TECHNICAL REPORT 03

Updated flooding and hydrology assessment

Appendix Q Alternative flooding assessment for Bohena Creek

NARROMINE TO NARRABRI PROJECT

10 August 2022

Duncan Mitchell
ARTC Project Manager
Australian Rail Track Corporation
Level 16, 180 Ann Street
BRISBANE QLD 4000

Our ref: 2-0001-250-IHY-00-LT-0017
Your ref:

Dear Richard

Contract 2500-0001 – Phase 2 Narromine to Narrabri TACS
VO-064 – Alternative Flooding Assessment for Bohena Creek

1 Background

Submissions received on the EIS Technical Report 3 - Flooding and Hydrology Assessment Report (FHAR) identified concerns with the magnitude of predicted flooding from Bohena Creek. In particular, historical flood information for Bohena Creek was not available during Reference Design to reconcile peak discharges estimated by the RORB hydrology model against other independent estimates due to the lack of high quality recorded stream data. As a result, the calculated peak flood values were perceived to be conservative and it was noted that they were greater than peak flood values presented in the Bohena Creek Flood Study (2019) undertaken by WRM on behalf of Narrabri Shire Council (Attachment 1). It is also to be noted that the Bohena Creek Flood Study (2019) undertook an at-site flood frequency analysis with the available recorded stream data to reconcile the peak discharges for the design flood events estimated by the XPRAFTS hydrology model.

DPE provided an email on 18 February 2022 suggesting options to address perceived issues with N2N modelling at Bohena Creek which essentially comprised:

- Option A – adjust JGHD modelling to match WRM peak flows
- Option B – remodel Bohena Creek with revised inputs, consult with DPE and Council and reassess all impacts.

At the N2N project flooding meeting on 1 March 2022 it was agreed to proceed with a version of Option A, as clarified by correspondence from ARTC on 2 March 2022 (Aconex IR2500-GCOR-004328).

This approach was presented and discussed at the Hydrology Working Group (HWG) meeting on 2 March 2022. The scope below has been adjusted slightly to account for comments made at the HWG meeting.

2 Scope

The scope of the alternative flooding assessment for Bohena Creek as per the proposed approach to Option A includes the following:

- Scale down JGHD adopted flow hydrographs for design flood events for Bohena Creek to match peak flows adopted by WRM.

- Re-run N2N1 GDA1994 TUFLOW model for the following scenarios and flood events using peak flows estimated by WRM:
  - Existing case – 20%, 5%, 2%, and 1% AEP flood events
  - Operational phase – 20%, 5%, 2%, and 1% (with and without blockage) AEP flood events
- Prepare selected flood impact maps for the above scenarios and flood events.
- Analyse data in a new spreadsheet, separate from previous analysis undertaken for the FHAR. This spreadsheet would contain updated data for the N2N1 model only.
- Prepare a brief summary letter (this letter) of results for ARTC review.

A summary of the estimated peak flood flows and adopted scaling factors is provided in Table 1.

Table 1- Peak Flows in Bohena Creek and the adopted Scaling Factors

Flood Event (AEP)	JGHD Peak Flow [m^3/s]	WRM (2019) Peak Flow [m^3/s]	Adopted Scaling Factor
20%	1,392	113	0.081
5%	3,096	644	0.208
2%	4,377	1,145	0.262
1%	4,870	1,565	0.321

3 Results

The N2N1 TUFLOW model was run both for the existing condition and post-developed condition with the N2N project for the 1%, 2%, 5% and 20% AEP events using the scaled RORB inflow hydrographs to match peak flows for Bohena Creek estimated by WRM (2019) as shown in Table 1.

TUFLOW modelling results for both the existing condition and post-developed condition with the N2N project have been post-processed to prepare flood inundation and flood impact maps.

Modelled flood behaviour for the existing condition based on the alternative assessment has been compared with modelled flood behaviour reported in the FHAR and WRM (2019). In general, the extent and depth of flooding reported in the FHAR for the 1%, 2%, 5% and 20% AEP events are reduced significantly with the alternative estimates. The extent and depth of flooding in the existing case with the alternative estimate for the 1%, 2%, 5% and 20% AEP events are generally similar to WRM (2019).

Flooding impacts to buildings have been assessed with the alternative estimate and a comparison between the original estimate and the alternative are summarised in Table 2.

Table 2 shows that the alternate estimate results in huge reductions in the number of both habitable and non-habitable buildings which are subject to above floor flooding in the existing conditions. These results are more consistent with observations reported by local Narrabri residents and the WRM report.

Table 2 – Summary of buildings with modelled above floor flooding and afflux

TUFLOW N2N1 Model	20%	5%	2%	1%AEP
Number of Habitable Buildings modelled with above floor flooding				
Existing Environment				
Original estimate	9	34	44	48
Alternate estimate	1	2	4	12
Operational Phase				
Original estimate	8	32	43	47
Alternate estimate	1	1	4	12
Number of Non-Habitable Buildings modelled with above floor flooding				
Existing Environment				
Original estimate	67	167	200	211
Alternate estimate	11	18	53	90
Operational Phase				
Original estimate	67	165	200	212
Alternate estimate	11	11	53	90
AFFLUX				
Operational Phase – Number of Habitable Buildings with Afflux >10mm				
Original estimate	0	3	3	3
Alternate estimate	0	0	0	0
Operational Phase – Number of Non-Habitable Buildings with Afflux >20mm				
Original estimate	0	10	3	5
Alternate estimate	0	1	0	0

4 Discussion

The alternative flooding assessment for Bohena Creek shows reduced extent and depth of flooding for the existing condition in the 1%, 2%, 5% and 20% AEP events than that shown in the FHAR. This is due to the fact that peak flows in Bohena Creek adopted in the FHAR have been scaled to match peak flows adopted in WRM's Flood Study Report for Bohena Creek (2019).

Commentary on the alternative methodologies available for estimating flood flows is provided in the report in Attachment 2. This also discusses uncertainties in stream data from the Bohena Creek gauging station.

Figures provided in Attachment 3 illustrate the difference in flood extents and the associated property impacts between the original flood estimates and the alternative estimate. It should be noted that many of the properties with predicted above floor flooding are located some distance downstream of the proposed N2N Alignment. The original flooding assessment only reported three residential buildings being subject to an afflux greater than 10 mm and five non-residential properties being subject to an afflux of greater than 20 mm in the 1% AEP event. These impacts have both reduced to zero for the 1% AEP event, although there is one non-residential building that is now subject to an afflux of greater than 20 mm in the 5% AEP event. Irrespective of which method is used to estimate the flood magnitude, the number of impacted buildings from the Inland Rail N2N project is considered small.

It is recommended that the flooding assessment Bohena Creek should be updated during detailed design with revised inputs through further investigation of historic flood data and consultation with Narrabri Shire Council.

5 Conclusions

Submission comments received on the EIS along with consultations with local residents, Narrabri Council and WRM all indicate that in this instance, flood levels in Bohena Creek presented in the FHAR may be overestimated, compared to what has been observed in the area over the past 40 years or so. With this in mind, the number of properties reported with above floor flooding is likely to be less than reported in the FHAR.

Revising the analysis from the original values to the alternative assessment reduces the number of residential buildings subject to an afflux greater than 10 mm from three to zero in the 1% AEP event. However, there is one non-residential building that is now subject to an afflux of greater than 20 mm in the 5% AEP event with the alternative assessment.

In the absence of further information on historic flood data for Bohena Creek, a precautionary approach should be adopted for detailed design of bridge and culvert structures that considers the risks associated with floods estimated from the original and alternate analysis methods.

Regards

Richard Hackett
JGHD Project Manager

APPENDIX Q

Attachment 1 Flood study report for bohena creek WRM (2019)

NARROMINE TO NARRABRI PROJECT

Bohena Creek Flood Study

Narrabri Shire Council

0328-09 B DRAFT, 9 October 2019

Report Title	Bohena Creek Flood Study
Client	Narrabri Shire Council 45-48 Maitland St, Narrabri, NSW, 2390
Report Number	0328-09 B DRAFT

Revision Number	Report Date	Report Author	Reviewer
DRAFT	9 October 2019	RN	GR

For and on behalf of WRM Water & Environment Pty Ltd
Level 9, 135 Wickham Tce, Spring Hill
PO Box 10703 Brisbane Adelaide St Qld 4000
Tel 07 3225 0200

Greg Roads
Principal Engineer

Contents

List of Figures

List of Tables

1 Introduction

1.1 OVERVIEW

The township of Narrabri is located on the Namoi River floodplain and is drained by a number of smaller tributaries. There have been several studies prepared to define the flood risk from the Namoi River, however, the impacts of Bohena Creek on flood levels in the area have not been assessed. The location of the Bohena Creek catchment and the drainage characteristics of the area of interest are shown in Figure 1.1.

It is understood that Narrabri Shire Council (NSC) propose to rezone and develop land adjacent to Bohena Creek between Yarrie Lake Road and Culgoora Road. The land is currently zoned as RU1 and can be described as follows:

- Part Lot 4 DP757093 (portion south of Culgoora Road); and
- Lot 158 DP711841.

WRM have been commissioned by NSC to prepare a flood study of the Bohena Creek catchment and investigate the potential inundation of the proposed development. This report presents the results of the first stage of the study to define the existing flood risk to the development site.

The primary objectives of this phase of the study are to:

- determine the flood behaviour including design flood levels over the full range of flood events up to and including the Probable Maximum Flood (PMF) from Bohena Creek and the local stormwater catchments;
- provide hydrological and hydraulic models that can establish the effects on flood behaviour of future development; and
- determine the existing conditions flood risk at the site and in particular to determine whether the existing flood hazards would render the site suitable for development.

Subsequent phases of the study, if existing hazards are acceptable, will investigate the flood impacts of the proposed earthworks and development layout.

1.2 ADOPTED APPROACH

The approach adopted for this phase of the study involved:

- a review of available recorded flow data at stream gauges in and around Bohena Creek;
- developing and calibrating a computer based hydrological model (XP-RAFTS) to estimate design flood discharges throughout the study area;
- developing and calibrating a computer based hydraulic model (TUFLOW) to simulate the movement of floodwaters across the floodplain; and
- preparation of maps showing peak flood depth, extent and level and provisional hazard for a range of design flood events.

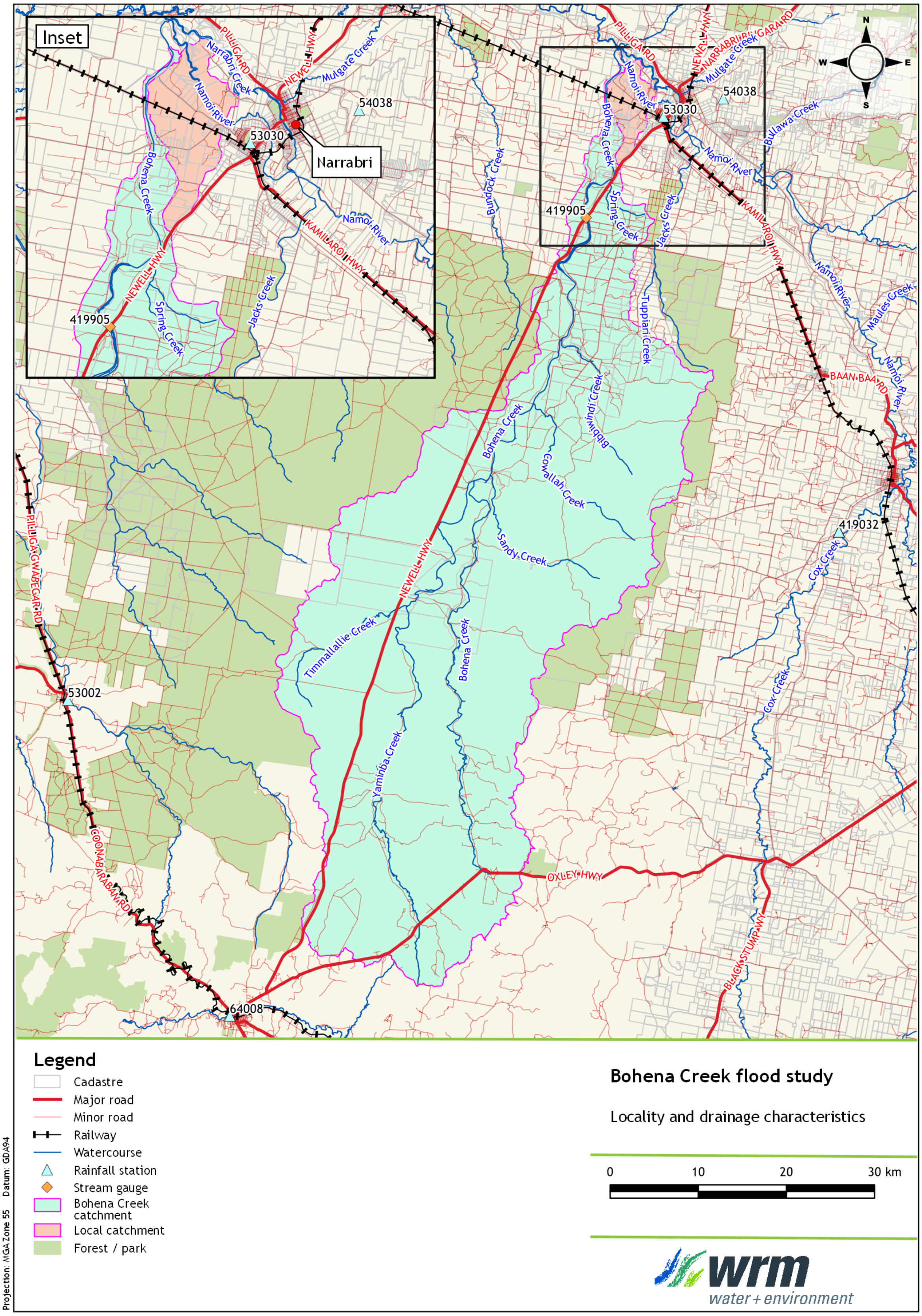


Figure 1.1 – Bohena Creek locality and drainage characteristics

1.3 REPORT STRUCTURE

The report is structured as follows:

- Section 2 describes the background and available data for the study:
- Section 3 describes the development and calibration of the XP-RAFTS model;
- Section 4 describes the methodology and validation process undertaken to determine design discharges;
- Section 5 describes the development and calibration of the TUFLOW model;
- Section 6 describes the design event flood mapping;
- Section 7 describes the hydraulic hazard category analysis and provides the provisional flood hazard categories proposed for the study area;
- Section 8 provides a summary of the findings for the study; and
- Section 9 is a list of references.

Three appendices are attached:

- Appendix A provides XP-RAFTS model box and whisker plots of the design event modelling;
- Appendix B provides the design event flood mapping; and
- Appendix C provides provisional flood hazard mapping.

2 Background

2.1 STUDY AREA DRAINAGE

Bohena Creek drains in a northerly direction into the Namoi River about 10 km downstream of Narrabri. It has a catchment area of over 2,100 km^2 to the confluence of Namoi River. The majority of the catchment is within the Pilliga Forest, which consists of State Forest, Nature Reserve or National Park. The geology of the catchment is dominated by the Pilliga Sandstone, with Cypress Pine as the dominant vegetation. The creek is ephemeral experiencing long periods (sometimes years) with little to no flow.

East of Bohena Creek, local catchments totalling 17 km^2 drains runoff northward to rail culverts located at Narrabri Walgett Railway. Downstream of the railway, local catchment runoff drains to the confluence of Bohena Creek and Namoi River. The Bohena Creek catchment to the confluence of Namoi River and the local catchment are shown in Figure 1.1.

2.2 AVAILABLE DATA

A review of the available rainfall and water level data showed that sufficient data is available for the 1998 and 2004 events to calibrate the hydrology model.

2.2.1 Rainfall data

Recorded rainfalls (pluviograph records) were available at the following nearby stations (shown in Figure 1.1) for the 1998 and 2004 historic flood events:

- Narrabri West Post Office (53030);
- Narrabri AWS (54038) (2004 only);
- Baradine Forestry Station (53002);
- Cox Creek at Boggabri (419032); and
- Coonabarabran (64008).

Synoptic data was sourced from the Bureau of Meteorology (BOM) and the Office of Water NSW (Water NSW). Note that there are no rainfall stations with available data within the Bohena Creek catchment for either event.

2.2.2 Stream flow data

Stream flows have been recorded by Water NSW in Bohena Creek at the Newell Highway (station number 419905) since May 1995. Data at the gauging station was used for hydraulic model calibration and discharge estimation. The location of the gauge is shown in Figure 1.1. The highest recorded peak water level at this station of 2.977 m gauge height (GH) occurred in July 1998. The recorded peak annual discharges at this gauge are given in Table 2.1.

Figure 2.1 shows the gaugings and the derived water level discharge relationship at the Newell Highway gauge. The historical gaugings are physical measurements of the stream flow, which are used to derive the rating curve when sufficient gaugings have been undertaken across a range of water levels. There have only been two gaugings undertaken at the station. Water NSW note that the rating is “not quality coded or subject to change”.

Figure 2.1 also shows the rating curve derived from the TUFLOW model (described in Section 5). The TUFLOW model rating curve is reasonably close to the Water NSW rating curve and the historical gaugings, which provides a level of confidence that the peak discharges derived from the recorded water levels is suitable for this study.

Table 2.1 - Historical annual maximum peak discharges, Bohena Creek at Newell Highway (419905)

Water year (Oct-Sep)	Peak discharge (m^3/s)	Water year (Oct-Sep)	Peak discharge (m^3/s)
1995/96	0.0	2007/08	0.0
1996/97	136.6	2008/09	0.0
1997/98	496.5	2009/10	25.0
1998/99	27.2	2010/11	167.8
1999/00	21.0	2011/12	18.6
2000/01	284.7	2012/13	0.0
2001/02	0.0	2013/14	0.0
2002/03	0.0	2014/15	0.0
2003/04	7.2	2015/16	15.2
2004/05	312.5	2016/17	0.0
2005/06	0.0	2017/18	0.0
2006/07	0.0	2018/19	0.0

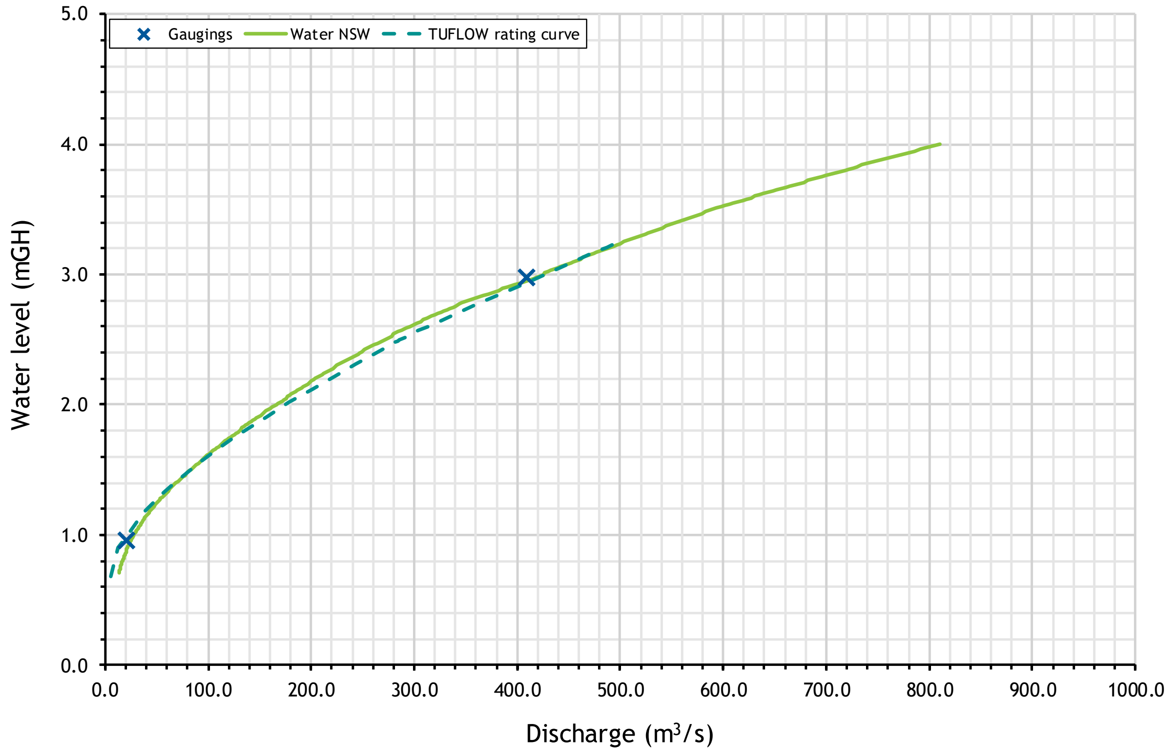


Figure 2.1 - Water level discharge relationship (rating) and stream gaugings, Bohena Creek at Newell Highway (419905)

3 Hydrologic model development and calibration

3.1 OVERVIEW

The XP-RAFTS rainfall runoff routing model (XP Software, Version 2018.1.2) was used to estimate discharge hydrographs for the two historical flood events. The calibrated XP-RAFTS model was then used to derive flood discharges for a range of design events (see Section 4).

The hydrologic model was calibrated to the available stream flow data for two historical flood events, the September 1998 event (the 1998 event) and the December 2004 event (the 2004 event).

The purpose of model calibration was to match as close as possible the predicted and recorded flood discharges at the Bohena Creek gauge at Newell Highway using a single set of hydraulic parameters and more specifically, to derive appropriate rainfall losses suitable to adopt for design event modelling.

Given there are considerable uncertainties using rainfall temporal patterns obtained from rainfall station data outside of the Bohena Creek catchment, the purpose of model validation was to ensure the model would reproduce recorded peak flood discharges rather than to match the recorded peak timing.

3.2 MODEL CONFIGURATION

Figure 3.1 shows the subcatchments and routing link configuration of the Bohena Creek XP-RAFTS model. XP-RAFTS uses a network of nodes to represent subcatchments and links to represent the drainage systems between subcatchments. Subcatchments are defined at each node based on total area, impervious area, average catchment slope and roughness. The model was delineated into three main catchments for design event purposes as follows:

- The Bohena Creek catchment to Newell Highway, where the Bohena Creek gauge is located (referred to as the Bohena Creek gauge catchment);
- The Bohena Creek catchment downstream of Newell Highway to the confluence of Namoi River (referred to as the Bohena Creek confluence catchment); and
- The local catchment adjacent to Bohena Creek draining to the confluence of Namoi River downstream of Culgoora Road (referred to as the local catchment).

The Bohena Creek gauge catchment consists of 45 subcatchments and has a total catchment area of 2,034 km^2. The Bohena Creek confluence catchment consists of 50 subcatchments and has a total catchment area of 2,104 km^2, including the 45 subcatchments form the Bohena Creek gauge catchment. The local catchment consists of 14 subcatchments and has a total catchment area of 35 km^2. Overall, the subcatchments range in size from 0.4 km^2 to 117.5 km^2. Details of the adopted XP-RAFTS subcatchment areas and links are given in Table 3.1 and Table 3.2 respectively.

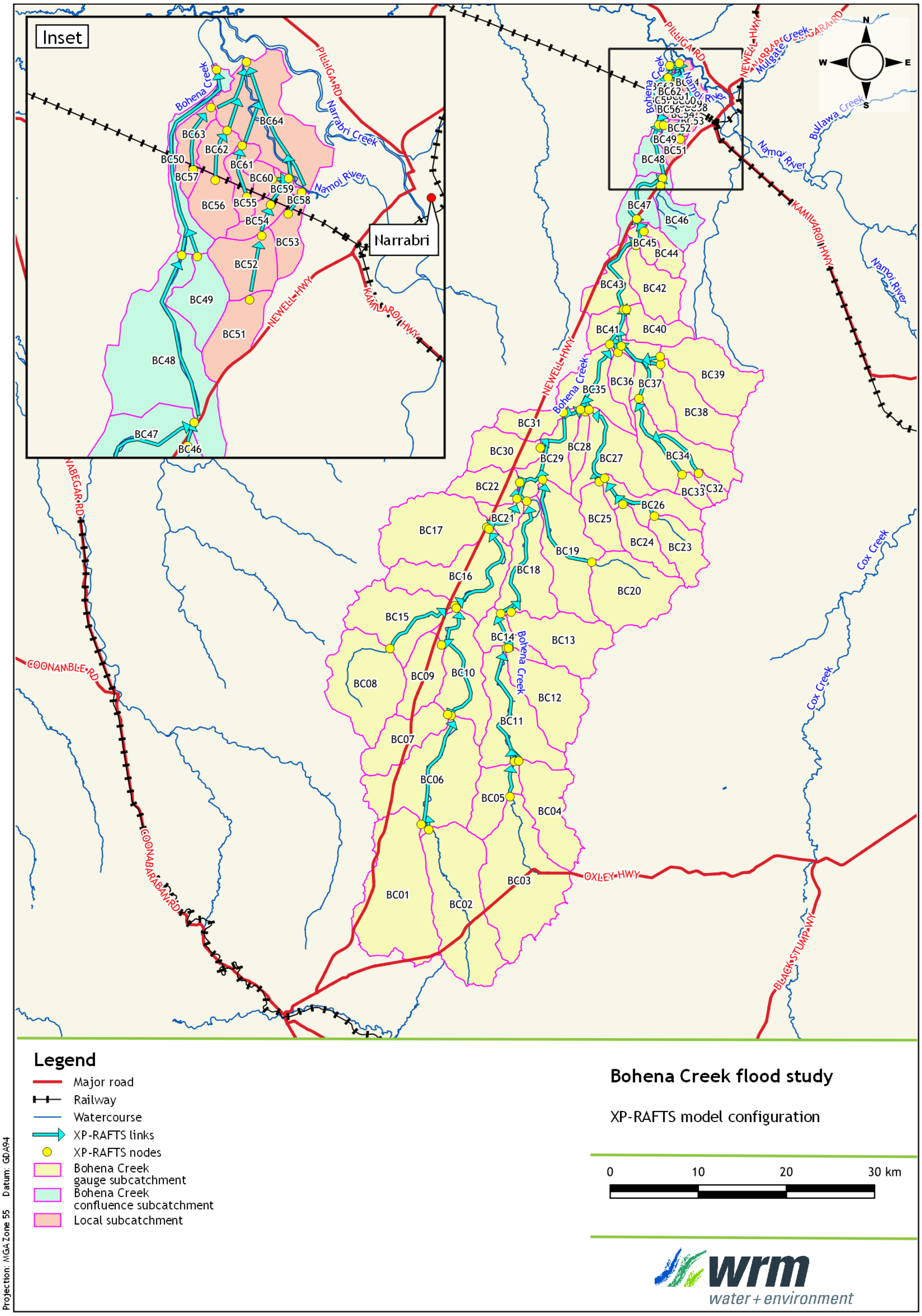


Figure 3.1 – XP-RAFTS model configuration

Table 3.1 – XP-RAFTS catchment parameters

Sub-catchment ID	Area (ha)	Vectored slope (%)	Sub-catchment ID	Area (ha)	Vectored slope (%)
BC01	117.5	1.17	BC33	9.6	1.74
BC02	109.1	1.22	BC34	59.1	0.94
BC03	112.6	0.97	BC35	39.3	0.29
BC04	51.8	1.00	BC36	15.5	0.45
BC05	32.3	1.35	BC37	33.6	0.58
BC06	105.8	1.02	BC38	42.9	0.86
BC07	39.4	1.30	BC39	52.6	0.73
BC08	79.3	1.09	BC40	22.5	0.38
BC09	33.6	1.27	BC41	17.9	0.25
BC10	59.3	0.66	BC42	32.4	0.51
BC11	69.4	0.79	BC43	30.3	0.34
BC12	57.4	0.94	BC44	12.8	0.82
BC13	54.8	0.86	BC45	9.4	0.91
BC14	20.3	2.02	BC46	22.8	0.48
BC15	63.4	0.77	BC47	23.7	0.30
BC16	72.7	0.66	BC48	16.2	0.24
BC17	77.6	0.77	BC49	4.1	0.21
BC18	56.3	0.54	BC50	3.6	0.17
BC19	70.4	0.58	BC51	4.2	0.19
BC20	66.2	1.03	BC52	4.5	0.23
BC21	14.9	1.13	BC53	2.1	0.24
BC22	26.4	0.86	BC54	1.5	0.26
BC23	30.4	1.24	BC55	0.9	0.28
BC24	24.5	1.18	BC56	3.1	0.31
BC25	24.9	1.12	BC57	0.8	0.35
BC26	31.0	1.02	BC58	0.4	0.88
BC27	49.8	0.72	BC59	0.9	0.59
BC28	10.5	0.62	BC60	1.0	0.41
BC29	35.9	0.61	BC61	1.4	0.10
BC30	30.9	0.75	BC62	2.1	0.25
BC31	20.8	0.71	BC63	1.8	0.19
BC32	7.0	1.89	BC64	10.4	0.12

