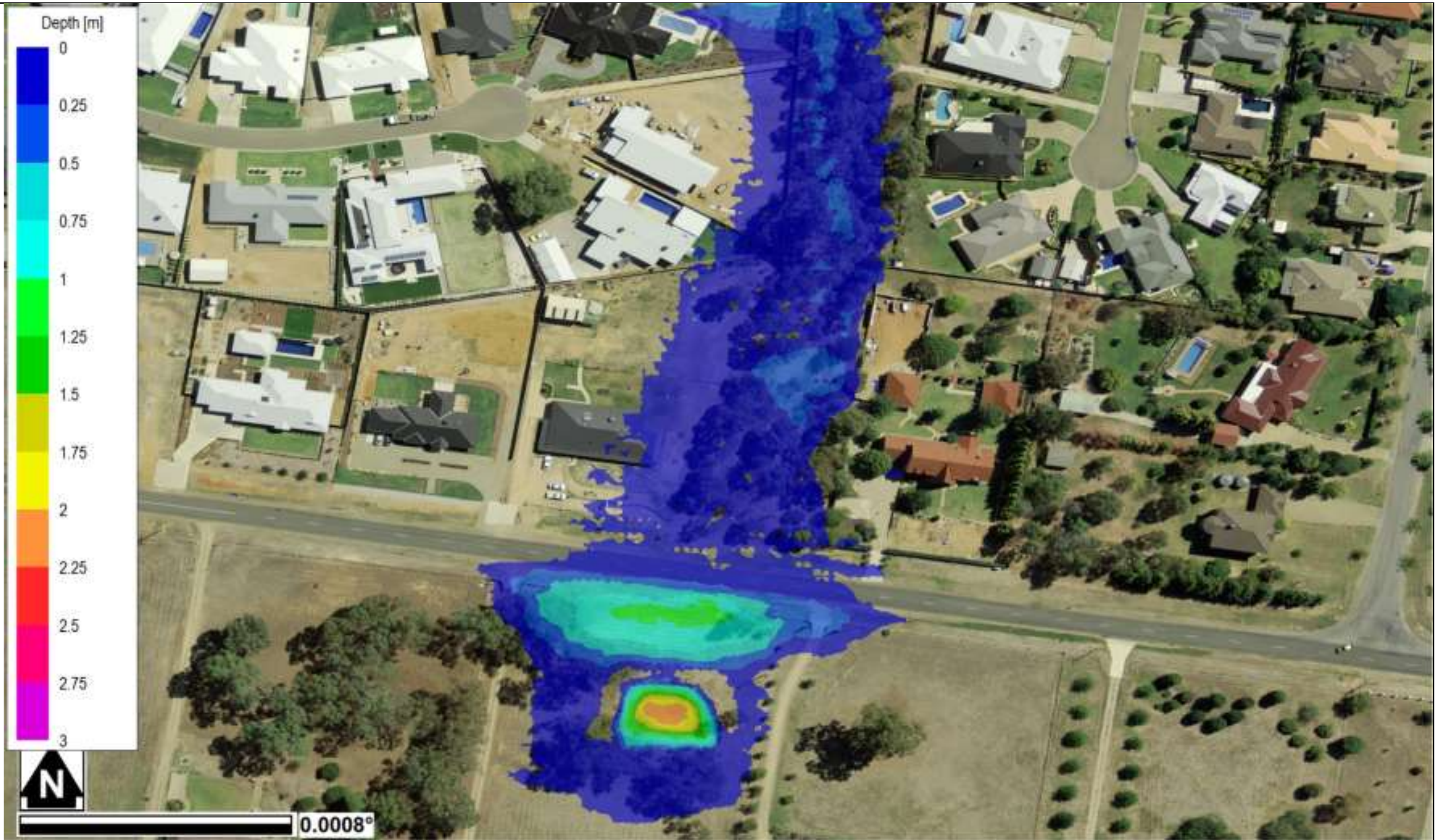


Figure B17: The 1%, 5% and 20% AEPs output hydrographs for catchment 3.



Wagga Wagga City Council	Figure B18: Culvert3-1% AEP-Depth All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 09:59 **Printed By:** Amir Abbasnia **Document Version:** 1.0A

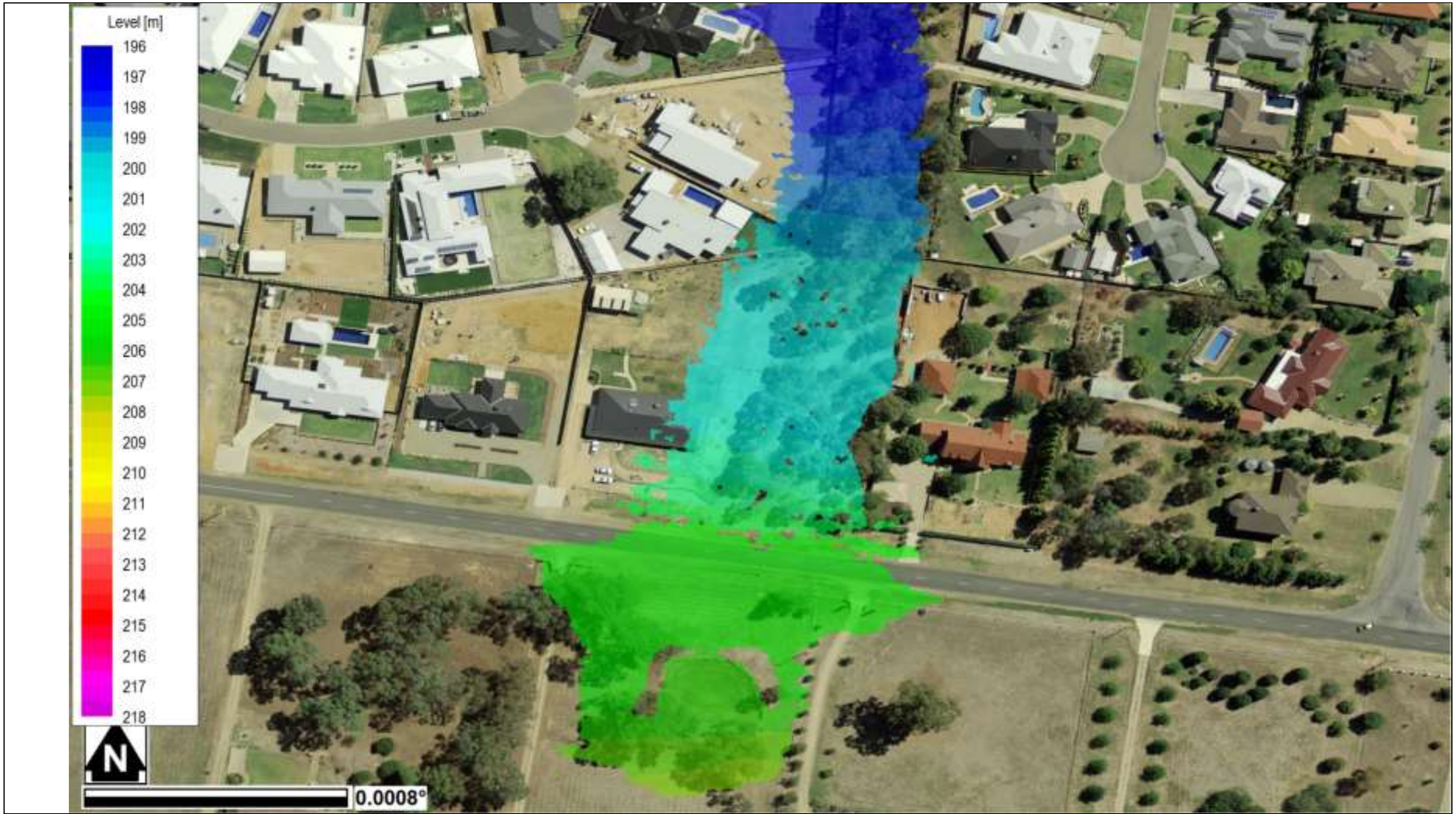


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Figure B19: Culvert3-1% AEP-Level

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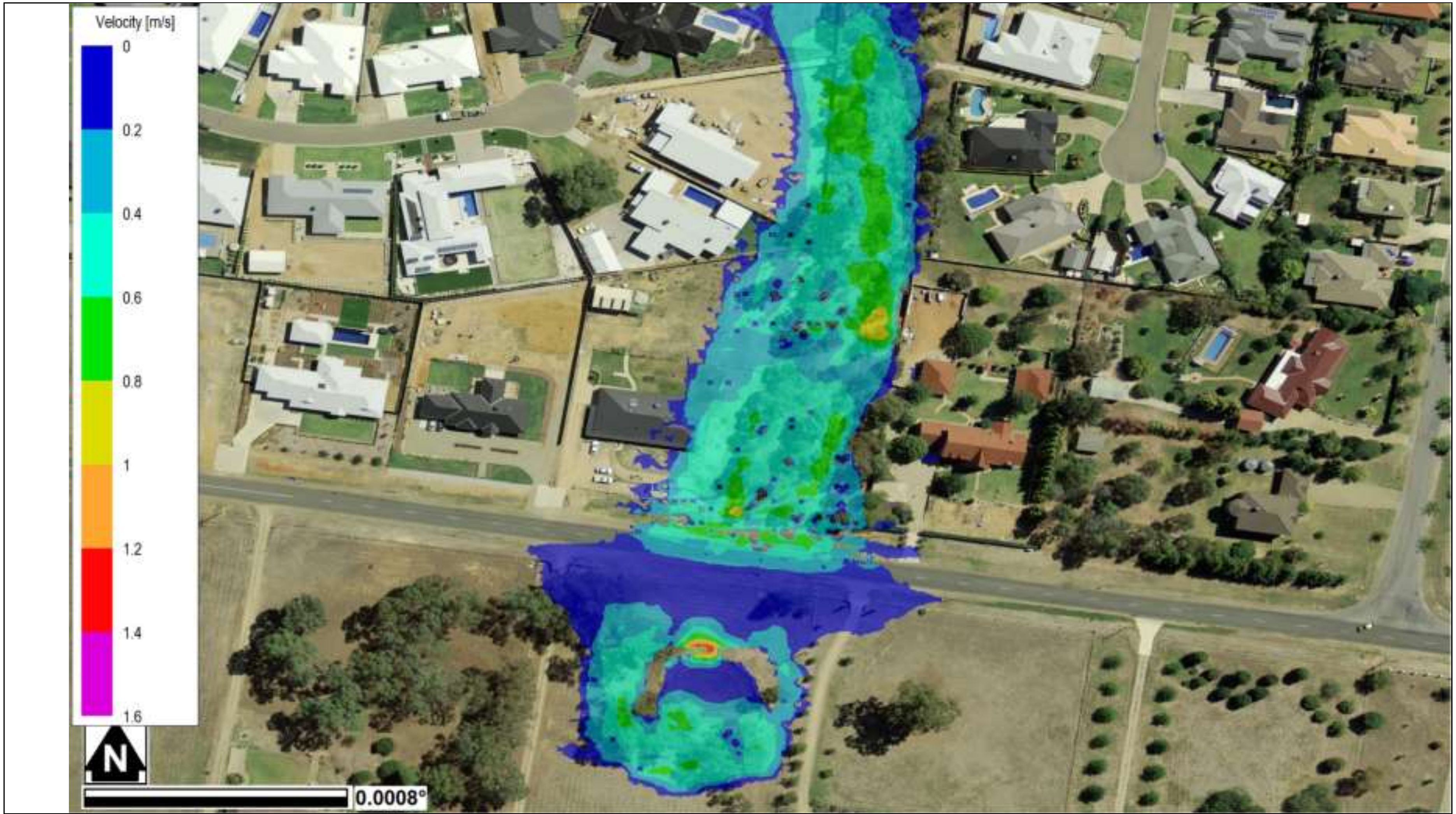

