Department of
Environment, Climate Change and Water NSW

WAGGA WAGGA CITY COUNCIL

MURRUMBIDGEE RIVER MODEL CONVERSION PROJECT

FINAL REPORT

SEPTEMBER 2010

wma water

Level 2, 160 Clarence Street
Sydney, NSW, 2000

Tel: 9299 2855
Fax: 9262 6208
Email: wma@wmawater.com.au
Web: www.wmawater.com.au

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Client Wagga Wagga City Council	**Client's Representative** Brad Jeffrey/Bryan Short
Authors Stephen Gray, Ivan Varga	**Prepared by**
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WAGGA WAGGA MURRUMBIDGEE RIVER MODEL CONVERSION PROJECT

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EXECUTIVE SUMMARY

The existing Murrumbidgee River flood model for Wagga Wagga is a one-dimensional (1D) RUBICON model which was built as part of the 2004 Flood Study (Reference 1) and further utilised/reviewed as part of the subsequent Floodplain Risk Management Study and Risk Management Plans (Reference 3 and 4 respectively). More recently established best practice for a flooding situation such as is found at Wagga Wagga, particularly with respect to result interpretation and presentation, is for the application of a two-dimensional (2D) model. As such, Wagga Wagga City Council (WWCC) has requested that WMAwater (previously trading as Webb McKeown and Associates Pty Ltd) carry out the conversion of the existing 1D RUBICON model to a 2D TUFLOW model.

TUFLOW is a 2D hydrodynamic modelling system which is widely used in Australian practice and has been shown numerous times to produce high quality results of inundation extent, depth and flow velocity.

The majority of data for the construction of the 2D model was derived from Airborne Laser Survey (ALS) data collected during 2008 by Fugro Spatial Solutions Pty Ltd (Fugro). The ALS dataset is accurate to +/- 0.15 m and is collected at such a density that a meaningful 1 m raster can be created from it (see Appendix B for a review of the ALS data set). Details on structures were extracted from the existing RUBICON model and where necessary RUBICON data was utilised in the construction of the 2D model. A key inclusion was the alignment and elevation of the Main and North Wagga levees based on data utilised as part of the 2004 study (Reference 1).

In order to establish the accuracy of the results from the 2D model a number of calibration/validation events were run through it and results were compared to those produced by a comparable version of the previous RUBICON model as well as to original gauge and observed data. Results from these demonstrated the accuracy of the 2D model and its suitability for utilisation in WWCC riverine flood planning activities.

The model was then used to develop design flood information for the 10, 5, 2 and 1% AEP events as well as the PMF and plotted results for these runs are presented herein.

In addition to producing design flood information the model has been used to define design levee heights and also to assess the plausibility of reducing flood levels by undertaking some vegetation management between the River and North Wagga. With respect to vegetation management the runs undertaken establish that the vegetation management as proposed by Council will not have a discernible impact on flood levels.

1. INTRODUCTION

The "Murrumbidgee River Wagga Wagga Flood Study" (Reference 1) was completed in 2004 and included a review of previous modelling and the construction of a hydrodynamic model for the study area (Malebo Gap to Braehour) using the 1D hydraulic modelling package called RUBICON. The RUBICON model of the Murrumbidgee River at Wagga Wagga was subsequently reviewed and modified as necessary during the Floodplain Risk Management Study (Reference 3) and Floodplain Risk Management Plan (Reference 4). Key outputs from the previous studies (References 1, 3 and 4) carried out for flooding at Wagga Wagga due to the Murrumbidgee River relevant to this work are:

- Flood frequency analysis (FFA) which examined approximately 150 years of records and produced design peak flow estimates for a range of different events as well as a PMF;
- Inflow hydrographs developed iteratively based on model routing and a comparison to recorded hydrographs at Hampden Bridge gauge;
- The stage/discharge relationship compiled based on Hampden Bridge measured stage/discharge data presented in Pineena (130 years of record); and
- Flood level profile results for the calibration and design flood events modelled.

As noted above, subsequent to the flood study (Reference 1) being finalised in 2004, a floodplain risk management study (Reference 3) and a floodplain risk management plan (Reference 4) were carried out. The Risk Management Study examined works that could be carried out, including planning options,that would produce positive outcomes with respect to removing residents from high risk flooding. The plan laid out an actual action list for WWCC to carry out in order to achieve a reduction in flood risk that was compatible with WWCC funding priorities

Following the completion of the Floodplain Risk Management Study (Reference 3) Council acted upon a key recommendation which was to collect Airborne Laser Survey (ALS) of the broader Wagga Wagga floodplain. The aim of collecting such data was to facilitate 2D modelling which in turn would lead to the ability to derive more accurate estimates of design floods throughout the Study area.

WWCC obtained ALS data and engaged WMAwater to convert the existing 1D RUBICON model of the Murrumbidgee River between Braehour and Kullaroo into a full 2D TUFLOW model.

The primary objectives of the study were to:

- Convert the existing Wagga Wagga RUBICON model into a 2D TUFLOW model.
- Confirm that the 2D model can reproduce observed flood behavior for a series of three events. These events are the 1974, 1975 and 1976 flood events;
- Compare the 2D model results, particularly for peak water level profile, against those previous RUBICON model results; and following endorsement of calibration/validation results by WWCC;

- Carry out design modeling and produce detailed inundation information for the study area at model grid resolution. Outputs should include flood flows, velocities, levels and depths for a range of design events including the PMF;
- Carry out runs which can be used to determine (i) the required design height of the Main City and North Wagga levees in order for them to protect residents from the 1% and 5% AEP design events respectively and (ii) flood planning levels for the Study area; and
- Carry out runs which assess the likely impact of proposed vegetation management by Council in the area between the River and North Wagga.

This report is not intended to be a flood study but rather is for the purpose of detailing the conversion and 2D model build. The key elements of the report are:

- a summary of data used in the model build process;
- a summary and explanation of the steps taken in order to build the 2D TUFLOW model;
- presentation of calibration/validation results which confirm the suitability of the TUFLOW model for the representation of Wagga Wagga flooding behavior; and
- results for design modeling including mapping;
- results which describe the required design heights of the Main City and North Wagga levees and revised flood planning levels; and
- results which indicate the likely impact Council intensively managing vegetation to the north of the River will have on flood levels.
- to provide files to allow use of software such as WaterRide to assess development applications.

All levels provided in this report are in metres (m) to Australian Height Datum (AHD) (which is the standard national survey reference with 0 mAHD approximating mean sea level) unless otherwise stated. The magnitude of floods are referred to in this report according to their Annual Exceedance Probability (AEP) which is expressed as the probability (as a percentage) that the flood magnitude will be achieved (or exceeded) within any given year. So for example a 1% AEP flood flow is that flow which has a 1% chance of being achieved (or exceeded) in any given year (Reference 2).

1.1. Study Area - City of Wagga Wagga

The Murrumbidgee River at Wagga Wagga has a catchment area of approximately 26,400 km^2. The original settlement of North Wagga Wagga is situated on the northern floodplain with the majority of the city and recent developments now located on the high ground of the southern bank. A large part of the city remains on the floodplain and is protected from flooding by levee banks, termed the North Wagga Wagga levee and the Main Town levee (south). The main road crossing point used to be Hampden Bridge but this is now closed and has been replaced by the nearby Wiradjuri Bridge (1995) and then supplemented by the more recently constructed Gobbagombalin Bridge (1997). At Hampden Bridge the floodplain is some 3 km wide but this reduces to approximately 1.4 km at Gobbagombalin Bridge. Upstream of Wagga Wagga the river is crossed by the Main Southern Railway and then further upstream the Eunony Road Bridge. The extent of the study area is shown in Figure 1.

2. AVAILABLE DATA

A variety of different data was used in the model build process and that data is detailed here.

2.1.1. RUBICON Model

Limited information has been extracted from the RUBICON model as generally other data sets, most noticeably the ALS data, made RUBICON information redundant. Nevertheless the following information was extracted from RUBICON and used in the TUFLOW model build:

- 14 of 24 total cross-sections in the RUBICON model were used in order to inform triangulated irregular network (TIN) generation over the study area. Specifically what was done was that at 14 locations RUBICON cross-sections were used to inform the digitised river width and also the river invert. Further information on how the RUBICON cross-section data was utilised is given in Section 3.2.3. Note that in-river data was not available from the ALS dataset as it does not penetrate water;
- During the course of the RUBICON work documented in Reference 1 inflow hydrographs, for the modelling of calibration/validation events, were developed based on stage measurements at Hampden Bridge. The inflow hydrographs have been used in the study, albeit with some modifications which are documented in Section 3.2.7. Additionally, RUBICON design flood hydrographs were used for the design 2D model runs; and
- RUBICON results were also used in order to provide some context for the reader when presenting the TUFLOW calibration and design results.

2.1.2. 2004 Flood Study for Murrumbidgee River at Wagga Wagga (Reference 1)

A variety of information has been extracted from Reference 1. Discussed below are the historical changes that need to be considered regarding river flow and floodplain topography since the calibration events occurred in the 1970's.

2.1.2.1. Historical changes to hydraulics in the study area

Relevant to calibration of the 2D model to historical events (1974, 1975 and 1976) is that in the period between the seventies and 2008 (when ALS data was collected) some changes have occurred in topography. A substantial change to the floodplain (e.g. construction of a levee bank, bridge, channel, excavation or other structure or activities) may affect flood behaviour and hence the distribution of flows across the floodplain. There is no accurate chronological history of when such changes have occurred. The best available summary of the significant changes which are known is provided in Table 1 (sourced from Reference 1).

Table 1: Historical changes to flood impacting structures in Wagga Wagga

Date	Works on the Floodplain	Comment
Various	Narrung Street Sewage Treatment Ponds: • 1914 - The site was first developed as a sewage plant for the town of Wagga Wagga. • early 1950's - A formalised series of treatment ponds were constructed between the plant and the river. • 1967/1968 - The ponds were upgraded to the current configuration including construction of four ponds west of the Bomen rising main. • approx. 1977 - Three ponds west of the Bomen rising main were removed in order to reduce upstream flood levels. The bank around the emergency overflow pond (the remaining pond to the west) may have also been lowered at the same time. • mid 1990's - A floodway was partially constructed through the ponds. • 2007 to 2010 – Treatment Works reconstructured and use of ponds reduced substantially	Council is aware of the restriction caused by construction of the banks around the treatment ponds (Reference 3) and is currently addressing this issue including the associated environmental/public health issues.
1930s	Gobba weir and levee	(Upgrading to eastern end in late 1960's/early 70's)
1960	Main Town levee constructed on southern floodplain.	Limited the width of floodplain.
1975	Raising of East Street and Mill Street levee to 179.3 mAHD.	Up to 1 m high and 200 m long. This prevents floodwaters up to 9.3 m on the gauge (179.35 mAHD) from entering the northern floodway and cutting the Junee Road.
1975	Eunony Bridge was completed. In the August 1974 flood the bridge was only partially constructed with the approaches constructed by the time of the October 1975 flood.	
1975	The Gumly Gumly levee was temporarily raised to its present level following the August 1974 flood.	
1978-1983	The Main Town levee was upgraded to approximately 1 m above the 1974 flood level.	
1978	A private levee was constructed around the Allonville Motel and the access road to the Murray Cod Hatchery was raised.	
Late 1980's	The Sturt Highway was raised by up to 0.2 m.	
1990	Construction of the North Wagga Wagga levee to the 1 in 20 ARI +0.3m freeboard event	
1992	The Gumly Gumly levee was formalised to approximately the 1 in 10 ARI event.	
1995	Construction of Wiradjuri Bridge	Minor alterations to access road between Wiradjuri and Parken Pregan bridges
1997	Construction of Gobbagombalin Bridge	Changes to northern edge of floodplain from Gobba lagoon to Coolamon Road

In addition to the above, there are also various quarries, buildings and in fill and development on the floodplain that have or will impact on the distribution of flood flows. In constructing the 2D model (using ALS topographical data) an effort has been made to alter the topography in order to match the calibration/validation events. In order to model current conditions (for design flood modelling purposes) these changes have been reversed.

2.1.2.2. Calibration Data

All calibration data was sourced from Reference 1. This includes the stage hydrograph at Hampden Bridge for the 1974 flood event as well as the various observed flood levels for the gauged events. More information on the provenance of this data can be found in Reference 1. Note that the estimated ARI for the calibration/validation events is as follows:

- 1974 – 60 year ARI
- 1975 – 13 year ARI and
- 1976 – 11 year ARI

2.1.2.3. Design Flood Heights

In order to provide context to Council we have extracted RUBICON design flood results from previously presented results (see Reference 1 and 3). The RUBICON results used are the values which Reference 3 (Appendix D) recommended for use as the flood planning event (1% AEP). These RUBICON results are based on a scenario which includes the assumption that the Main City Levee is upgraded to the 1% AEP level plus freeboard (hence no failure during the 1% AEP event) and that no increase in roughness, attributable to increased density of vegetation on the floodplain, is required (i.e. Council actively carry out vegetation management). It is noteworthy that the vegetation management options considered (Reference 3, Appendix A) in the previous RUBICON modelling found a localised increase in flood levels when thicker floodplain vegetation was modelled. As such it was stated that a lack of vegetation management will impact on the design heights for the Main City and North Wagga levees. Subsequent 2D modelling suggests impacts of vegetation change have only minimal impacts on flood levels.

Please note that it is not necessarily the case that the 2D model results should be expected to match the RUBICON results as it is considered that the 2D model is likely to give more accurate results than did the previously applied RUBICION model. Also it should be noted that whilst RUBICON water levels results will be the same at any point in a cross-section, 2D results may vary across a similar extracted cross-section. That is the 2D model may, in some cases, correctly indicate variance in water level between main channel and floodplain and this may be a source of variation when results from the RUBICON and 2D models are compared.

2.1.3. Airborne Laser Survey

The ALS data was flown in 2008 and delivered to WWCC at the start of May 2009. Details of this data set along with a brief report which examines the accuracy of the ALS data set is provided in Appendix B.

Note that Fugro Spatial Systems Pty Ltd (Fugro), the party which obtained and processed the ALS data, provided Council with a 1 m raster for the study area. This was subsequently obtained by WMA and it is this 1 m raster which is the fundamental data set used in the 2D model build process. The DTM constructed is shown in Figure 2.

3. MODEL BUILD

3.1. Hydrology

Hydrology utilised in modelling herein reported upon is based on Reference 1. That is, the hydrographs utilised previously, which are based on flood frequency analysis reported upon in Reference 1, have been re-used, albeit with some modification as documented in Section 3.2.7.