Table 3.2 – XP-RAFTS routing link parameters

Link ID	Link length (km)	Channel routing, K (hours)	Link ID	Link length (km)	Channel routing, K (hours)
BC01toBC06	14.6	2.03	BC32toBC34	12.4	1.73
BC02toBC06	15.2	2.11	BC33toBC34	10.6	1.47
BC03toBC05	3.8	0.53	BC34toBC37	7.8	1.08
BC04toBC11	15.3	2.12	BC35toBC41	4.4	0.61
BC05toBC11	15.2	2.10	BC36toBC41	5.4	0.75
BC06toBC10	14.6	2.03	BC37toBC41	5.5	0.76
BC07toBC10	14.9	2.08	BC38toBC37	5.4	0.74
BC08toBC15	9.4	1.30	BC39toBC37	5.3	0.74
BC09toBC10	5.4	0.75	BC40toBC41	0.2	0.03
BC10toBC16	13.7	1.90	BC41toBC43	10.4	1.44
BC11toBC14	4.0	0.56	BC42toBC43	0.2	0.03
BC12toBC11	4.0	0.56	BC43toBC45	2.8	0.39
BC13toBC18	16.0	2.22	BC44toBC45	1.6	0.22
BC14toBC18	17.1	2.38	BC45toBC47	7.4	1.03
BC15toBC16	13.6	1.89	BC46toBC47	0.5	0.07
BC16toBC21	5.4	0.76	BC47toBC48	6.4	0.89
BC17toBC21	5.3	0.73	BC48toBC50	7.7	1.06
BC18toBC29	15.6	2.16	BC49toBC50	7.8	1.09
BC19toBC29	11.2	1.55	BC51toBC52	2.3	0.31
BC20toBC19	12.5	1.73	BC52toBC54	1.0	0.14
BC21toBC22	1.5	0.21	BC53toBC58	0.8	0.11
BC22toBC29	13.3	1.85	BC54toBC59	1.2	0.16
BC23toBC26	7.5	1.05	BC55toBC61	3.0	0.42
BC24toBC26	3.5	0.49	BC56toBC62	1.7	0.24
BC25toBC27	9.4	1.31	BC57toBC63	2.4	0.33
BC26toBC27	9.6	1.33	BC58toBC64	6.4	0.89
BC27toBC35	8.4	1.16	BC59toBC64	5.8	0.81
BC28toBC35	8.4	1.17	BC60toBC59	0.5	0.07
BC29toBC35	8.3	1.15	BC61toBC64	3.1	0.44
BC30toBC29	7.8	1.09	BC62toBC64	2.7	0.38
BC31toBC29	1.9	0.26	BC63toBC64	2.6	0.36

The following is of note:

- Catchment slopes were derived from available LiDAR;
- A global Catchment Manning's 'n' value of 0.08 was derived during model calibration;
- All subcatchments were assumed to be pervious;
- Channel routing was determined using the Muskingum method with 'K' values (in hours) calculated based on link length and an assumed channel velocity using:
    - A constant channel velocity of 2.0 m/s adopted for all links; and
    - A channel storage exponent 'x' of 0.30 adopted for all links.

The channel routing parameters, which are unusually high, were derived as part of model calibration.

3.3 HYDROLOGIC MODEL CALIBRATION

Total event rainfalls for each sub-catchment of the XP-RAFTS model was estimated by weighting recorded rainfall data based on the square of the inverse distance from the centroid of each sub-catchment to the nearest four rainfall stations, using the method described by Malone (2000). The rainfall temporal pattern for each sub-catchment was then obtained by applying the temporal rainfall distribution derived from the nearest pluviograph station.

The XP-RAFTS model uses initial and continuing losses to estimate the volume of runoff for a particular rainfall event. The net rainfall (after appropriate losses are deducted) is then routed through the drainage network and the result is a surface runoff hydrograph at the catchment outlet and nominated nodes. The predicted surface runoff hydrographs were compared to the recorded hydrographs at Bohena Creek gauge at Newell Highway, and calibration losses were iterated to achieve a predicted peak discharge that matched the recorded data.

3.3.1 September 1998 event

3.3.1.1 Recorded rainfall

Table 3.3 shows the daily rainfalls recorded at four rainfall stations in the vicinity of the study area over the four days to 0900 hours on 7 September 1998. The highest recorded rainfalls occurred in the 24 hours to 0900 hours on 5 September 1998.

Table 3.3 - Recorded daily rainfalls for the September 1998 event

Station name	Station no.	Daily rainfall (mm) to 0900 hours			
		4 Sep	5 Sep	6 Sep	7 Sep
Narrabri West Post Office	53030	0.0	57.2	41.4	0.0
Baradine Forestry Station	53002	0.0	8.0	-	47.6
Cox Creek at Boggabri	419032	0.0	39.5	11.0	0.0
Coonabarabran	64008	0.0	24.6	19.2	0.0

- Missing data

Figure 3.2 shows the cumulative rainfall depths and adopted temporal patterns over the four days at Narrabri West Post Office, Cox Creek at Boggabri and Coonabarabran stations during the event. Note that it was assumed there was incomplete data at Baradine Forestry station and therefore Baradine Forestry station subcatchments adopted the total rainfall and were distributed using the Coonabarabran temporal pattern.

A comparison of recorded rainfalls at Narrabri West Post Office to design rainfalls obtained from BOM (2016) was undertaken. An analysis suggests that the 12-hour rainfall duration at this station had an annual exceedance probability (AEP) of about 7% (15 years annual recurrence interval (ARI)).

An initial loss (IL) of 2.5 mm and a continuing loss (CL) of 2.5 mm/hr were adopted for the simulation based on the model calibration results. Antecedent rainfall conditions were moderately wet prior to the September 1998 event with 54 mm recorded at the Narrabri West Post Office gauge in the 10 days prior to 4 September.

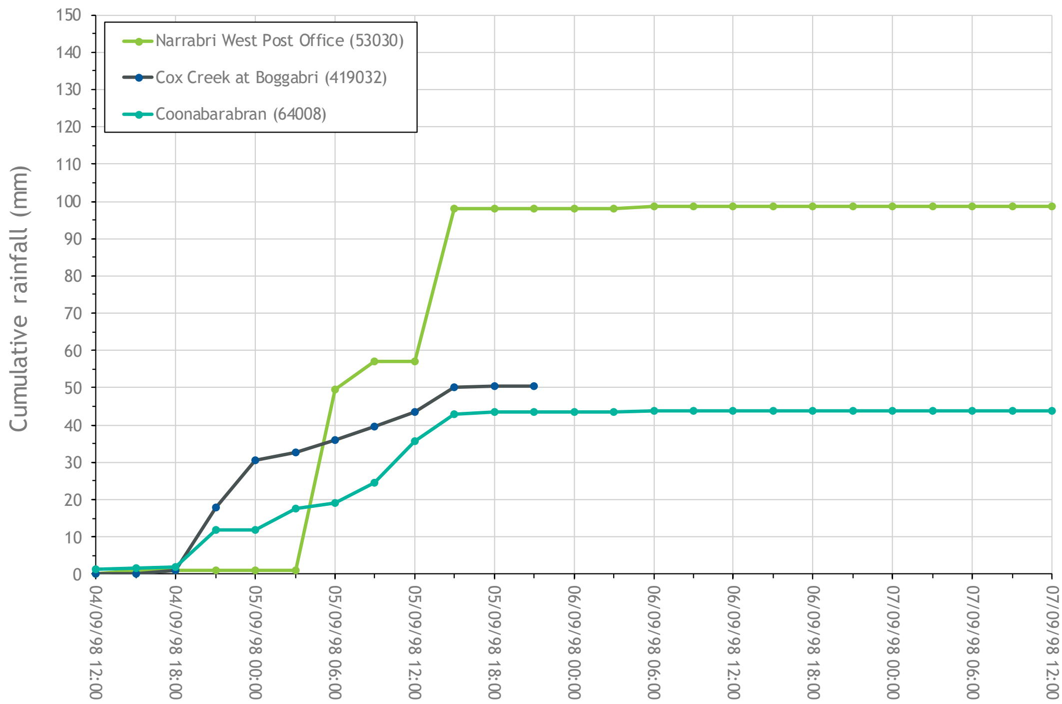


Figure 3.2 – Cumulative rainfalls and temporal patterns at the available stations, September 1998 event

3.3.1.2 Calibration results

Figure 3.3 shows the predicted vs recorded discharge hydrographs at the Bohena Creek gauge for the September 1998 event. The comparison shows that the timing of the predicted water level peaks at 2000 hours on 5 September 1998 compared to the recorded peak of 1300 hours on 5 September 1998. The recorded and predicted peak discharge was 497 m^3/s and 518 m^3/s respectively.

There is discrepancy in the timing of flood peaks with the predicted peak occurring 7 hours later than the recorded peak. It was not possible to reconcile the timing any better using the adopted temporal patterns.

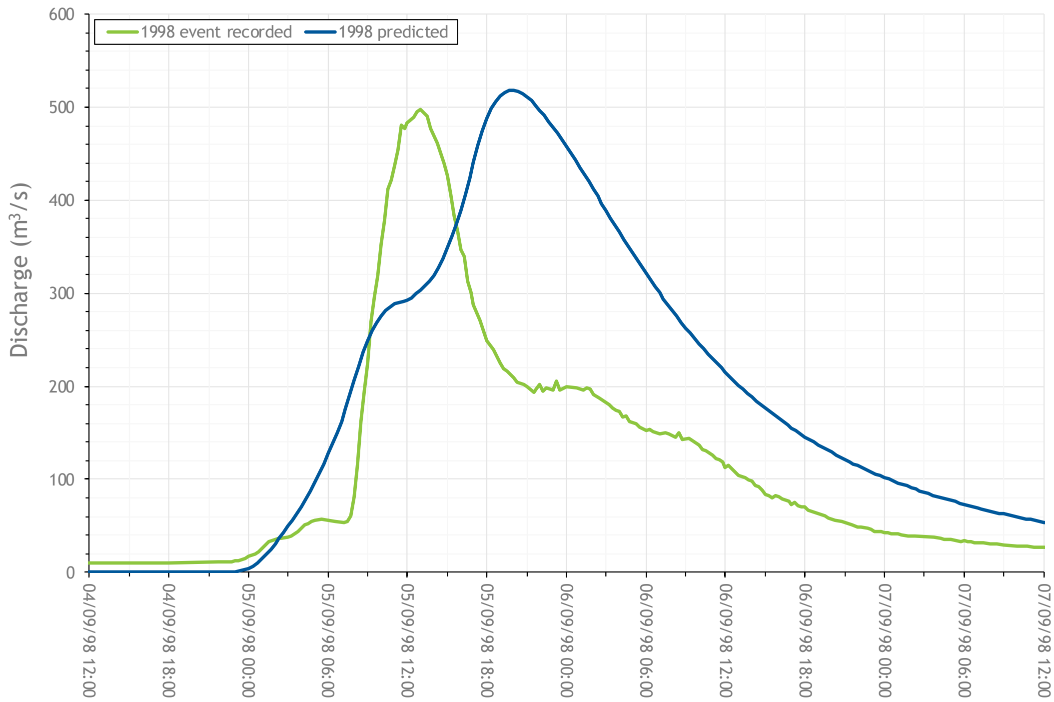


Figure 3.3 – Comparison of predicted vs recorded discharge hydrographs at Bohena Creek at Newell Highway, September 1998 event

3.3.2 December 2004 event

3.3.2.1 Recorded rainfall

Table 3.4 shows the daily rainfalls recorded at four rainfall stations in the vicinity of the study area over the seven days to 0900 hours on 13 December 2004. The highest recorded rainfalls occurred in the 24 hours to 0900 hours on 10 December 2004.

Table 3.4 - Recorded daily rainfalls for the December 2004 event

Station name	Station no.	Daily rainfall (mm) to 0900 hours						
		7 Dec	8 Dec	9 Dec	10 Dec	11 Dec	12 Dec	13 Dec
Narrabri Airport AWS	53030	15.6	14.2	0.2	125.2	27.4	1.0	2.6
Baradine Forestry Station	53002	8.0	-	-	50.2	3.6	-	35.8
Cox Creek at Boggabri	419032	7.5	7.0	21.0	77.0	10.5	1.5	-
Coonabarabran	64008	1.2	10.6	18.6	9.6	11.4	8.2	0.4

- Missing data

Figure 3.4 shows the cumulative rainfall depths and adopted temporal patterns at Narrabri Airport AWS, Cox Creek at Boggabri and Coonabarabran stations during the event. Note that it was assumed there was incomplete data at Baradine Forestry station and therefore Baradine Forestry station subcatchments adopted the total rainfall and were distributed using the Coonabarabran temporal pattern.

A comparison of recorded rainfalls at Narrabri Airport AWS to design rainfalls obtained from BOM (2016) suggests that rainfalls of 12 to 24 hours duration at this station had an annual exceedance probability (AEP) of about 4% (25 years annual recurrence interval (ARI)). The rainfall at other locations were less severe.

An IL of 50.0 mm and a CL of 4.7 mm/hr were adopted for the simulation based on the model calibration results. Antecedent rainfall conditions were moderately wet prior to the September 1998 event with 45.2 mm recorded at the Narrabri Airport AWS gauge in the 10 days prior to 9 December.

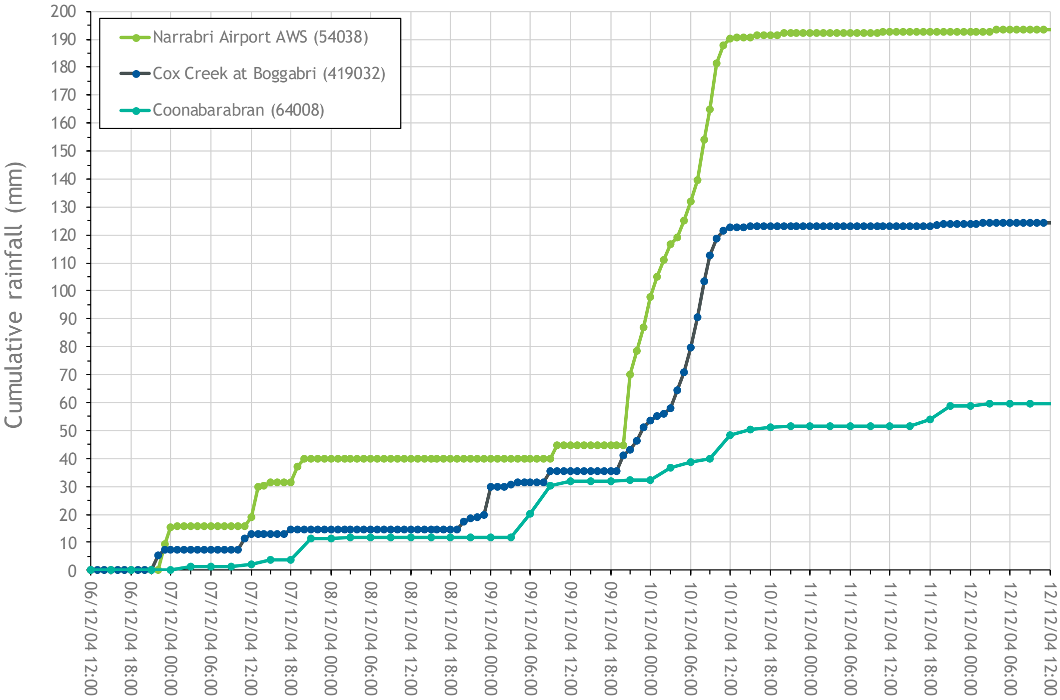


Figure 3.4 – Cumulative rainfalls and temporal patterns at the available stations, December 2004 event

3.3.2.2 Calibration results

Figure 3.5 shows the predicted vs recorded discharge hydrographs at the Bohena Creek gauge for the December 2004 event. The comparison shows that the timing of the predicted water level peaks at 1830 hours on 10 December 2004 compared to the recorded peak of 1100 hours on 10 December 2004. The recorded and predicted peak discharge was 314 m^3/s and 310 m^3/s respectively.

There is discrepancy in the timing of flood peaks with the predicted peak occurring 4 hours later than the recorded peak. It was not possible to reconcile the timing any better using the adopted temporal patterns.

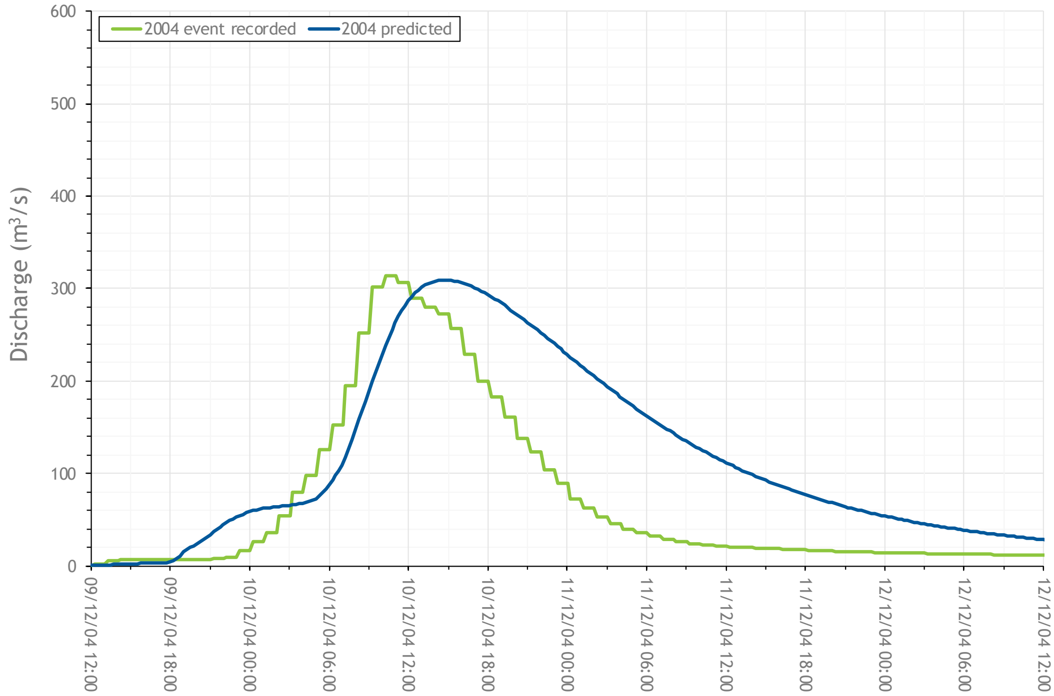


Figure 3.5 – Comparison of predicted vs recorded discharge hydrographs at Bohena Creek at Newell Highway, December 2004 event

3.4 DISCUSSION OF RESULTS

The discrepancy in peak timing between predicted and recorded discharge hydrographs for both historical flood events is likely due to differences in rainfall temporal patterns and the lack of recorded rainfall.

Although the timing of the predicted and recorded data does not match, the peak discharges at the Bohena Creek gauge at Newell Highway are replicated reasonably well. The hydrologic model should be acceptable to predict design discharges for the Bohena Creek catchment.

4 Estimation of design discharges

The calibrated hydrologic model was used to derive design discharges for the 20%, 10%, 5%, 2%, 1% AEP events and the PMF for existing conditions.

Design discharges were determined using the ensemble methodology defined in Australian Rainfall & Runoff (ARR) (Ball, et al, 2019). An ensemble of 10 temporal patterns is modelled for each storm duration to derive a range of estimated peak discharges for each location and AEP of interest. For each location and AEP, the storm duration with the highest median peak discharge of the ensemble is selected and the temporal pattern that produces the peak discharge just above the ensemble median is used for design event modelling.

To assist with defining rainfall losses for design event modelling, the Bohena Creek catchment discharges defined using the XP-RAFTS model were validated against an annual series flood frequency analysis (FFA) of the recorded flows at the Bohena Creek gauge at Newell Highway as well as design discharges derived using the Regional Flood Frequency Estimation (RFFE) methodology.

4.1 FLOOD FREQUENCY AND TERMINOLOGY

In this report, the frequency of floods is referred to in terms of their Annual Exceedance probability (AEP). The frequency of floods may also be referred to in terms of their Average Recurrence Interval (ARI). The relationship between AEP and ARI is given in Table 4.1.

Table 4.1 – Design events investigated

Annual exceedance probability (AEP) %	Average recurrence interval (ARI) years
20%	4.48
10%	9.49
5%	20
2%	50
1%	100
Probable Maximum Precipitation (PMP) flood	Theoretical maximum flood that could occur

The AEP of a flood represents the percentage chance of its being equalled or exceeded in any one year. A 1% AEP flood, which is equivalent to a 100 year ARI, has a 1% chance of being equalled or exceeded in any one year and would be experienced, on the average, once in 100 years.

4.2 DESIGN RAINFALLS

4.2.1 Events up to the 1% AEP

Rainfall depths for the 20%, 10%, 5%, 2%, 1% AEP design events were taken from the Bureau of Meteorology's (BoM) 2016 Intensity-Frequency-Duration (IFD) database and are provided in Table 4.2. An IFD located approximately in the centre of the Bohena Creek catchment was adopted.

Table 4.2 – Bohena Creek catchment design rainfalls

Duration (hours)	Rainfall depth (mm)					
	20%	10%	5%	2%	1%	PMP
1	36.4	43.8	51.2	61.3	69.4	-
2	45.4	54.5	63.5	76	85.8	-
3	51.7	61.8	72	85.9	96.9	-
6	65.1	77.4	89.9	107	121	-
9	74.9	88.9	103	123	138	-
12	82.9	98.4	114	136	153	670
18	95.5	113	132	157	177	730
24	105	125	146	174	196	800
36	119	143	167	200	226	940
48	129	155	182	218	248	1070
72	142	172	202	243	277	1290
96	150	181	213	258	294	1470
120	154	186	219	266	303	1550
144	157	188	222	269	307	-
168	158	189	222	270	307	-

4.2.2 Areal variability

Areal reduction factors (ARFs) based on the Bohena Creek catchment area were applied for design rainfalls up to 1% AEP as per the recommendation in AR&R (Ball et al., 2019). No ARF was adopted for PMP rainfalls due to catchment area already being incorporated into the PMP rainfall estimation.

4.2.3 PMP Flood

The probable maximum precipitation (PMP) rainfall depths for the Bohena Creek confluence catchment (Table 4.2) were estimated using the generalised tropical storm method revised (GTSMR) (BOM, 2003b) from the Bureau of Meteorology (BOM). The GTSMR can be applied to catchments with area up to 150,000 km^2 and durations up to 120 hours. The PMP has an AEP of approximately 1 in 800,000. The parameters used to determine GTSMR rainfalls include:

- The Bohena Creek confluence catchment has a total area of 2,104 km^2 to just downstream of Culgoora Road;
- Located in the coastal zone;
- Annual Moisture Adjustment Factor, AMAF equals to 0.65;
- Winter Moisture Adjustment Factor, WMAF equals to 0.60;
- Decay Amplitude Factor, DAF equals to 0.82;
- Topographical Adjustment Factor (TAF) equals to 1.28.

4.3 SELECTION OF APPROPRIATE RAINFALL LOSSES

The NSW Office of Environment and Heritage (OEH) in conjunction with WMA Water (2019) have reviewed the ARR design inputs for use in design flood estimation in NSW. This review was to address concerns raised by practitioners of the underestimation bias in the standard ARR 2016 method for deriving design events and to develop advice on any changes needed in the methods or parameters used for flood estimation in NSW.

For Bohena Creek, the two calibration events (September 1998 and December 2004) rainfall losses can be averaged to provide an estimate on appropriate losses to use in design event modelling. For this study, the rainfall losses were also derived by reconciling the design flows against FFA estimates at Bohena Creek gauge at Newell Highway. It is noted WMA Water (2019) has not derived rainfall losses for this station. Nearby catchments are also unrepresentative of the Bohena Creek catchment and therefore WMA Water (2019) losses are unlikely to be applicable.

4.4 ANNUAL SERIES FLOOD FREQUENCY ANALYSIS

Figure 4.1 shows the annual series FFA of the 24 years of recorded flows over water year's (October to September) at the Bohena Creek gauge at Newell Highway (419905). A Log-Pearson Type III (LP III) distribution was fitted to the annual series using the Bayesian inference methodology recommended in ARR (Ball et al, 2019) using the TUFLOW FLIKE Software version 5.0.251.0 (BMT, 2017). Nineteen low flows were censored from the dataset below 100 m^3/s. The peak annual discharges used in the analysis are given in Table 2.1. The expected range of design discharges from the FFA is given in Table 4.3.

ARR recommends the use of prior information for any FFA involving the LP III distribution unless there is evidence that the regional prior is not applicable to the catchment of interest. The prior information has been developed as part of the Regional Flood Frequency Estimation (RFFE), which calculates the mean, standard deviation and skew of the regional LP III model.