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Figure B20: Culvert3-1% AEP-Velocity

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Figure B21: Culvert3-1% AEP-Hazard-ARR 2016

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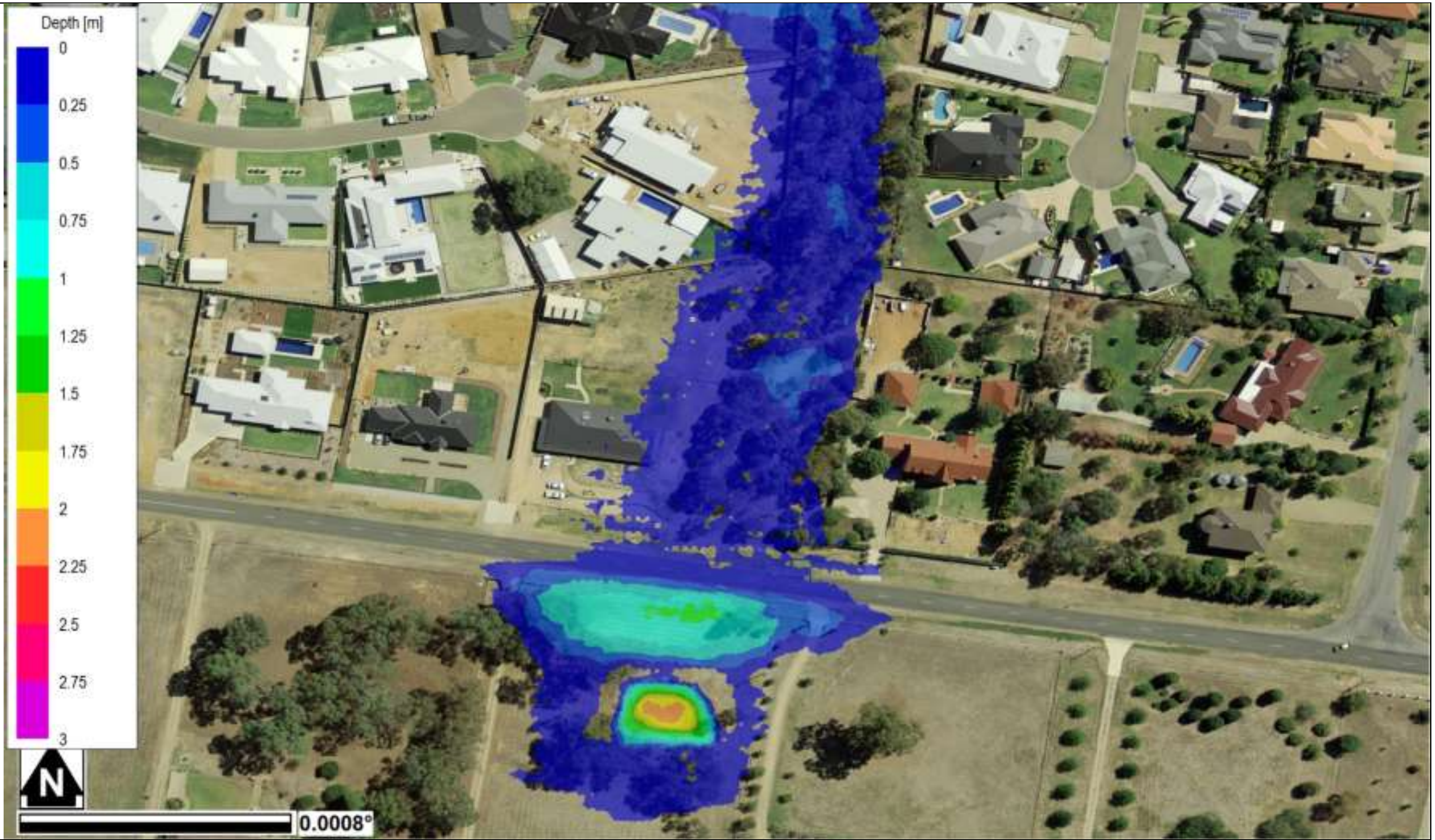

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Figure B22: Culvert3-5% AEP-Depth

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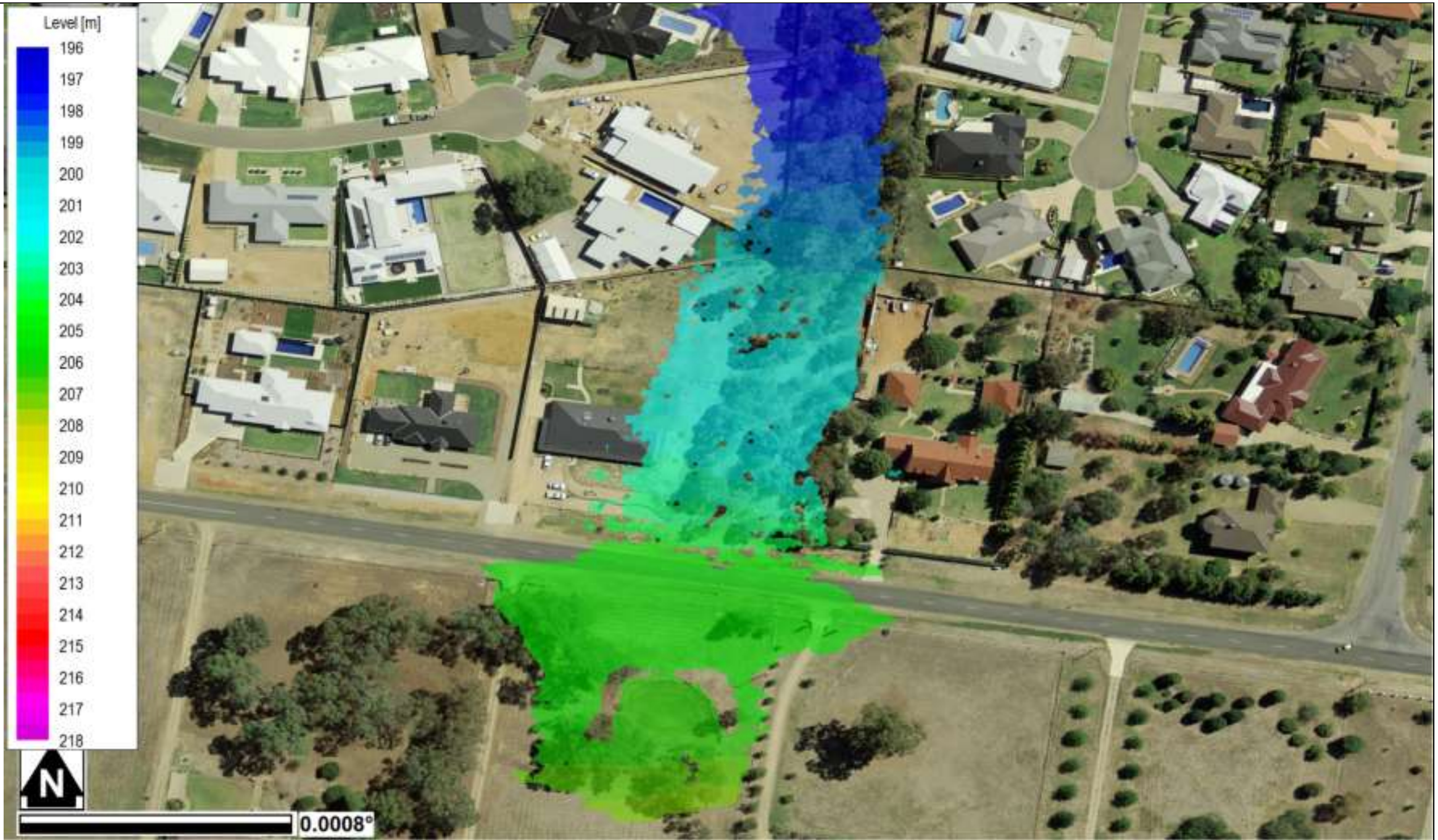

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Figure B23: Culvert3-5% AEP-Level

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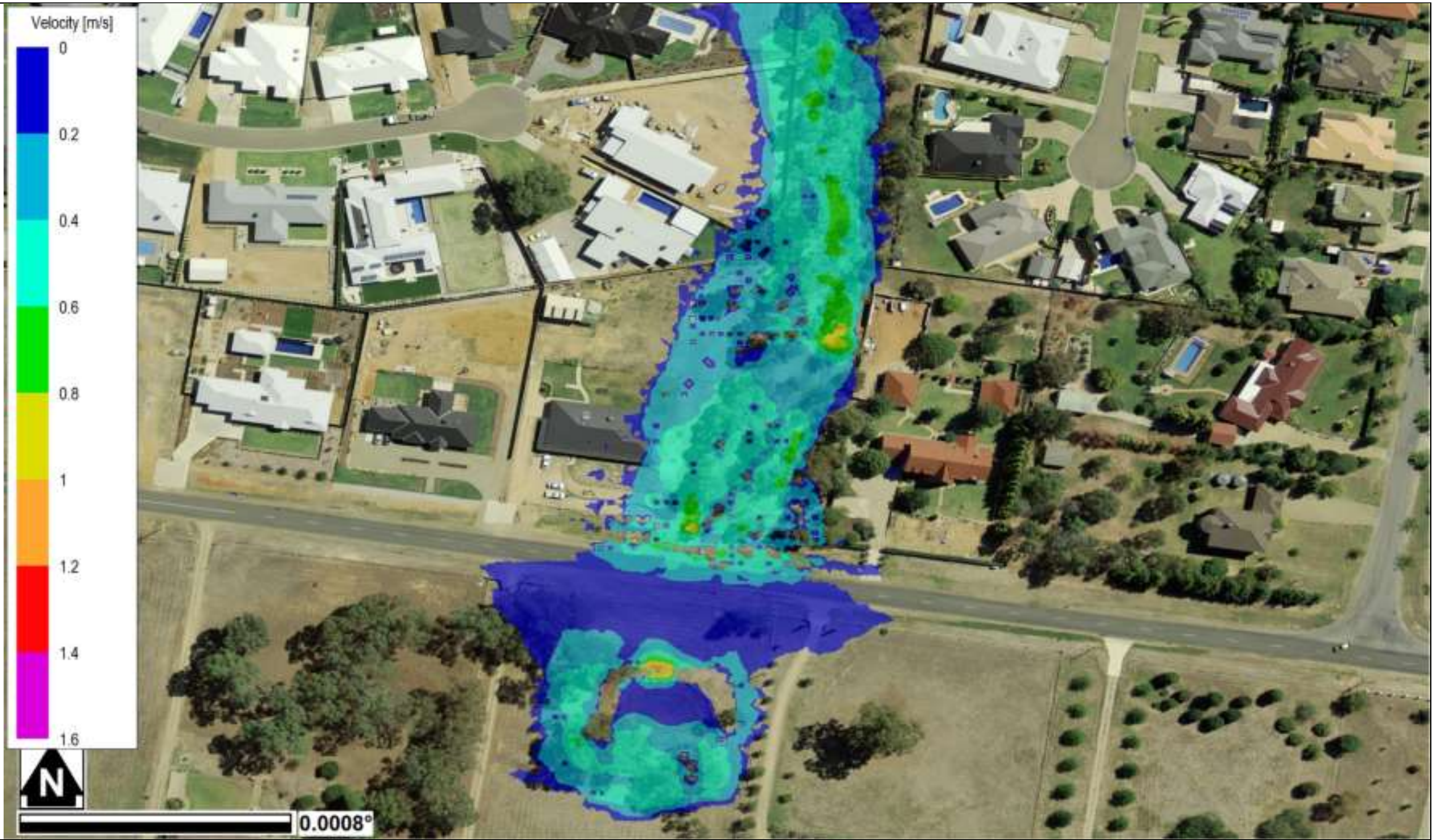