3.2. Hydraulics

3.2.1. Model Domain

The model domain over which the 2D model applies is indicated in Figure 1, outlined in red. The model covers the same reach of the Murrumbidgee River as did the RUBICON model (Reference 1). The total area of the model domain is approximately 87 km^2.

3.2.2. Model Grid Size

The model is built using a 20 m by 20 m finite difference grid. That is, each square grid cell represents an area equivalent to 400 m^2. Note that the actual resolution of the model is 10 m by 10 m, as the nature of TUFLOW is that unlike some other finite difference grid based models, it uses three points per cell not one. This resolution was utilised because it was considered that it adequately resolved in-bank and other critical hydraulic features whilst not causing unreasonably long model run times. A key restriction to the grid size was that a resolution of at least three to four cells was required inside the banks of the Murrumbidgee River.

The raster from which the TUFLOW model grid was built was constructed in the following way: the source 1 m raster (from Fugro) was aggregated into a 10 m by 10 m raster using a mean method of aggregation (the mean of all heights used to determine the resultant grid cell height). The actual model grid (at a resolution of 20 m) was then sampled from the 10 m grid. This method was found to produce a stable model which is important for subsequent modelling that will take place (i.e. design and mitigation runs).

A DTM covering the study area is shown in Figure 2.

3.2.3. River reach and cross sections

As stated previously only 14 of 24 RUBICON cross-sections were used in the TUFLOW model build process (see Figure 5 for cross-section locations). At these cross-sections the river width and invert were taken and implemented in the topography of the model. The inclusion of RUBICON cross-section data was an important addition to the model grid in that it facilitated better representation of low river level conveyance. This was critical to emulating the observed stage/discharge relationship at Hampden Bridge and also key in achieving good validation results for the relatively smaller 1975 and 1976 events.

The process of utilising the RUBICON cross-sections depended on digitised polylines which connected similar features between the cross-sections such as the invert, left top of bank and right top of bank. So for example the invert of each included cross-section was linked by an interpolating polyline, so that the invert would be applied to TUFLOW cells in-between the two cross-section locations. Polylines were digitised so that they ran parallel to the known River centreline.

3.2.4. Structures

Five bridges are located within the study area, namely (from downstream to upstream): Gobbagombalin, Wiradjuri, Hampden, Railway and Eunony bridges. As detailed bridge information was not provided in the RUBICON model, the obstruction of the bridges' piers across the river were modelled by a local increase in Manning's "n" value in the section of the river where they are located. A value of 0.065 for Manning's 'n' was used at bridge locations in order to emulate head loss due to piers. This locally applied roughness value was in contrast to the general river value of 0.025.

3.2.5. Roughness Values

In hydraulic modelling, one of the factors that have a direct impact on flow velocities and depths is bed resistance, represented by the Manning's 'n'. One of the steps involved in the calibration process is the adjustment of roughness coefficients to obtain the desired water elevation at locations for which the peak flood level is known. The final adopted roughness values found by calibration are presented in Table 2. Note these are roughness values found by iteration in calibrating the 1974 event and then validated using the 1975 and 1976 events. A map of the roughness values is also shown in Figure 3.

Table 2: Roughness coefficients used in the model

Land use	Manning's "n"
General Floodplain vegetation	0.040
River	0.025
Red Gum trees in overbank	0.080
Yellow Box in overbank	0.080
Urban areas	0.055
Properties with mixed trees/houses	0.055
Cropping areas	0.060
Industrial areas	0.045
Parks	0.050
Golf courses	0.060
Open areas within the city	0.060
Bridges	0.065

Different roughness values will be utilised for design runs in order to represent the landscape changes that have occurred since the events used in the calibration/validation process (see Section 5.2.4).

3.2.6. Levee banks

Generally the DECC (Department of Environment and Climate Change) 2002 survey data identifying the spatial location and height of the levee, supplied to WMAwater by Council, has been used in defining the levee for all runs. An exception is at Narrung St where Reference 1 identified that the DECC alignment was in error and for this section Councils 2001 survey has been used in conjunction with heights taken from the ALS derived 1 m raster. The levee bank locations used in the model setup are shown in Figure 5.

For the calibration event of 1974 and verification events of 1975 and 1976, the North Wagga Wagga levee was removed from the model (as it was constructed in 1990) and the elevation at Hampden Avenue, in North Wagga Wagga were also reduced by approximately 0.1 m. Gumly Gumly levee was not included in modelling of the 1974 event (at which time it did not exist) however it was incorporated into all other runs (it was built in 1975). For further details refer to Table 1.

Topography conditions for design events included the current elevations for North Wagga Wagga levees and the ALS indicated elevations at Hampden Avenue as well.

Note that in all runs it is presumed that sand bags are utilised at the Sturt Highway at Marshall's Creek and that these sandbags are placed such that crest height is approximately equivalent to the levee height immediately adjacent (i.e. approximately 182.4 mAHD).

3.2.7. Boundary Conditions

Upstream boundary conditions: Inflows were applied at the upstream extent of the model (approximately at Braehour) with hydrographs initially taken from Reference 1. Hydrographs were then subsequently manipulated in order to improve calibration/validation results[1]. The 1974 hydrograph was reduced by 5% and timing was also slightly altered relative to the hydrograph employed in the RUBICON modelling. The 1975 hydrograph was increased by 5% and the 1976 hydrograph by 10%. The finalised input hydrographs used in the modelled calibration/validation events are presented in Figure 4.

Downstream boundary conditions: The downstream end of the model is located approximately at Kullaroo, 5 km's west of the Wagga Wagga. A fixed water level boundary condition was established 10 km's downstream of Kullaroo to improve stability problems and issues with stage-discharge tables in a location where it is extremely difficult to obtain due to the extent of the floodplain. The channel slope was set such that the resulting backwater profile did not have any significant effects on upstream water levels.

3.2.8. Hampden Bridge Stage/Discharge Characteristics

A key component to the model build was confirming that the 2D model was able to replicate the

[1] Note that this method of adjusting inflow hydrographs in order to make a match with Hampden Gauge is as per the method used in Reference 1.

rating curve for Hampden Bridge gauge, established through approximately 100 individual gaugings. It was found necessary to modify lower flow conveyance through the manipulation of the DTM and RUBICON sections were used to do this. Once the manipulation of the DTM was made, the general characteristics of the rating curve were well matched by the model. A comparison of the TUFLOW model stage/discharge relationship with the actual rating curve for the gauge is shown in Figure 6.

4. MODEL CALIBRATION AND VALIDATION

4.1. Introduction

This section of the report details the process undertaken. Results of calibration/validation work are presented in Section 6 of this report.

In this phase of the work results from the 2D model are compared to:

- Actual observations. This includes surveyed flood marks (both in-river and on the floodplain) as well as gauged hydrographs; and
- RUBICON results.

It is to be stressed that although the comparison with RUBICON is of interest, the main criteria for calibration success is how well the 2D model results match observed calibration data.

The 1974, 1975 and 1976 events were utilised for model calibration/validation work.

The 1974 calibration event did not include Gumly Gumly levee and Eunony Bridge. The Gumly Gumly levee raised in 1975 to its present level, therefore was used for the 1975 and 1976 validation events. Eunony bridge was only included in the validation events since its construction ended in 1975. Both of these inclusions had a negligible effect on results.

4.2. Calibration

As per Reference 1 the 1974 event, which is the most significant historical flood for which detailed records exist, has been used for calibration of the TUFLOW model.

The main elements of the calibration data set utilised to ascertain the quality of the calibration are the gauged hydrograph from Hampden Bridge (see Figure 7), the gauged stage/discharge relationship at the Hampden Bridge gauge (see Figure 6) and the observed flood levels along the Murrumbidgee River (both in river and on the floodplain).

Prior to beginning iterative calibration, changes were made to the 2008 ALS data set to best represents conditions on the ground at the time of the 1974 flood event, as per Table 1. Specifically this included the following:

- Eliminating the Gumly Gumly levee which was actually built in 1975;
- Eliminating any representation in the DTM of Eunony Bridge;
- Removed the North Wagga Wagga levee; and
- Reduced the level of Hampden Avenue by 0.1m.

The following was the calibration process. Initially the 1974 inflow hydrograph developed in the previous flood study was utilised (Reference 1). Roughness values were allocated based on land use mapping, with initial values estimates primarily based on the modellers experience with previous similar projects. The model was run and the modelled profile was compared to observed (in-river) flood marks as well as the previous (Reference 1) RUBICON results. The stage discharge relationship of the model at the location of Hampden Bridge was also compared to the gauged stage-discharge relationship at Hampden Bridge. This comparison revealed that lower stage conveyance was overestimated in the TUFLOW model. In order to correct this, the rather blocky representation of river width at invert depth was altered so that from the invert cell, the river bed rose steeply to meet the top of bank cell on either the right or left. Note that RUBICON cross-section data, as described in Section 3.2.3, was used to do this.

Once the gauged stage-discharge relationship was reasonably matched by the model, roughness values were modified in order to improve the match between observed peak flood levels and the model results and also to improve the match between the gauged stage hydrograph at Hampden Bridge and the modelled stage hydrograph.

During the calibration it was found that the land use which most impacted the flood level profile result was the general floodplain landuse. In using a Mannings ‘n’ roughness value of 0.04 for general floodplain roughness the 1974 flood profile result was still too high relative to observed flood marks. Using a roughness value lower than a Mannings ‘n’ of 0.04 on the general floodplain was not considered reasonable and so the peak flow of hydrograph input to the model was reduced by 5% instead. Note that the development of the inflow hydrographs is discussed at length in Reference 1 but essentially was done using a trial and error basis. A hydrograph was input to the upstream end of the RUBICON model and when the stage hydrograph at Hampden Bridge was replicated then the process ended.

Following the alteration of the inflow hydrograph the results seemed to indicate a sound calibration (refer to Figure 7) and the roughness values utilised seemed reasonable (refer to Figure 3). As such the calibration was at that stage considered to be finished.

4.3. Validation

The events of 1975 and 1976 were chosen for validation purposes because they represent two of the most recent large events for which there is a reasonable amount of recorded data.

For validation purposes, besides the inclusion of the Gumly Gumly levee, no modifications in topographical conditions were made.

The Manning’s “n” coefficients were not changed from the 1974 event. However, peak flow values for the input hydrographs were changed. In order to achieve a good match, the 1975 inflow hydrograph generated for RUBICON modelling was increased by 5% whilst the 1976 inflow hydrograph was increased by 10%.

5. DESIGN EVENT MODELLING

5.1. Design Event Model Build Issues

Design modelling was carried out in order to define flood levels for events of various probability using the new 2D model. Prior to applying the model to design flood work it was necessary to update some parameters and alter the model setup in order to reflect changes that have occurred since the occurrence of the events used in the calibration/validation process.

As such the following changes were made to the 2D model:

- two new bridges were added to the model, namely Wiradjuri Bridge and Gobbagombalin Bridge (see Section 3.2.4 for more detail of how they were modelled);
- modifications were made to the terrain for design conditions. These modifications correspond to the addition of sandbags on Sturt Highway (at bridge over Marshall's Creek) and Copland Street. At these locations total blockage at levee local levee height was presumed. Roughness values were altered to reflect the fact that since the 1970's there has been a substantial increase in the density of vegetation on the floodplain in the vicinity of Wagga Wagga. It is noteworthy that higher roughness values used in the 2D design modelling (relative to the RUBICON modelling carried out previously to establish design flood levels (Reference 3, Appendix D) undermines the comparability of RUBICON design results and design results reported upon herein. The changes made to roughness values are as follows:
    - The general floodplain roughness co-efficient was increased to 0.045 (an increase of 0.005 from calibration/validation runs);
    - The Parken Pregan Lagoon (adjacent of North Wagga) roughness co-efficient was increased to 0.105 from 0.08;
    - The roughness co-efficient for the floodplain between Wagga Wagga and North Wagga, currently with values of 0.065 and 0.08, was increased to 0.095;
    - The roughness co-efficient for the floodplain between North Wagga and Cartwrights Hill was increased to 0.060 from 0.045; and
    - roughness co-efficient increased to 0.060 from 0.045 for the area between Travers Street and Olympic Hwy.

The design roughness values used as described above are shown in Figure 8. For comparison with values used in calibration please refer to Figure 3.

5.2. Scenarios Run

5.2.1. Introduction

A variety of scenarios were run using the converted and calibrated/validated 2D model setup. Three main varieties of scenarios were run, these are as follows:

- Design runs in order to establish design flood levels for planning purposes;
- Levee design runs in order to establish what height various levees need to be in order to provide flood protection during specific design floods; and
- Runs which examine how vegetation management on the floodplain near the Wagga Wagga CBD might help manage flood levels.

5.2.2. Flood design levels

As per the proposal the 10, 5, 2 and 1% AEP flood events and the PMF were modelled.

Basic design runs were run using the following assumptions regarding levee behaviour. Note that for smaller events (the 10 and 5% AEP flood events) no levee failure occurred as flood waters did not reach the levee height failure criteria:

- The Main City levee will be assumed to fail at the locations specified in Figure 9 as follows:
  - Failure at each location will start when the flow reaches the 1974 flood level. The levee breach at each location is approximately 400 m wide;
  - Failure will occur during a period of 5 minutes (that is the time when the levee starts to fail until reaching final cross section elevation);
  - Final levee height would be half the height at the 1974 flood level, taking as base, a ground point in the city side of the levee; and
  - Side slope of failure will be 1 in 2 (1 unit of rise per 2 units of run). See Figure 10 for a detailed drawing of the levee failure cross-section.
- The North Wagga Wagga levee was represented in the model using a breakline to ensure adequate definition of levee height. This same breakline was able to resolve the spillway and within the model, as water level exceeded the spillway invert, the model effectively represented the spillway as a broad crested weir.

In order to make a reasonable match with FFA derived design flows some adjustment was made to the RUBICON (Reference 1) derived design hydrographs applied to the TUFLOW model. The changes were as follows:

- 10% AEP – no change;
- 5% AEP – reduced flows by 3%;
- 2% AEP – reduced flows by 2%; and

- 1% AEP – reduced flows by 5%.

Note that the same process was followed during the course of the RUBICON modelling reported upon in Reference 1. That is, inflow hydrographs were altered in order that FFA derived peak flows at the Hampden Bridge gauge were approximately matched. Results showing the match between the design peak flows (at Hampden Bridge I.D.9) and those derived by FFA are below in Section 6 Table 9.

5.2.3. Levee Upgrade Scenarios

Two further runs were carried out in order to find what height of levee would be required in order to prevent ingress of flood waters into either the main CBD of Wagga Wagga (1% AEP) or North Wagga (5% AEP). In these runs design floods were used in conjunction with exaggerated levee heights.