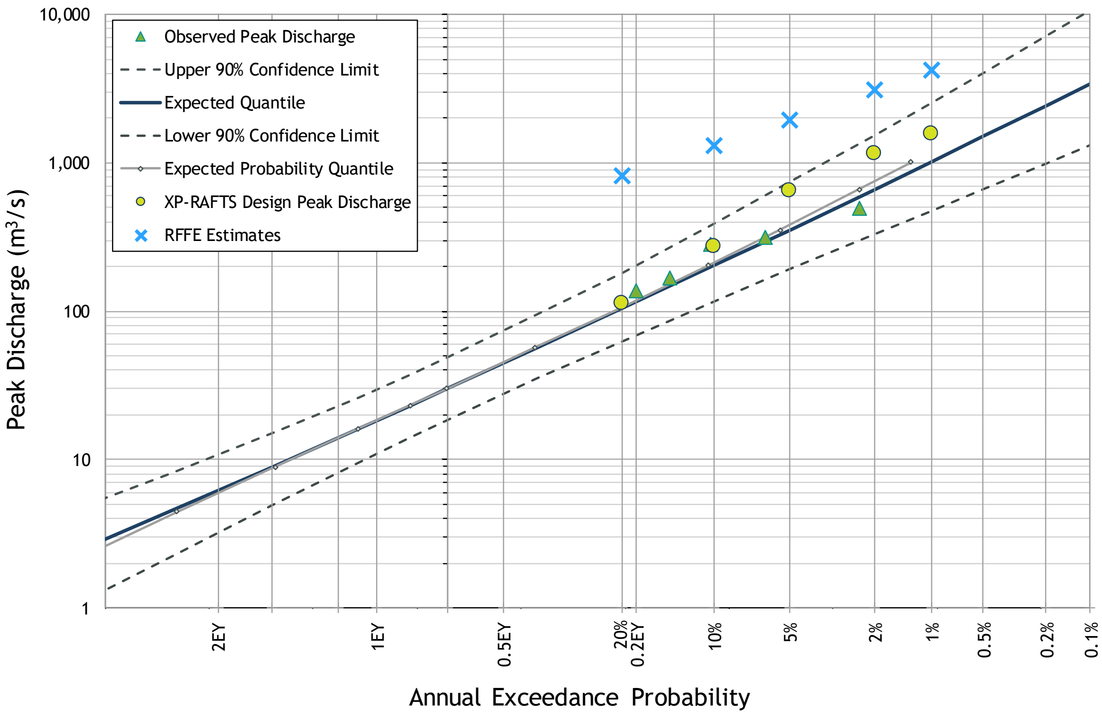


Figure 4.1 - Comparison of design discharges from XP-RAFTS, RFFE and FFA estimates with regional information

Table 4.3 - Comparison of design discharge estimates for Bohena Creek gauge catchment (FFA with prior information)

AEP	Adopted XP-RAFTS design discharge (m^3/s)	FFA discharge (m^3/s) (with prior information)			RFFE discharge (m^3/s)
		Lower 90% confidence limit	Expected parameter quantile	Upper 90% confidence limit	
20%	113	63	105	183	812
10%	273	116	203	388	1,310
5%	644	190	353	734	1,950
2%	1,142	329	663	1,534	3,080
1%	1,565	474	1,012	2,517	4,180

4.4.1 Regional Flood Frequency Estimation Model

Table 4.3 and Figure 4.1 shows the design discharges estimates using the RFFE methodology obtained from the ARR Datahub. The RFFE approach is recommended for use when a peak discharge estimate is required for small to medium sized ungauged catchments (Ball, et al, 2019). However, RFFE have estimates with a lower accuracy for catchments with a catchment greater than 1,000 km^2, such as Bohena Creek. The comparisons in Table 4.3 and Figure 4.1 show that the RFFE estimate is well above the 90%ile upper confidence limit from the FFA and has therefore been ignored.

4.4.2 XP-RAFTS design discharges

4.4.2.1 Up to 1% AEP event

Table 4.3 and Figure 4.1 compare the XP-RAFTS design peak discharges for the Bohena Creek gauge catchment to FFA estimates. The following is of note:

- For all AEP's, design rainfalls were obtained from BOM.
- Areal reduction factors (ARFs) were determined in accordance with ARR19 methodology.
- An initial rainfall loss of:
  - 80 mm was applied to the 20%, 10% and 5% AEP events;
  - 75 mm was applied to the 2% AEP event; and
  - 70 mm was applied to the 1% AEP event.
- A continuing loss of 4.7 mm/hr was adopted for all design events up to the 1% AEP event.

4.4.2.2 Probable maximum flood event

Design rainfalls for the PMF were determined in accordance with the Generalised Tropical Storm Method (revised) (BoM, 2005). An IL of 0 mm and CL of 1 mm/hr was applied. The critical duration storm for the catchment is the 12 hour event. The PMF discharge was derived using the XP-RAFTS model and is approximately 23,248 m^3/s.

4.5 BOHENA CREEK DESIGN DISCHAGRES

Table 4.4 shows the XP-RAFTS peak design peak discharges adopted and the corresponding critical durations and temporal patterns for Bohena Creek corresponding to 20%, 10%, 5% 2% and 1% AEP events.

For the PMF event, GTSMR specified temporal patterns were applied for design storm durations that are longer than 24 hours. Both GTSMR and GSDM temporal patterns were applied for design storm durations that are less than 24 hours and the critical temporal pattern was chosen.

To illustrate the variation in peak discharges from the ensemble of 10 temporal patterns for each storm duration for each event up to the PMF, Figure A.1 to Figure A.6 (in Appendix A) provide box and whisker plots (box plots) showing the distribution of peak discharges in Bohena Creek confluence for the six design events. For each duration, the rectangle box represents the 25%ile and 75%ile (1st and 3rd quartile, the interquartile range or IQR) bound of the estimate. The horizontal line at the top and bottom (whiskers) represents the upper and lower estimates for 1.5 times of the IQR. The horizontal line within the box is the median value and the “X” represents the mean value.

Table 4.4 – XP-RAFTS design discharges and critical durations for the Bohena Creek catchment

AEP	XP-RAFTS design discharge (m^3/s)	Critical duration (hours)	Adopted Temporal Pattern
20%	113	36	6
10%	273	72	10
5%	644	72	10
2%	1,145	72	3
1%	1,565	72	3
PMF	23,248	12	9

4.6 DISCUSSION OF RESULTS

The comparison of design discharge estimates at the Bohena Creek gauge at Newell Highway indicate that the regional method estimates using the RFFE vary significantly from the FFA estimates and therefore are unlikely to be suitable for the estimation of design discharges in Bohena Creek.

The XP-RAFTS results show a reasonable agreement with the FFA estimates with prior information for generally all design storm events using the adopted losses specified in Section 4.4.2. Due to the uncertainty around losses for the catchment, these higher rainfall losses were required to match the FFA estimates. The use of averaged calibration losses resulted in large overestimates in peak design discharges by XP-RAFTS, producing a discharge of 2,020 m^3/s which is well above the expected parameter quantile FFA estimate of 1,012 m^3/s. Given this, it was concluded that varying the IL as per Section 4.4.2 and adopting a CL of 4.7 mm/hr was appropriate for the design events in order to match the FFA with prior information.

5 Hydraulic model development and calibration

5.1 OVERVIEW

A TUFLOW (BMT, 2018) two-dimensional hydrodynamic model was developed to estimate regional flood levels, extents and depths along the channel and floodplain of Bohena Creek and the local overland flow catchments. TUFLOW estimates flood levels and velocities on a fixed grid pattern by solving the full two-dimensional depth-averaged momentum and continuity equations for free surface flow.

The hydraulic model was calibrated to the recorded water level data for two historical flood events, the September 1998 event (the 1998 event) and the December 2004 event (the 2004 event). The calibrated XP-RAFTS model flood discharge hydrographs from the two events were input to the TUFLOW model.

The purpose of model calibration was to match as close as possible the predicted and recorded peak water level at Bohena Creek gauge at Newell Highway using a reasonable Manning's 'n' value to represent the channel.

5.2 MODEL CONFIGURATION

Figure 5.1 shows the extent of the TUFLOW model. The model covers an area of approximately 195 km^2 and extends between Newell Highway (upstream) and 6.5 km downstream of Culgoora Road to the confluence of Bohena Creek (downstream). A 10 m grid cell size was adopted for the model.

5.3 TOPOGRAPHIC DATA

Model topography was configured based on one-metre ascii grids converted into digital elevation models (DEM) obtained by remote sensing light detection and ranging (LiDAR) techniques, captured in July 2014. Data was obtained from the Foundation Spatial Data Framework - Elevation and Depth portal (http://elevation.fsdf.org.au/) (referred to as ELVIS). Supplementary 5 m LiDAR captured in November 2017 was used where 1 m LiDAR was not available. The specified accuracy of the 1 m LiDAR is ± 0.3 m vertically and ± 0.8 m horizontally at the 95% confidence interval and the 5 m LiDAR is ± 0.9 metre vertically and ± 1.25 m horizontally at the 95% confidence interval on open bare ground.

The crest level of the Narrabri Walgett Railway was specified as break lines derived from the LiDAR. The location of the rail is shown in Figure 5.1.

5.3.1 Surface roughness

The TUFLOW model uses Manning's 'n' values to represent hydraulic resistance (notionally channel or floodplain roughness). The higher the roughness number, the more the flow would be impeded.

Discrete regions of continuous vegetation types and land uses were mapped, and appropriate roughness values assigned to each region. Vegetation and land use mapping were based on a combination of aerial photographs and topographic data. The Manning's 'n' values were selected during model calibration and were applied to all model scenarios. Table 5.1 shows the adopted Manning's 'n' values used in the model and Figure 5.2 shows the locations of the Manning's 'n' regions.

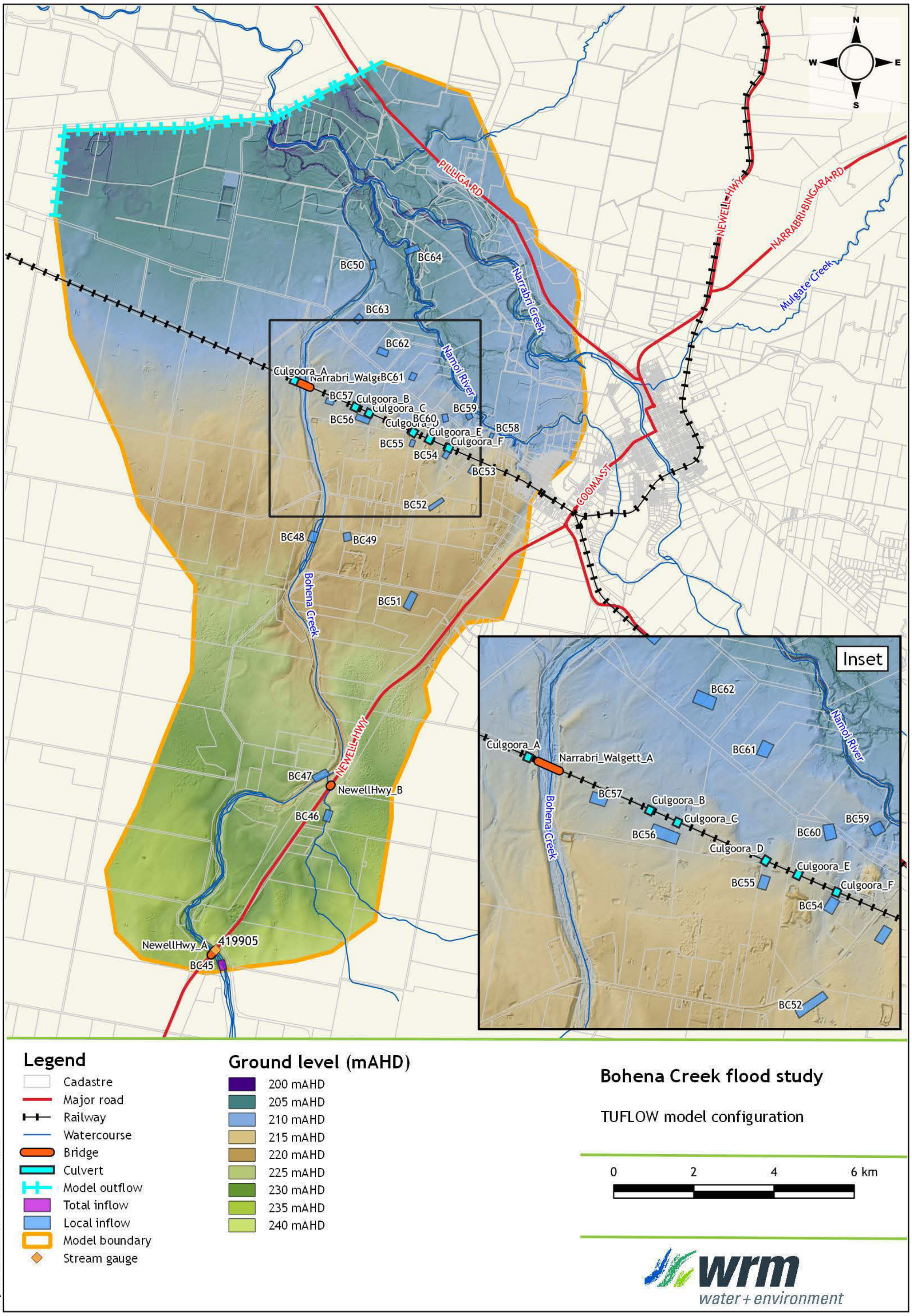


Figure 5.1 – TUFLOW model configuration

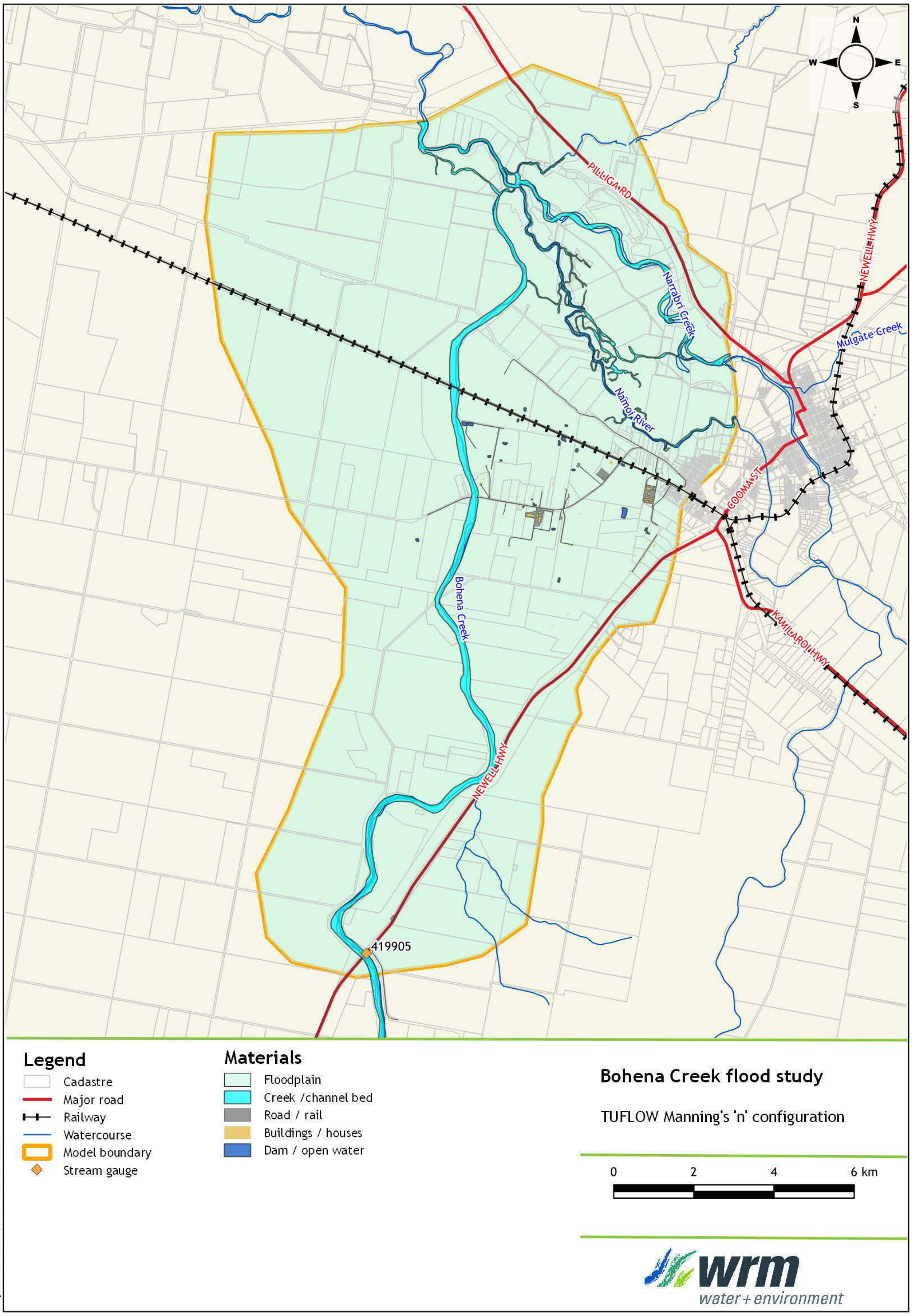


Figure 5.2 – Manning's 'n' configuration

Table 5.1 – Adopted hydraulic roughness Manning's 'n' values

Area	Manning's 'n'
Floodplain / dense vegetation	0.080
Creek / river channel	0.060
Road / rail	0.025
Buildings / houses	0.300
Dams / open water	0.035

5.3.2 Inflow and outflow boundaries

Figure 5.1 shows the locations of inflow and outflow boundaries used in the hydraulic model. A total of 20 inflow source areas (SA, flow versus time over an area) were used to represent the XP-RAFTS model subcatchment inflows. Water level versus flow outflow boundaries (HQ) were used at the downstream boundary. The adopted outflow boundary slopes were derived using LiDAR.

An analysis of the adopted tailwater boundary showed that the outflow boundary was far enough downstream that peak flood levels were not affected at the development site.

5.3.3 Hydraulic structures

A total of three bridges were modelled (Figure 5.1), one located on the Newell Highway at Bohena Creek gauge, one located on the Newell Highway at the Spring Creek crossing and one located on the Narrabri Walgett Railway west of the development site.

Bridges were modelled as 2D layered flow constrictions, with points snapped onto the lines to represent the road/rail elevation. A 1 m thick bridge slab and a 0.5 m high guardrail were adopted to model the bridges. Note that the bridge structures were estimated based on aerial imaging, with the bridge inverts estimated using LiDAR.

Culverts were modelled as a 1D structures, and were sized based on the site visit undertaken by WRM. Culvert invert elevations were estimated based on LiDAR information and aerial photos.

Details of the culvert and bridge structures included in the modelled area are given in Table 5.2 and Table 5.3.

Table 5.2 - Culvert details

ID	Dimension*	No. of barrels	U/S invert (mAHD)	D/S invert (mAHD)	Source
CulgooraRd_ A	900 mm CSP	1	211.81	211.42	Site visit
CulgooraRd_ B	600 mm CSP	8	211.42	211.39	Site visit
CulgooraRd_ C	900 mm CSP	11	211.42	211.39	Site visit
CulgooraRd_ D	750 mm CSP	4	211.84	211.63	Site visit
CulgooraRd_ E	900 mm CSP	4	212.95	212.85	Site visit
CulgooraRd_ F	900 mm CSP	15	211.55	211.50	Site visit

*CSP = corrugated steel pipe

Table 5.3 – Bridge details

ID	Deck span (m)	U/S invert (mAHD)	D/S invert (mAHD)	Source
NewellHwy_ A	200	235.40	235.29	Estimated
NewellHwy_ B	105	224.48	224.43	Estimated
Narrabri_Walgett_ A	285	214.95	214.90	Estimated

5.4 HYDRAULIC MODEL CALIBRATION

5.4.1 September 1998 event

Figure 5.3 shows the recorded and predicted water levels at the Bohena Creek gauge at Newell Highway. The predicted peak water level of 232.92 mAHD is slightly above the recorded peak of 232.84 mAHD. Overall, the model provides a reasonable representation of the 1998 event at Bohena Creek gauge using the limited information available based on the peak water level results.

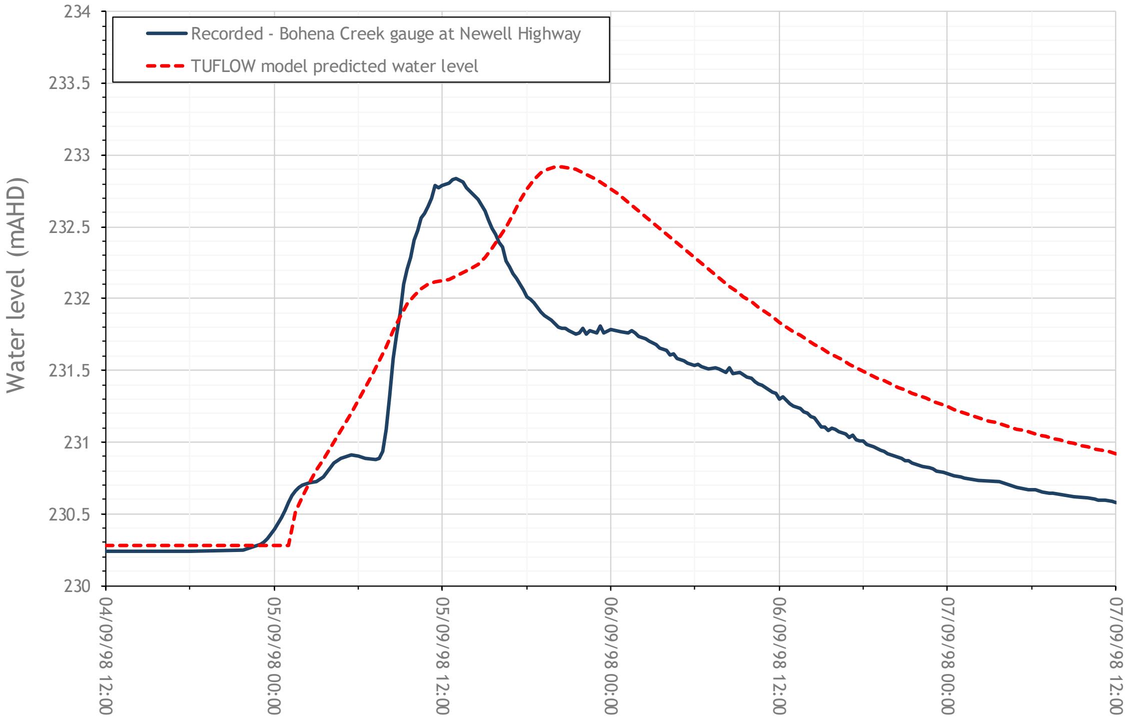


Figure 5.3 – Recorded and predicted water level hydrographs, September 1998 event

5.4.2 December 2004 event

Figure 5.4 shows the recorded and predicted water levels at the Bohena Creek gauge at Newell Highway. The predicted peak water level of 232.20 mAHD is slightly below the recorded peak of 232.27 mAHD. Overall, the model provides a reasonable representation of the 2004 event at Bohena Creek gauge using the limited information available based on the peak water level results.

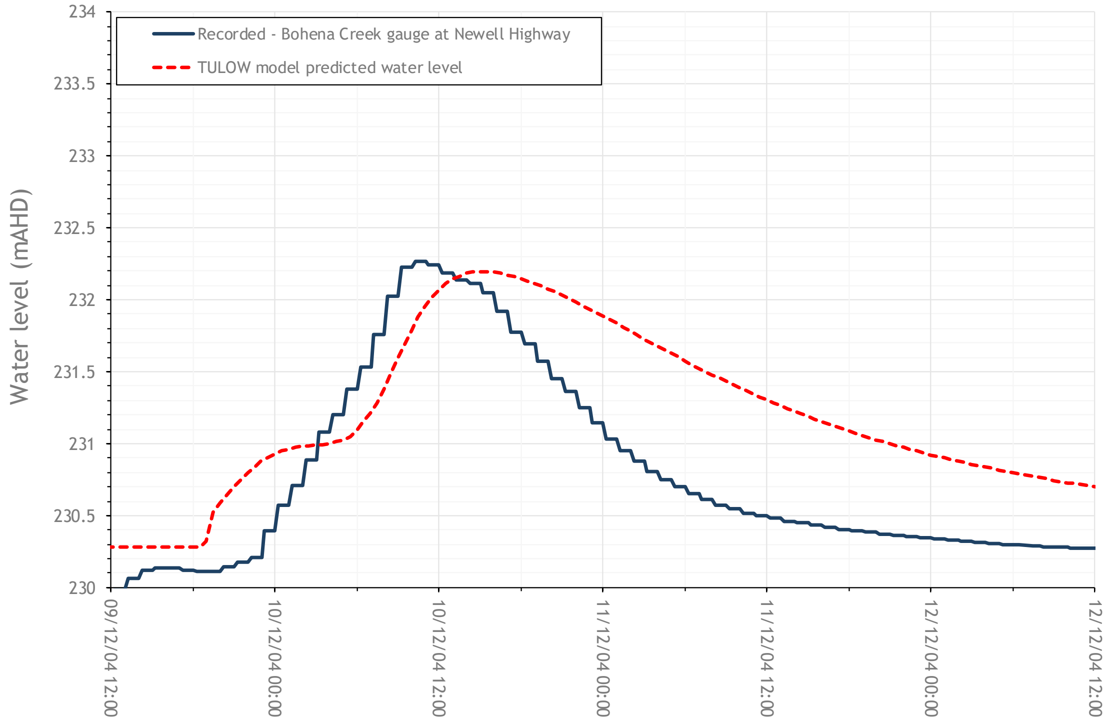


Figure 5.4 - Recorded and predicted water level hydrographs, December 2004 event

5.4.3 Rating curve review

The review of the stream flow rating curves at Narrabri, discussed in Section 2.3, shows that the hydraulic model was able to replicate the rating curve derived at Bohena Creek gauge at Newell Highway (419905) using the adopted Manning's roughness of 0.060 to represent the channel. The model predicts peak discharges and water levels reasonably well for both calibration events and therefore, the model should be suitable for the estimation of design flood levels, depths and extents within the Bohena Creek catchment.

6 Estimation of design flood levels

6.1 OVERVIEW

The calibrated TUFLOW model described in Section 5 was used to estimate peak depths, levels and extent of flooding for the 20% (5 year ARI), 10% (10 year ARI), 5% (20 year ARI), 2% AEP (50 year ARI) and 1% AEP (100 year ARI) design events and the PMF event for the Bohena Creek catchment. All model parameters derived via the model calibration remained unchanged for the design event modelling, with the exception of the design storm losses, as discussed in Section 4.4.2.

6.2 DESIGN FLOOD LEVELS, DEPTHS AND EXTENTS

Predicted flood extents, depths and flood contours for the six design events are shown in Appendix B. Figure 6.1 shows a longitudinal profile along Bohena Creek of peak flood levels for the September 1998 event, December 2004 event and the six design flood events. The longitudinal section begins just downstream of Narrabri Walgett Railway and finishes upstream of Newell Highway.