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Figure B24: Culvert3-5% AEP-Velocity

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Figure B25: Culvert3-5% AEP-Hazard-ARR 2016

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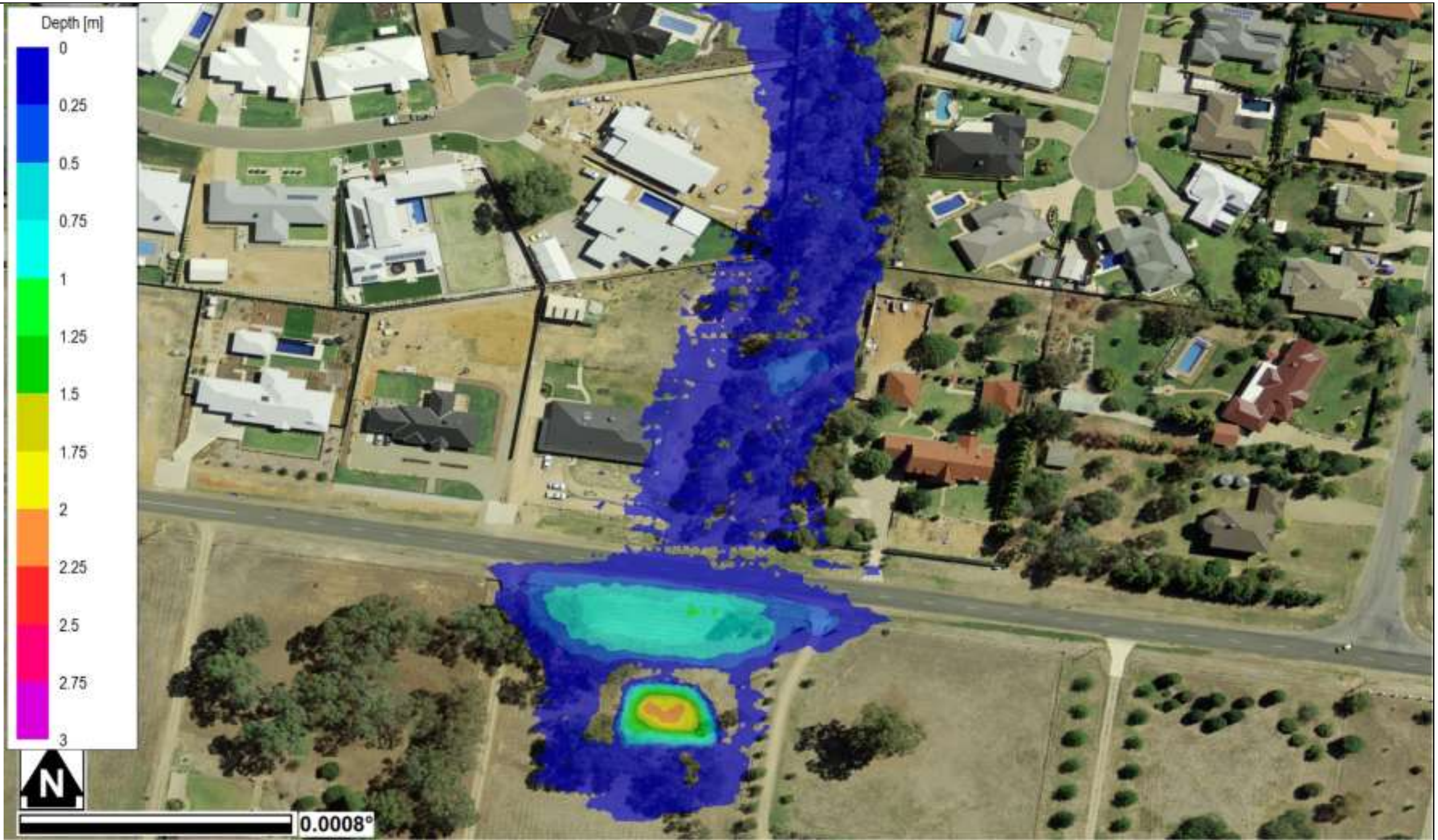
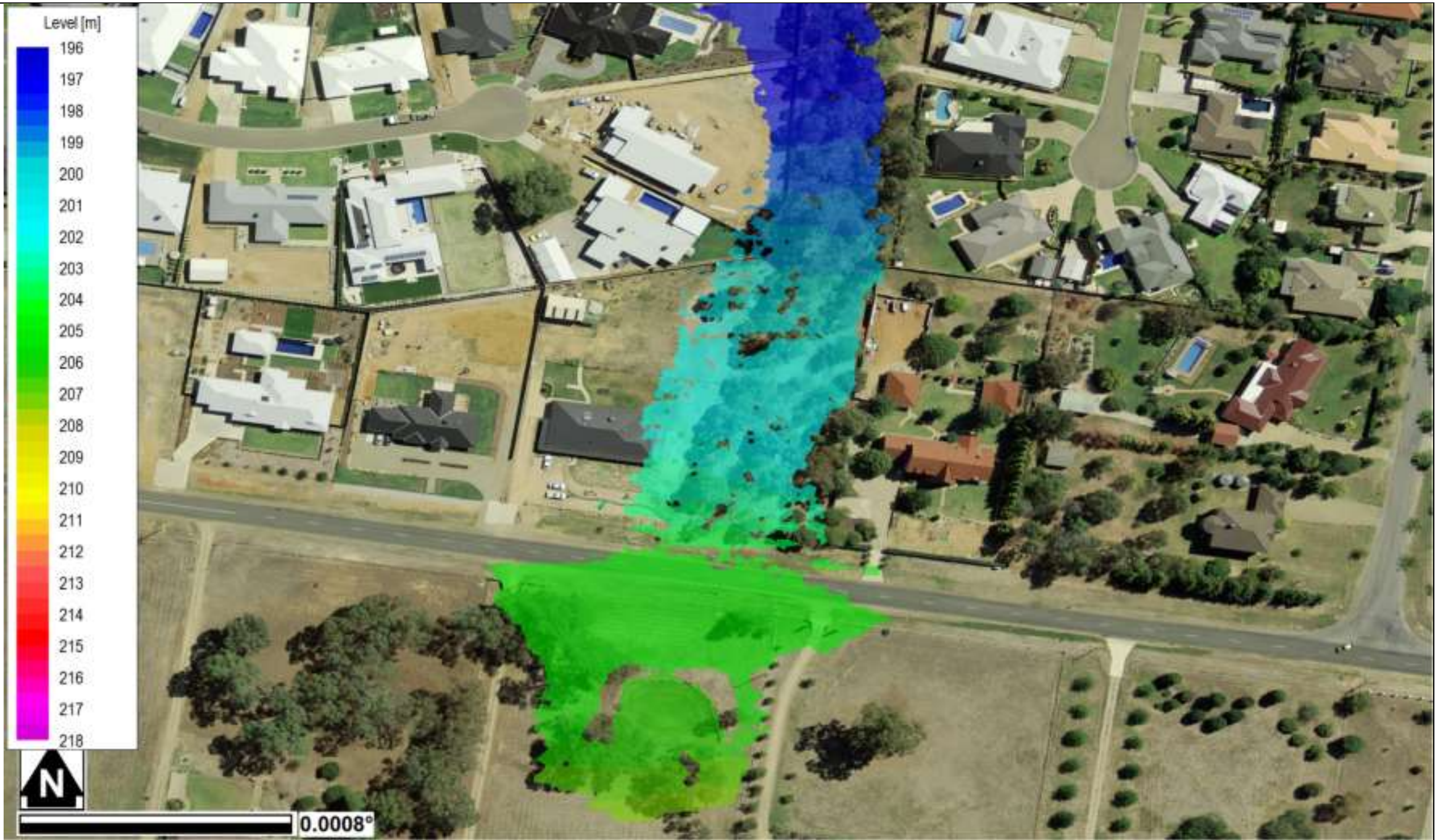
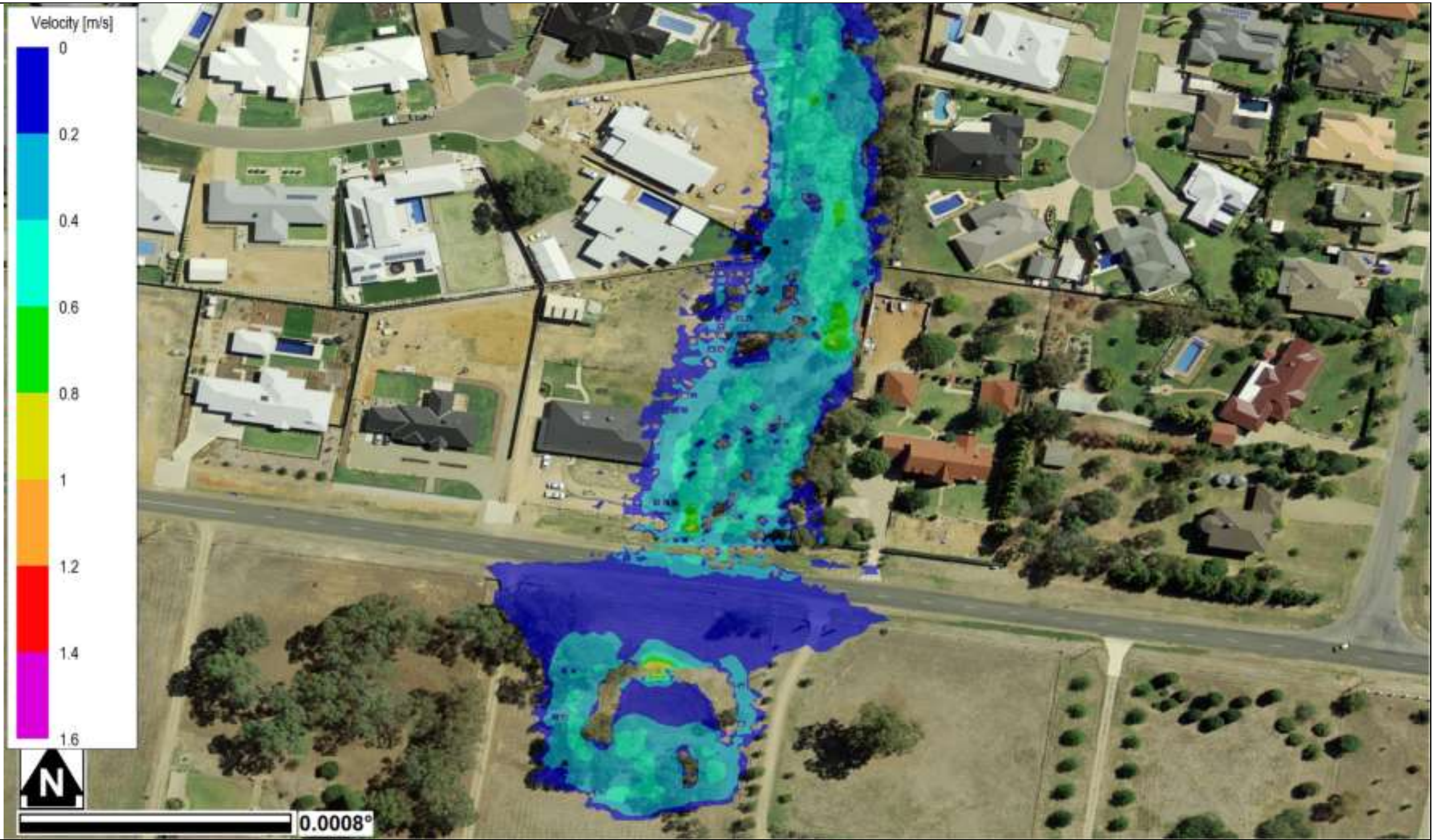
Document Version: 1.0A