5.2.4. Vegetation Management Scenarios

5.2.4.1. Introduction

Vegetation management runs examine the impact of maintaining an overbank flow path at levels of roughness which are lower than found elsewhere in the general floodplain. Scenario 2 trials a 50 m wide mown strip and compares flood level results with those from the base case 1% AEP design run (Scenario 1).

In a previous study (Reference 3) vegetation management was also modelled using the RUBICON model. To follow up on these results scenarios 3 to 5 have been run. Scenario 3 is simply a base case (equivalent to Scenario 1 except for omission of some detailed areas of land use as described below) against which the vegetation management works entailed in scenarios 4 and 5 can be compared to.

5.2.4.2. Description of runs undertaken

Various model configurations were run (as described below) however in all cases it was the 1% AEP design flood event (complete with levee failure) which was used with a varying roughness map then forming the basis of each of the different runs described below:

- **Scenario 1**: The design 1% AEP event (see Section 5.2.2) serves as the base case (with respect to comparison) for the Scenario 2 run whilst Scenarios 4 and 5 are compared to Scenario 3. Scenario 1 is then simply the 1% AEP design event as described in Section 5.2.2 above;
- **Scenario 2**: In this scenario, a 50m mown-wide strip running alongside Wall street in North Wagga, which is expected to be kept mown to reduce water levels in this area. This area is to have a roughness co-efficient of 0.050 (see Figure 11);
- **Scenario 3**: Roughness co-efficient will be taken as previously used in the Rubicon model. This model only includes the vegetation regrowth in the floodplain between North Wagga Wagga and Wagga Wagga, and the Parken Pregan Lagoon. The floodplain

between North Wagga Wagga and Cartwrights Hill and the area between the Olympic highway and Travers street will not be differentiated (with respect to roughness) in the modelling as these were not differentiated in the RUBICON model. Instead these two areas will be modelled as general floodplain with roughness co-efficients of 0.045 (see Figure 12);

- **Scenario 4**: The base scenario for this case is Scenario 3. This scenario will include a 50m mown-wide strip running alongside Wall street in North Wagga (see Figure 13); and
- **Scenario 5**: The base scenario for this case is Scenario 3. This scenario will include a 100 m mown-wide strip running alongside Wall street in North Wagga (see Figure 14).

6. RESULTS

The main presentation of results is by plan plots of peak flood behaviour and also, in some cases, profile plots of peak flood height versus river chainage. All figures are presented at the rear of the report. Tabulated results presented in this section as well as figures shown at the rear of the document are discussed in Section 7.

6.1. Calibration/Validation

For calibration runs profiles are shown which compare model results from the 2D model to observed in-river flood marks as well as RUBICON results. The tables below summarise the comparison of model results versus observed in-river flood marks for the calibration and validation events. The 1974 calibration profile, which uses the same data as presented in Table 3 below, is shown in Figure 15.

Subsequently observed flood marks, located on the floodplain, were compared to the modelled peak water level. This comparison indicated that the model was achieving a good match compared to the observed levels. The average absolute error is 0.13 m with a standard deviation of 0.14 m. The median absolute error is 0.09 m. A comparison of the observed and modelled levels is shown in Figure 16.

Validation results for the 1975 event are shown in Figure 17 (as a profile) and Figure 18 (comparison of floodplain levels and model). Profile results for the 1976 validation event are shown in Figure 19 (1976). Generally calibration/validation results are also summarised below in Table 3 to Table 5.

In summary the validation results indicate a good match. In comparing the 1975 floodplain observations with modelling absolute average error is 0.11 m as is the absolute median error. The standard deviation of the error is 0.09 m.

Table 3: Calibration results - 1974 in-river water levels

River Chainage (Km)	Water levels Observed 1974 (mAHD)	Water levels TUFLOW 1974 (mAHD)	Absolute Difference (m)
0.00		184.41	
4.02	183.39	183.14	0.25
9.43	182.29	182.15	0.13
14.42	181.32	181.37	0.05
15.39		181.17	
15.94		181.12	
16.36	181.13	181.11	0.02
16.74	180.91	181.00	0.09
17.91 (Hampden Br)	180.85	180.81	0.04
18.21	180.79	180.74	0.05
18.38		180.70	
19.65	180.57	180.59	0.02
20.43	180.33	180.34	0.01
21.87		179.66	
22.35	179.36	179.42	0.06
24.21	179.18	179.07	0.11
25.28	178.76	178.98	0.22
		Average diff. (m)	0.09

Table 4: Validation results - 1975 in-river water levels

River Chainage (Km)	Water levels Observed 1975 (mAHD)	Water levels TUFLOW 1975 (mAHD)	Absolute Difference (m)
0.00		183.48	
4.02		182.40	
9.43		181.45	
14.42		180.45	
15.39		180.15	
15.94		180.00	
16.36		179.97	
16.74		179.81	
17.91 (Hampden Br)	179.63	179.52	0.11
18.21	179.52	179.42	0.10
18.38		179.38	
19.65		179.24	
20.43		179.01	
21.87		178.61	
22.35		178.44	
24.21		178.28	
25.28		178.22	
		Average diff. (m)	0.10

Table 5: Validation results - 1976 in-river water levels

River Chainage (Km)	Water levels Observed 1976 (mAHD)	Water levels TUFLOW 1976 (mAHD)	Absolute Difference (m)
0.00		183.31	
4.02		182.26	
9.43		181.28	
14.42		180.26	
15.39	180.17	179.97	0.20
15.94	179.73	179.81	0.08
16.36		179.76	
16.74		179.62	
17.91 (Hampden Br)	179.64	179.30	0.34
18.21	179.43	179.19	0.24
18.38	179.37	179.14	0.23
19.65		178.99	
20.43		178.75	
21.87	178.40	178.42	0.01
22.35		178.26	
24.21	178.01	178.11	0.10
25.28		178.06	
		Average diff. (m)	0.17

6.2. Design Runs

Design runs have been carried out for two scenarios. The first, Scenario 1, includes the levees as they currently are (based on 2005 survey of the Main City Levee, see Reference 1 for details) and thus assumes levee failure. Results are presented for Scenario 1 for the 5%, 2%, 1% AEP and PMF events (See Figure 20 to Figure 24 and Figure 28) Hazard is also presented for the 5% and 1% AEP events since both of these events are impacted by proposed levee upgrade work (North Wagga for the 5% AEP event and the Main City Levee for the 1% AEP event) and the hazard maps may assist Council staff in demonstrating the implications should the levee's not be upgraded.

Given that in the future it is likely the levee will be upgraded it has been Council policy for some time to utilise post levee upgrade design flood levels for flood planning purposes. For this reason also presented are the results in Figure 25 to Figure 27. These show the flood extent, hazard and peak flood height profile for the 1% AEP event presuming that the Main City Levee is upgraded such that no failure occurs.

So that design flood levels (assuming no levee failure) can be compared to the 1% AEP levels based on Scenario 1 (i.e. with levee failure) contours are also presented in Figure 23 and Figure 25. Additionally these contours have been provided to Council electronically for mounting on their internal GIS system.

Note that in comparing the RUBICON results to the 2D model results, that with respect to roughness, the RUBICON results assume roughness conditions as per the 1970's (low roughness values) whilst the 2D model results incorporate the higher roughness values found on-site currently (for more on this please see Section 2.1.2.3 and 5.1). As such the values are not fully comparable and should not necessarily be the same. The two sets of results do constitute the basis for adopted design flood levels by Council however, with the RUBICON results presumably being made redundant by the new design levels coming from the 2D modelling. For this reason, it was considered a useful exercise to present them side by side.

A comparison of the RUBICON derived design flood levels (Reference 3, Appendix D) with the TUFLOW derived design flood levels is made below (see Table 6 to Table 8 below).

Table 6: Comparison of Peak Design Heights for 10% AEP flood event

River Chainage ID	River Chainage (Km)	Water levels Rubicon model (mAHD)	Water levels Tuflow model (mAHD)	Difference (m)
1	0	182.96	183.42	0.46
2	4.02	182.04	182.39	0.35
3	9.43	180.97	181.31	0.34
4	14.42	180.01	180.38	0.37
5	15.39	179.87	180.12	0.25
6	15.94		180.00	
7	16.36		179.97	
8	16.74	179.69	179.84	0.16
9	17.91	179.34	179.51	0.17
10	18.21	179.16	179.39	0.23
11	18.38	179.05	179.35	0.30
12	19.65	178.76	179.14	0.38
13	20.43	178.08	178.80	0.72
14	21.87	177.82	178.45	0.63
15	22.35		178.30	
16	24.21		178.14	
17	25.28		178.08	
18	26.68	177.30	177.90	0.60

Table 7: Comparison of Peak Design Heights for 5% AEP flood event

River Chainage ID	River Chainage (Km)	Water levels Rubicon model (mAHD)	Water levels Tuflow model (mAHD)	Difference (m)
1	0	183.69	183.89	0.20
2	4.02	182.63	182.75	0.12
3	9.43	181.55	181.64	0.09
4	14.42	180.64	180.73	0.09
5	15.39	180.50	180.51	0.01
6	15.94		180.43	
7	16.36		180.41	
8	16.74	180.31	180.30	-0.01
9	17.91	180.03	180.00	-0.03
10	18.21	179.83	179.89	0.06
11	18.38	179.70	179.84	0.14
12	19.65	179.44	179.70	0.26
13	20.43	178.74	179.43	0.69
14	21.87	178.49	178.93	0.44
15	22.35		178.74	
16	24.21		178.53	
17	25.28		178.46	
18	26.68	177.93	178.29	0.36

Table 8: Comparison of Peak Design Heights for 1% AEP flood event

River Chainage ID	River Chainage (Km)	Water levels Rubicon model (mAHD)	Water levels Tuflow model (mAHD)	Difference (m)
1	0	185.20	184.81	-0.39
2	4.02	183.80	183.63	-0.17
3	9.43	182.80	182.71	-0.09
4	14.42	182.10	182.12	0.02
5	15.39	181.90	181.96	0.06
6	15.94		181.93	
7	16.36		181.91	
8	16.74	181.70	181.82	0.12
9	17.91	181.40	181.54	0.14
10	18.21	181.30	181.42	0.12
11	18.38	181.20	181.37	0.17
12	19.65	181.00	181.10	0.10
13	20.43	180.40	180.50	0.10
14	21.87	179.90	179.90	0.00
15	22.35		179.93	
16	24.21		179.45	
17	25.28		179.34	
18	26.68	179.30	179.10	-0.20

The comparison shows that TUFLOW results are overall a reasonable match to the RUBICON results. The trend, for the 1% AEP event, seems to be that TUFLOW predicts lower flood levels in the upper part of the model domain (Gumly Gumly) but higher flood levels elsewhere. The demonstrated trend for the smaller flood events modelled (10 and 5% AEP events) is that generally the TUFLOW results are higher when compared to the RUBICON results. It is highly likely that the higher design flood levels computed by TUFLOW are due to the higher roughness values used in the model (relative to RUBICON).

Shown below in Table 9 is a comparison of the 2D modelled peak flow at Hampden Bridge with the peak flow as derived by FFA. FFA analysis methods and results are reported upon in References 1 and 3. The comparison shows a good match and although differences do exist between the modelled discharge and the flood frequency derived discharge none of the discrepancies, as percentage, exceed the likely error in the FFA estimates which is likely at least 10%.

Table 9: Comparison of Peak Flow (FFA and Design) at Hampden Bridge Gauge

Flood event	FFA Discharge (m^3/s)	Discharge (m^3/s) - Rubicon model[2]	Discharge (m^3/s) – 2D Model[3]
10% AEP	2,000	2008	2070
5% AEP	3,000	3013	3000
2% AEP	4,900	4906	4693[4]
1%AEP	6,900	6920	6813

Plots which demonstrate the required levee heights for the North Wagga and Main City levees are shown in Figure 29 to Figure 31.

6.3. Vegetation Management Runs

Results from the vegetation management runs are shown as per the following. Note that Figure 32 shows the locations at which comparisons (in tabular form) are made between the various vegetation management scenario outputs:

- Figure 33 shows the peak flood level difference for Scenario 2 versus the 1% AEP base case. Note that roughness values are as per Figure 11 for Scenario 2 and the base case 1% AEP design run uses roughness values as described in Figure 8;
- Figure 34 shows the peak flood level difference for Scenario 3 (RUBICON roughness values adopted) versus the 1% AEP base case. Note that roughness values are as per Figure 12 for Scenario 3 and the base case 1% AEP design run uses roughness values as described in Figure 8;
- Figure 35 shows the peak flood level difference for Scenario 4 versus Scenario 3. Note that roughness values are as per Figure 13 for Scenario 4 and Scenario 3 uses

[2] Values sourced from Reference 1.
[3] Please note that flows presented here are extracted from the runs in which no levee failure has been allowed i.e. all flow is retained in river for the purposes of the flow calculation.
[4] Note that in the RUBICON result no levee failure occurred whilst in the TUFLOW result levee failure did occur. The levee failure in TUFLOW is attributed to the higher roughness values used and is further discussed in Section 7.2.

roughness values as described in Figure 12; and

- Figure 36 shows the peak flood level difference for Scenario 5 versus Scenario 3. Note that roughness values are as per Figure 14 for Scenario 5 and Scenario 3 uses roughness values as described in Figure 12.

Also shown in Figure 37 on one plot is a summary of all peak level profiles for the Vegetation Management runs (i.e. peak flood levels from Scenarios 1 to 5). The table below summarises the impact of the vegetation management runs on flood levels (selected locations can be viewed on Figure 32).

Table 10: Impact of Vegetation Management at selected locations

	Maximum water level (mAHD) for 1% AEP flood event				
	Scenario 1	**Scenario 2**[5]	**Scenario 3**	**Scenario 4**[6]	**Scenario 5**
Location 1	181.61	181.60	181.58	181.58	181.57
Location 2	181.61	181.61	181.59	181.58	181.57
Location 3	181.37	181.37	181.35	181.34	181.32
Location 4	181.35	181.35	181.33	181.33	181.31
Location 5	181.20	181.20	181.17	181.17	181.17
Location 6	181.19	181.19	181.17	181.17	181.17
Location 7	181.14	181.14	181.13	181.13	181.13

[5] Note that Scenario 2 results are only comparable to Scenario 1
[6] Note that Scenario 4 and 5 results are comparable to Scenario 3

7. DISCUSSION

7.1. Calibration/Validation

Generally the calibration is very good. For the 1974 event the modelled results show a similar gradient to the twelve observed points. The difference between the modelled and observed levels averages 0.09 m, closer than the mean difference of 0.3 m obtained in the previously undertaken RUBICON modelling (Reference 1). The stage hydrograph at Hampden Bridge (Figure 7) shows a very close match particularly in the upper levels of the rising limb and to peak. The falling limb of the observed hydrograph appears steeper than the modelled hydrograph however overall the match is very good. The profile results for the 1974 result are overall very good and this is particularly the case in the area of the river adjacent to the CBD, where the overall match is far superior to that of the previous RUBICON model (refer to Reference 1). Further a comparison of thirty floodplain flood levels with the model results indicates a good match with median error being 0.09 m and the standard deviation of the error at 0.14 m.