The following is of note:

- The longitudinal sections show that the Narrabri Walgett Railway bridge has at least 1% AEP flood immunity.
- Flows are generally contained within channel upstream of Narrabri Walgett Railway up to the 5% AEP event. The proposed development site (Lot 4 DP757093 and Lot 158 DP711841) is generally not inundated by Bohena Creek overbank flows for events up to the 5% AEP.
- Inundation via local catchment runoff draining to the rail culverts is generally shallow at less than 0.25 m. These shallow flows eventually drain across the rail to the floodplain between Namoi River and Bohena Creek. Local runoff generally ponds at the rail before draining through the rail culverts or overtopping the rail.
- Local runoff from catchments east of the proposed development does not affect the site.
- For the 2% and 1% AEP events, the creek has insufficient channel capacity and outbreak flows occur at several locations. At the proposed development, outbreak flows inundate the site by generally less than 0.25 m with the exception of the western part of Lot 4 DP757093, where flood depths exceed 0.50 m.
- Downstream of the Narrabri Walgett Railway, flows breakout into the floodplain for events equal to or greater than the 5% AEP.
- Substantial inundation occurs for the PMP Flood.

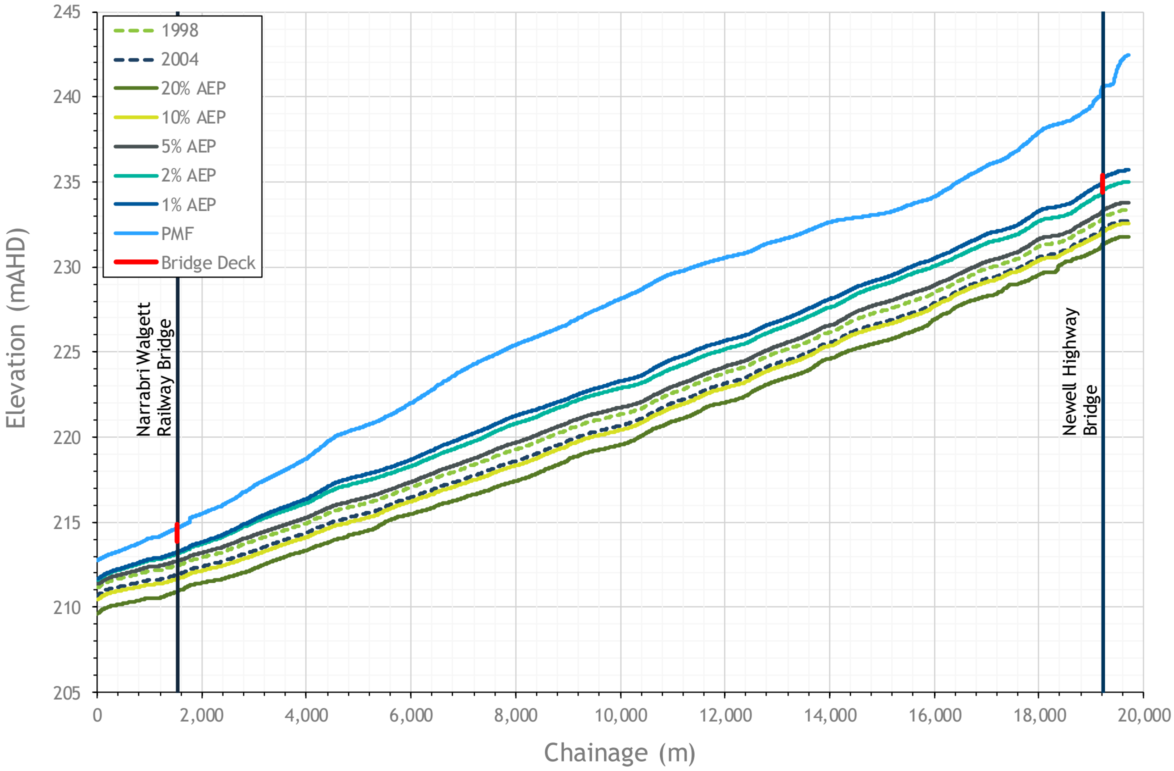


Figure 6.1 – Design and historical event longitudinal flood profiles, Bohena Creek

6.3 SENSITIVITY ANALYSIS

6.3.1 Changes in floodplain roughness

The hydraulic model was used to assess the sensitivity of peak flood levels to changes in channel roughness for the 1% AEP event. For the purpose of this assessment, the adopted channel Manning's n values were increased and decreased by 25%. The results of the sensitivity analysis are shown in Figure 6.2 and Figure 6.3.

The results show that increases in Manning's 'n' values along the channel bed increase peak flood levels along Bohena Creek by up to 0.50 m. At the development site, peak food levels increase by generally less than 0.10 m. The higher roughness value increases the number of breakout flows along Bohena Creek. The lower roughness produced lower peak flood levels and less breakout flows occurred, notably at just upstream of the railway and the proposed development.

6.3.2 Climate change

The Floodplain Development Manual (NSW Government, 2005a) recognises the need for analysis of the consequences of climate change on flood levels and flood behaviour. For this assessment, sensitivity to climate change was tested by increasing peak rainfall and storm volume by 30% (NSW Government, 2007) for the 1% AEP flood. This represents the 'worst case' of the three climate change sensitivity analyses recommended by the NSW Government (2007). The result of this sensitivity analysis is shown in Figure 6.4. The results show that climate change could increase peak 1% AEP flood levels significantly across the study area with an increase of up to 0.70 m at the proposed development. The increased rainfall intensities would significantly increase the flood extent and flood levels through the Bohena Creek floodplain.

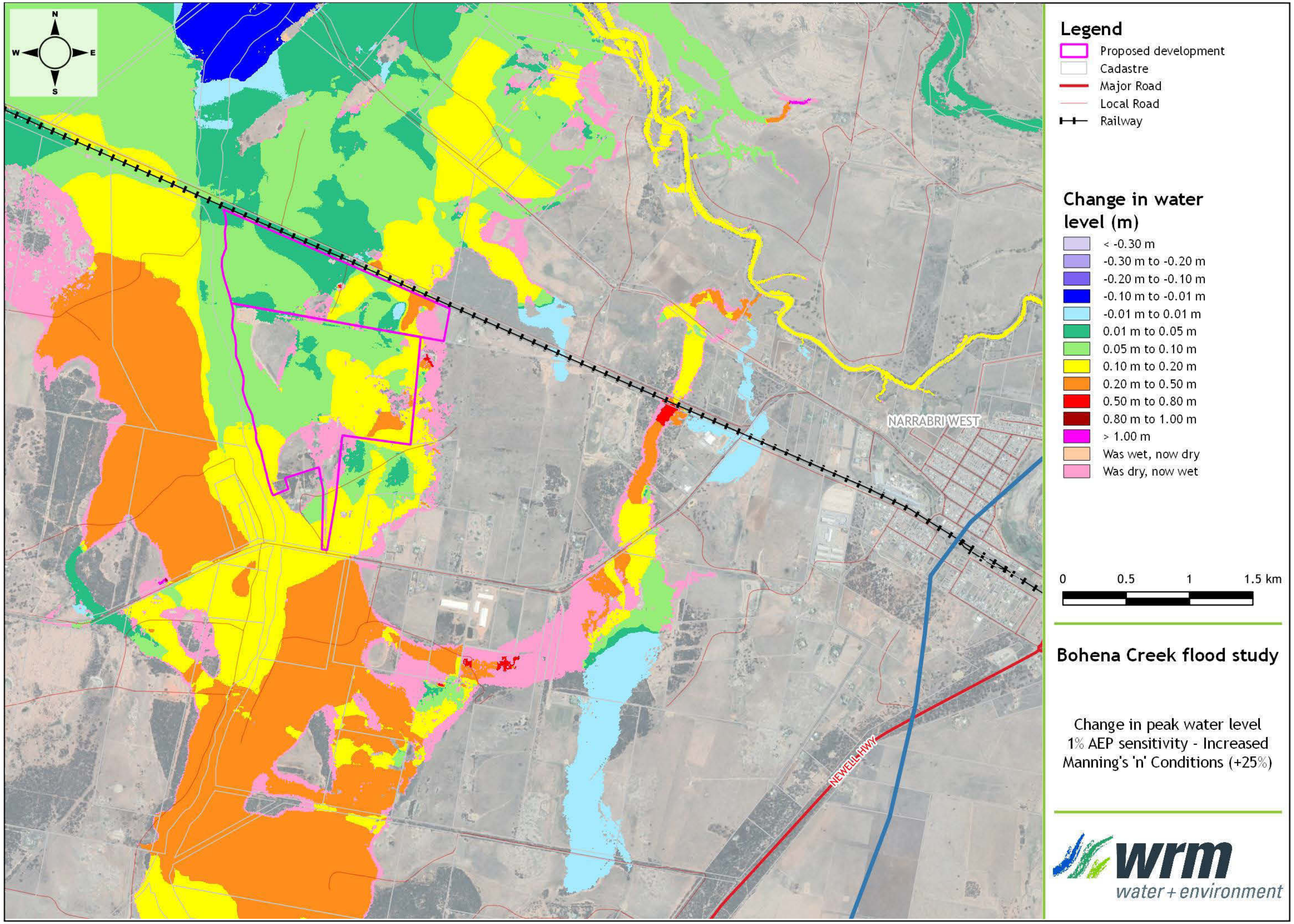


Figure 6.2 – Hydraulic model sensitivity to a 25% increase in channel Manning's roughness, 1% AEP event

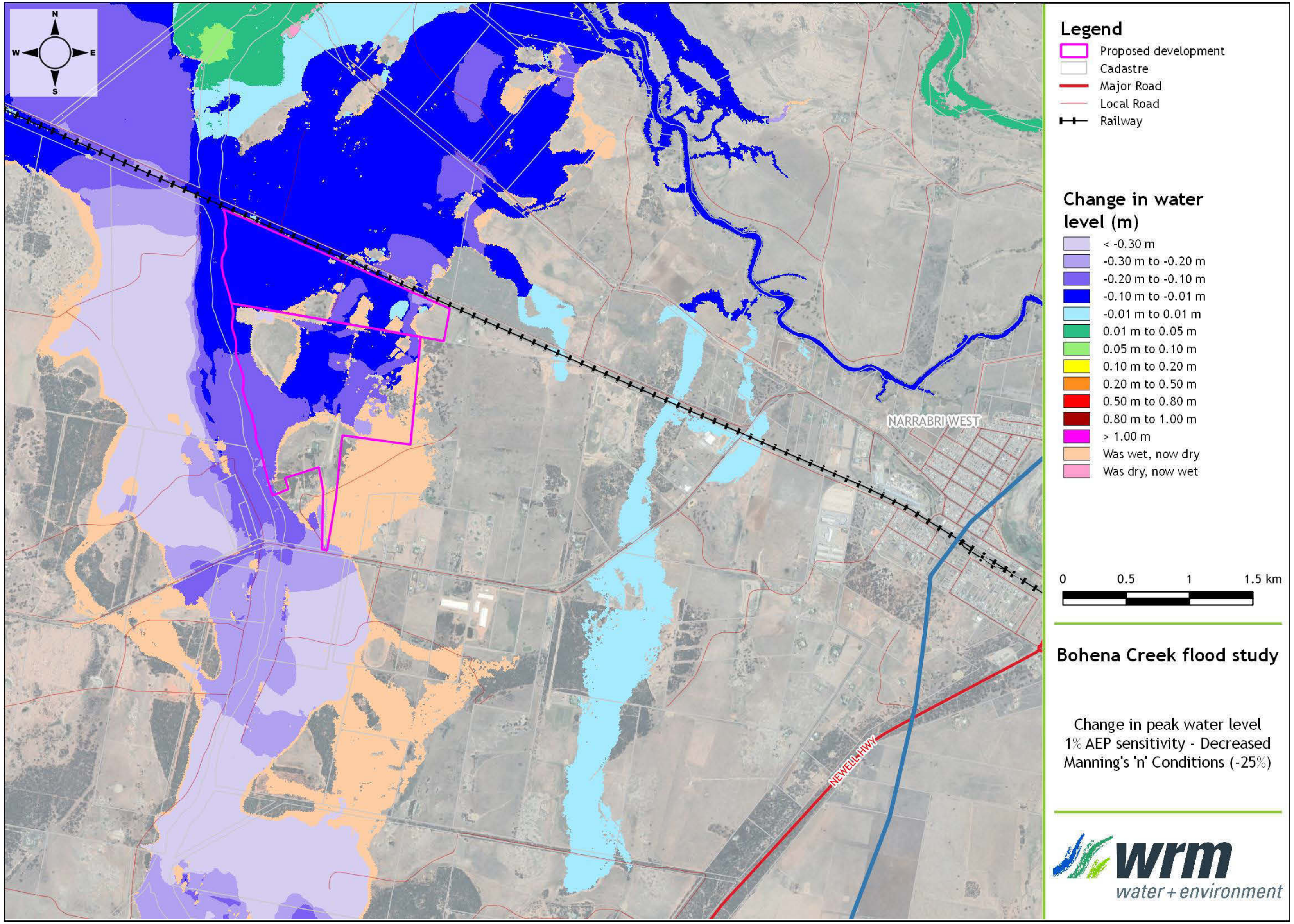


Figure 6.3 – Hydraulic model sensitivity to a 25% decrease in channel Manning's roughness, 1% AEP event

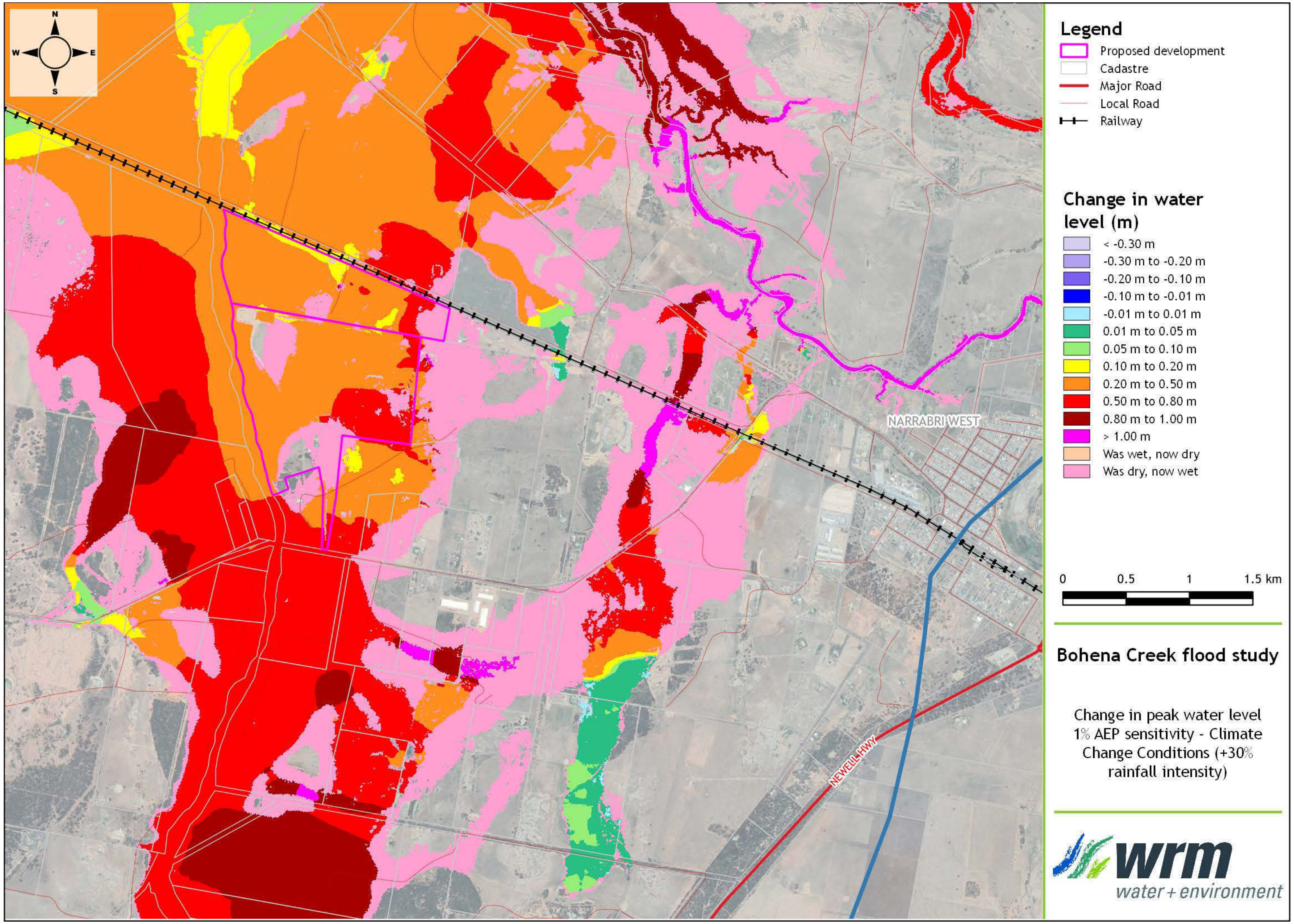


Figure 6.4 – Hydraulic model sensitivity to climate change, 1% AEP event

7 Provisional hazard mapping

7.1 OVERVIEW

Bohena Creek flooding does not affect heavily populated urban areas, however, any development within the catchment affected by flooding would be considered to be in a flood hazard zone as they are prone to damage if mitigation measures are not implemented. Provisional hazard mapping has been prepared for Bohena Creek flooding.

7.2 PROVISIONAL FLOOD HAZARD AND PRELIMINARY TRUE HAZARD

Figure C.1 to Figure C.6 in Appendix C show the provisional hazard categories in the study area assessed for the 20%, 10%, 5%, 2% and 1% AEP events and the PMF event. Provisional hydraulic hazards have been defined using the depth and velocity of the floodwaters calculated using the flood model determined in accordance with Figure 7.1 as outlined by *Australian Disaster Resilience Guideline 7-3 Flood Hazard* (AIDR, 2017).

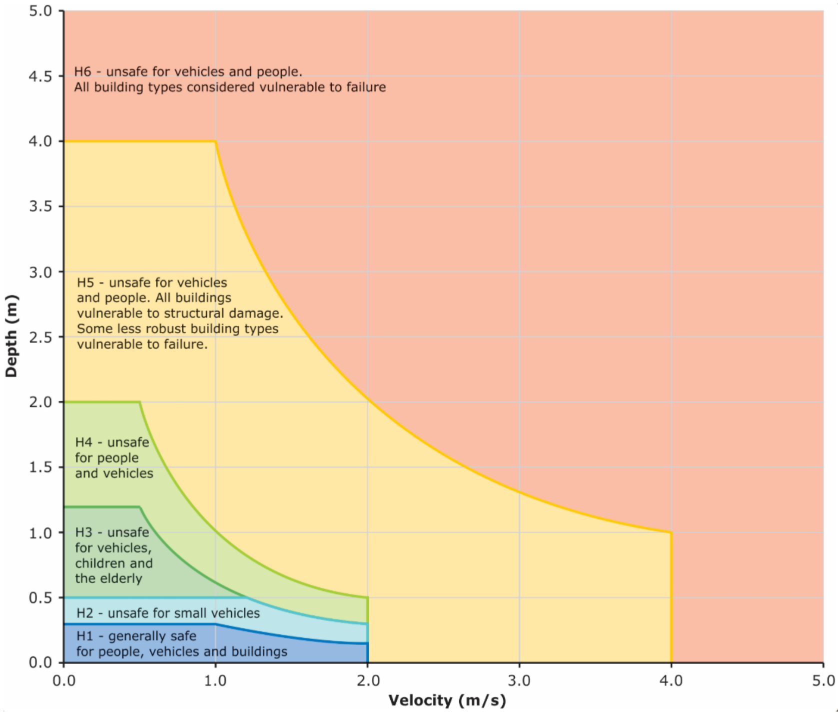


Figure 7.1 - Provisional hydraulic hazard categories (Source: AIDR, 2017)

Table 7.1 provides the assessable factors that determine the above hazard definitions for flood prone land. For Bohena Creek, those factors with a high weighting in relation to assessment of true hazard relate to the depth, velocity and duration of flooding. however, Bohena Creek flooding generally does not affect a large urban population. It is likely that most residents would not evacuate their properties for the moderate floods, which may mean evacuation for a very large flood could be a significant issue if roads are cut. Effective warning and management strategies are key to minimising the community risk should a large flood occur.

Table 7.1 - Combined Hazard Curves - Vulnerability Thresholds

Hazard Vulnerability Classification	Description	Classification Limit (D and V in combination)	Limiting Still Water Depth (D)	Limiting Velocity (V)
H1	Generally safe for vehicles, people and buildings.	D*V ≤ 0.3	0.3	2
H2	Unsafe for small vehicles.	D*V ≤ 0.6	0.5	2
H3	Unsafe for vehicles, children and the elderly.	D*V ≤ 0.6	1.2	2
H4	Unsafe for vehicles and people.	D*V ≤ 1.0	2	2
H5	Unsafe for vehicles and people. All buildings vulnerable to structural damage. Some less robust buildings subject to failure.	D*V ≤ 4.0	4	4
H6	Unsafe for vehicles and people. All building types considered vulnerable to failure.	D*V > 4.0	-	-

8 Summary

Narrabri Shire Council engaged WRM Water & Environment Pty Ltd (WRM) to prepare a flood study for a range of design events for the Bohena Creek catchment at a proposed development site between Yarrie Lake Road and Culgoora Road. The primary focus of the study is to map the flood risk for the design events across the development site. A XP-RAFTS hydrologic model and TUFLOW hydraulic model calibrated to two historical flood events, the September 1998 event and December 2004 event, were developed for the assessment.

Design discharges for the 20%, 10%, 5%, 2% and 1% AEP events were estimated using methodology recommended in AR&R19 (Ball et al., 2019) and validated to design discharges estimated from an annual series flood frequency analysis of recorded flows at the Bohena Creek gauge at Newell Highway. The Probable Maximum Flood (PMF) event was determined using the generalised tropical storm method revised (GTSMR) (BOM, 2003b) from the Bureau of Meteorology (BOM).

Hydraulic modelling of the study area has been undertaken to derive design flood levels, depths and extents for the 20%, 10%, 5%, 2% and 1% AEP flood events and an extreme flood. Preliminary flood hazard mapping has also been prepared.

Under Existing Conditions at the proposed development:

- Local catchment runoff from the site is shallow at generally less than 0.25 m.
- The site is inundated during events equal or greater than the 2% AEP event due to Bohena Creek breakout flows.

9 References

AIDR, 2017	*'Australian Disaster Resilience Handbook Collection – Flood Information to Support Land-use Planning'*, The Australian Institute for Disaster Resilience, Commonwealth of Austrlaia, 2017.
AEMI, 2014	*'Technical flood risk management guideline: Flood Hazard'*, Australian Emergency Management Institute, Barton, ACT, 2014.
Ball et al., (2019)	*'Australian Rainfall and Runoff: A Guide to Flood Estimation'*, Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors) Commonwealth of Australia (Geoscience Australia), 2019.
BMT (2018)	*'TUFLOW Classic/HPC User Manual Build 2018-03-AD'*, BMT WBM Pty Ltd, 2018.
BoM (2005)	*'Guidebook to the Estimation of Probable Maximum Precipitation: Generalised Tropical Storm Method'*, Hydrometeorological Advisory Service, Commonwealth Bureau of Meteorology, September 2005.
BoM (2016)	*'Rainfall IFD Data System: Water Information,* <http://www.bom.gov.au/water/designRainfalls/revised-ifd/>, Commonwealth of Australia, Bureau of Meteorology, 2019.
Geoscience Australia, 2019	*AR&R Data Hub (software), Geoscience Australia, Version 2019,* <http://data.arr-software.org/>.
GHD, 2016	*'Narrabri Gas Project – Environmental Impact Statement Hydrology and Geomorphology'*, GHD, 2016.
IEAust (1998)	*'Australian Rainfall & Runoff – A Guide to Flood Estimation'*, Pilgrim, DH, (ed), Institution of Engineers, Australia, Barton, ACT, 1998
Malone (2000)	*'Using URBS for Real Time Flood Modelling'*,T. Malone in Water 99 Joint Congress, Institution of Engineers, July 1999.
NSW Government (2005a)	*'Floodplain Development Manual – the management of flood liable land'*, New South Wales Government, Department of Infrastructure, Planning and Natural Resources, April 2005.
NSW Government (2007)	*'Floodplain Risk Management Guideline - Practical Consideration of Climate Change'*, New South Wales Government, Department of Environment and Climate Change, October 2007.
XP-Software, 2018	*'XP-RAFTS User Manual'*, XP Software, Australia, 2018.