Wagga Wagga City Council	Figure B26: Culvert3-20% AEP-Depth All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 10:00 **Printed By:** Amir Abbasnia **Document Version:** 1.0A



Wagga Wagga City Council	Figure B27: Culvert3-20% AEP-Level All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 10:00 **Printed By:** Amir Abbasnia **Document Version:** 1.0A



Wagga Wagga City Council	Figure B28: Culvert3-20% AEP-Velocity All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 10:00 **Printed By:** Amir Abbasnia **Document Version:** 1.0A

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Figure B29: Culvert3-20% AEP-Hazard-ARR 2016

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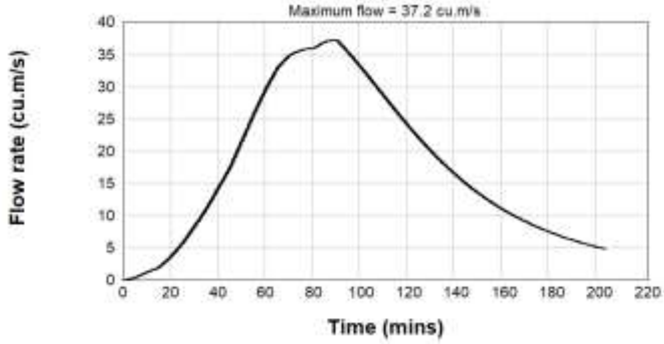
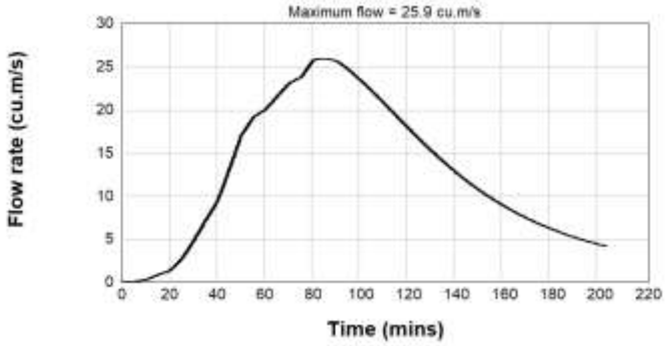
1% AEP (1.5 hr, storm 1)



5% AEP (1.5 hr, storm 9)



20% AEP (1.5 hr, storm 7)

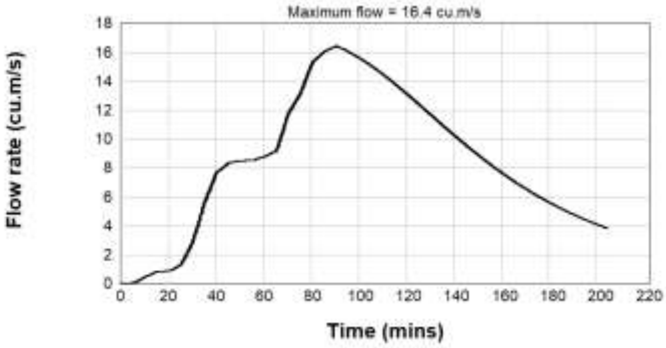
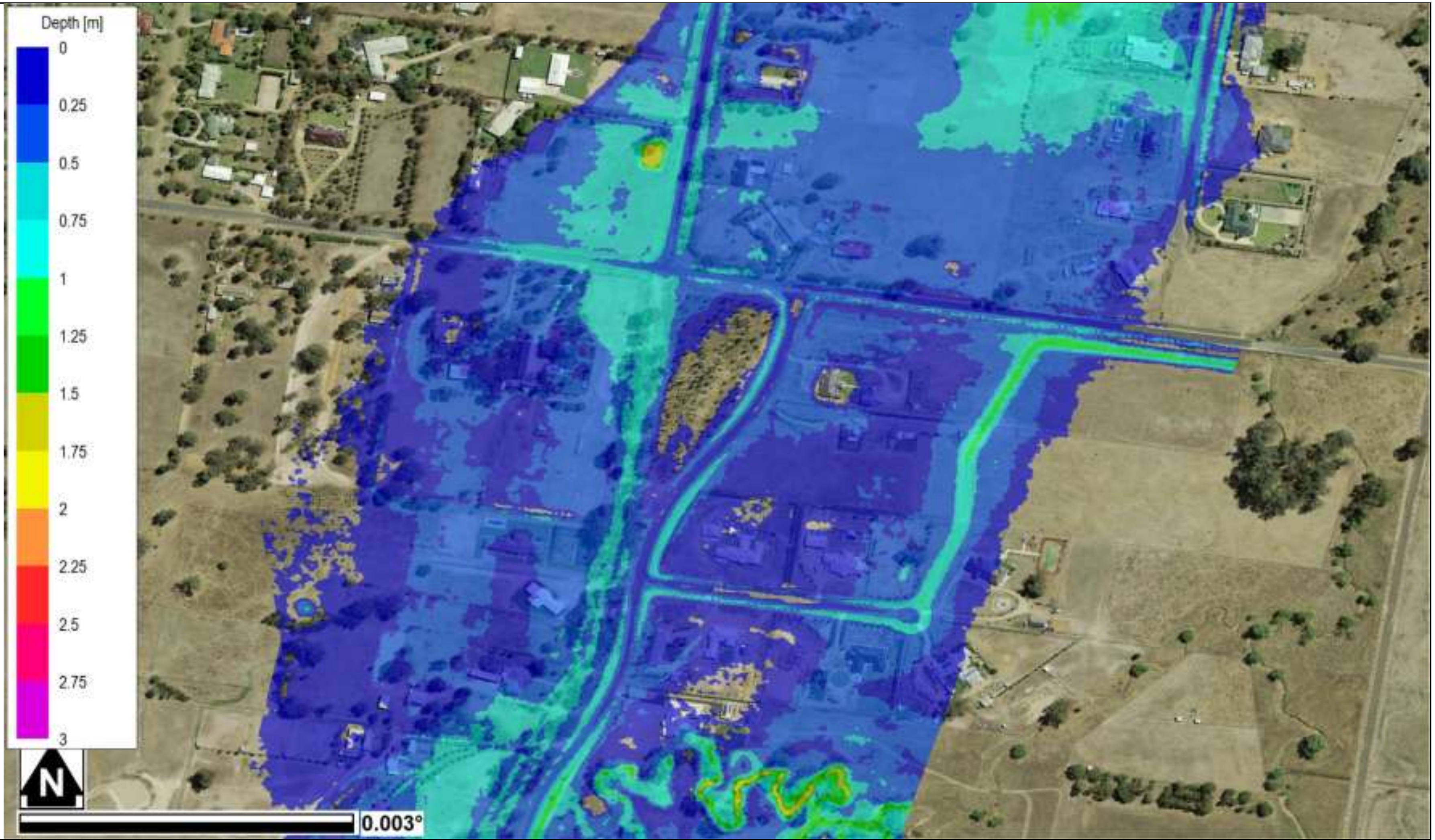
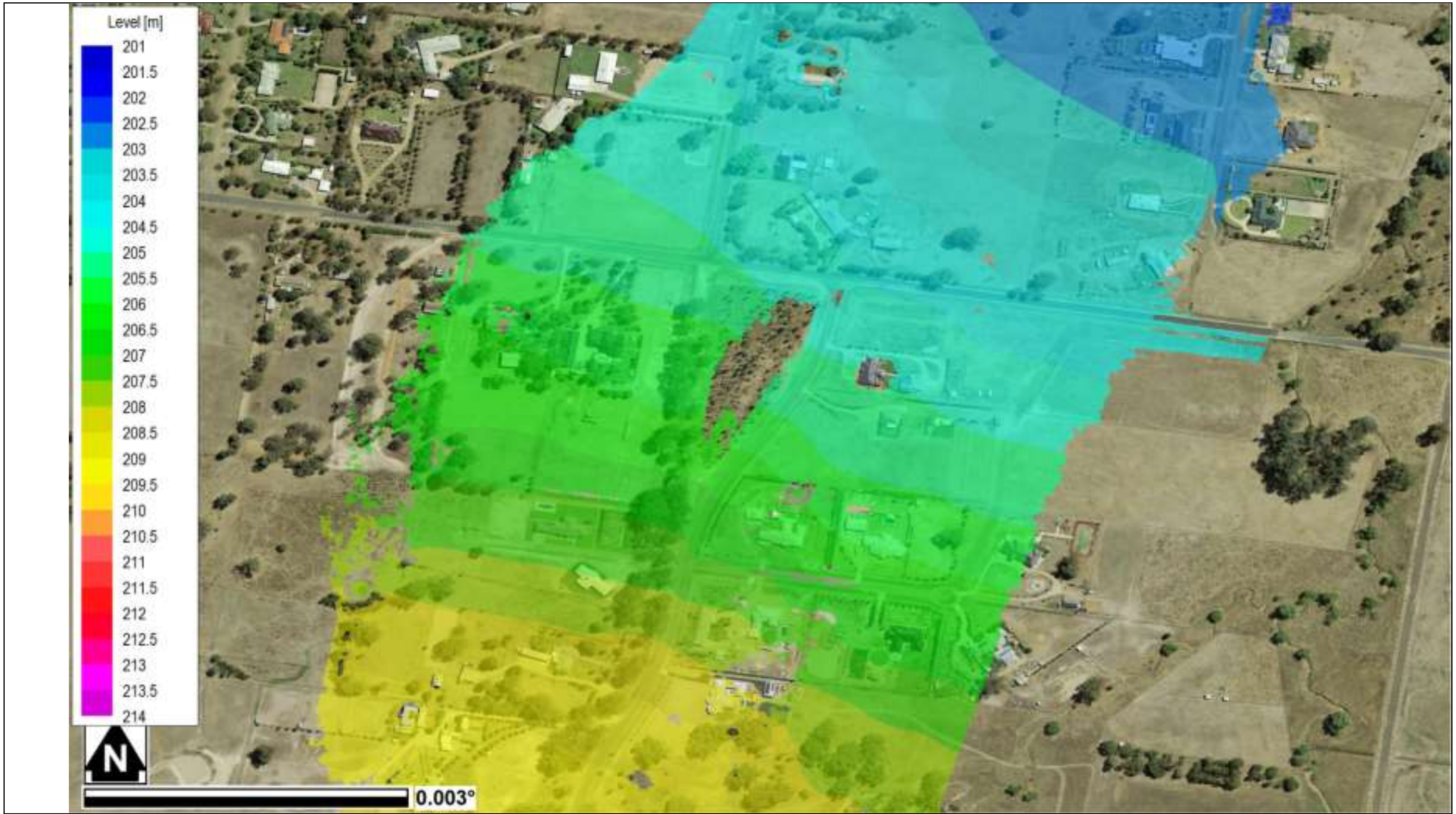