The 1975 validation results show a good match to the two observed levels available albeit the model results are consistently low. Note however that whilst TUFLOW model results are lower in the CBD area they are consistently higher than RUBICON results both upstream and downstream.

Validation results for the 1976 run follow a similar trend to the 1975 run validation results in that upstream and downstream of the CBD TUFLOW results are consistently higher than RUBICON results. The mean discrepancy over the 1976 set of observed points is 0.17 m and whilst flood levels are over estimated for some of these points in the main the error is an underestimate of flood height, particularly in the reach of the river immediately upstream and downstream of Hampden Bridge.

Overall the calibration/validation results show a good match between the TUFLOW 2D model results and observed data. The models ability to emulate the stage/discharge rating is good as is the match for the 1974 event which is key given its large magnitude. The match between the model and the smaller validation events is not as good and does tend to underestimation however it is still a decent match. An additional consideration is that the models purpose is levee design and Development Application floor level advice for 1 in 100 year events. Hence it is far more important that the model do a good job with very large flood events (such as the 1974 event) than the smaller events (1975 and 1976).

7.2. Design Runs

Levee failure is an integrated part of the design runs (for Scenario 1 runs) and as explained in previous sections levee failure will occur when flood levels reach the height of the 1974 event (approximately). In the Scenario 1 design runs levee failure has occurred for four of the total of six runs, i.e. it is only the 10% and 5% AEP events for which no levee failure occurs.

Note that in the 2% AEP event upstream failure of the levee does occur[7] but failure of the downstream levee (Flowerdale lagoon) does not[8]. As a result of this particular configuration (i.e. failure of the upstream levee which allows flow into the CBD but no failure of the downstream levee which means flow has limited ability to leave the CBD) flood results (level, depth and hazard) are in some areas worse for the 2% AEP event than they are for the 1% AEP event, most noticeably this is the case in the CBD where the build up of impounded waters has meant greater flood depth and hence higher hazard.

Results for the design runs (for selected events) include figures (Figure 20 – 28) which show colour plots of flood level and flood extent. Hazard maps (Figure 21, 24 & 26) then provide information on those areas impacted by floodwaters and define, at individual grid size resolution, the hazard associated with such inundation as per Appendix L of the Floodplain Development Manual (Reference 2). That is hazard is identified as being either low, transitional between low and high or high.

The 1% AEP event (no levee failure or alternatively, post levee upgrade) profile is also presented (Figure 27) and this provides an opportunity to compare the 2D results (for the post levee upgrade scenario) with those previously achieved by RUBICON (Reference 3, Appendix D). It is not the case that matching RUBICON results is a requirement of the study, nor perhaps even desirable from a pure modelling point of view. There is also a change in roughness assumptions, however it is certainly of interest to see how the 2D model defines important design flood levels relative to the previous work.

The trend is that for smaller events the 2D model will tend to produce flood levels that are higher than those found by RUBICON whilst for larger events the opposite will be true. So for example for the 10% AEP event the 2D model predicts significantly higher levels than the RUBICON modelling[9]. For the 1% AEP event the results are similar however the 2D results are slightly lower. In the case of the PMF however 2D results are on average around 2 m lower than those established by RUBICON modelling. An explanation for this observed relationship between the 2D design results and the RUBICON design results is that for smaller events the 2D approach does not achieve the same efficiency of conveyance as the RUBICON model does and hence results are higher. This difference is no longer present at the 5% AEP event. For the larger results the divergence between the 2D and RUBICON results is most likely because the RUBICON model artificially constrains the flow whilst in the 2D model the entire floodplain can be used and hence a higher level of attenuation is achieved. Also further downstream near Wagga town centre the 2D results are expected to be higher than the RUBICON results due to the higher roughness values used in the former.

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[7] Given that levee failure occurs when the 1974 flood level is reached and the 1974 event is larger than the 2% AEP event the levee failure described requires further explanation. In brief, floodplain conditions have become rougher since the 1970's and hence although the 2% event has less flow than the 1974 event, flood levels are comparable.

[8] The "trigger" height for failure is several millimetres higher than the flood level. Possible manual opening of the Flowerdale Lagoon levee has also not been allowed for in this run.

[9] Low flow conveyance in the 2D model was addressed in order to ensure that the 2D model could, at lower levels of flow, match the rated relationship between stage and discharge (see Section 3.2.3 and 3.2.8 for more details).

7.2.1. Accuracy of Design Levels

7.2.1.1. Introduction

This section gives an estimate as to the expected accuracy of design flood levels achieved in this study. The accuracy of the design flood levels is important as it influences the amount of freeboard incorporated into levee design. Reference 1 stated that the accuracy of the RUBICON design flood levels was +/- 0.5 m.

The accuracy of the design flood levels derived from 2D modelling relates to many factors and in brief these are as follows:

- Accuracy of the topographic and bathymetric data. The ALS data used for example has an accuracy of +/- 0.15 m. Typically ground based survey error is more in the order of +/- 0.005 m;
- The accuracy with which flows are calculated via FFA. Where flows are derived from FFA such as in this case, the accuracy of the design flow estimates relates directly to the accuracy of the rating work done on the gauge as well as any interpolation/extrapolation error. For elevated levels of flow Australian Rainfall and Runoff (Reference 5) states that gauge error is likely to be in the order of +/- 25%. Hampden Bridge gauge has been rated however, at high levels of flow, numerous times (note observation points on Figure 6). Significantly it also has been rated during the 1974 flood which as previously discussed was a larger than 2% AEP event (Stage at Hampden Bridge of 181.13 mAHD). The presence of many ratings for the gauge over the historical record as well as the presence of a large flood event rating reduces the likely error in the gauge and hence in the FFA used to derive peak design flows;
- The accuracy with which various parameters are assigned such as roughness, eddy viscosity and others; and
- The resolution of the model. So for example it's likely that a very high resolution model will include all hydraulic features and as such would be likely to be more accurate for a given sample group of test locations.

Fundamentally, the design flood level estimates are the product of many factors, each of which has an error associated with it (many of them unknown). If an error calculation were to be properly carried out (where uncertainty associated with each element is multiplied together) then the error estimate would likely be high.

In order to reduce potential error in design flood estimates two techniques are used, usually in concert. These are calibration/validation and sensitivity testing.

7.2.1.2. Calibration/Validation

By using a calibrated and validated model we improve our confidence that the model is doing a reasonable job when it comes to defining design flood behaviour. When carrying out calibration/validation it is useful to be able to use an event which is similar in magnitude to the design events of greatest interest. The design event of greatest interest in most studies is the

1% AEP event. In this study we are fortunate to have as a calibration event the 1974 flood which was slightly larger than a 2% AEP event. Calibration results show that for in-river observations the mean absolute error is 0.09 m with an equal split between positive and negative differences (i.e. too high/low). The largest error occurs at the upstream and downstream ends of the model whilst in the vicinity of the levee error is typically less than 0.05 m. A further set of observed and surveyed floodmarks on the floodplain for the 1974 event shows a very good match with modelled flood levels as well. Mean absolute error for the set of thirty points is 0.13 m (median absolute error is 0.09 m) with a standard deviation of 0.14 m. The floodplain calibration points once again indicate that the model achieves a better fit to observation away from the upper and lower extremes of the model.

7.2.1.3. Sensitivity Testing

Further confidence can be gained in model estimates by looking at the models sensitivity to changes in input values, i.e. by carrying out sensitivity testing.

A principle input to the model is the design flow rate and so it is of interest to examine how design flood levels change as the input discharge changes. For example in the 10% AEP event the peak flow is 2,000 m^3/s and for River Chainage ID 8 (see Table 6) the modelled flood level is 179.84 mAHD. In the 5% AEP event flow increases by 50% to 3,000 m^3/s and the flood level at ID 8 increases to 180.30 mAHD, an increase of 0.46 m (an approximately 0.1 m difference per 10% increase in discharge). At the same location the 1% AEP event (peak flow of 6,900 m^3/s) generates a flood level of 181.82 mAHD. So a 130% increase in flow (relative to the 5% event) gives an increase in the flood level of 1.52 mAHD (an increase in flood level of 0.12 m per 10% increase in peak discharge). Note that these relationships hold for River Chainage 8 which is located at Hampden Bridge and thus impacted by the levees. For areas which flow on the floodplain the increase in flood level for a given percentage increase in discharge will be much less.

Another significant input to the model is roughness. The runs carried out in order to explore vegetation management scenarios provide an insight into how roughness impact change flood levels. For example at Location 3 (refer to Figure 32) the Scenario 2 roughness values produce no change in flood level relative to the Scenario 1 run. Further the runs carried out in Scenarios 4 and 5 alter flood levels by 0.01 and 0.03 m respectively relative to Scenario 3. Whilst the changes made to the model are not large these runs still indicate a general lack of sensitivity to roughness settings.

7.2.1.4. Summary

Calibration results (for the largest event modelled the 1974 event) indicate that the model has a mean accuracy (over a total of 42 in-river and floodplain flood marks) of 0.12 m. This mean error estimate includes both over and under estimates of flood level. Generally it is found that the model accuracy is better in the model interior (away from boundary ends) and hence design flood level estimates for areas protected by levee are expected to have an error of approximately 0.1 m. Sensitivity testing indicates that, due to the constriction of the levee, flood level changes by approximately 0.1 m for every 10% change in discharge whilst generally the model is relatively insensitive to roughness values used. As such a reasonable estimate of model accuracy in determining 1% AEP flood levels is +/- 0.25 m. It is recommended however that during the detailed design process for the Main City Levee upgrade works that some allowance is made for further model sensitivity testing.

7.3. Vegetation Management Runs

Overall the runs show that there is very little impact on flood results from those measures proposed with respect to flood levels. Both Scenario 2 versus Scenario 1 and Scenarios 4 and 5 relative to Scenario 3 indicate no practical improvement.

It is considered however that vegetation management is still a positive and should be considered for implementation by Council. A focus on vegetation management is important because it will maintain an awareness at Council that floodplain conditions are important with respect to resultant flood levels at Wagga Wagga. Maintaining such a sensibility is vital because if overall floodplain roughness does increase it is the case that flood levels will be significantly impacted. This sensitivity was established during the calibration process where it was found that the overall floodplain roughness value was a critical parameter with respect to flood levels.

8. CONCLUSIONS

The previous 1D RUBICON model has been converted successfully into a 2D TUFLOW model. The credibility of the 2D model is established by comparison of results with three large flood events from the 1970's (1974, 1975 and 1976). The model has then been used to define design flood heights for multiple events of probability ranging from 10% to 1% AEP as well as the PMF. Outputs suitable for Council planning purposes, i.e. raster grids of flood level, flood depth, flow velocity and flood hazard have been generated as part of this process and this data is available for transfer to Council. The accuracy of the 1% AEP design flood levels is assessed as being accurate to within +/- 0.25 m.

Vegetation Management runs have demonstrated that the limited works proposed by Council in the area north of the Murrumbidgee River will not have any demonstrable impact on reducing flood levels. However other runs conducted have demonstrated that if the general floodplain roughness is caused to increase then flood levels will be impacted and this has implications for the required levee height if populated areas of Wagga Wagga are to be protected from flooding for some large events.

Overall the conversion process has resulted in Council now having a tool which can be used in the:

- Planning process. i.e. to examine the impact proposed filling may have on adjoining properties upstream and downstream of the proposed development site, to examine how other flow scenarios/levee configurations may interact with flood prone land, files for importation into software suc as WaterRide for DA assessments;
- Flood mitigation design process. Various physical works such as levee rasing, structure improvement etc can be tested and hence optimised using the model and its results;
- Bank stability works. The 2D model can certainly be used to examine different, relatively low, flow scenarios and how these impact on sheer forces acting on the southern bank of the river near the town centre and the implications this has for long term bank stability given on going flow levels from the upstream Burrinjuck Dam; and
- Integration of Murrumbidgee River flow scenarios with Wagga Wagga overland flows both north and south of the river.

9. ACKNOWLEDGEMENTS

WMAwater wish to acknowledge the assistance of Wagga Wagga City Council staff in carrying out this work as well as The Department of Environment, Climate Change and Water for providing funding assistance towards the Study under the NSW Floodplain Management Program. Also our thanks to Fugro Spatial Solutions Pty Ltd and the Lands Department.

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   The Council of the City of Wagga Wagga. September, 2004.

2. **NSW Government**

   Floodplain Development Manual (2005)
   April 2005

3. **WMAwater Pty Ltd**

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   The Council of the City of Wagga Wagga. May, 2009.

4. **WMAwater Pty Ltd**

   Murrumbidgee River Wagga Wagga Floodplain Risk Management Plan
   The Council of the City of Wagga Wagga. May, 2009.

5. **Pilgrim H (Editor in Chief)**

   Australian Rainfall and Runoff – A Guide to Flood Estimation
   Institution of Engineers, Australia, 1987.

6. **WMAwater Pty Ltd**

   Short report on Airborne Laser Survey Data collected for WWCC by Fugro Spatial Solutions Pty Ltd
   The Council of the City of Wagga Wagga. May, 2009.