Appendix A - XP-RAFTS design discharge box and whisker plots

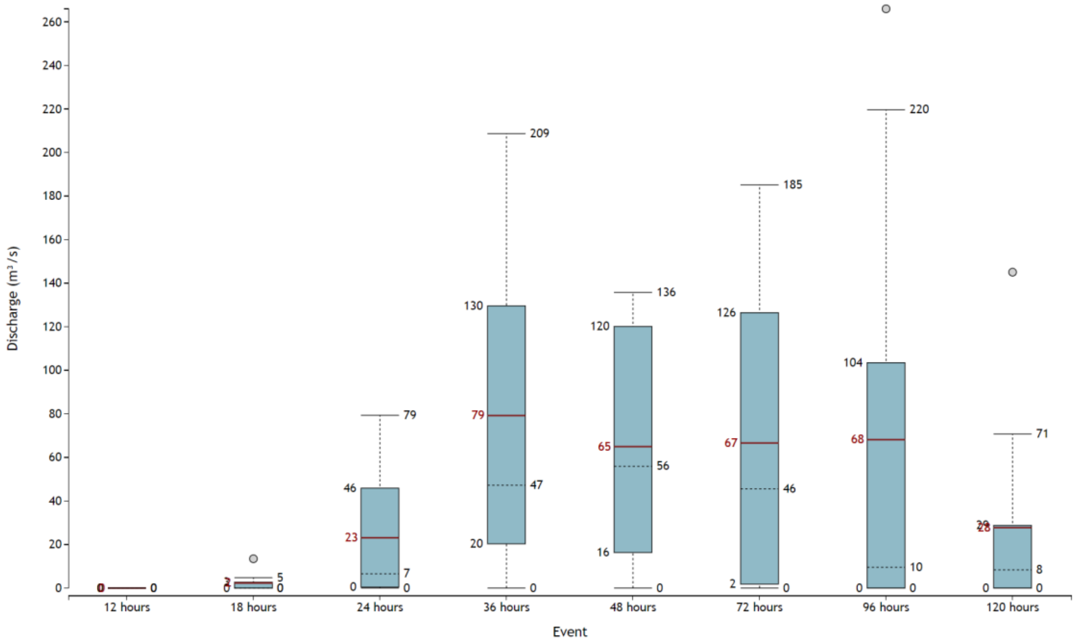


Figure A.1 – Box plot of 20% AEP design discharge ensemble, Bohena Creek

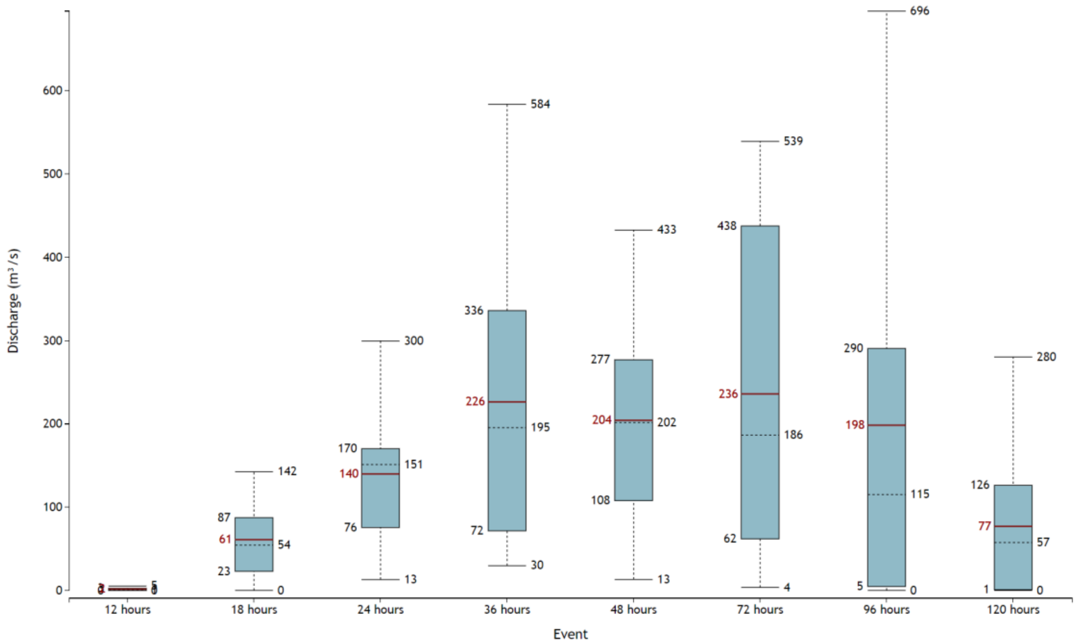


Figure A.2 – Box plot of 10% AEP design discharge ensemble, Bohena Creek

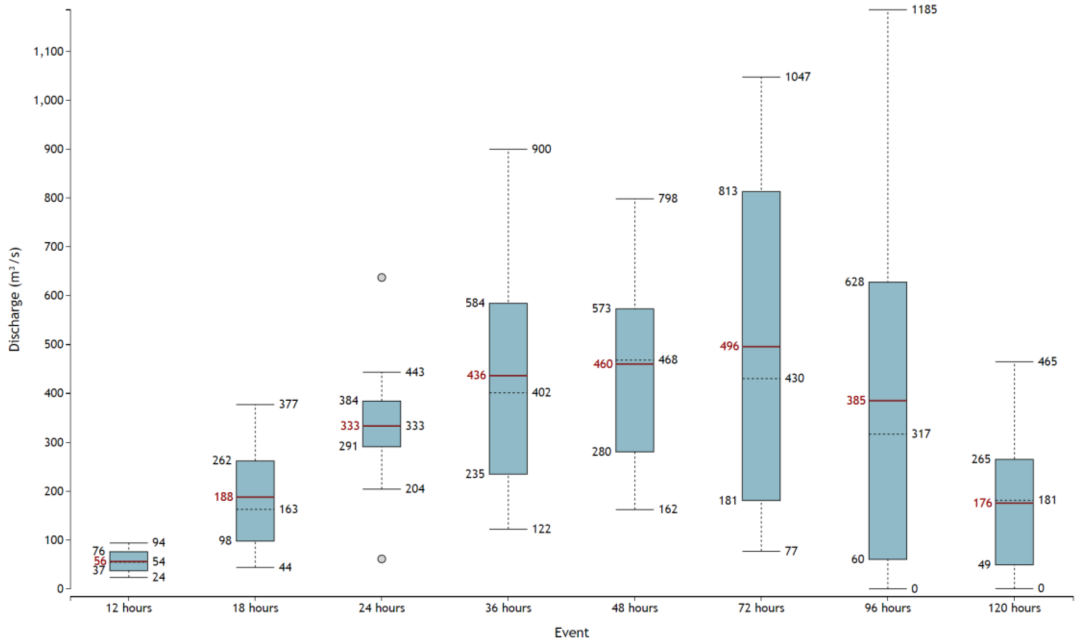


Figure A.3 – Box plot of 5% AEP design discharge ensemble, Bohena Creek

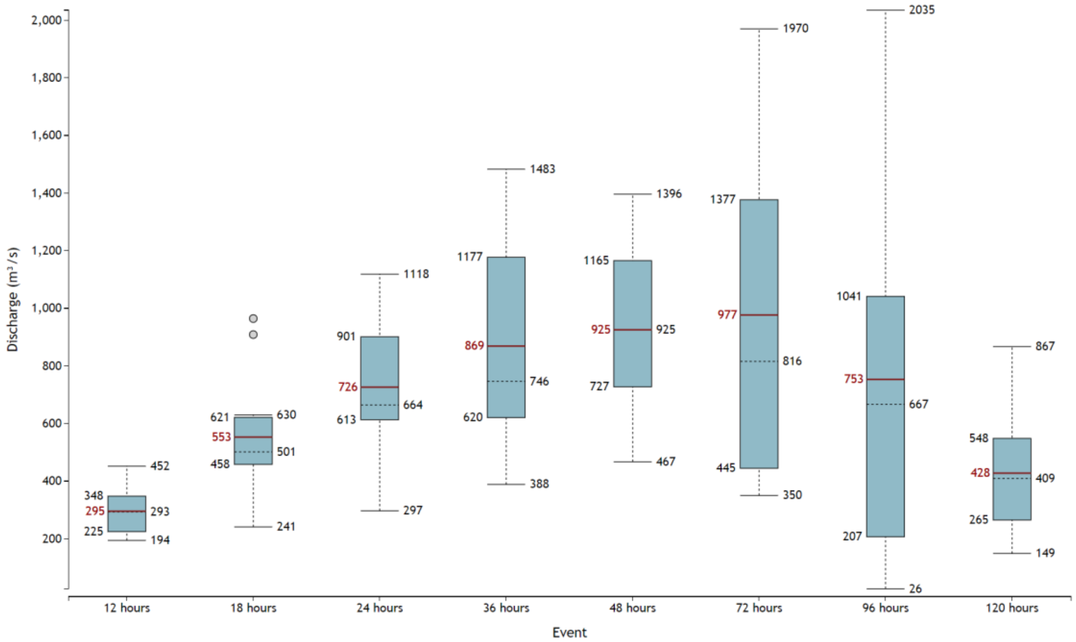


Figure A.4 – Box plot of 2% AEP design discharge ensemble, Bohena Creek

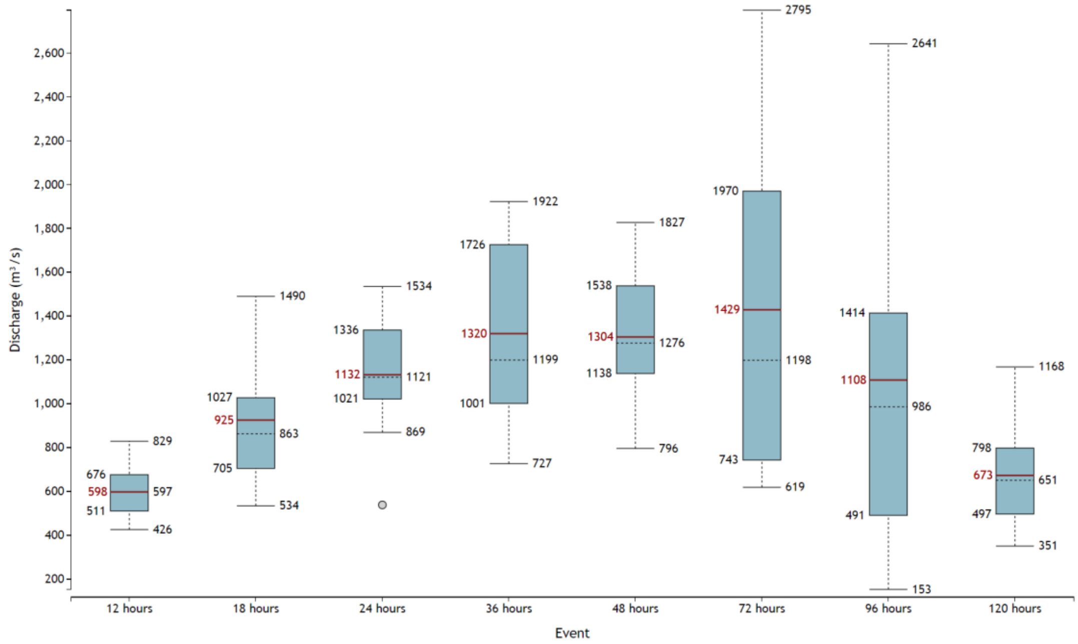


Figure A.5 – Box plot of 1% AEP design discharge ensemble, Bohena Creek

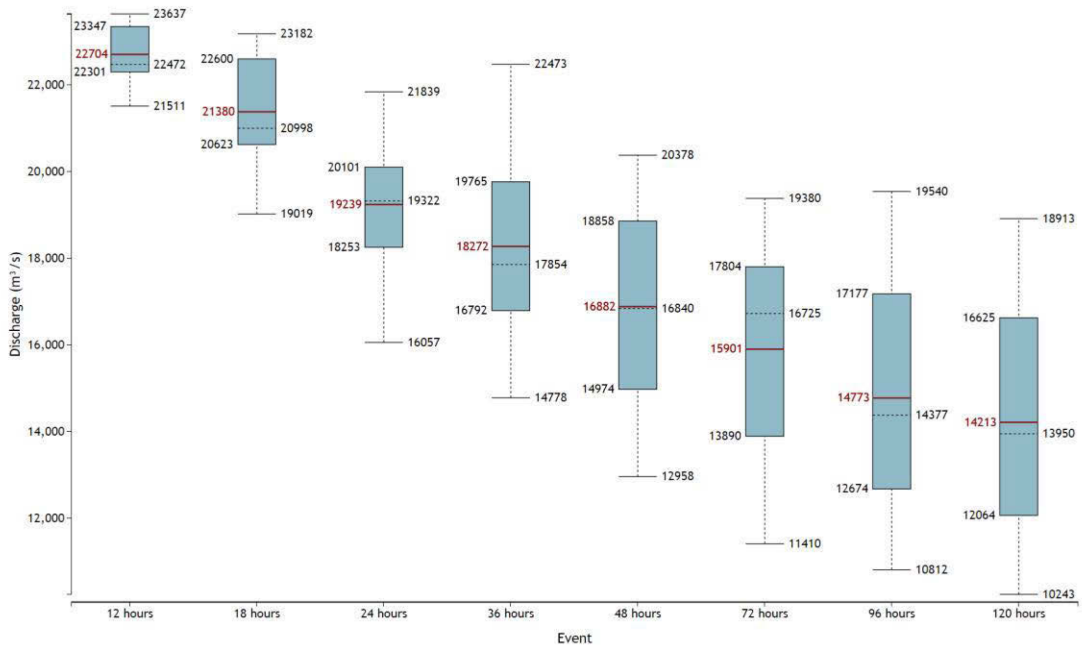


Figure A.6 – Box plot of PMF design discharge ensemble, Bohena Creek

Appendix B - Predicted flood extents, levels and depths

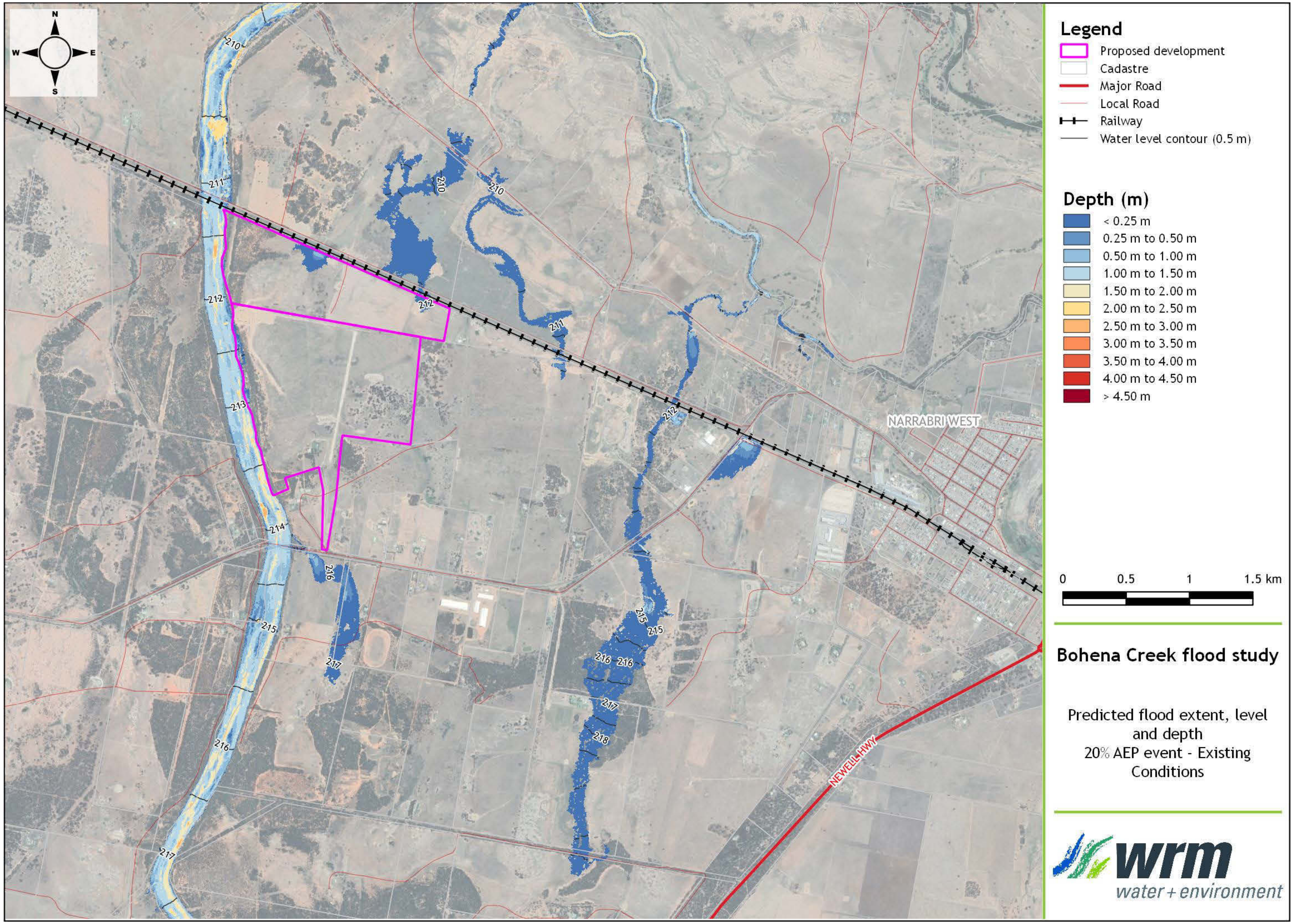


Figure B.1 – Predicted flood extent, level, and depth – 20% AEP event

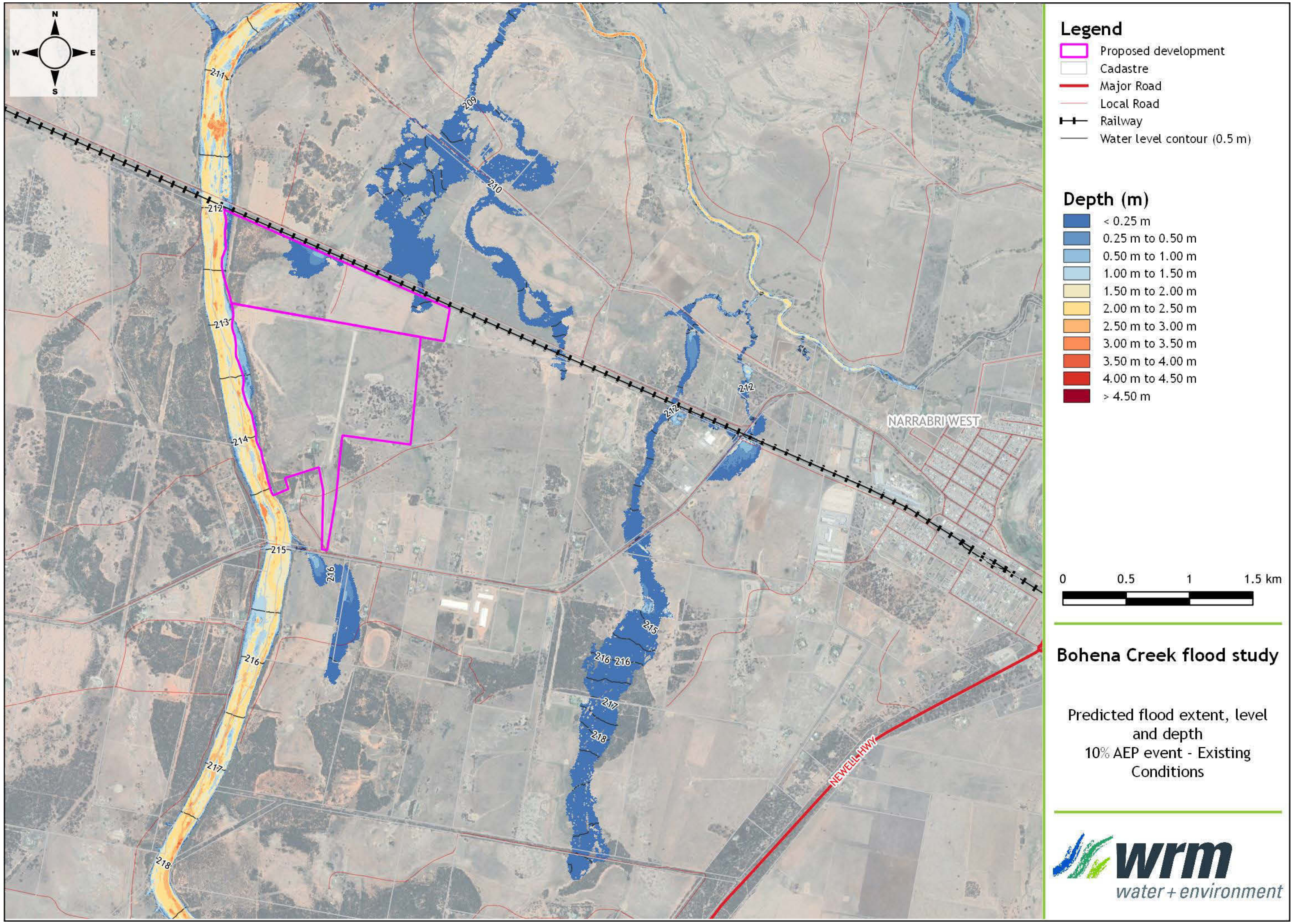


Figure B.2 – Predicted flood extent, level, and depth – 10% AEP event

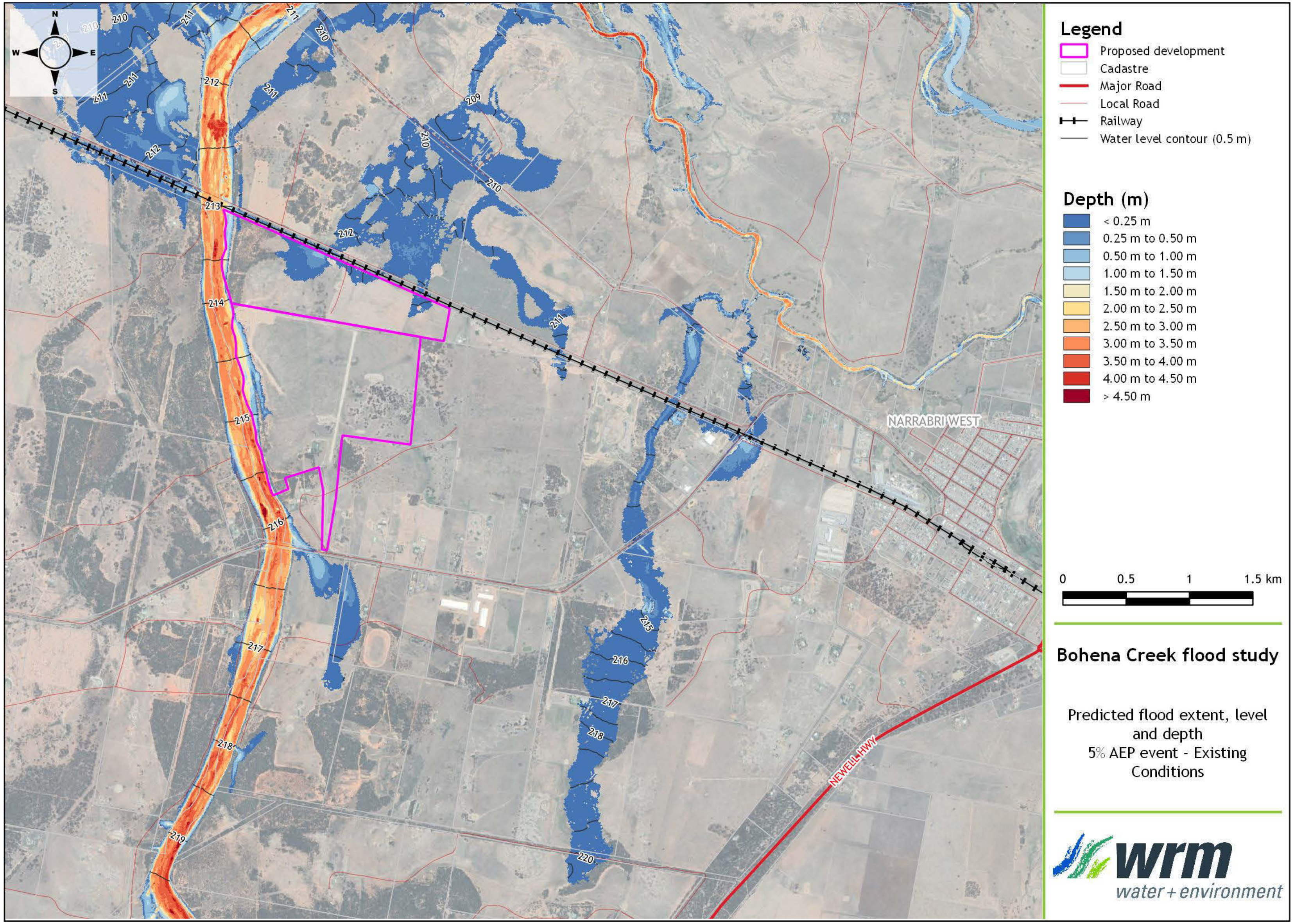


Figure B.3 – Predicted flood extent, level, and depth – 5% AEP event

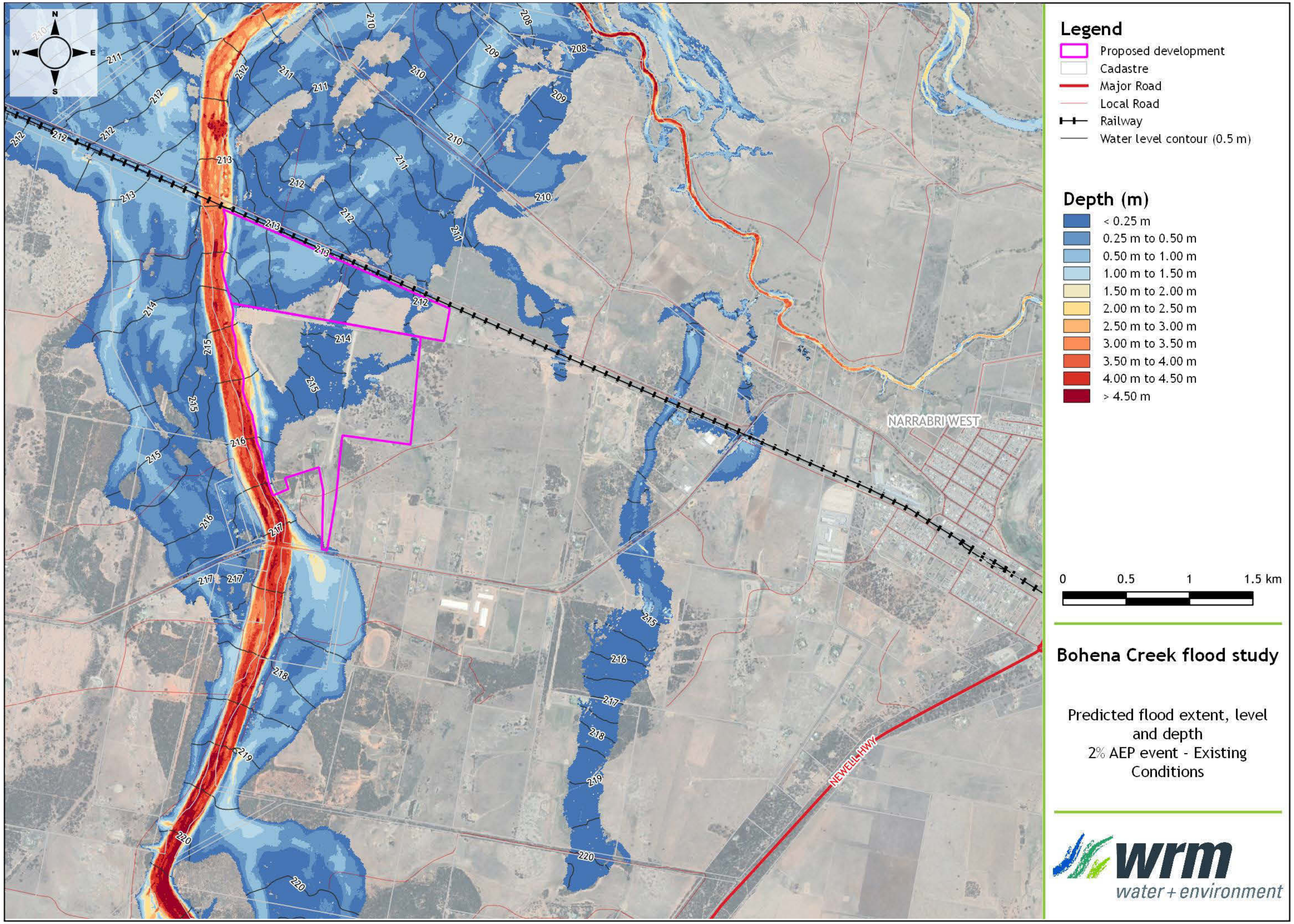


Figure B.4 – Predicted flood extent, level, and depth – 2% AEP event

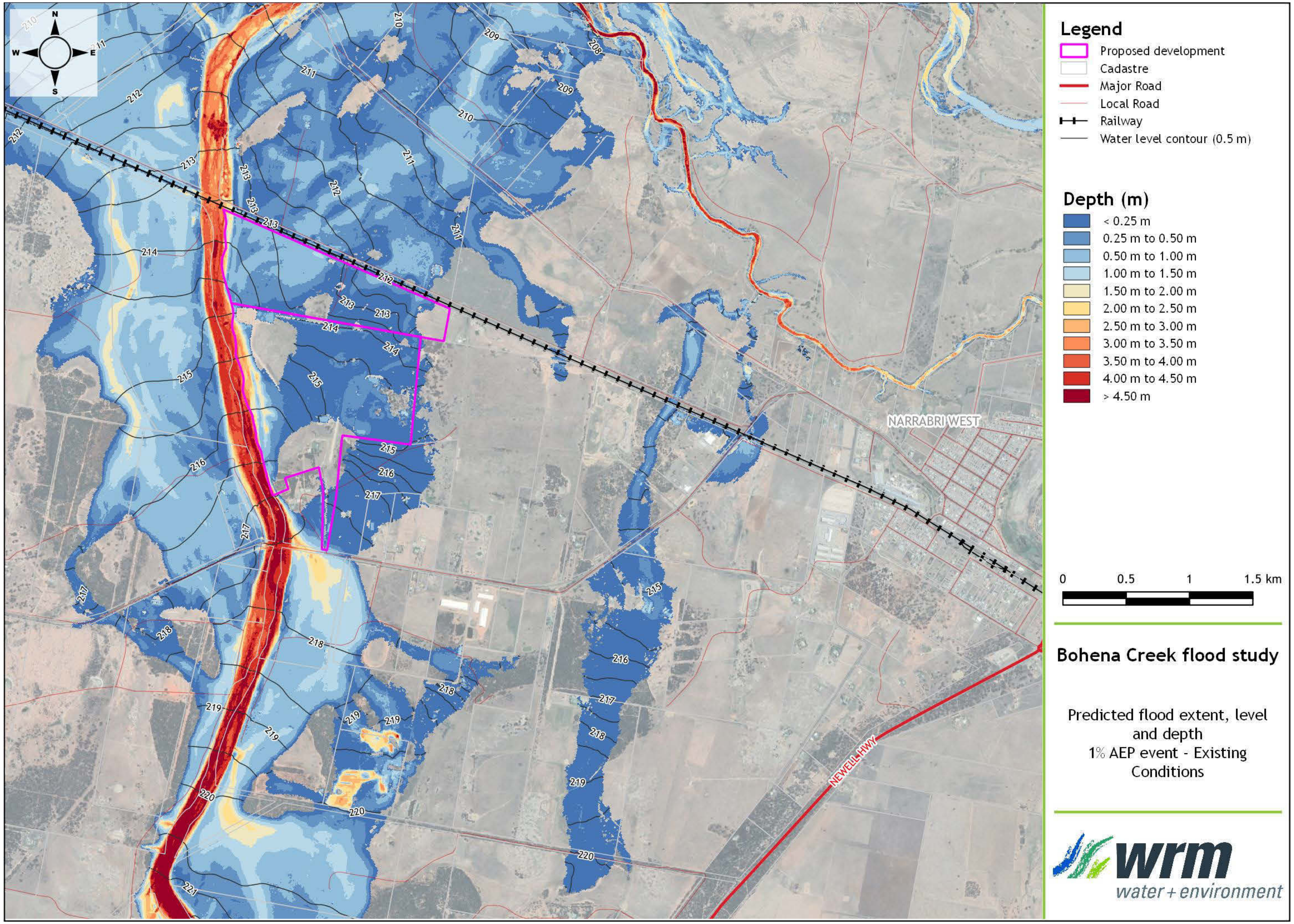


Figure B.5 – Predicted flood extent, level, and depth – 1% AEP event

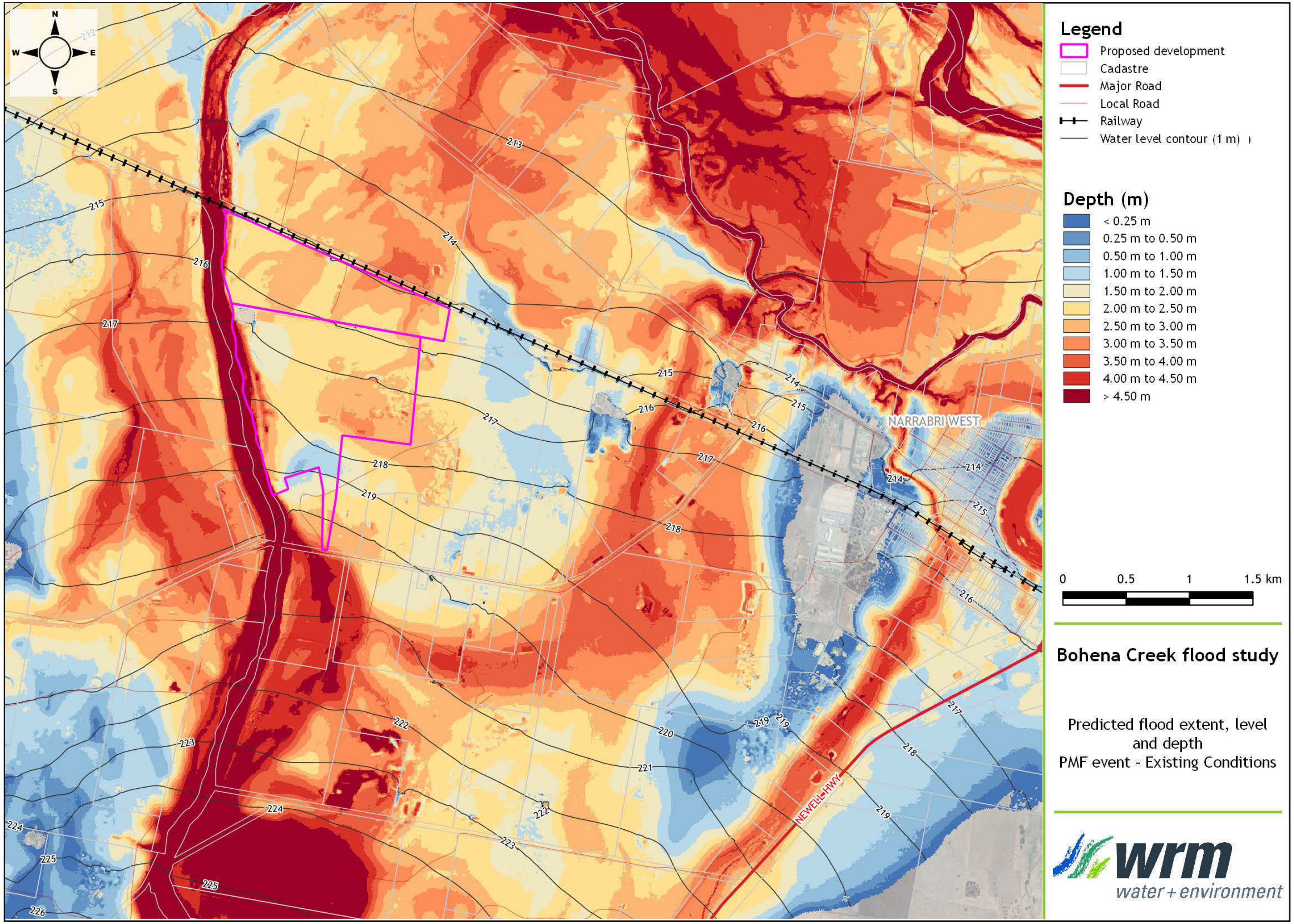


Figure B.6 – Predicted flood extent, level, and depth – PMF event