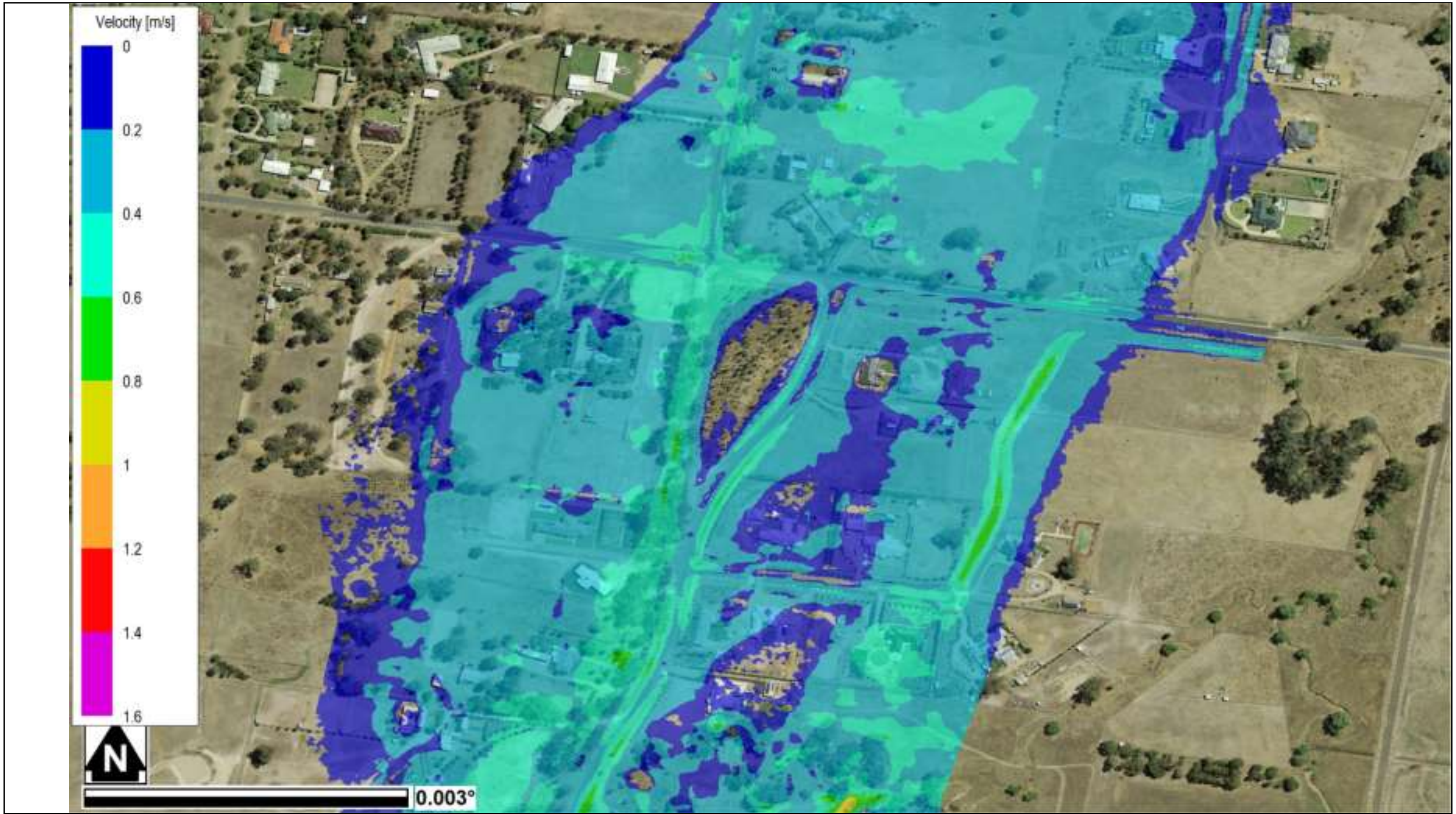
Figure B30: The 1%, 5% and 20% AEPs output hydrographs for catchment 4.



Wagga Wagga City Council	Figure B31: Culvert4-100yr-Depth All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 21:07 **Printed By:** Amir Abbasnia **Document Version:** 1.0A



Wagga Wagga City Council	Figure B32: Culvert4-100yr-Level All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 21:07 **Printed By:** Amir Abbasnia **Document Version:** 1.0A



Wagga Wagga City Council	Figure B33: Culvert4-100yr-Velocity All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 21:07 **Printed By:** Amir Abbasnia **Document Version:** 1.0A