Figures

FIGURE 1
STUDY AREA

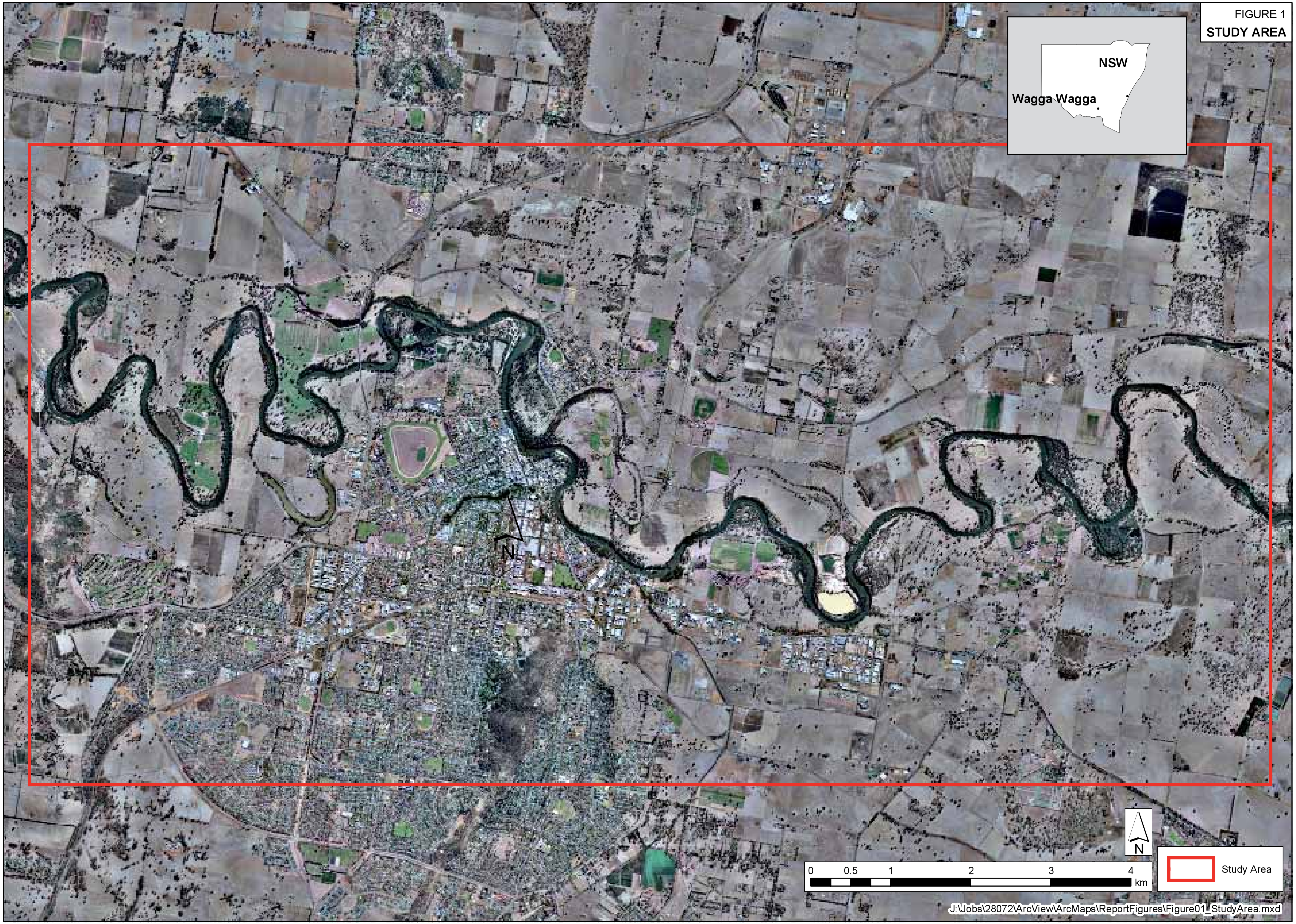

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FIGURE 2
DTM FOR STUDY AREA

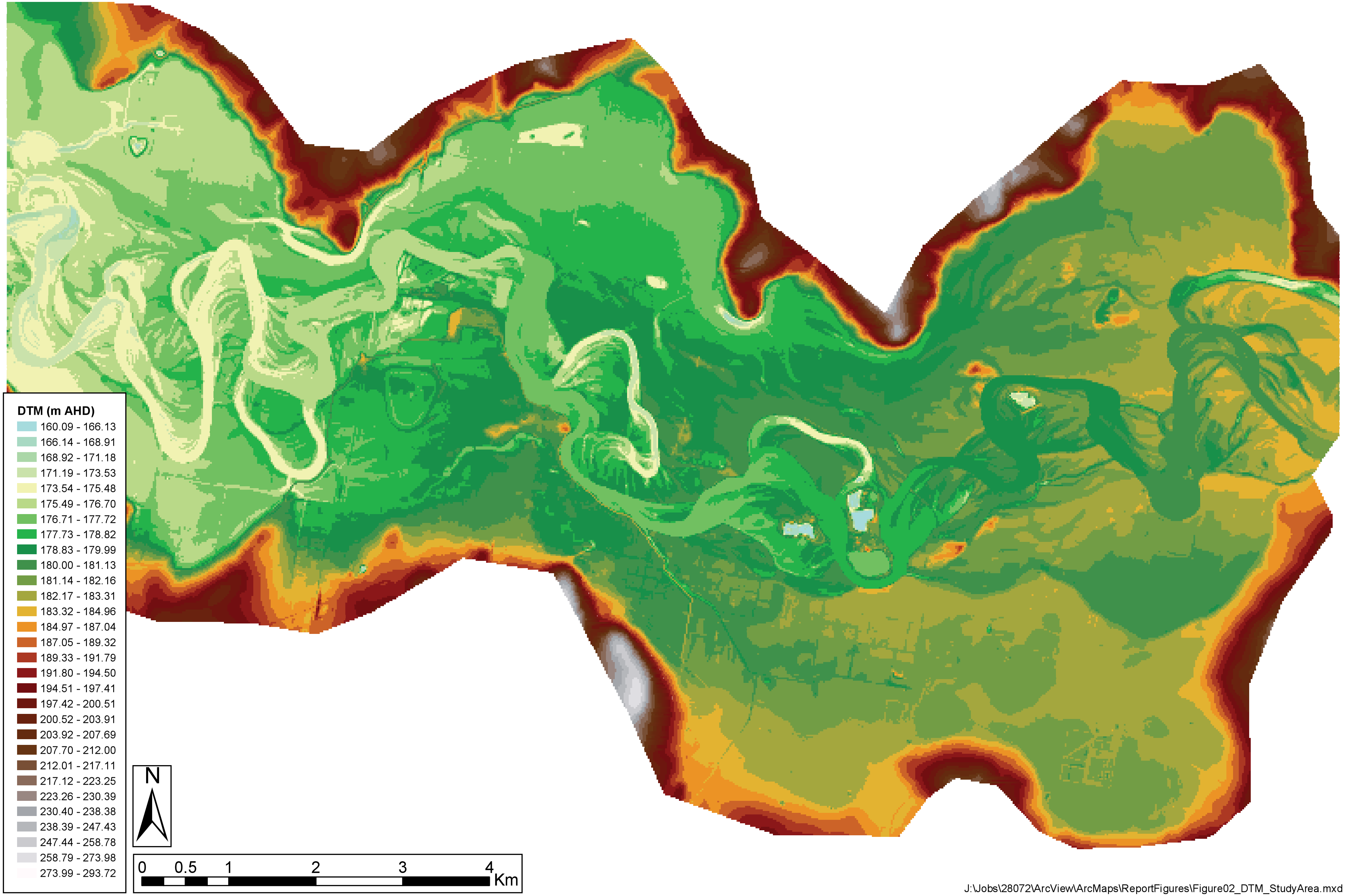

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FIGURE 3

Calibration/Validation Roughness Map

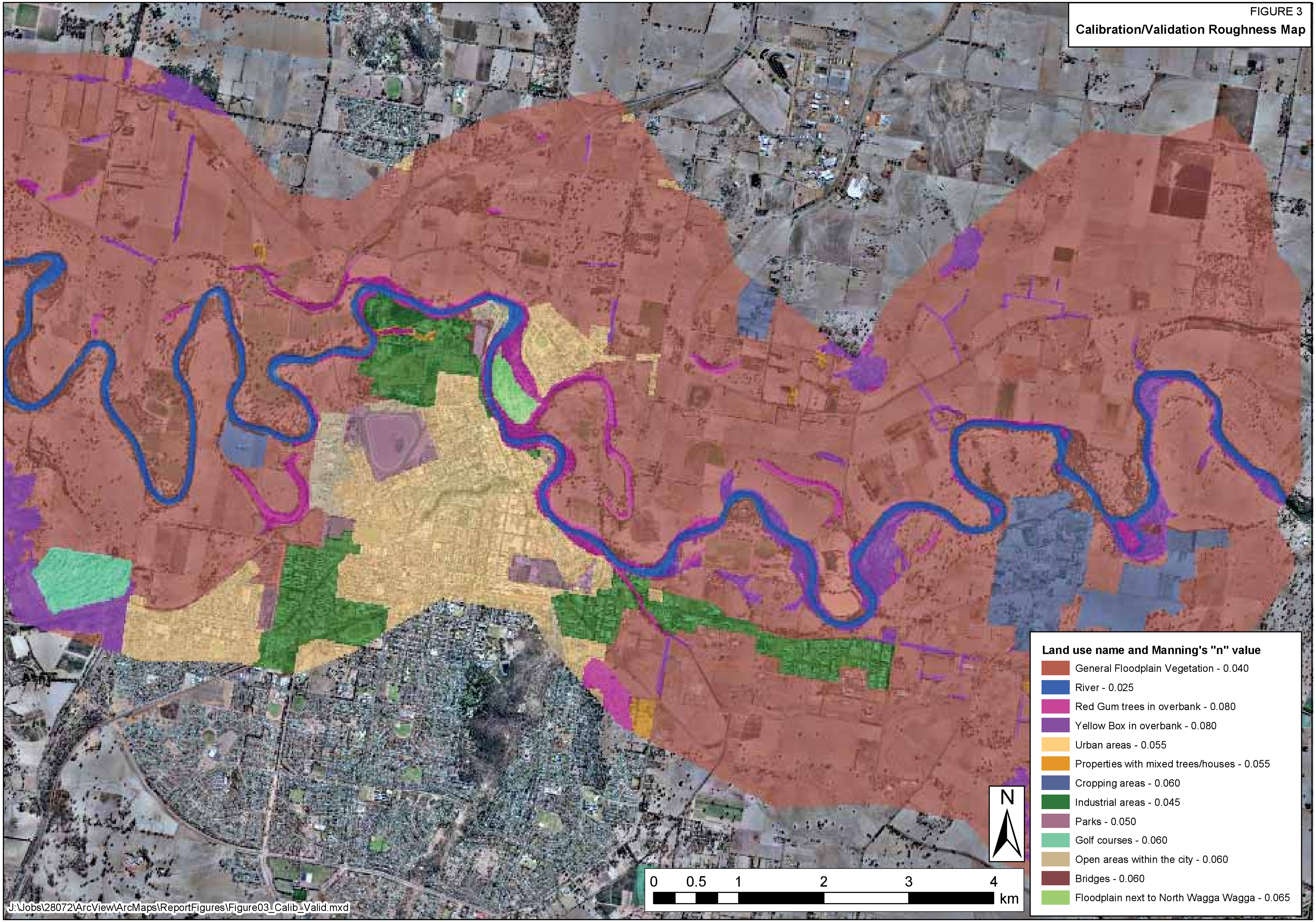

FIGURE 4

INPUT HYDROGRAPHS - 1974, 1975 AND 1976

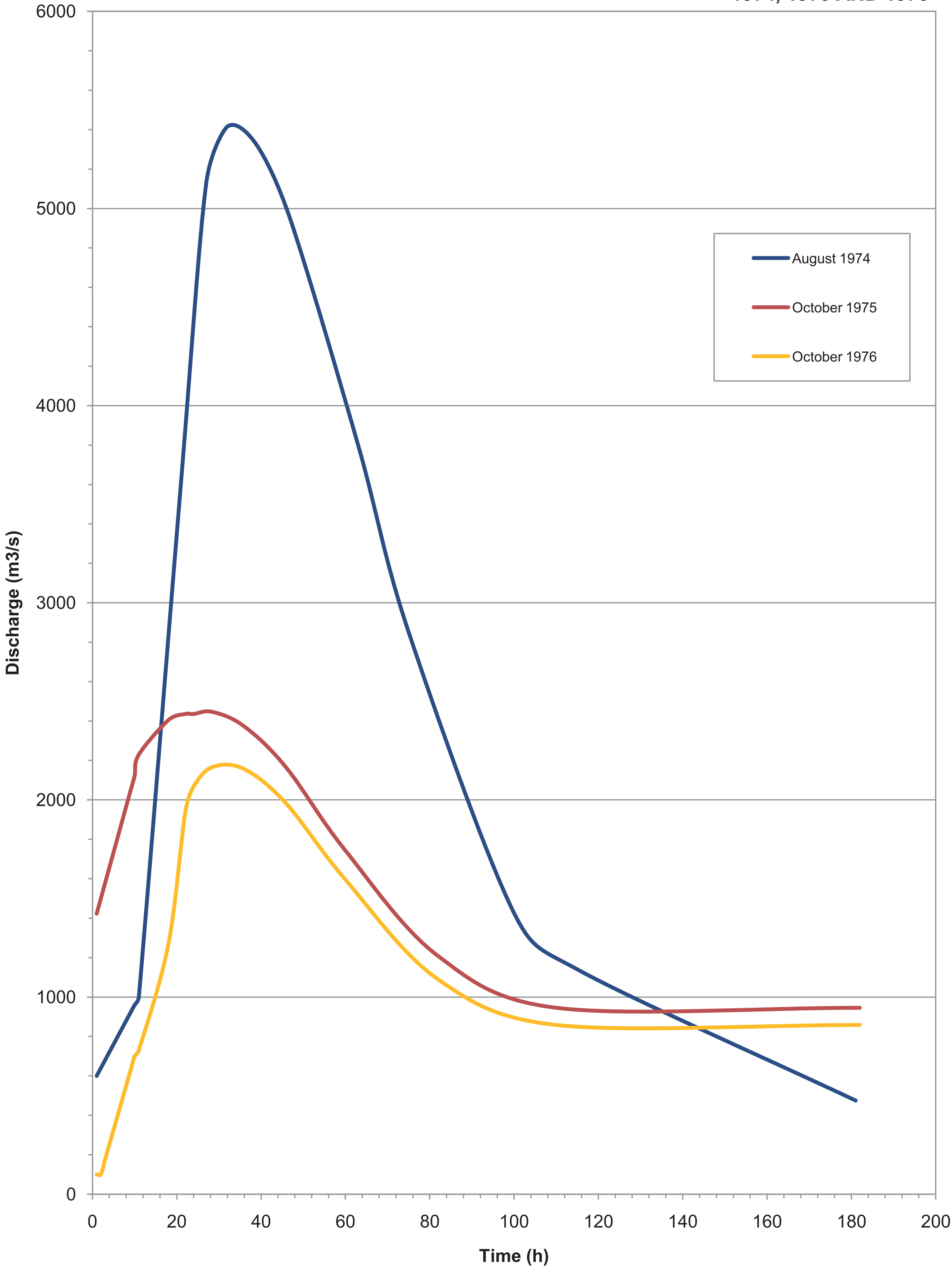

FIGURE 5
Model Layout

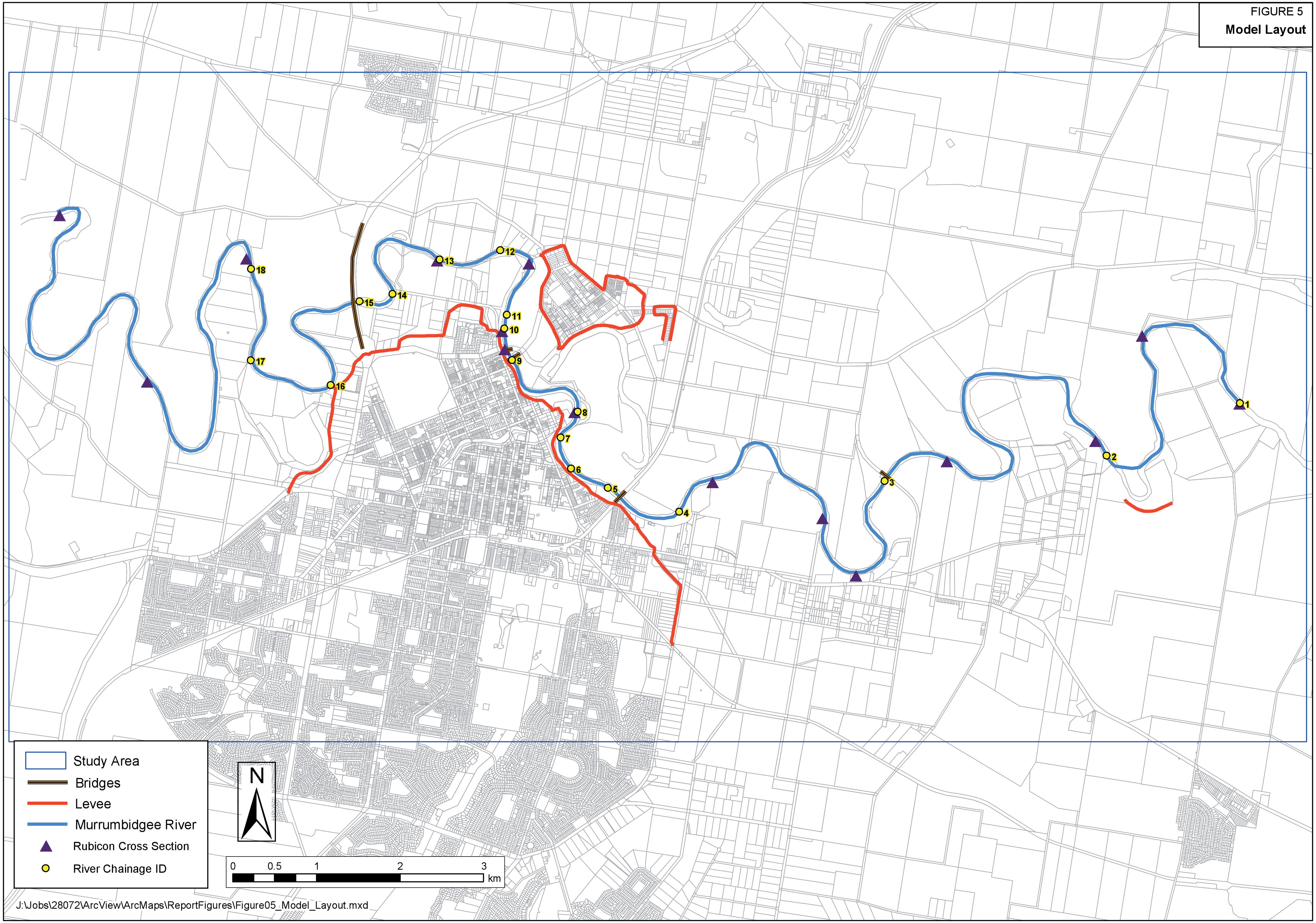

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FIGURE 6

STAGE/DISCHARGE RATING COMPARISON - GAUGED VERSUS MODELLED

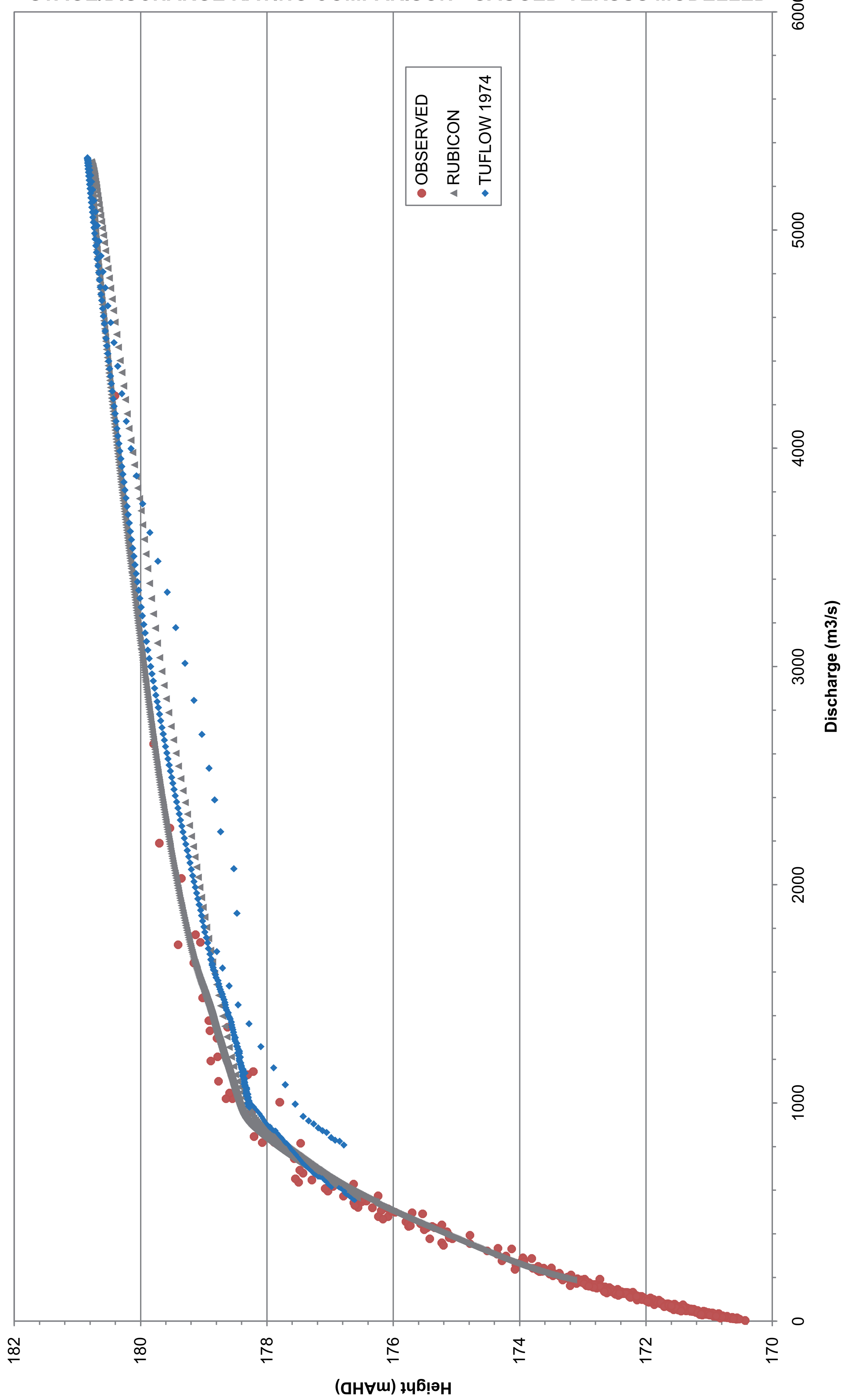
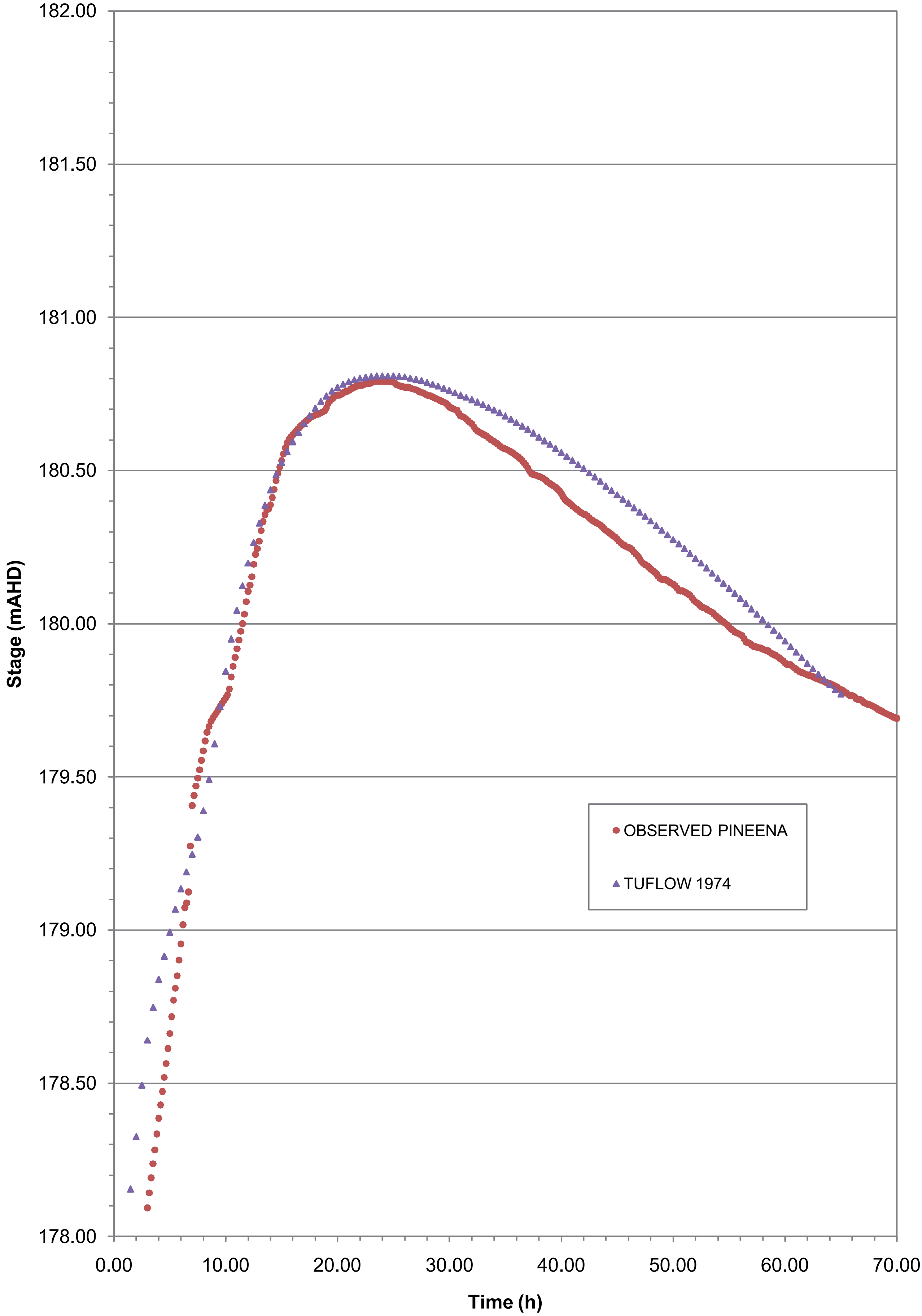


FIGURE 7