Appendix C - Provisional hydraulic hazards

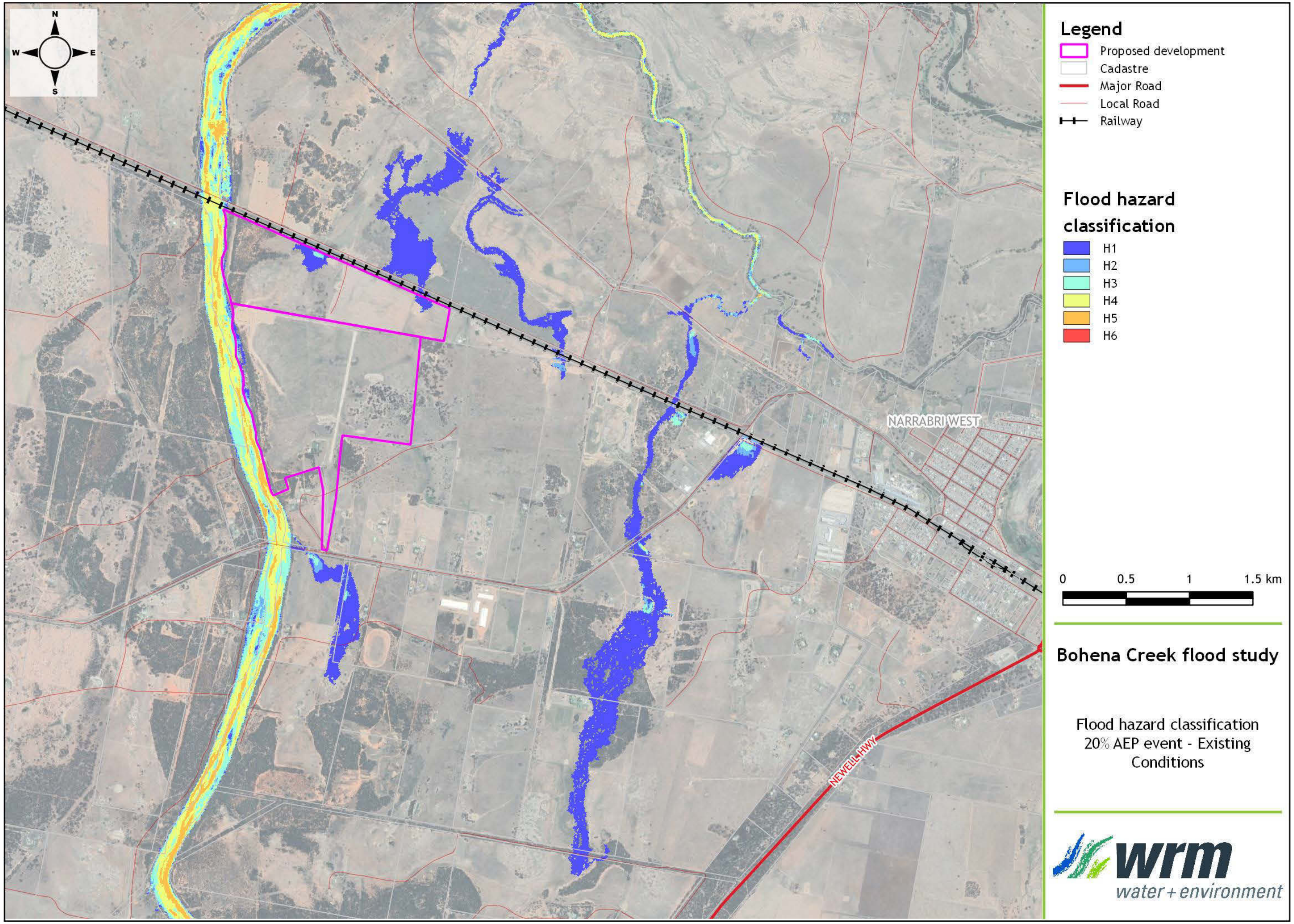


Figure C.1 – Provisional hydraulic hazard – 20% AEP event

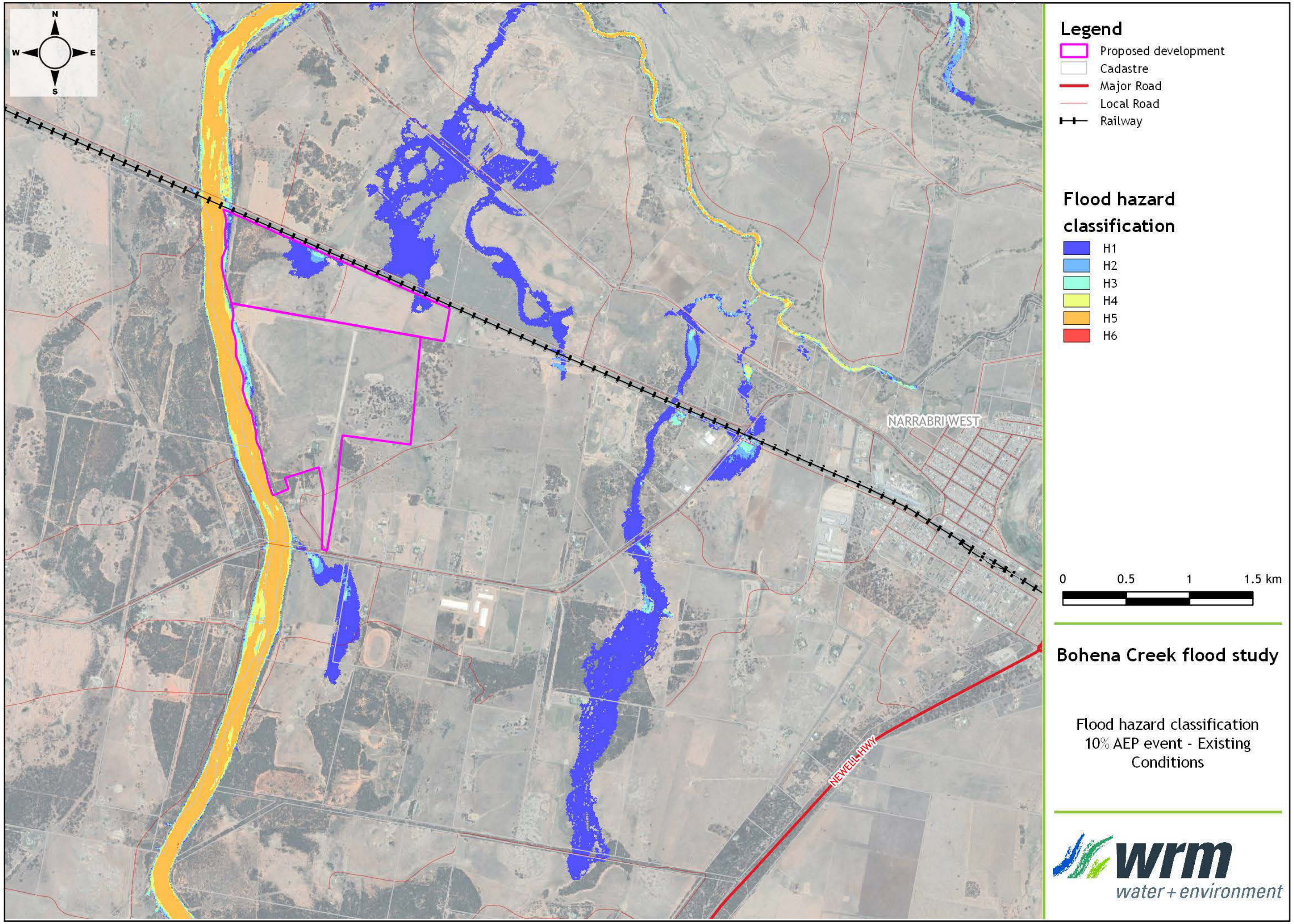


Figure C.2 – Provisional hydraulic hazard – 10% AEP event

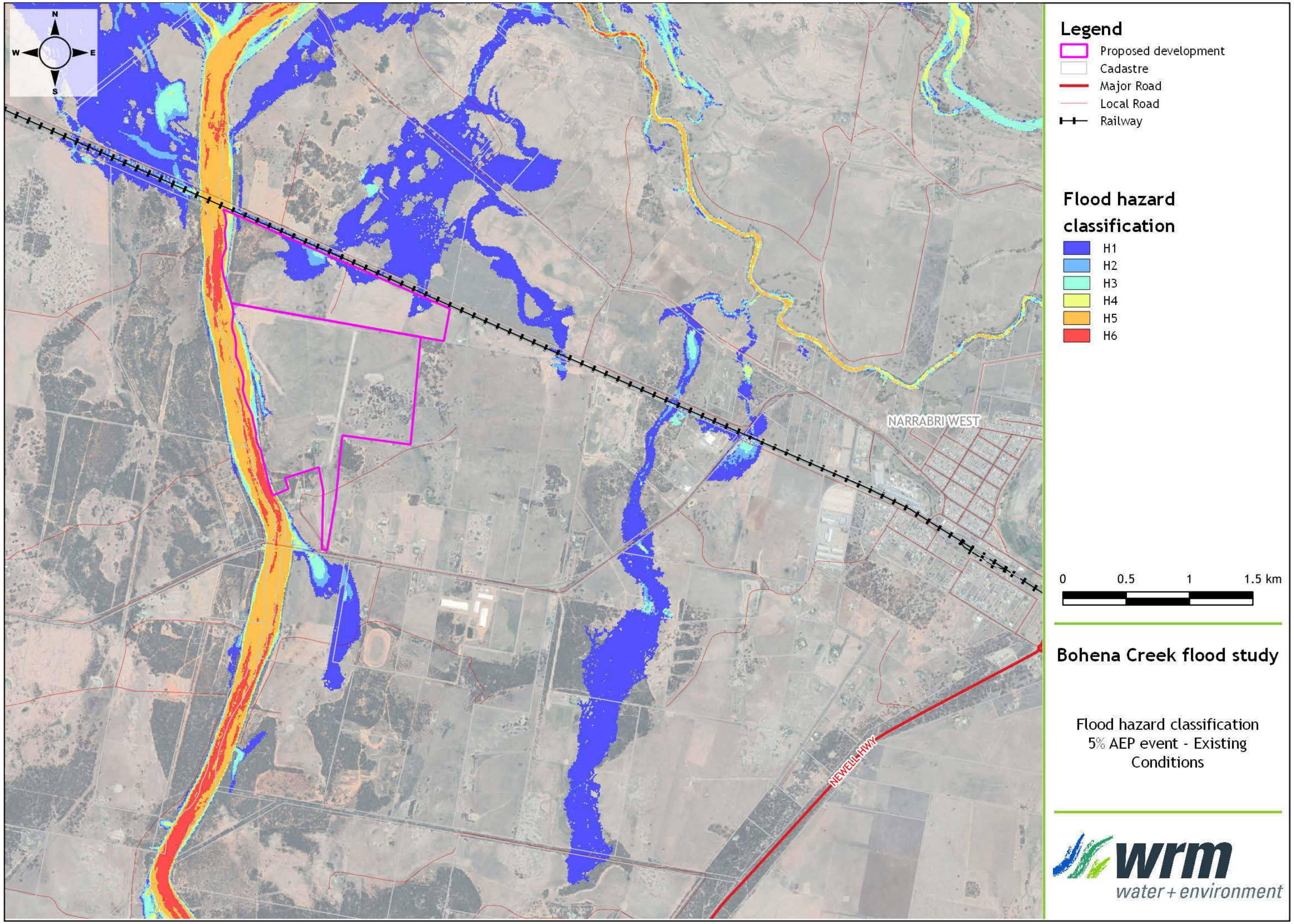


Figure C.3 – Provisional hydraulic hazard – 5% AEP event

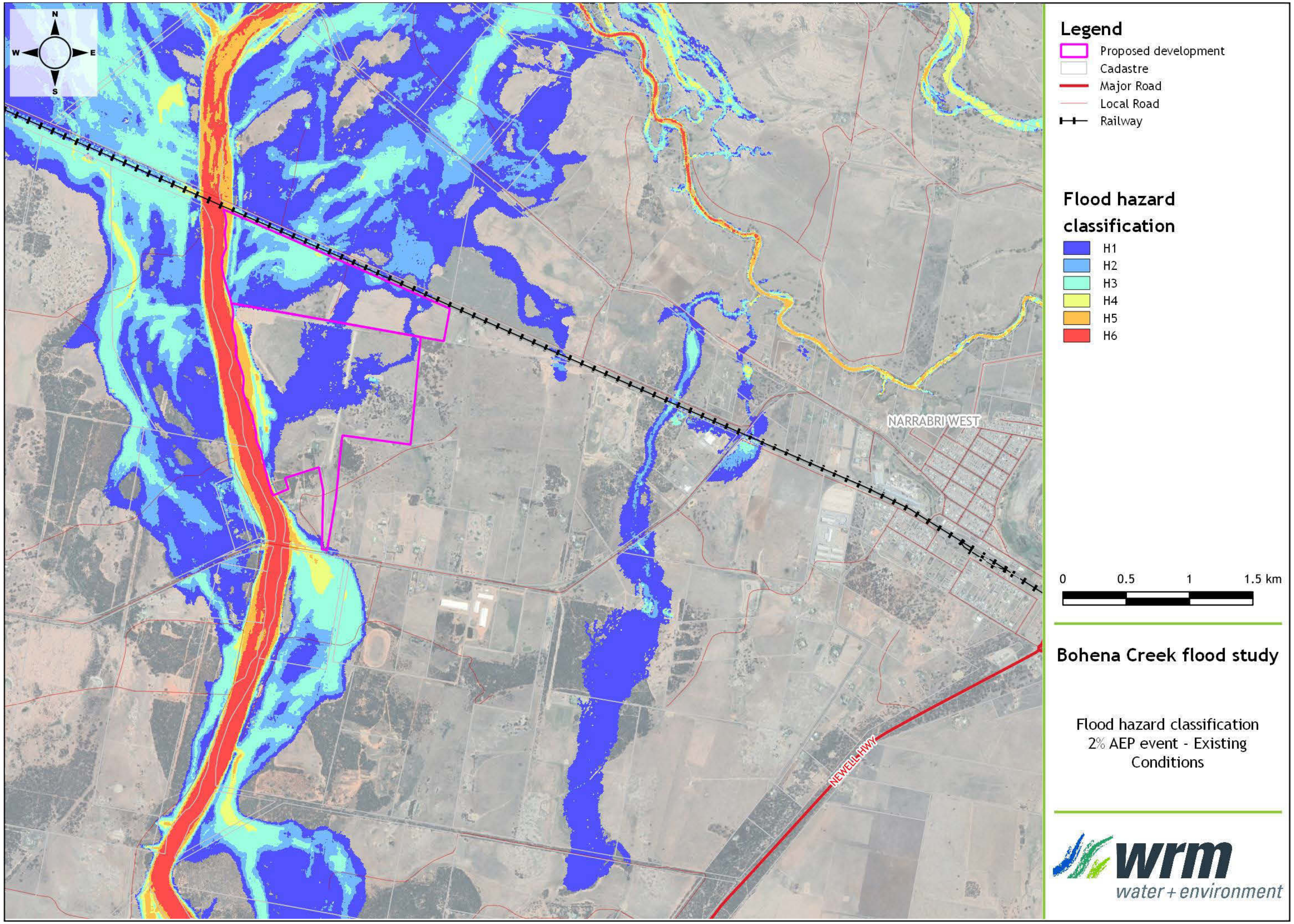


Figure C.4 – Provisional hydraulic hazard – 2% AEP event

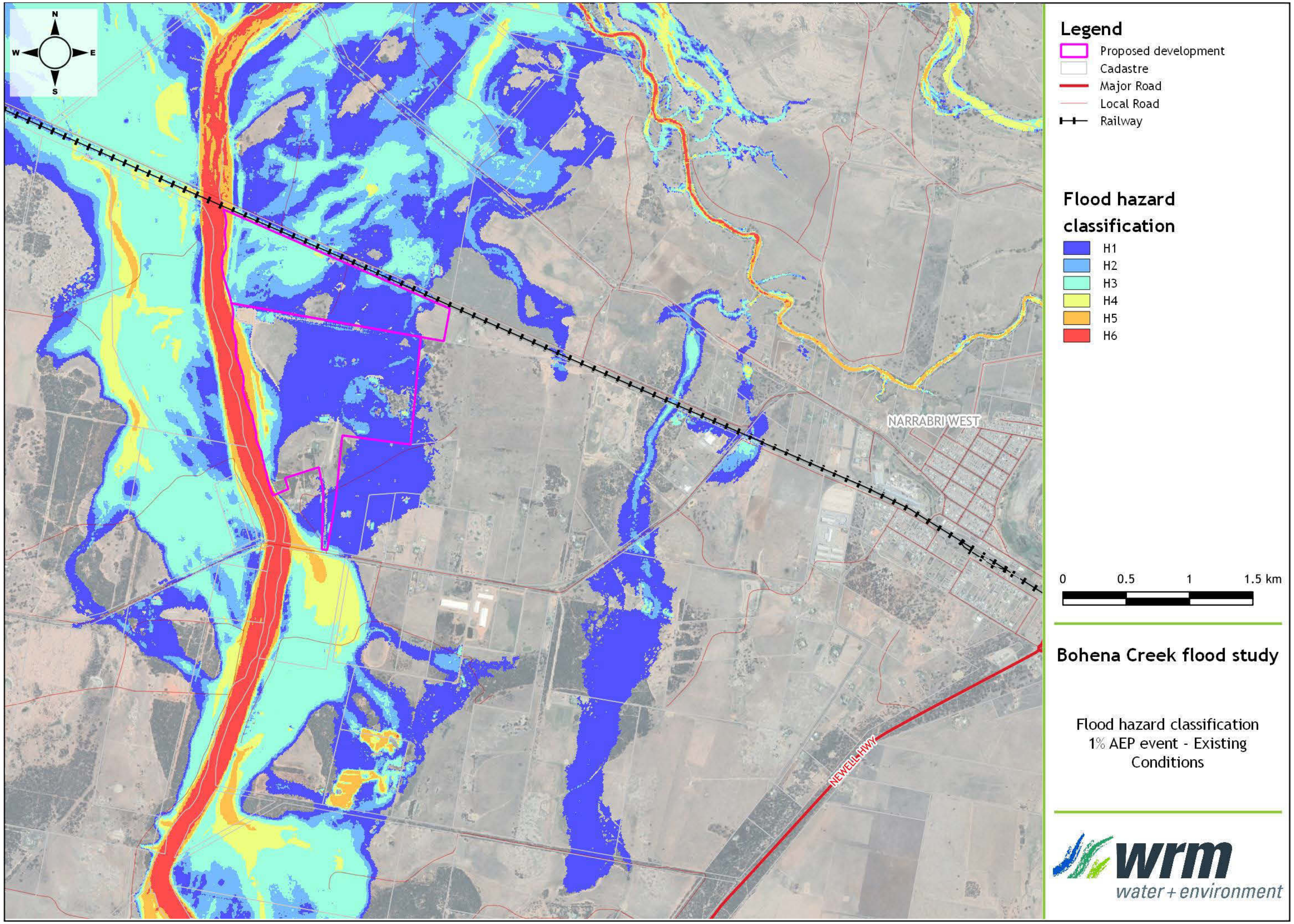


Figure C.5 – Provisional hydraulic hazard – 1% AEP event

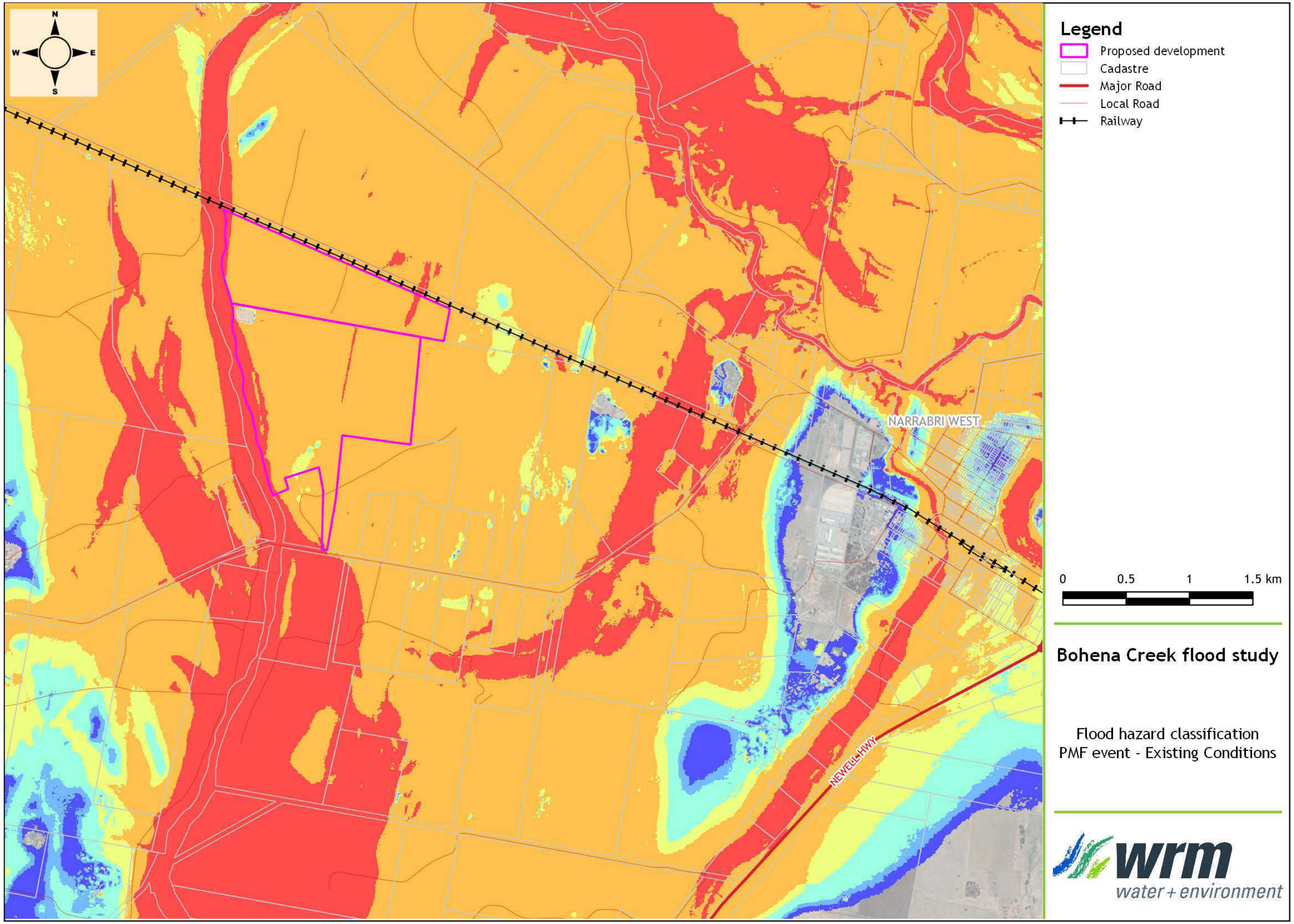


Figure C.6 – Provisional hydraulic hazard – PMF event

APPENDIX

Q

Attachment 2 Narromine to Narrabri—Technical note 6 (2-0001-250-IHY-00-RP-0016), JGHD, August 2021

NARROMINE TO NARRABRI PROJECT

ARTC Inland Rail

Narromine to Narrabri (N2N)

Technical Note 6 –Bohena Creek

Revision 0

2-0001-250-IHY-00-RP-0016.doc

Document control

Client	Australian Rail Track Corporation
Project:	Narromine to Narrabri (N2N)
Document title:	Technical Paper – Flood Modelling for Bohena Creek
Date issued:	02/08/2021
Revision:	0
Prepared by:	Akhter Hossain
Purpose:	For Information
Reviewed by:	Richard Hackett
Approved by:	Richard Hackett
Date approved:	02/08/2021
Issued to:	ARTC
Filename:	2-0001-250-IHY-00-RP-0016.doc
Status	Final

Revision	Date issued	Description
0	02/08/2021	ARTC Comments Addressed

Table of contents

Table index

Figure index

.