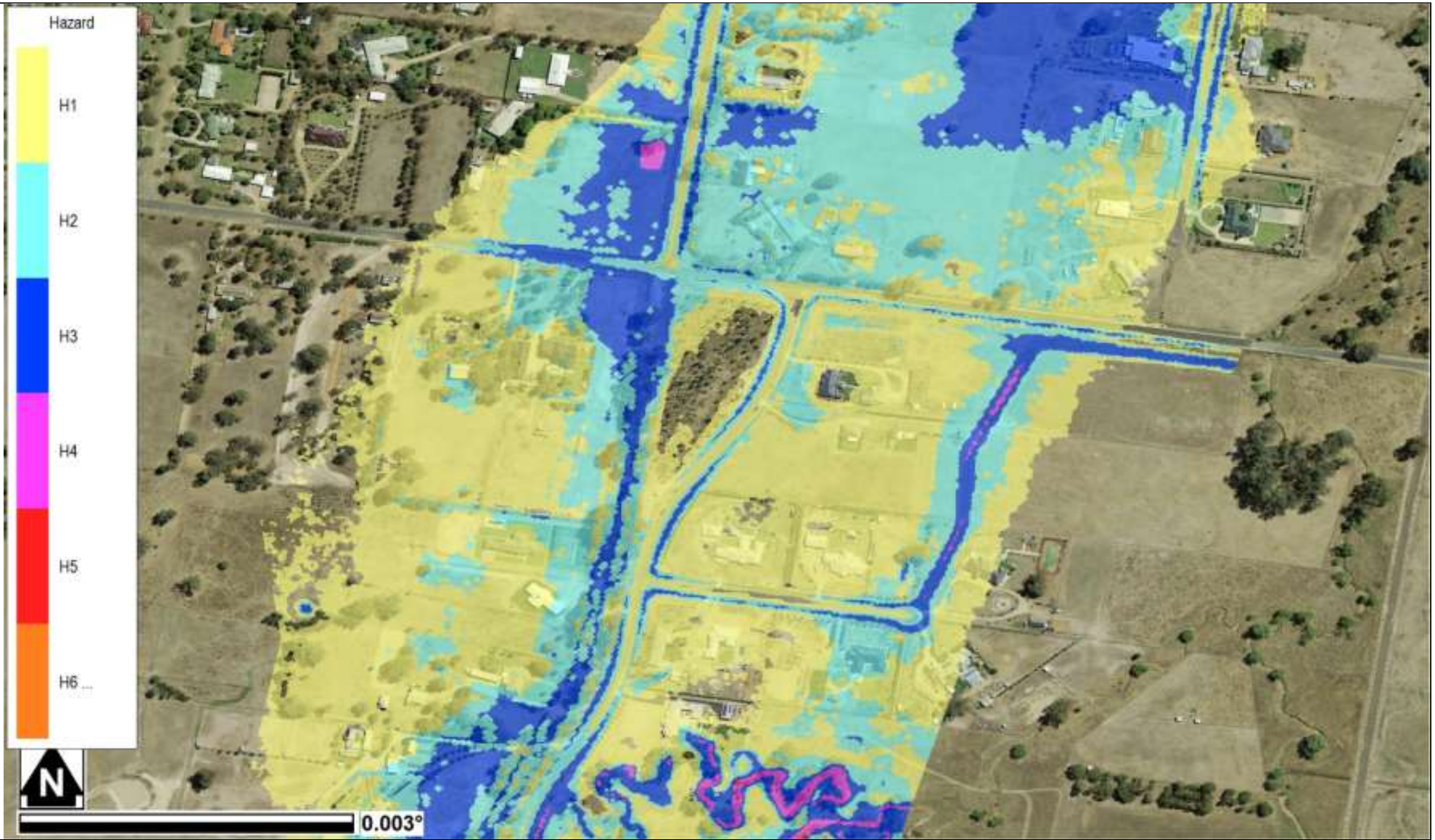


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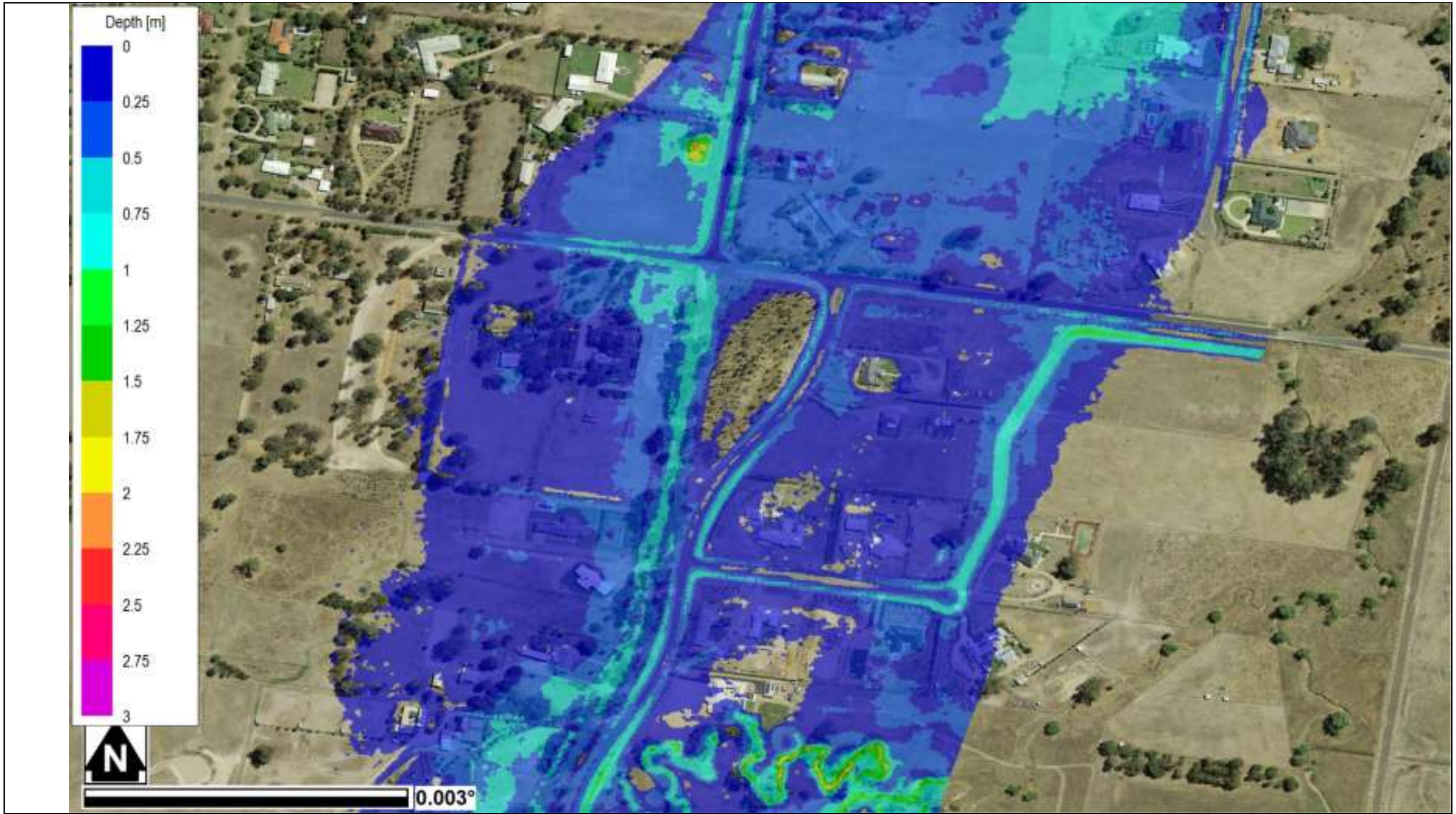
Figure B34: Culvert4-100yr-Hazard-ARR 2016

All information is provided "as is" and represents current information at the time of printing.

Date Printed: 09-04-20 21:07
Printed By: Amir Abbasnia
Document Version: 1.0A



Wagga Wagga City Council	Figure B35: Culvert4-20yr-Depth All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 21:11 **Printed By:** Amir Abbasnia **Document Version:** 1.0A

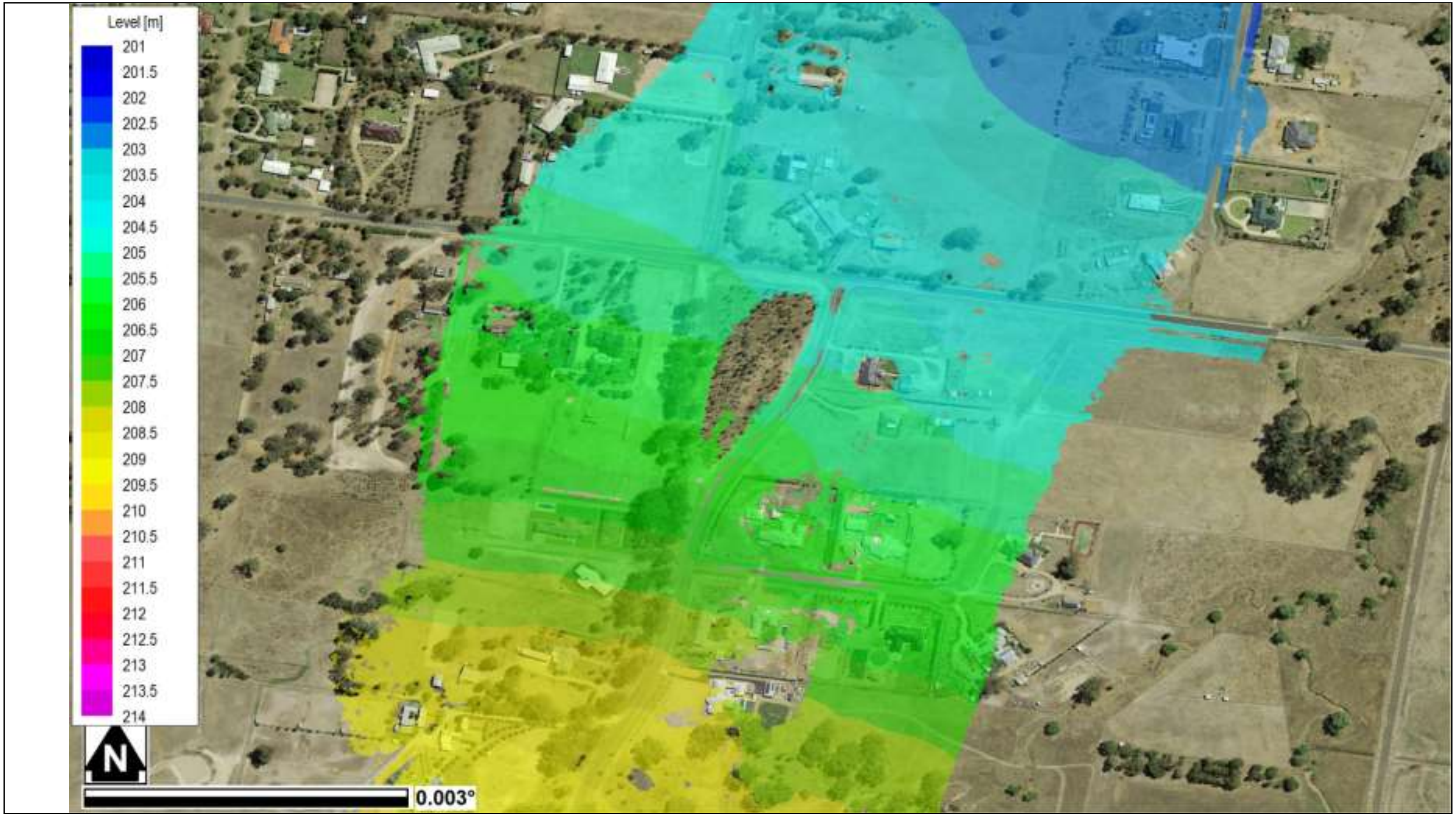


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Figure B36: Culvert4-20yr-Level

All information is provided "as is" and represents current information at the time of printing.

Date Printed: 09-04-20 21:11
Printed By: Amir Abbasnia
Document Version: 1.0A

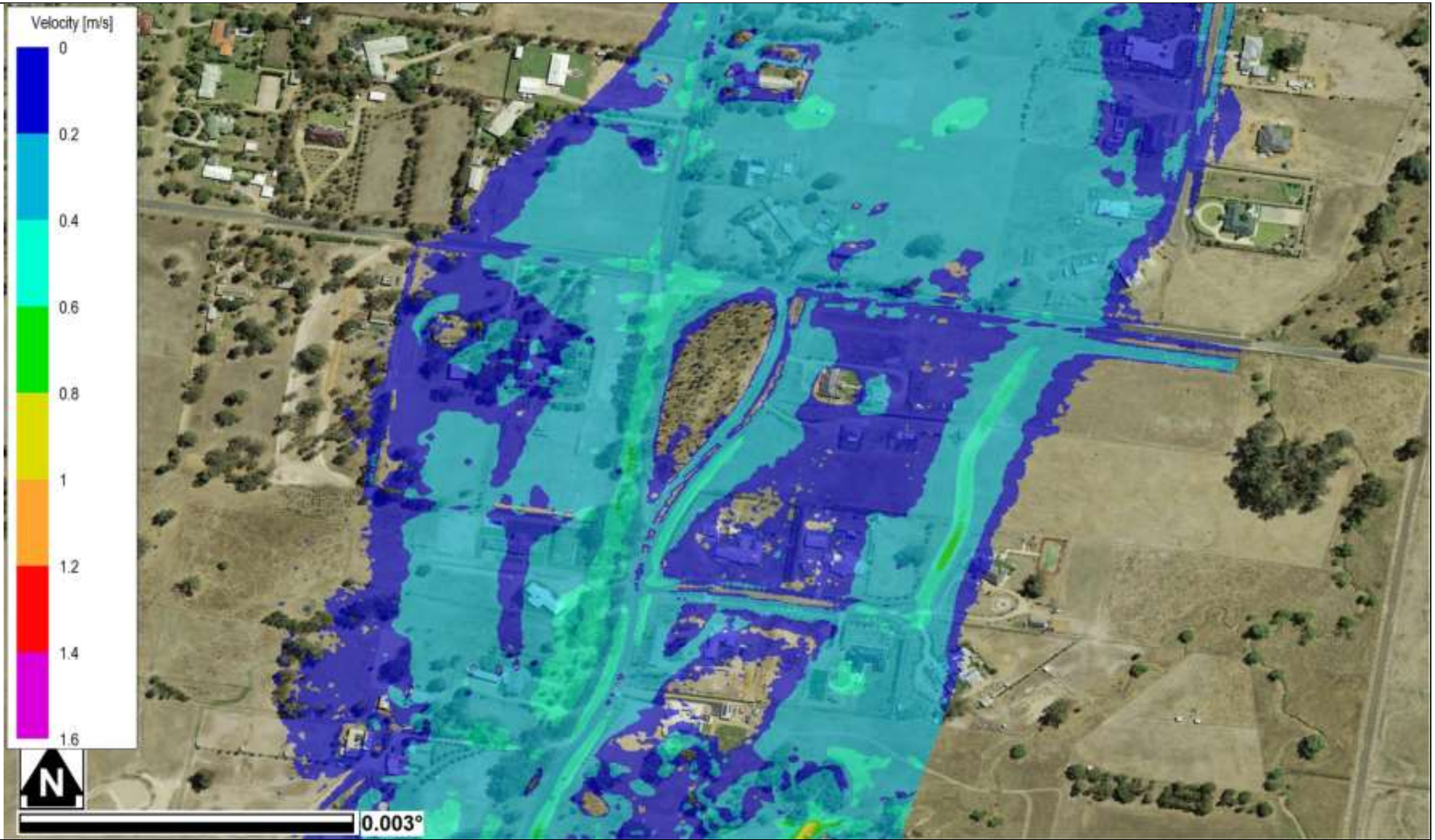

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Figure B37: Culvert4-20yr-Velocity

All information is provided "as is" and represents current information at the time of printing.