1974 HYDROGRAPH COMPARISON - GAUGED VERSES MODELLED



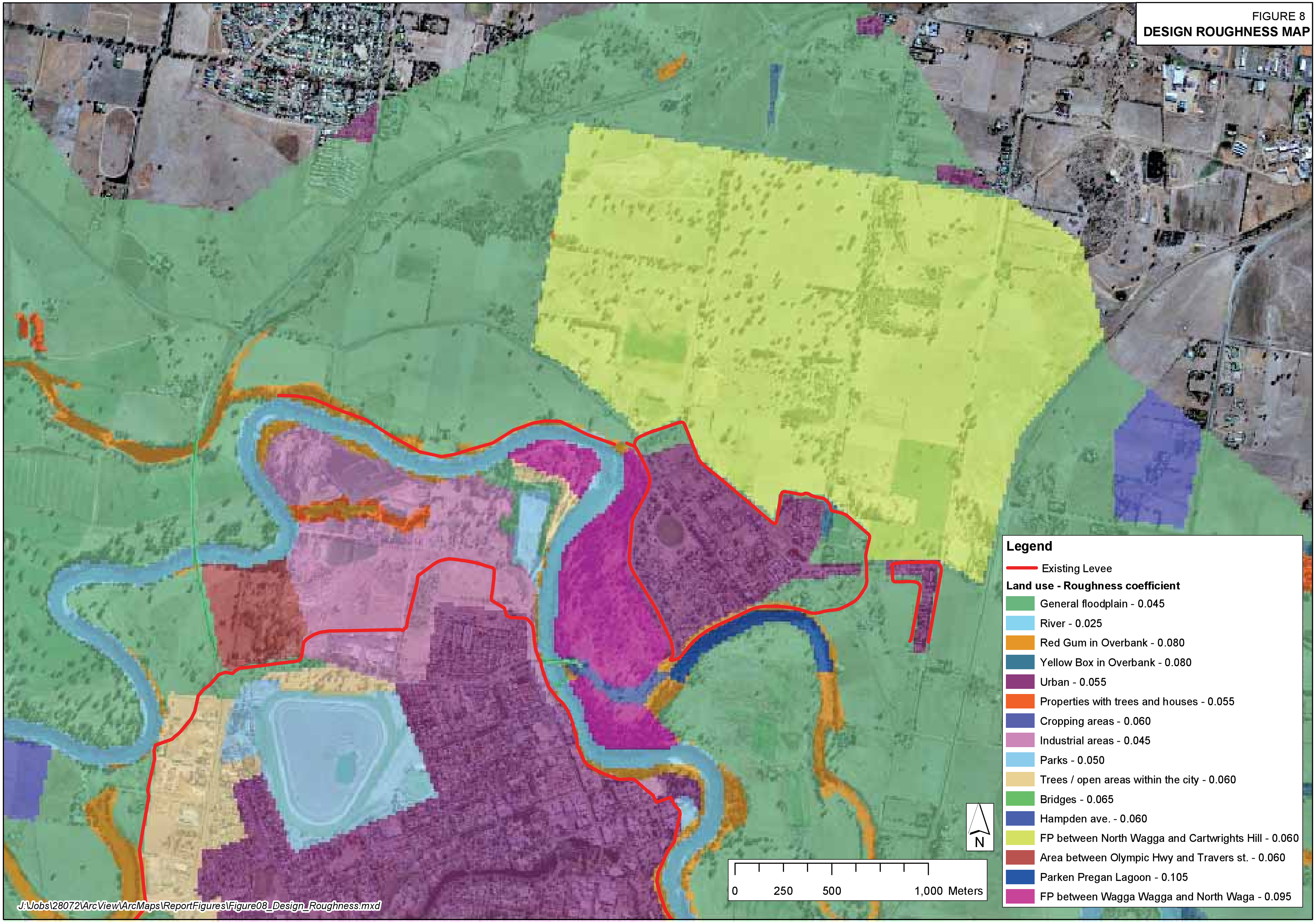


FIGURE 8
DESIGN ROUGHNESS MAP
Legend
Existing Levee
Land use - Roughness coefficient
General floodplain - 0.045
River - 0.025
Red Gum in Overbank - 0.080
Yellow Box in Overbank - 0.080
Urban - 0.055
Properties with trees and houses - 0.055
Cropping areas - 0.060
Industrial areas - 0.045
Parks - 0.050
Trees / open areas within the city - 0.060
Bridges - 0.065
Hampden ave. - 0.060
FP between North Wagga and Cartwrights Hill - 0.060
Area between Olympic Hwy and Travers st. - 0.060
Parken Pregan Lagoon - 0.105
FP between Wagga Wagga and North Waga - 0.095
N
0 250 500 1,000 Meters
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FIGURE 9