1. Introduction

1.1 Background

ARTC is seeking planning approval to construct the Narromine to Narrabri (N2N) section of Inland Rail. The project has been declared Critical State Infrastructure and an Environmental Impact Statement (EIS) was submitted to the NSW Department of Planning, Industry and Environment (DPIE) in September 2020.

The EIS has been placed on public exhibition and a number of comments have been received relating to the assessment of flooding impacts. DPIE has also provided comments on Technical Report 3 – Flooding and Hydrology Assessment Report (FHAR) in the letter from Bewsher dated 18 March 2021.

Items 3.11 and 3.12 of the letter noted

"In regard to modelling through the Narrabri area, there are deficiencies in the modelling of both Bohena Creek and Mulgate Creek."

"The EIS predictions of flooding in Bohena Creek are much more extensive than suggested by this Council study. Further the predictions within Table 5.3 [s5.2.3 p96] of 72 buildings within Bohena Creek being inundated above floor level in a 20% AEP flood event is unlikely to be accurate. This indicates to the reviewer that the level of consultation with this Council has been inadequate."

Consequently, the reviewer recommends that the modelling of Mulgate Creek needs to be revised and the flood impacts of the Project re-assessed.

1.2 Purpose

The purpose of this technical note is to:

- Detail the approach adopted in the Flooding and Hydrology Assessment Report (FHAR) for undertaking a flooding impact assessment for Bohena Creek.
- Provide commentary on the statement *"shortcomings in the model documentation".*
- Outline the current approach for updating the flooding assessment for Bohena Creek to address the EIS submissions.

1.3 Limitations

This report has been prepared by JacobsGHD IR Joint Venture (JacobsGHD) for ARTC and may only be used and relied on by ARTC for the purpose agreed between JacobsGHD and the ARTC as set out in Section 1.2 of this report.

JacobsGHD otherwise disclaims responsibility to any person other than ARTC arising in connection with this report. JacobsGHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by JacobsGHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. JacobsGHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by JacobsGHD described in this report. JacobsGHD disclaims liability arising from any of the assumptions being incorrect.

JacobsGHD has prepared this report, including maps and figures, on the basis of information provided by ARTC and others who provided information to JacobsGHD (including Government authorities), which JacobsGHD has not independently verified or checked beyond the agreed scope of work. JacobsGHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

The opinions, conclusions and any recommendations in this report are based on information obtained from, and testing undertaken at or in connection with, specific sample points. Site conditions at other parts of the site may be different from the site conditions found at the specific sample points.

Investigations undertaken in respect of this report are constrained by the particular site conditions, such as the location of buildings, services and vegetation. As a result, not all relevant site features and conditions may have been identified in this report.

Site conditions (including the presence of hazardous substances and/or site contamination) may change after the date of this Report. JacobsGHD does not accept responsibility arising from, or in connection with, any change to the site conditions. JacobsGHD is also not responsible for updating this report if the site conditions change.

2. Comments from DPIE review

The relevant DPIE's review comments on Technical Report 3 – Flooding and Hydrology Assessment Report in the letter from Bewsher dated 18 March 2021 are:

Table 2-1 DPIE Comments Relating to Bohena Creek

3.	Flood Modelling
3.1	*Comprehensive flood modelling has been undertaken comprising some 14 TUFLOW hydraulic models in addition to hydrologic models. With the exception of the modelling of Bohena and Mulgate Creeks, the reviewer considers this modelling is likely to be of a good standard although, as noted in paragraph 3.7 below, there is currently insufficient documentation to confirm this*
3.7	*There has been an extensive amount of hydrologic and hydraulic modelling undertaken but only very limited details of these models are presented in Tech Report 3. The level of reporting falls well short of what is normally provided and is insufficient to allow the modelling to be reviewed except at a superficial level. Model parameters are not reported, nor is sufficient information provided regarding the calibration and validation of the models to allow the credentials of the models to be verified. An assessment of the accuracy of rating curves that have been relied upon has not been presented nor have details been provided of the flood frequency analyses used in model calibration.*
3.11	*In regard to modelling through the Narrabri area, there are deficiencies in the modelling of both Bohena Creek and Mulgate Creek. The Bohena Creek deficiencies are discussed in paragraph 4.2(i) below.*
4	***Consultation with Narromine and Narrabri Shire Councils***
4.2	*i) Bohena Creek Flood Study (draft): – refer document (f) above which was prepared by WRM for Narrabri Shire Council. It appears that ARTC are unaware of this study which was prepared in October 2019. The EIS predictions of flooding in Bohena Creek are much more extensive than suggested by this Council study. Further the predictions within Table 5.3 [s5.2.3 p96] of 72 buildings within Bohena Creek being inundated above floor level in a 20% AEP flood event is unlikely to be accurate[1]. This indicates to the reviewer that the level of consultation with this Council has been inadequate. (The result of revising the Bohena Creek hydrology will likely show that the Project is not as severely constrained by this creek as was reported in the EIS).*
	SUMMARY AND CONCLUSIONS
D	*Flood Modelling of Bohena and Mulgate Creeks. The modelling of these creek systems needs to be revised and the flood impacts of the Project re-assessed.*

[1] Note that for this very frequent event, only 13 buildings are predicted to be inundated above floor level in Narromine and 18 in Narrabri, but 72 within Bohena Creek. It would appear that there may be a significant error in the Bohena Creek hydrology.

3. Flooding assessment for Bohena Creek

3.1 Review of available data

Bohena Creek is a tributary of the Namoi River and creek has an upstream catchment area of about 2,180 square kilometres at the Newell Highway. The creek flows north-west across the proposal before turning north, meandering gently towards the Namoi River.

JacobsGHD checked the availability of previous flood studies and flood modelling data, terrain data, rainfall records, stream gauge data and historical flood intelligence from adjacent landholders prior to undertaking a flooding assessment for Bohena Creek. Details on the available data are provided in the Hydrology and Hydraulic Models Calibration Report (JacobsGHD, 2021). A review on the stream gauge data and the recently available draft Flood Study for Bohena Creek (WRM, 2019) is provided in the following sections.

3.1.1 Stream gauge data for Bohena Creek at Newell Highway

Only two flow events (https://realtimedata.waternsw.com.au/) were measured at the gauge since commissioning of the gauge in May 1995. The maximum flow measured (408.7 m^3/s) was on 28 July 1998 corresponding to a gauge height of 2.977 m. The maximum water level recorded at the gauge was 3.231 m on 05 September 1998. The top of bank is located at gauge height 5.0 m.

The available recorded data for the stream gauge was collected from WaterNSW in 2018. WaterNSW provided water level and discharge data for the gauge for the period 1 September 1995 to 16 January 2018. The data provided by WaterNSW included both point and mean gauge height and discharge data and quality codes for the recorded data were not provided. The point gauge height and discharge data for the gauge is shown in Figure 3-1. Figure 3-1 shows long gaps in the discharge data for the period between 2005 to 2018 during which the gauge was at or close to cease to flow levels. In the absence of the quality codes for the recorded gauge heights, it is not known whether there were no flows in the creek or the stream gauge was not in operation. The cease to flow level for the gauge is identified as being 0.35 m (https://realtimedata.waternsw.com.au/) however, the lowest height recorded at the gauge since 2005 is about 0.7 m.

Due to the limited flow gaugings and significant gaps in the available data during the period 2005 to 2018, a flood frequency analysis was not considered appropriate for this gauge. A comparison of the gauge rating curve to recorded peak flows (Figure 3-2) indicates that the rating curve is likely to provide a reasonable estimate of flood flows.

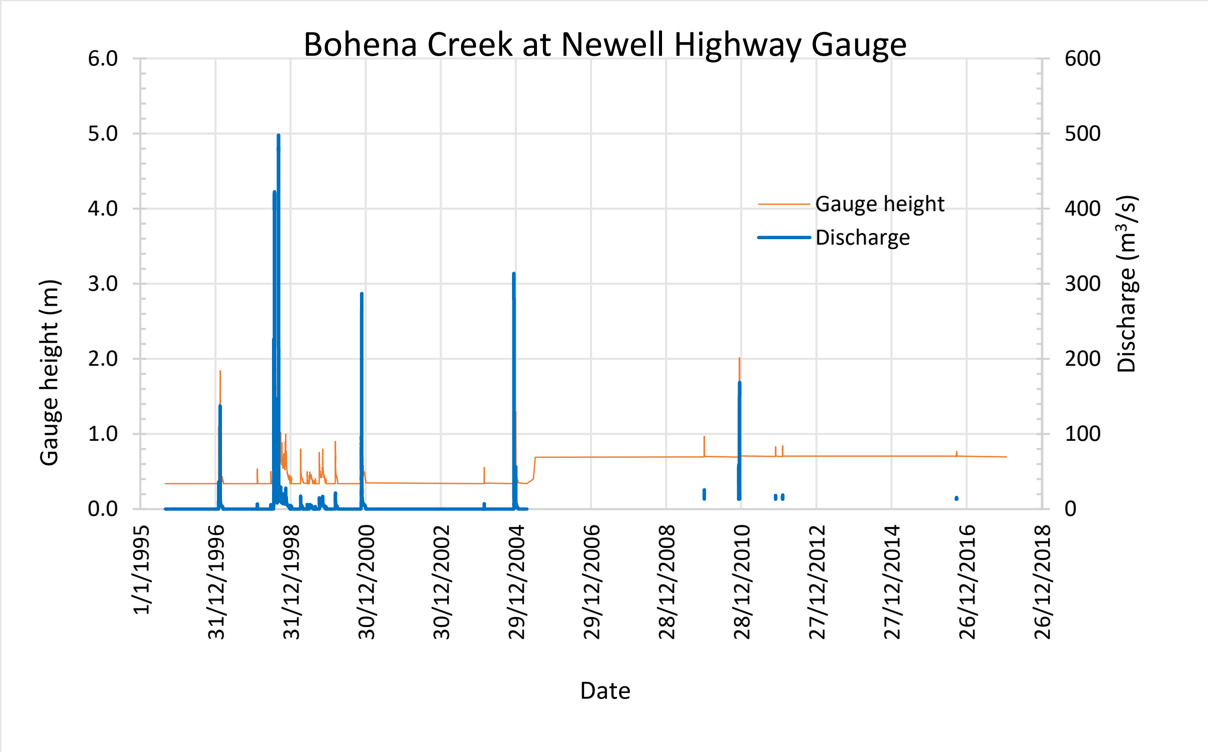


Figure 3-1 Recorded gauge height and flows - Bohena Creek

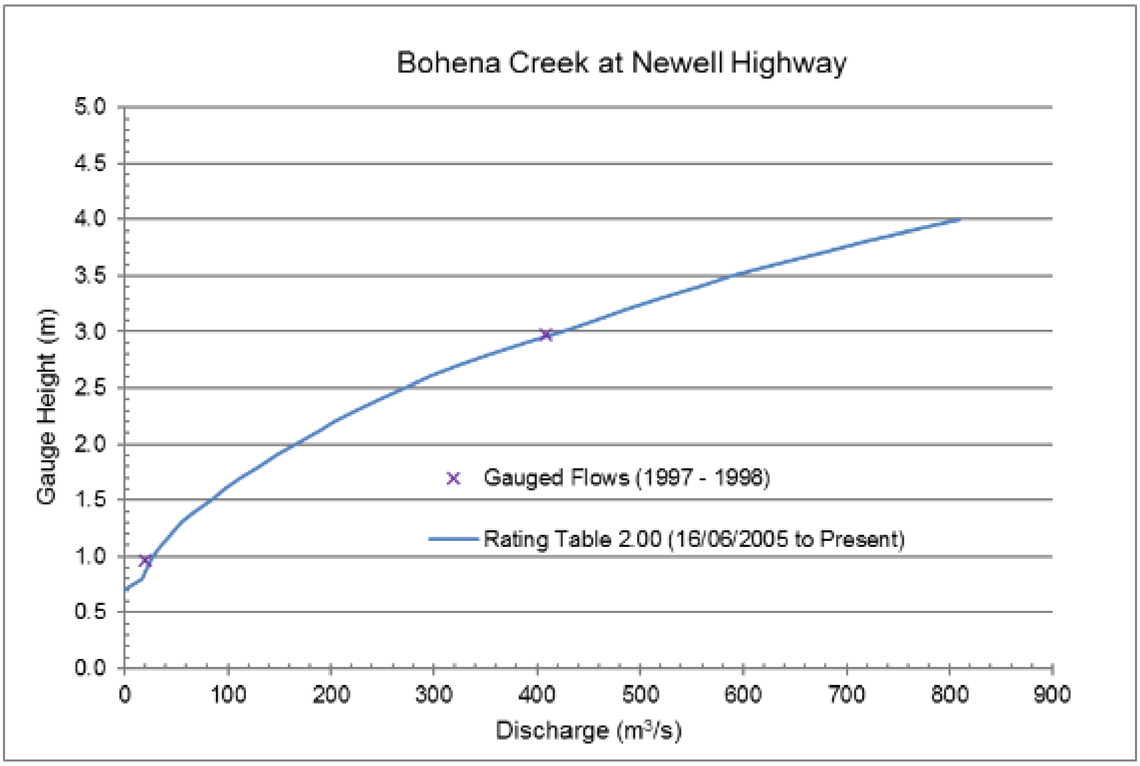


Figure 3-2 Rating curve and gauged flows - Bohena Creek

3.1.2 Bohena Creek Flood Study (WRM, 2019)

The draft Bohena Creek Flood Study (WRM, 2019) was prepared for Narrabri Shire Council to investigate and define existing flood risk at a proposed development site between Yarrie Lake Road and Culgoora Road. The extents of the WRM (2019) study are located within the study area for the proposal.

The primary focus of the study was to map the flood risk for the design events across the proposed development site. An XP-RAFTS hydrology model and a TUFLOW hydraulic model were developed for the assessment. The XP-RAFTS model was calibrated to two historical flood events, the September 1998 event and December 2004 event.

A flood frequency analysis was undertaken on the annual maximum flow series of the 24 years of recorded flows at the Bohena Creek gauge at Newell Highway. A Log- Pearson Type III (LP III) distribution was fitted to the annual series using the Bayesian inference methodology recommended in ARR 2019 (*Ball et al*, 2019) using the TUFLOW FLIKE Software. Nineteen low flows were censored from the dataset below 100 m^3/s.

The study identifies that RFFE provide estimates with a lower accuracy for catchments with areas greater than 1,000 km^2, such as Bohena Creek. A comparison between RFFE estimates and at-site flood frequency estimates shows that the RFFE estimates are well above the 90%ile upper confidence limit from the at-site flood frequency estimates and hence RFFE estimates were ignored.

Design discharges for the 20%, 10%, 5%, 2% and 1% AEP events were estimated using the methodology recommended in ARR 2019. However, it is not clear from the report (WRM, 2019) how initial loss and continuing loss rate were selected for the design flood events. The adopted initial loss was 70 mm for the 1% AEP event, 75 mm for the 2% AEP event and 80 mm for the 20%, 10% and 5% AEP events. A continuing loss rate of 4.7 mm/hour was adopted for 20%, 10%, 5%, 2% and 1% AEP events.

A 10 m grid TUFLOW model was developed for the Study Area. Model topography was configured based on 1 m DEM (captured in July 2014) and supplementary 5 m DEM captured in November 2017. Both DEMs were sourced from http://elevation.fsdf.org.au/. The TUFLOW models were calibrated to stream data for the September 1998 event and December 2004 event at the Bohena Creek gauge at Newell Highway. Inflow hydrographs simulated by the XP-RAFTS model for the two historic flood events were applied in the TUFLOW model to calibrate the model.

The calibrated TUFLOW model was run for the selected design flood events using inflow hydrographs simulated by the XP-RAFTS model. The TUFLOW model predicted flood levels, depths and extents for the 20%, 10%, 5%, 2% and 1% AEP flood events and an extreme flood. Preliminary flood hazard mapping has also been prepared.

The flood models and data from this study were not available for use in the Reference Design.

3.2 Inland Rail N2N Hydrological analysis and modelling

Details on the hydrological analysis and catchment modelling undertaken by JacobsGHD for Bohena Creek are presented in the Hydrology and Hydraulic Models Calibration Report (JacobsGHD, 2021). A summary on comparison of hydrological modelling and analysis undertaken by JacobsGHD and WRM for Bohena Creek catchment is presented in Table 3-1.

Table 3-1 Comparison of hydrological analysis and modelling

Item	JacobsGHD	WRM, 2019
Quality of stream gauge data	Quality codes for data are not available and there are gaps in discharge data after 2005 (refer Section 3.1.1.)	All data considered reliable.
Hydrology model	A RORB hydrology model developed	A XP-RFATS hydrology model developed

Item	JacobsGHD	WRM, 2019
Calibration of hydrology model	Model calibrated to three historic flood events: • February 1997 (137 m^3/s) • July 1998 (420 m^3/s) • September 1998 (497 m^3/s)	Model calibrated to two historic food events: • September 1998 (497 m^3/s) • December 2004 (314 m^3/s)
Calibration Results	Peak discharge estimates are in close agreement with the recorded data. Both the predicted rising limb and falling limb for three events agree closely with the recorded data.	Peak discharge estimates are in reasonable agreement with the recorded data. Significant differences between the predicted and recorded rising limbs and falling limbs for the two events .
At-site flood frequency analysis	Not undertaken due to concerns about the unknown quality and gaps in the recorded data	At-site flood frequency undertaken with 24 years of records and censored data for 18 years
Estimation of discharges for design flood events up to 1% AEP	ARR 2019. Areal reduction factors applied. Median values of k_c (21), initial loss (39.8 mm, prior to adjustment for pre-burst rainfall) and continuing loss rate (2.5 mm/hour) obtained from model calibration	ARR 2019. Areal reduction factors applied. Initial estimates based on average values of initial loss and continuing loss rate obtained from model calibration.
Verification of peak discharge estimates	RFFE	Peak discharges estimated by the XP-RAFTS model are compared to at-site flood frequency estimates. Adopted initial loss in the XP-RAFTS model varies between 70 mm (1% AEP) and 80 mm (5% to 20 % AEP event) and the continuing loss rate is 4.7 mm/hour for all flood events between 20% AEP and 1% AEP events.

Table 3-1 shows that in general, both JacobsGHD (2021) and WRM (2019) adopted consistent approach to predict design discharges for Bohena Creek. However, predicted peak discharges in both studies are considerably different as shown in Table 3-2. Peak discharges predicted by JacobsGHD are higher than RFFE estimates and RFFE estimates are considerably higher than peak discharges predicted by WRM. The following factors result in differences in predicted discharges for Bohena Creek between the two studies:

- Initial losses (70 mm to 80 mm) adopted by WRM (2019) for the design flood events up to and including the 1% AEP events are higher than the recommended regional initial loss value of 45 mm (prior to adjustment for preburst rainfall) in AR&R Data Hub for Bohena Creek.
- The continuing loss rate of 4.7 mm/hour adopted by WRM is the same loss rate recommended in AR&R Data Hub for Bohena Creek. However, the continuing loss rate of 4.7 mm/hour is considerably higher than 2.5 mm/hour loss rate obtained by JacobsGHD from model calibration results for three historic flood events.

- The flood frequency results adopted by WRM are highly sensitive to the threshold applied for censoring data. JacobsGHD analysed the same annual maxima adopted by WRM (2019) in TUFLOW Flike and estimated peak discharges for a range of censored annual maxima. Estimated peak discharges for the 20% AEP event were found to vary between 245 m^3/s and 450 m^3/s with the adopted threshold discharges for censoring annual maxima varying between 0 m^3/s and 30 m^3/s. In the case of the 1% AEP event, estimated peak discharges varied between 1,402 m^3/s and 8,319 m^3/s with the adopted threshold discharges for censoring annual maxima varying between 0 m^3/s and 30 m^3/s.
- JacobsGHD did not reconcile peak discharges estimated by the RORB model against other independent estimates.

Table 3-2 Peak discharges (m^3/s) for the Bohena Creek gauge at Newell Highway

Flood Event, AEP	RORB Model	RFFE	XP-RAFTS Model (WRM, 2019)	At-Site Flood Frequency (WRM, 2019)
20%	1,392	820	113	105
10%	2,450	1,320	273	203
5%	3,096	1,970	644	353
2%	4,377	3,110	1,145	663
1%	4,870	4,220	1,565	1,012

3.3 Hydraulic modelling

Details on the hydraulic modelling undertaken by JacobsGHD for Bohena Creek are presented in the Hydrology and Hydraulic Models Calibration Report (JacobsGHD, 2021). A summary on comparison of hydraulic modelling by JacobsGHD and WRM for Bohena Creek catchment is presented in Table 3-3.

Table 3-3 Comparison of hydraulic modelling

Item	JacobsGHD	WRM, 2019
Modelling software	TUFLOW, HPC	TUFLOW
Grid size	10 m	10 m
Terrain Data	1 m DEM captured by ARTC in 2017, 2018, 1 m and 5 m ELVIS DEM	1 m and 5 m ELVIS DEM
Calibration of hydraulic model	Model calibrated to three historic flood events: • July 1998 (420 m^3/s) • Sep 1998 (497 m^3/s)	Model calibrated to two historic food events: • Sep 1998 (497 m^3/s) • Dec 2004 (314 m^3/s)
Source of inflow hydrographs for calibration events	Available discharge data for the gauge	Hydrographs simulated by the XP-RAFTS model
Calibration Results	Calibration results against recorded data at the gauge are satisfactory	Limitation of calibration results for the XP-RAFTS model is reflected in calibration results for the TUFLOW model
Verification of model	Satisfactory agreement with the published rating curve	Satisfactory agreement with the published rating curve

Table 3-3 shows that both JacobsGHD and WRM (2019) adopted a consistent hydraulic modelling approach to predict flood behaviour for the full range of flood events. However, predicted flood behaviour for design flood events is different as the predicted discharges are different in both studies. Both studies did not validate flood behaviour against anecdotal flooding information collected from local residents, print media, Transport for NSW, rail authorities and NSW SES.

3.4 Flooding impacts to buildings

Impacts of flooding to buildings at Bohena Creek for the existing condition are presented in Technical Report 3 – Flooding and Hydrology Assessment Report (FHAR). The number of all buildings and residential buildings subject to above floor flooding for the existing condition are shown in Table 3-4. Table 3-4 shows that nine residential buildings at Bohena Creek are subject to above floor flooding in the 20% AEP event. Additional investigations would be undertaken during detailed design to validate flood behaviour in Bohena Creek.