Date Printed: 09-04-20 21:11
Printed By: Amir Abbasnia
Document Version: 1.0A

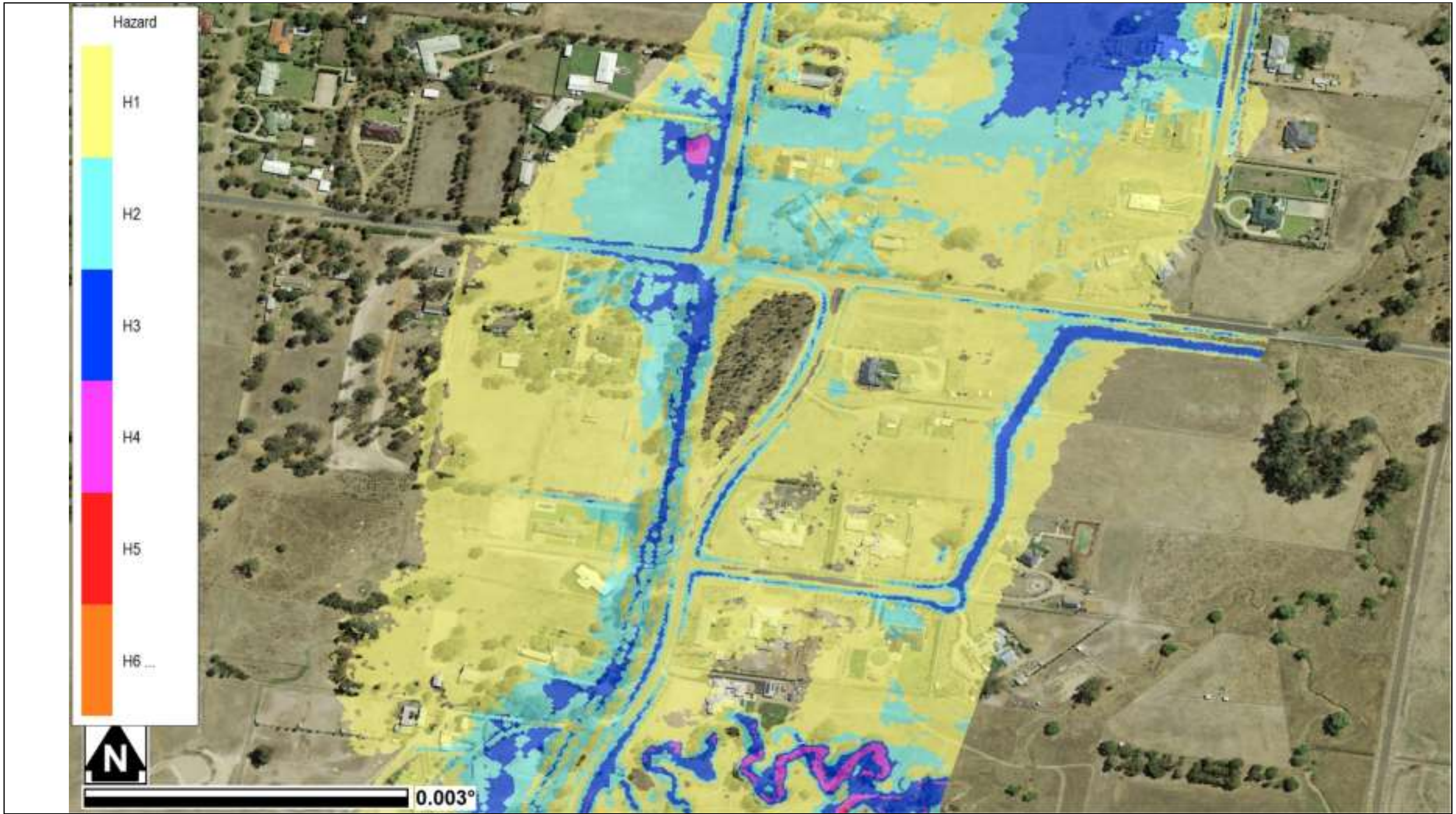

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Figure B38: Culvert4-20yr-Hazard-ARR 2016

All information is provided "as is" and represents current information at the time of printing.