LEVEE FAILURE LOCATIONS

FIGURE 10

LEVEE FAILURE CROSS SECTION

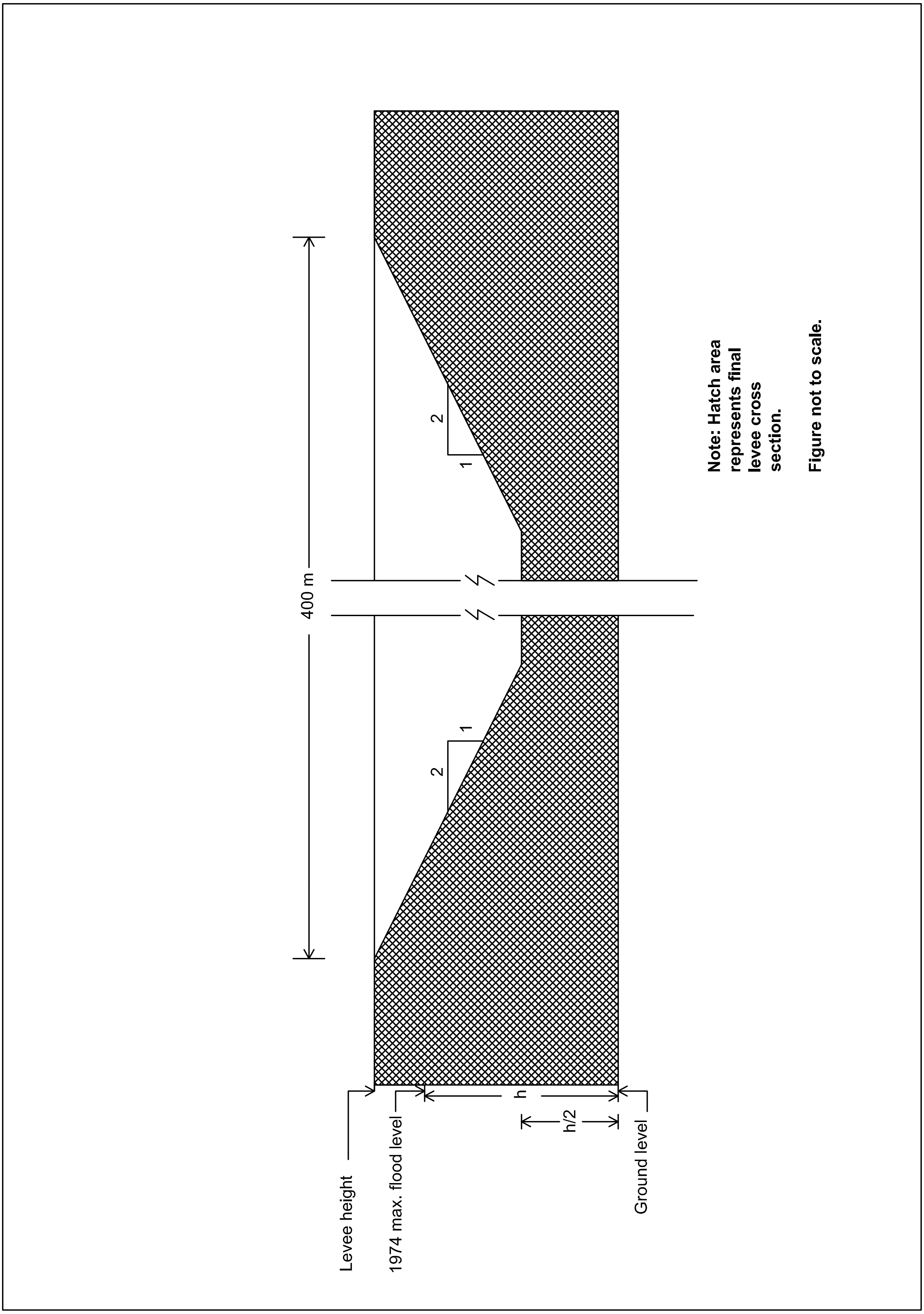

FIGURE 11
VEGETATION MITIGATION - SCENARIO 2
ROUGHNESS MAP

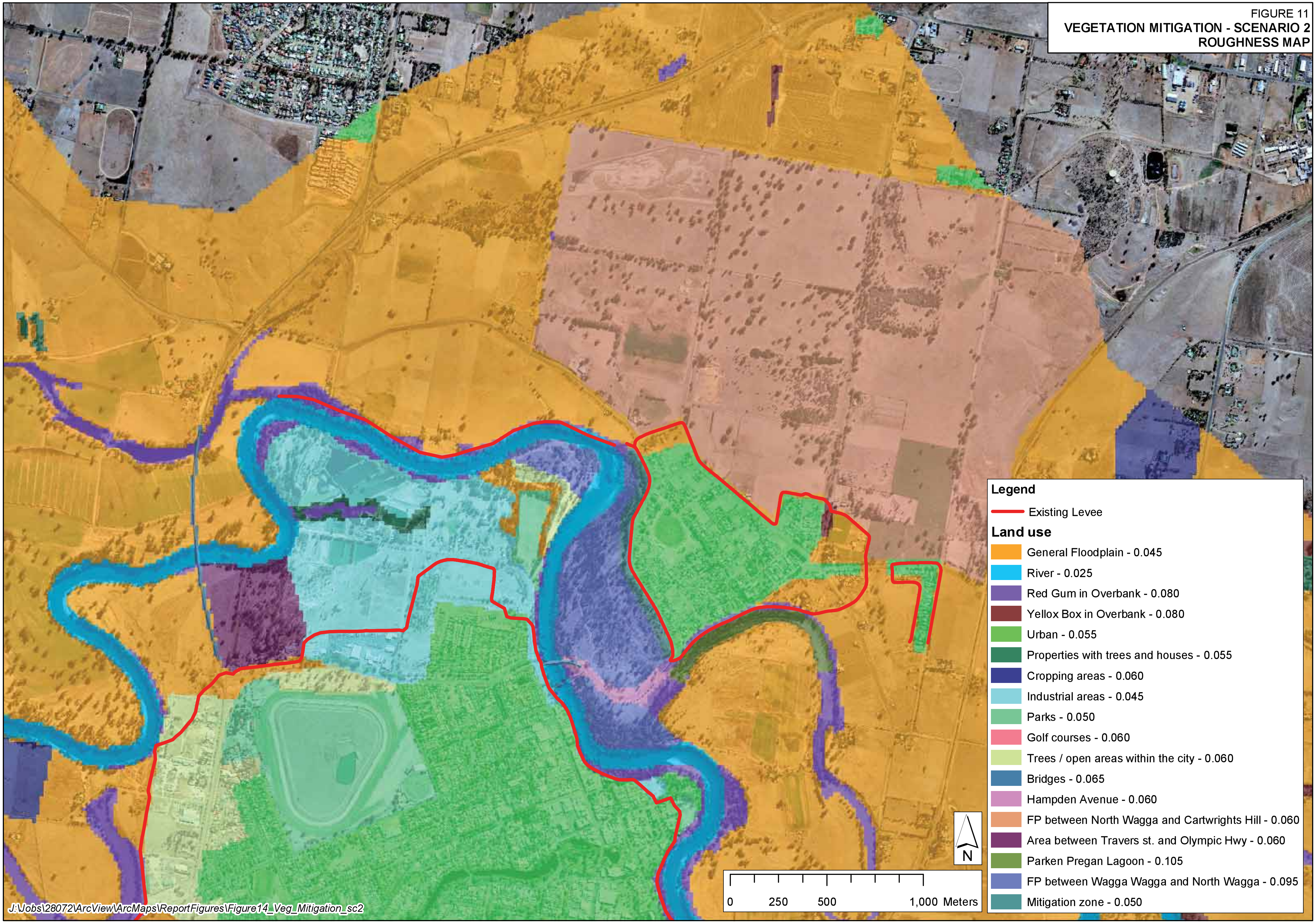

FIGURE 12
VEGETATION MITIGATION - SCENARIO 3
ROUGHNESS MAP

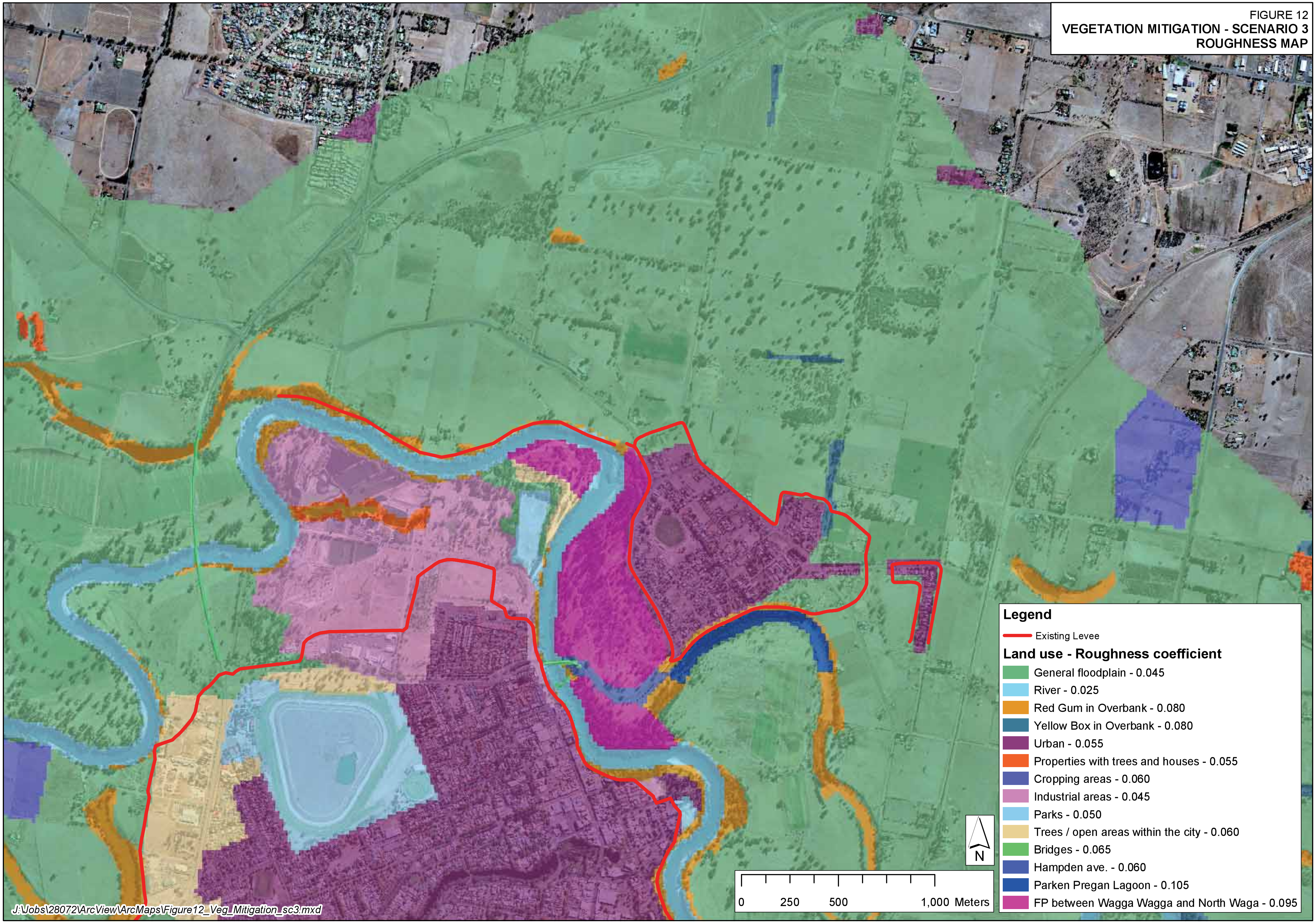

FIGURE 13
VEGETATION MITIGATION - SCENARIO 4
ROUGHNESS MAP

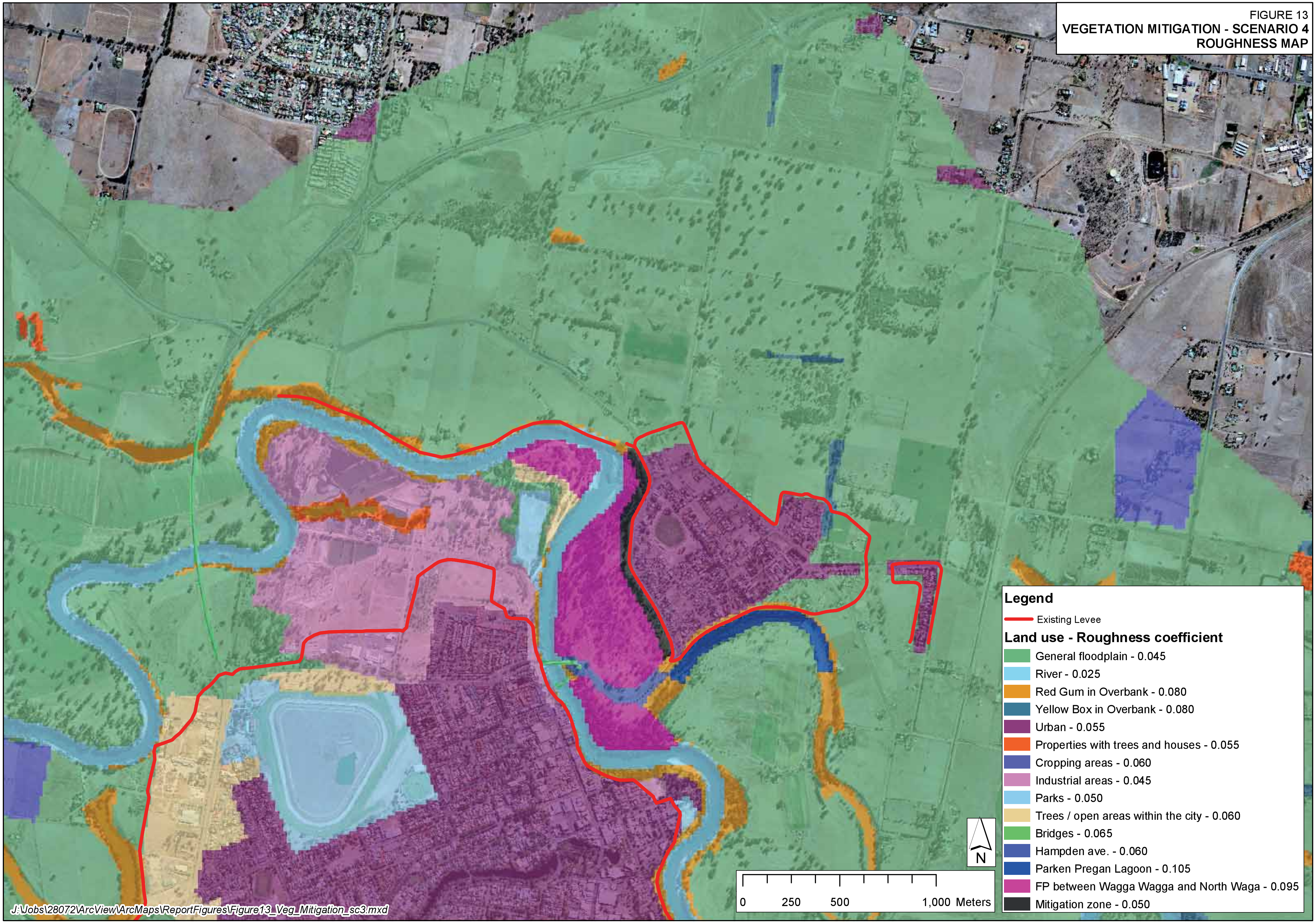

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FIGURE 14
VEGETATION MITIGATION - SCENARIO 5
ROUGHNESS MAP

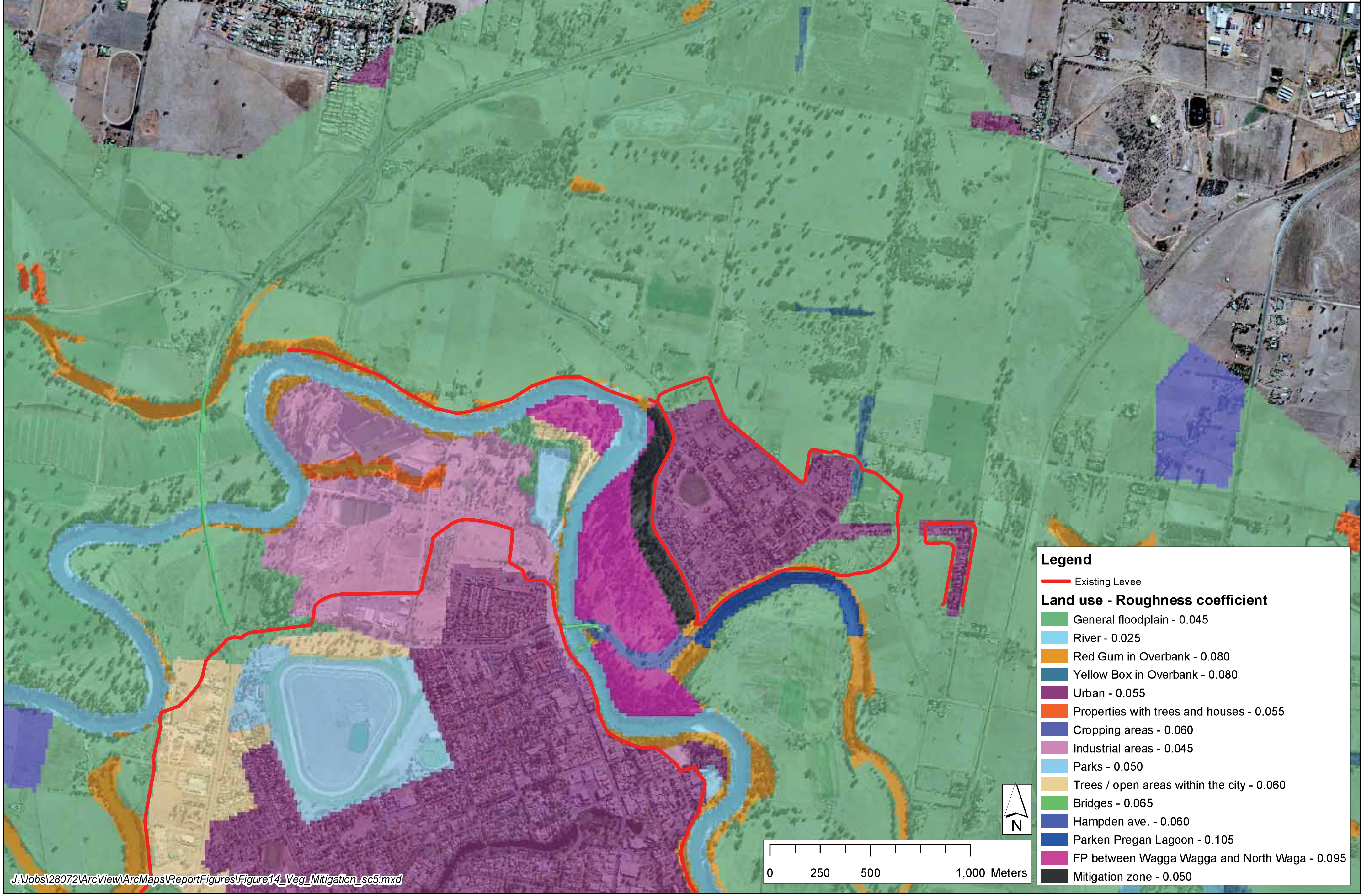

FIGURE 15

CALIBRATION RESULTS - 1974 PROFILE

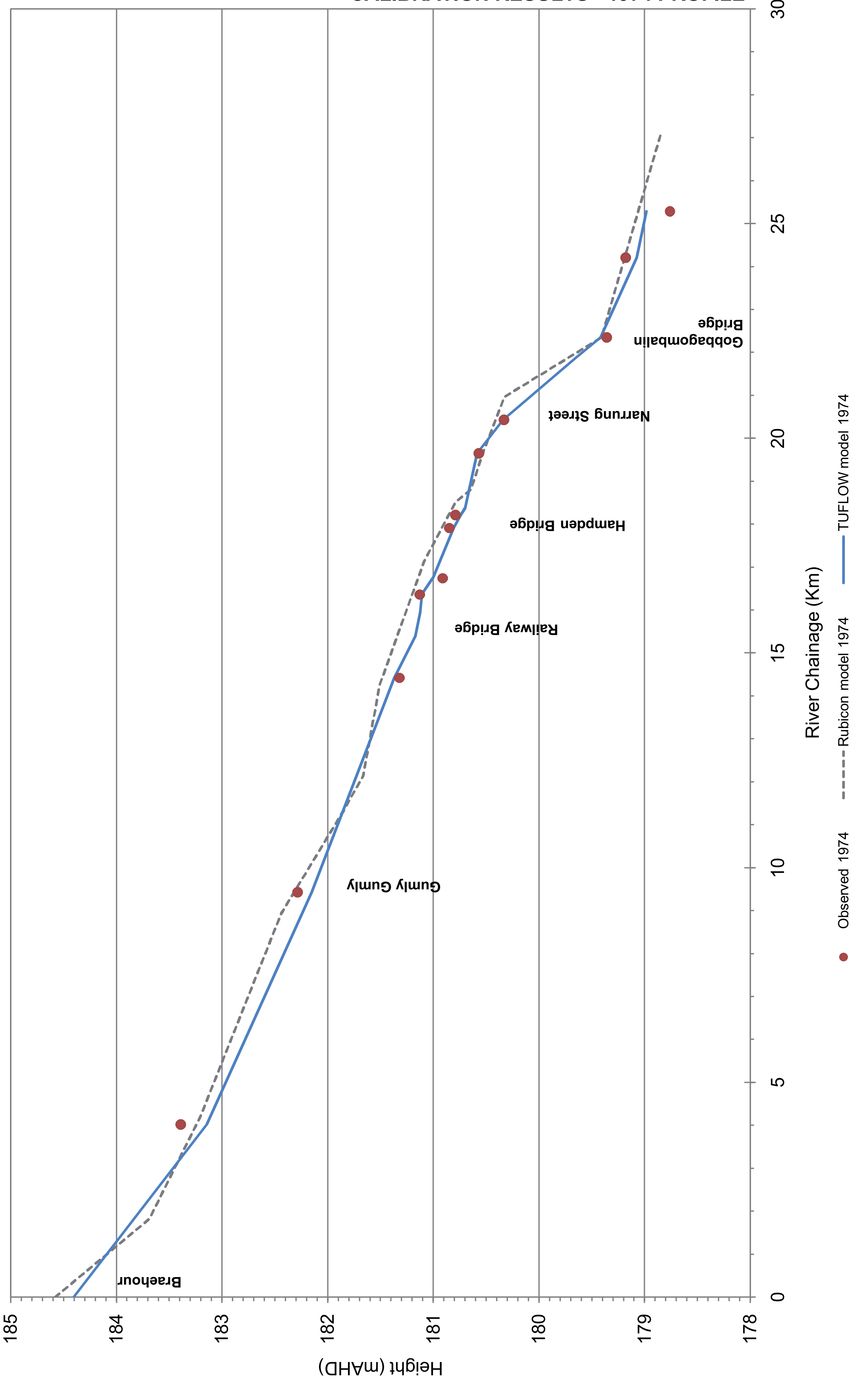

FIGURE 16

CALIBRATION RESULTS 1974 FLOODPLAIN LEVELS

Note 1: The flood extents shown on this map are approximate only and are only intended to be indicative. The map must not be used in isolation to determine whether a property is affected by flooding.