Table 3-4 Number of buildings subject to above floor flooding for the existing condition at Bohena Creek

Flood event	All Buildings	Residential Buildings
20% AEP	71	9
5% AEP	197	32
2% AEP	244	41
1% AEP	259	42
0.5% AEP	294	49
0.2% AEP	318	52
PMF	470	74

4. JacobsGHD responses to DPIE's review comments

4.1 Summary responses

Table 4-1 JacobsGHD Responses to DPIE Comments

Item	DPIE Review Comment	JacobsGHD Response
3.1	Comprehensive flood modelling has been undertaken comprising some 14 TUFLOW hydraulic models in addition to hydrologic models. With the exception of the modelling of Bohena and Mulgate Creeks, the reviewer considers this modelling is likely to be of a good standard although, as noted in paragraph 3.7 below, there is currently insufficient documentation to confirm this	Noted. See below re comments on shortcomings.
3.7	There has been an extensive amount of hydrologic and hydraulic modelling undertaken but only very limited details of these models are presented in Tech Report 3. The level of reporting falls well short of what is normally provided and is insufficient to allow the modelling to be reviewed except at a superficial level. Model parameters are not reported, nor is sufficient information provided regarding the calibration and validation of the models to allow the credentials of the models to be verified. An assessment of the accuracy of rating curves that have been relied upon has not been presented nor have details been provided of the flood frequency analyses used in model calibration.	The Calibration Report (JacobsGHD, 2021) provides details on the available data, a review of rating curves, calibration and validation of hydrology and hydraulic models for the Reference Design. Further details on flood modelling undertaken for regional flooding (i.e. Namoi River) and local catchment flooding (i.e. Mulgate Creek and Long Gully) are provided in this report. The flood model for Narrabri will be verified against the flood event of February 2020 as part of the detailed design. Any updates made to the flood model will be presented in the Flood Modelling Verification Report.
3.11	*In regard to modelling through the Narrabri area, there are deficiencies in the modelling of both Bohena Creek and Mulgate Creek. The Bohena Creek deficiencies are discussed in paragraph 4.2(i) below.*	**Bohena Creek** Modelling of Bohena Creek has been discussed with Narrabri Council and WRM. Further site investigations are proposed, including meetings with locals and investigations of historical flood marks. These investigations have been delayed by the current COVID travel restrictions which commenced in late June 2021. The flood modelling results provided in the EIS are considered to be conservative and will be reviewed as part of the detailed design. Any updates will be presented in the Flood Modelling Verification Report.

Item	DPIE Review Comment	JacobsGHD Response
		As the modelling presented in the EIS is generally considered to be conservative by Narrabri Council and WRM, JacobsGHD does not consider that this item should prevent approval of the project.
	SUMMARY AND CONCLUSIONS	
D	*Flood Modelling of Bohena and Mulgate Creeks. The modelling of these creek systems needs to be revised and the flood impacts of the Project re-assessed.*	The flood modelling results for Bohena Creek provided in the EIS are considered to be conservative and will be reviewed as part of the detailed design and any updates made to the flood model will be presented in the Flood Modelling Verification Report. JacobsGHD has undertaken separate flooding assessment for Narrabri due to local catchment flooding from Mulgate Creek and regional flooding in the Namoi River in response to submissions received from Narrabri Council. The flood model for Narrabri will be verified against the flood event of February 2020 as part of the detailed design. Any updates made to the flood model will be presented in the Flood Modelling Verification Report.

5. Conclusions

JacobsGHD has reviewed DPIE's comments relating to the flood modelling for Bohena Creek and conclude that:

- Information on the available data, review of stream gauge data, development of hydrologic and hydraulic models, calibration and validation of hydrologic and hydraulic model is included in the Hydrology and Hydraulic Models Calibration Report (JacobsGHD, 2021).
- Further details on flood modelling undertaken for Bohena Creek are included in this report. A detailed review on the draft Flood Study for Bohena Creek (WRM, 2019) has been undertaken. In particular, the approach adopted by JacobsGHD and WRM in the flooding assessment has been compared.
- At-site flood frequency results (WRM 2019) are highly sensitive to the adopted threshold for censoring annual maxima.
- The catchment area of Bohena Creek at the Newell Highway gauge is 2,180 km^2 and RFFE is applicable to catchment areas up to 1,000 km^2.
- Predicted peak discharges in Bohena Creek by JacobsGHD are considered conservative. However, historical flood information for Bohena Creek was not available during Reference Design to reconcile peak discharges estimated by the RORB hydrology model against other independent estimates due to the lack of high quality recorded stream data.
- ARTC is continuing to liaise with Narrabri Council and DPIE through the Flooding Working Group and Technical Meetings to provide clarifications on issues relating to flooding at Bohena Creek. Further consultation is planned with local landowners and other stakeholders to identify historic flood events which have resulted in flooding of properties, the Newell Highway and the Narrabri to Walgett railway line. The outcomes of these discussion may result in a reduction in peak flows being adopted for the detailed design. In the meantime, flooding assessment reported in the EIS have been based on a conservative approach.

6. References

Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors), 2019, Australian Rainfall and Runoff: A Guide to Flood Estimation, Commonwealth of Australia.

BMT, 2018, *TUFLOW Classic/HPC User Manual, Build 2018-03-AC.*

BOM, 2004, *The Estimation of Probable Maximum Precipitation in Australia: Generalised Short Duration Method.*

Laurenson, E. M., Mein, R. G. and Nathan, R. J., 2010, *RORB version 6 runoff routing program user manual*. Monash University Department of Civil Engineering in conjunction with Hydrology and Risk Consulting Pty Ltd and Melbourne Water Corporation. RORB version 6.31.

JacobsGHD, 2021*, Hydrology and Hydraulic Models Calibration Report*, Narromine to Narrabri (N2N), ARTC.

WRM, 2019, *Bohena Creek Flood Study,* Draft, October 2019, Narrabri Shire Council.

JacobsGHD

Level 3, 24 Honeysuckle Drive, Newcastle NSW 2300
PO Box 5403, Hunter Region Mail Centre NSW 2310
T: +61 2 4979 9999   F: +61 2 4979 9988   E: ntlmail@ghd.com

\Projects\22\19593 - ARTC IR N2N Feasibility Design & EIS\DESIGN DOCUMENTS\2-0001-250-IHY-00-RP-0016

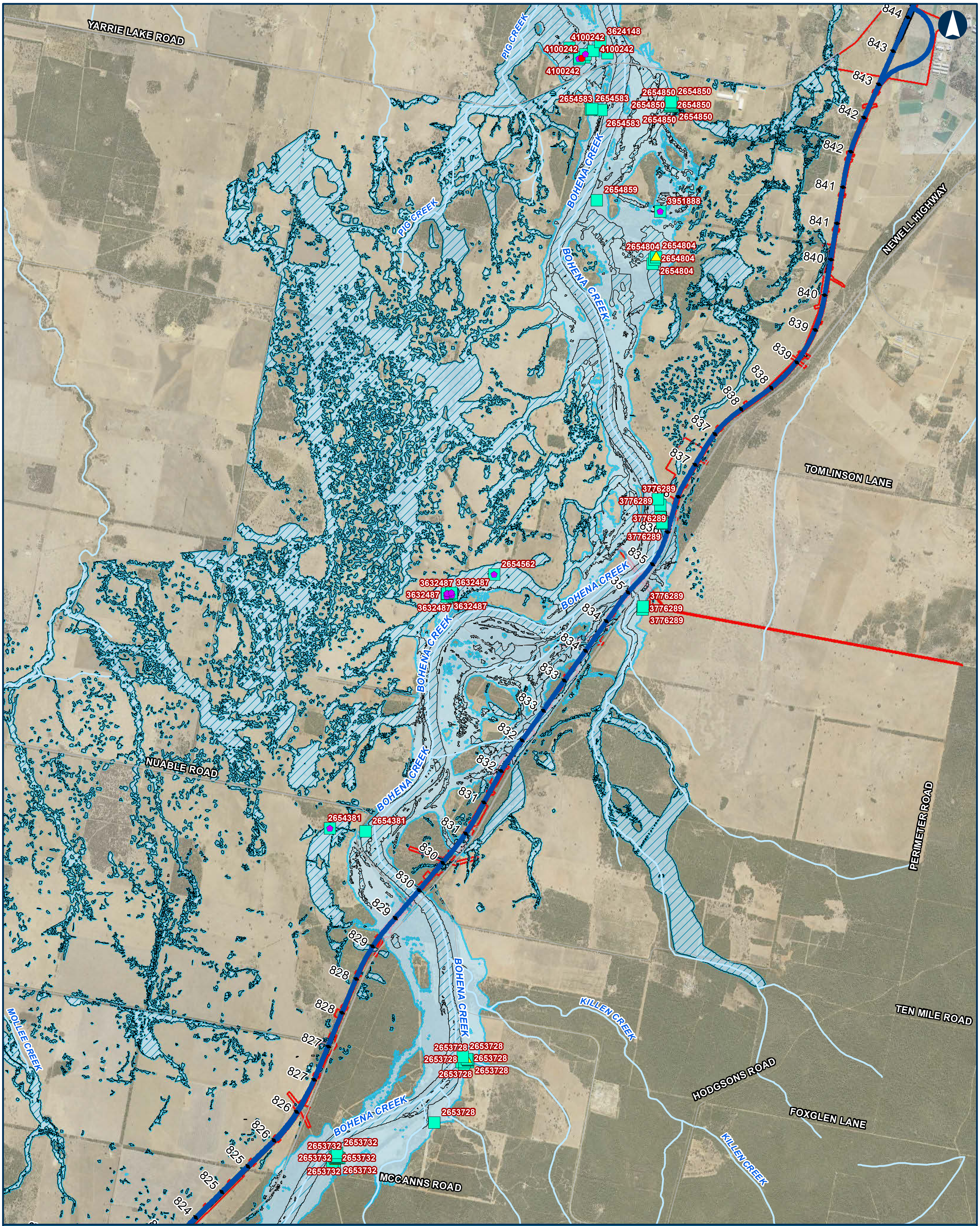
Jacobs GHD

APPENDIX

Q

Attachment 3 Modelled flood extents showing difference in property impacts between the updated FHAR and the alternative flooding assessment

NARROMINE TO NARRABRI PROJECT



NARROMINE TO NARRABRI

20% AEP Impacted Buildings Comparison

Figure 1.

0 690 1,380 Metres

Coordinate System: GDA 1994 MGA Zone 55

ARTC makes no representation or warranty and assumes no duty of care or other responsibility to any party as to the completeness, accuracy or suitability of the information contained in this GIS map. The GIS map has been prepared from material provided to ARTC by an external source and ARTC has not taken any steps to verify the completeness, accuracy or suitability of that material. ARTC will not be responsible for any loss or damage suffered as a result of any person whatsoever placing reliance upon the information contained within this GIS map.

Date: 11/05/2022 Paper: A3
Author: JacobsGHD Scale: 1:48,000
Data Sources: Basemap layers: NSWSS; all other layers: JacobsGHD

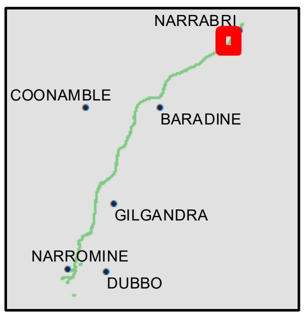
ARR 2019

- Habitable building flooded -20% Flood
- Non-habitable building flooded -20% Flood
- ARR 2019 20% AEP flood extent

Scaled Peak Flow

- Habitable building flooded -20% Flood
- Non-habitable building flooded -20% Flood
- Scaled Peak Flow 20% AEP flood extent

- Alignment
- Road
- Watercourse
- Draiange Control Area
- Rail Corridor

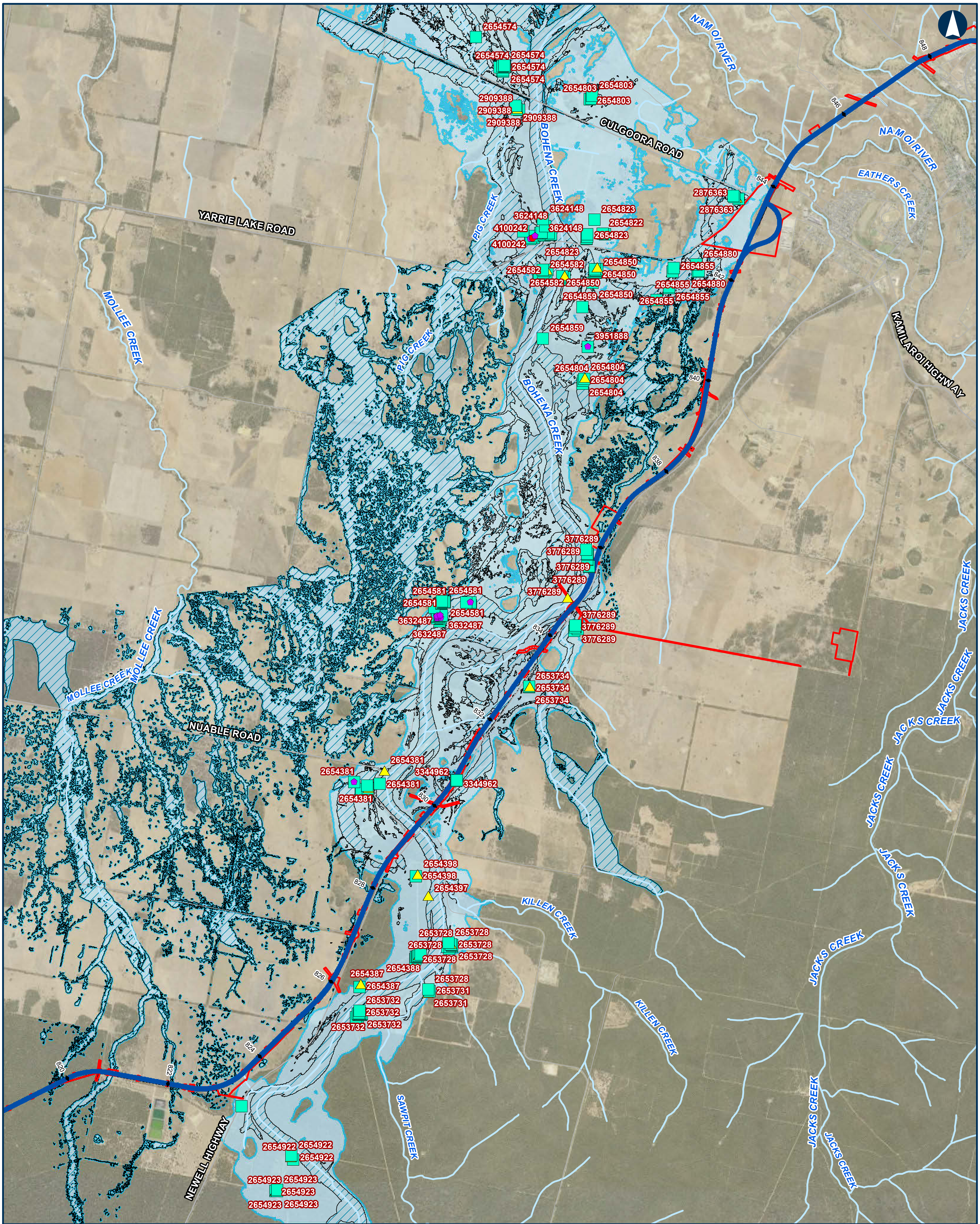


INLAND RAIL

ARTC

The Australian Government is delivering Inland Rail through the Australian Rail Track Corporation (ARTC), in partnership with the private sector.

\\ghdnet\ghd\AU\Newcastle\Projects\22\19593\GIS\GIS_2500_N2N_v2\Maps\ARTCNonDeliverable\2500_BohenaCreek_20pcAEPDesign_ImpactedBuildings.mxd



NARROMINE TO NARRABRI 5% AEP Impacted Buildings Comparison

Figure 1.

0 980 1,960
Metres

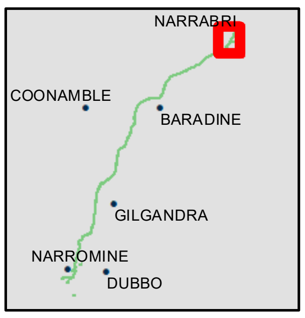
Coordinate System: GDA 1994 MGA Zone 55

Date: 11/05/2022 Paper: A3
Author: JacobsGHD Scale: 1:68,000
Data Sources: Basemap layers: NSWSS; all other layers: JacobsGHD

ARR 2019
- Habitable building flooded -5% Flood
- Non-habitable floors -5% Flood
- ARR 2019 5% AEP flood extent

Scaled Peak Flow
- Habitable building flooded -5% Flood
- Non-habitable building flooded -5% Flood
- Scaled Peak Flow 5% AEP flood extent
- Alignment

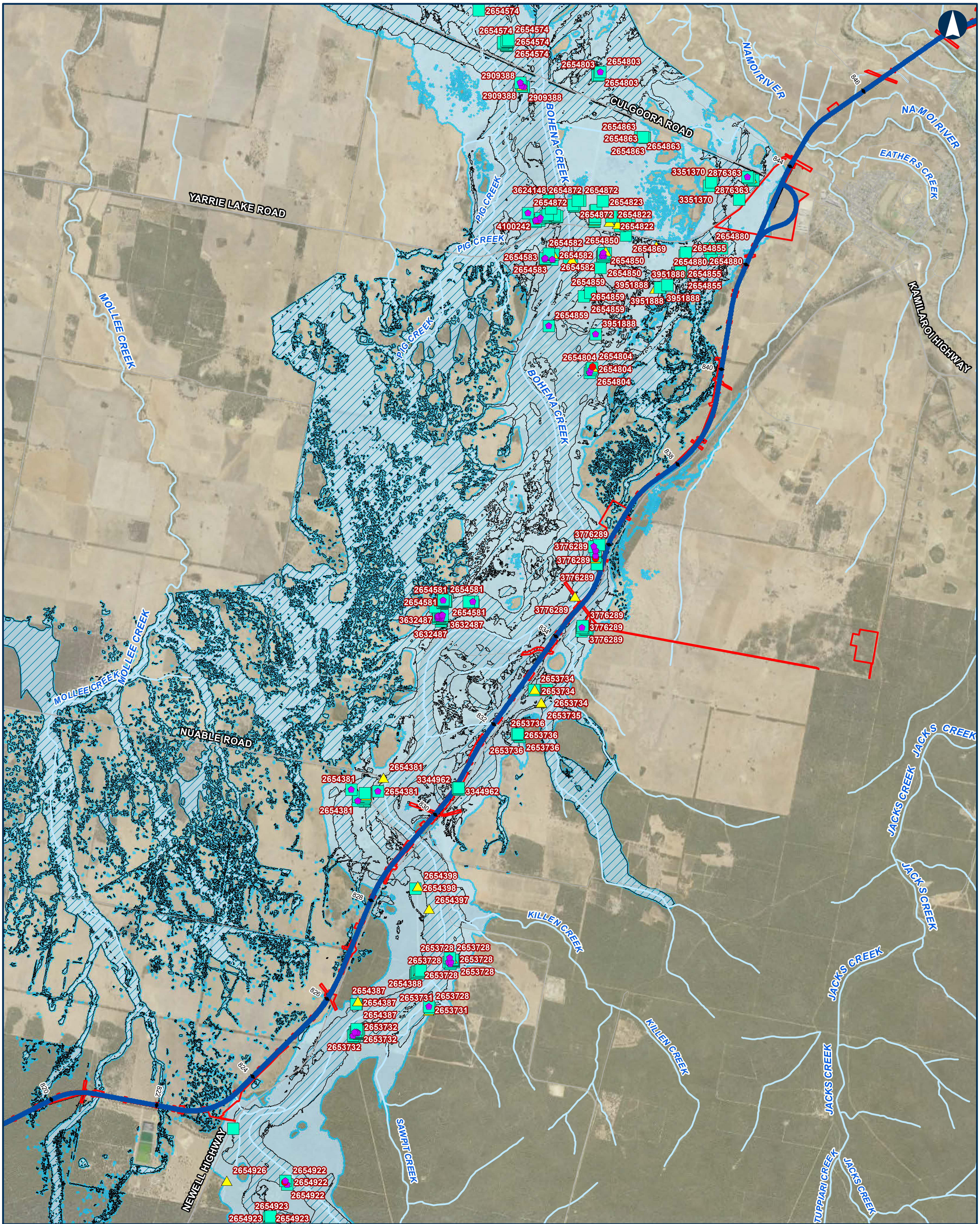
- Road
- Watercourse
- Draiange Control Area
- Rail Corridor



INLAND RAIL ARTC

The Australian Government is delivering Inland Rail through the Australian Rail Track Corporation (ARTC), in partnership with the private sector.

\\ghdnet\ghd\AU\Newcastle\Projects\22\19593\GIS\GIS_2500_N2N_v2\Maps\ARTCNonDeliverable\2500_BohenaCreek_5pcAEPDesign_ImpactedBuildings.mxd



NARROMINE TO NARRABRI 2% AEP Impacted Buildings Comparison

Figure 1.

0 940 1,880 Metres

Coordinate System: GDA 1994 MGA Zone 55

ARTC makes no representation or warranty and assumes no duty of care or other responsibility to any party as to the completeness, accuracy or suitability of the information contained in this GIS map. The GIS map has been prepared from material provided to ARTC by an external source and ARTC has not taken any steps to verify the completeness, accuracy or suitability of that material. ARTC will not be responsible for any loss or damage suffered as a result of any person whatsoever placing reliance upon the information contained within this GIS map.

Date: 11/05/2022 Paper: A3
Author: JacobsGHD Scale: 1:65,000
Data Sources: Basemap layers: NSWSS; all other layers: JacobsGHD

ARR 2019
- Habitable floors - 2% Flood
- Non-habitable floors - 2% Flood
- ARR 2019 2% AEP flood extent

Scaled Peak Flow
- Habitable building flooded -2% Flood
- Non-habitable building flooded -2% Flood
- Scaled Peak Flow 2% AEP flood extent
- Alignment

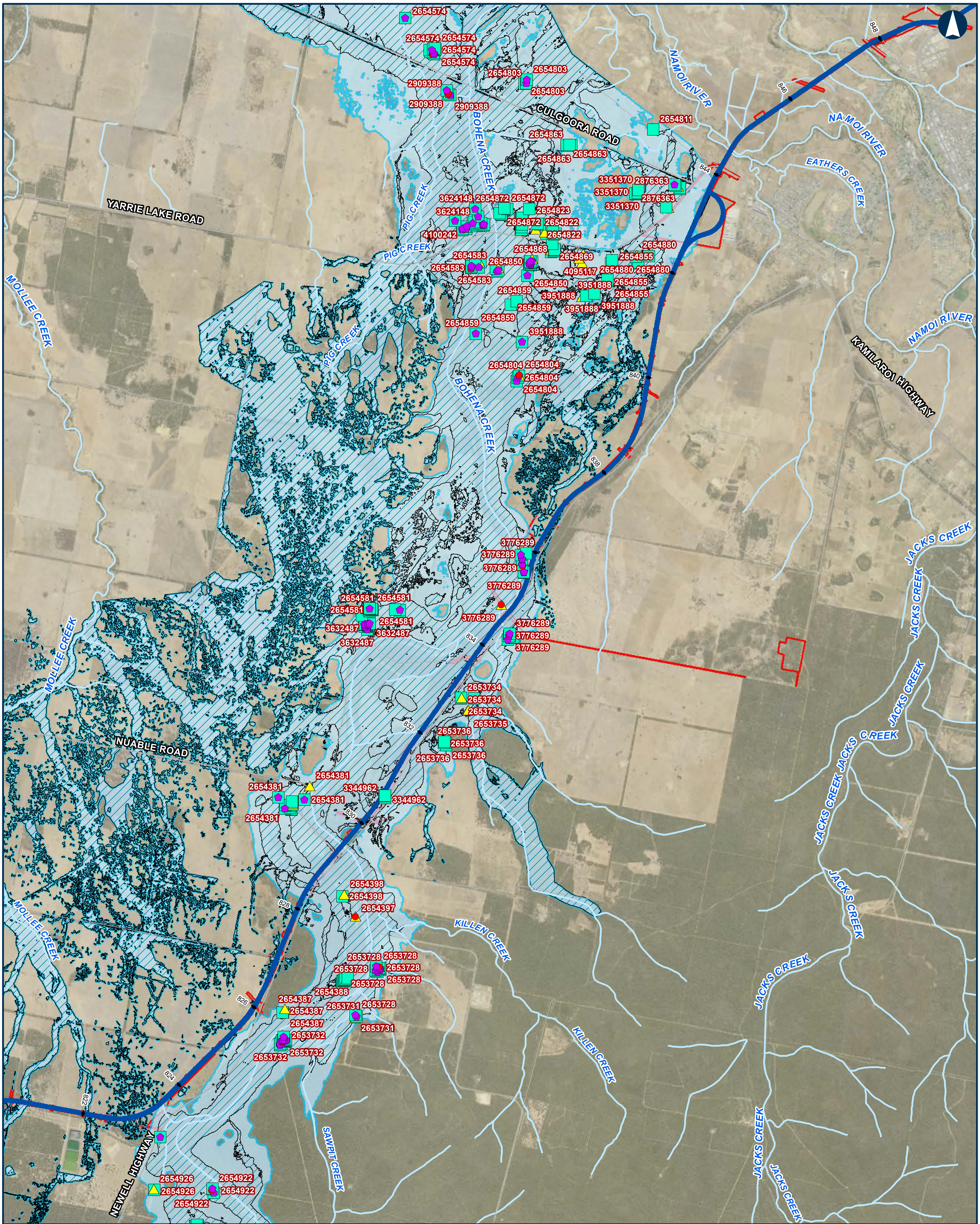
- Road
- Watercourse
- Draiange Control Area
- Rail Corridor

NARRABRI
COONAMBLE
BARADINE
GILGANDRA
NARROMINE
DUBBO

INLAND RAIL
ARTC

The Australian Government is delivering Inland Rail through the Australian Rail Track Corporation (ARTC), in partnership with the private sector.

\\ghdnet\ghd\AU\Newcastle\Projects\22\19593\GIS\GIS_2500_N2N_v2\Maps\ARTCNonDeliverable\2500_BohenaCreek_2pcAEPDesign_ImpactedBuildings.mxd



NARROMINE TO NARRABRI 1% AEP + Blockage Impacted Buildings Comparison

Figure 1.

0 940 1,880
Metres

Coordinate System: GDA 1994 MGA Zone 55

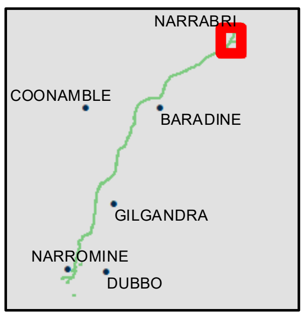
ARTC makes no representation or warranty and assumes no duty of care or other responsibility to any party as to the completeness, accuracy or suitability of the information contained in this GIS map. The GIS map has been prepared from material provided to ARTC by an external source and ARTC has not taken any steps to verify the completeness, accuracy or suitability of that material. ARTC will not be responsible for any loss or damage suffered as a result of any person whatsoever placing reliance upon the information contained within this GIS map.

Date: 11/05/2022
Paper: A3
Author: JacobsGHD
Scale: 1:65,000
Data Sources: Basemap layers: NSWSS; all other layers: JacobsGHD

ARR 2019
- Habitable building flooded -1% + Blockage Flood
- Non-habitable building flooded -1% + Blockage Flood
- ARR 2019 1% AEP + blockage flood extent

Scaled Peak Flow
- Habitable building flooded -1% Flood
- Non-habitable building flooded -1% Flood
- Scaled Peak Flow 1% AEP + blockage flood extent
- Alignment

- Road
- Watercourse
- Draiange Control Area
- Rail Corridor



INLAND RAIL
ARTC

The Australian Government is delivering Inland Rail through the Australian Rail Track Corporation (ARTC), in partnership with the private sector.

\\ghdnet\ghd\AU\Newcastle\Projects\22\19593\GIS\GIS_2500_N2N_v2\Maps\ARTCNonDeliverable\2500_BohenaCreek_1pcAEPBlock_ImpactedBuildings.mxd