Date Printed: 09-04-20 21:11
Printed By: Amir Abbasnia
Document Version: 1.0A

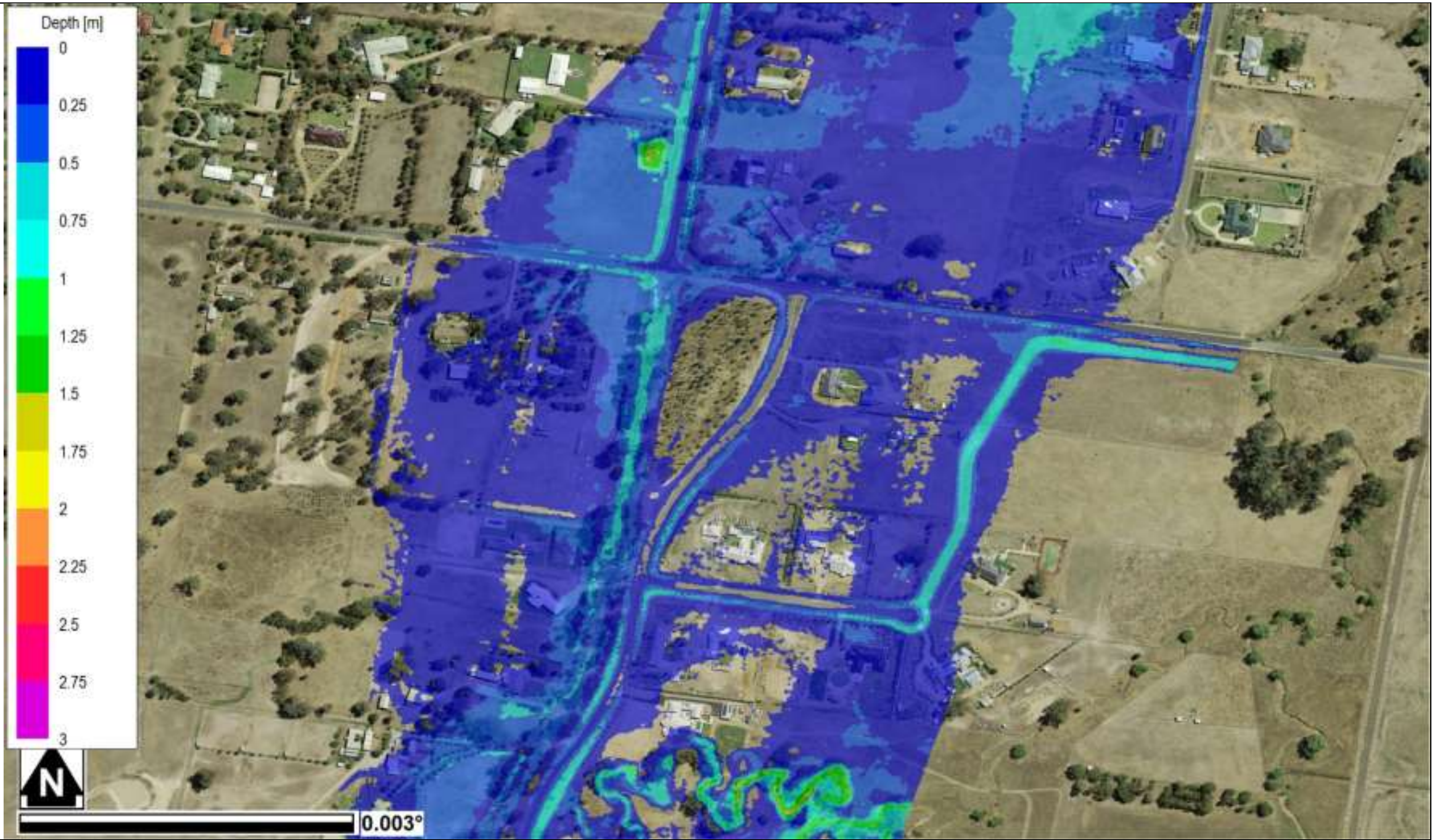

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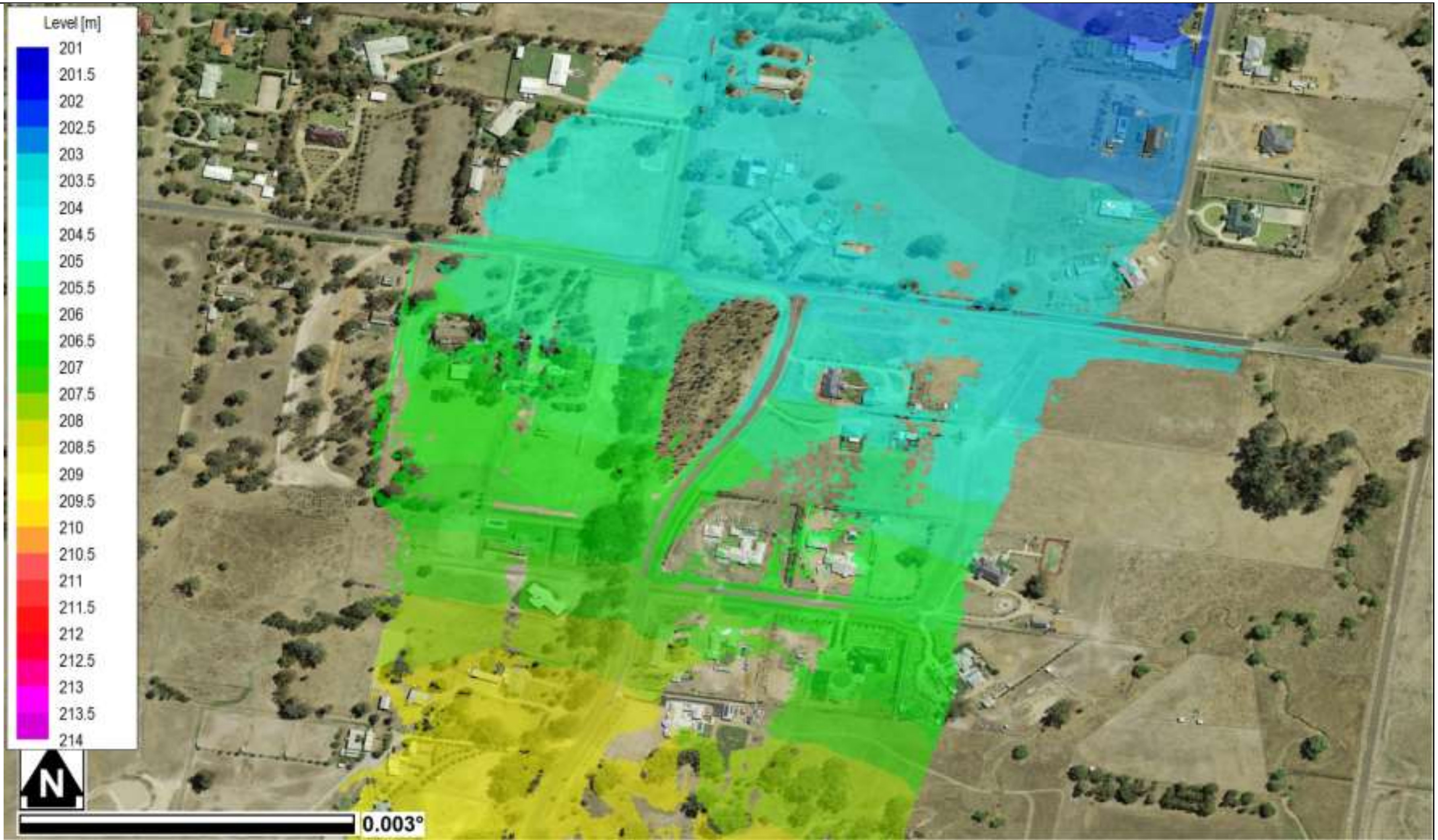
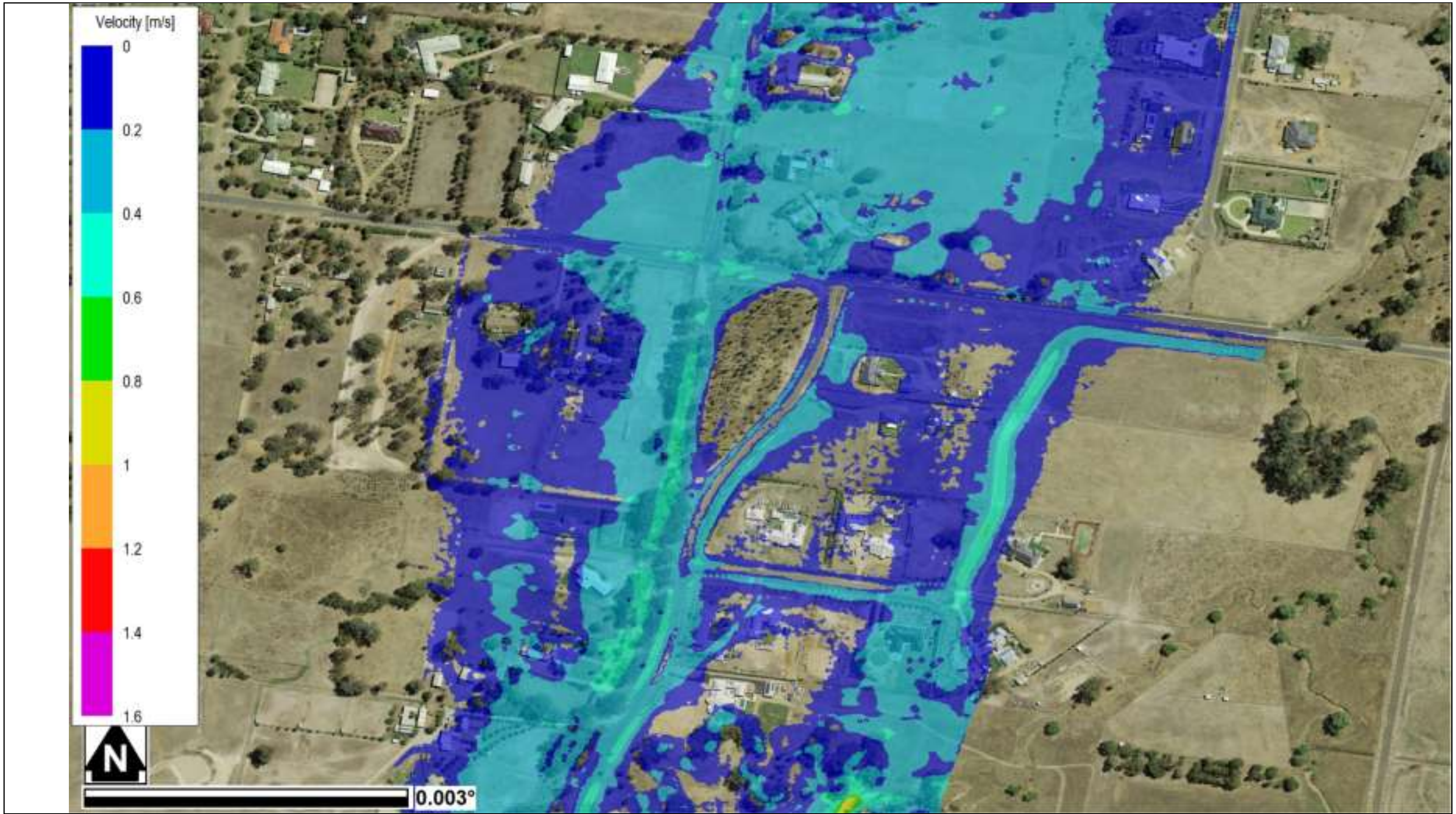
Figure B39: Culvert4-5yr-Depth

All information is provided "as is" and represents current information at the time of printing.

Date Printed: 09-04-20 21:12
Printed By: Amir Abbasnia
Document Version: 1.0A



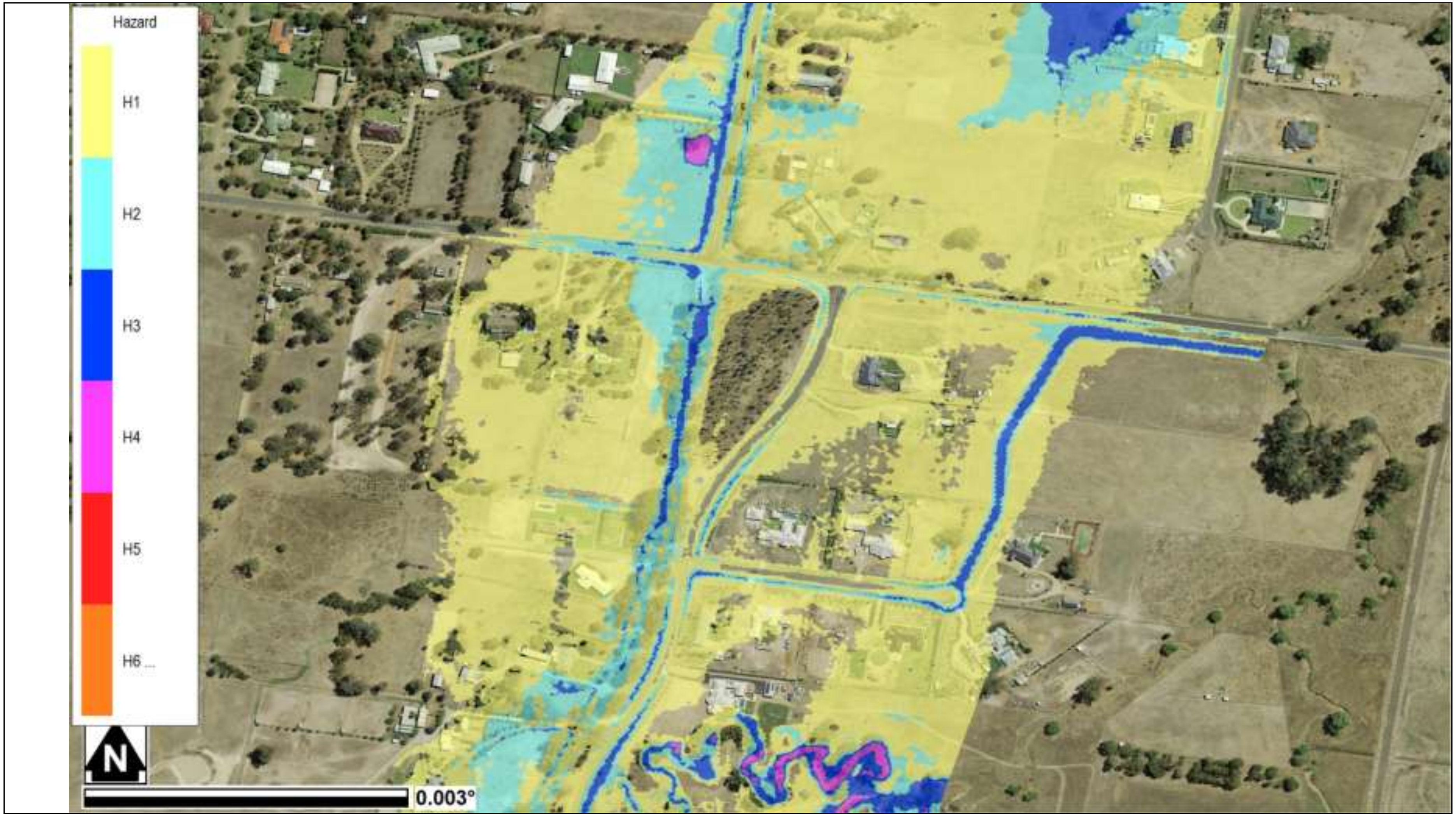
Wagga Wagga City Council	Figure B40: Culvert4-5yr-Level All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 21:13 **Printed By:** Amir Abbasnia **Document Version:** 1.0A



Wagga Wagga City Council

Figure B41: Culvert4-5yr-Velocity
All information is provided "as is" and represents current information at the time of printing.

Date Printed: 09-04-20 21:13
Printed By: Amir Abbasnia
Document Version: 1.0A



Wagga Wagga City Council	Figure B42: Culvert4-5yr-Hazard-ARR 2016 All information is provided "as is" and represents current information at the time of printing.	**Date Printed:** 09-04-20 21:13 **Printed By:** Amir Abbasnia **Document Version:** 1.0A