Note 2: This can only be confirmed by comparing estimated design flood level(s) for the property with detailed ground survey undertaken by a registered surveyor.

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FIGURE 17
VALIDATION RESULTS - 1975 PROFILE

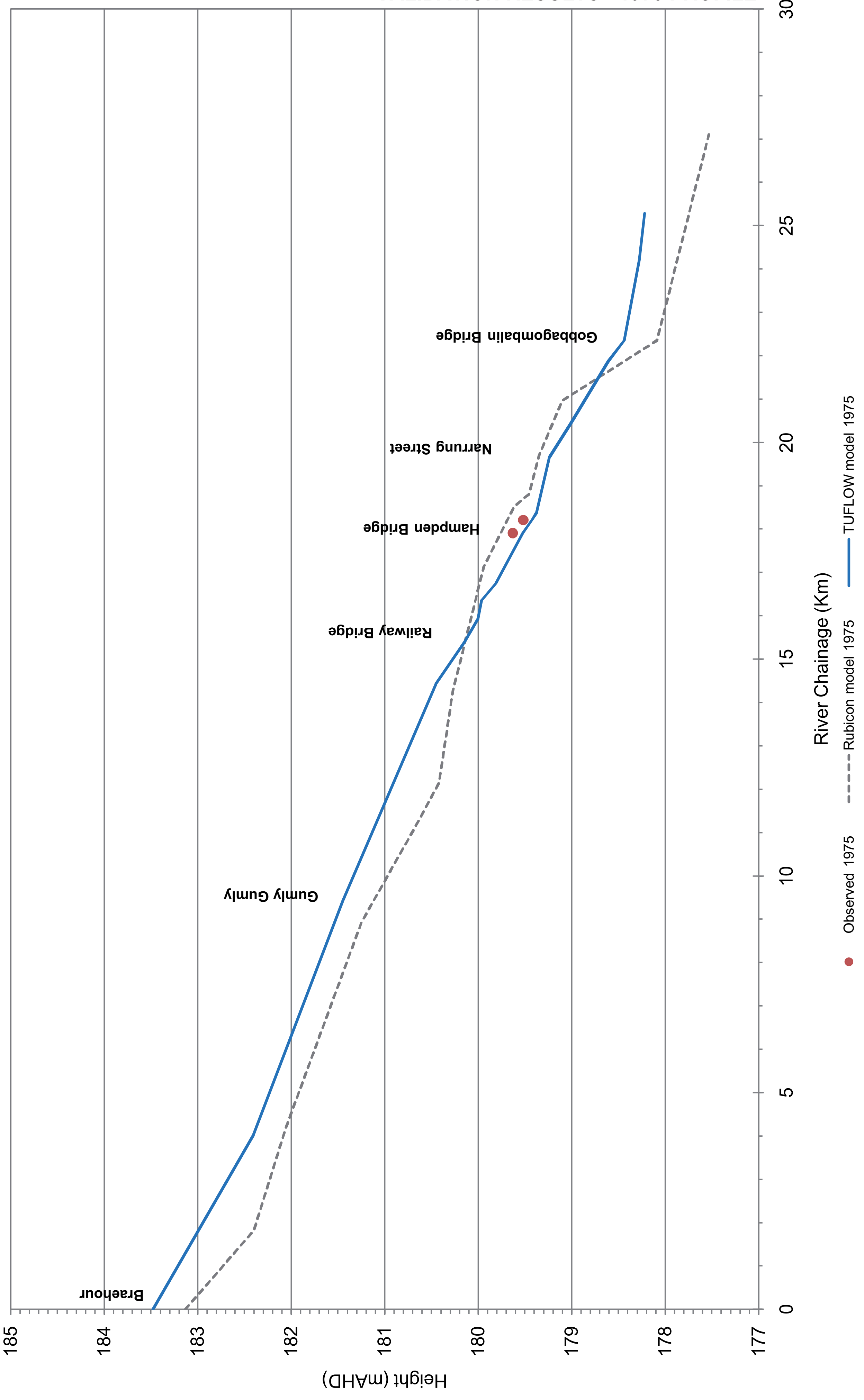

FIGURE 18

CALIBRATION RESULTS 1975 FLOODPLAIN LEVELS

Note 1: The flood extents shown on this map are approximate only and are only intended to be indicative. The map must not be used in isolation to determine whether a property is affected by flooding.

Note 2: This can only be confirmed by comparing estimated design flood level(s) for the property with detailed ground survey undertaken by a registered surveyor.

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FIGURE 19

VALIDATION RESULTS - 1976 PROFILE

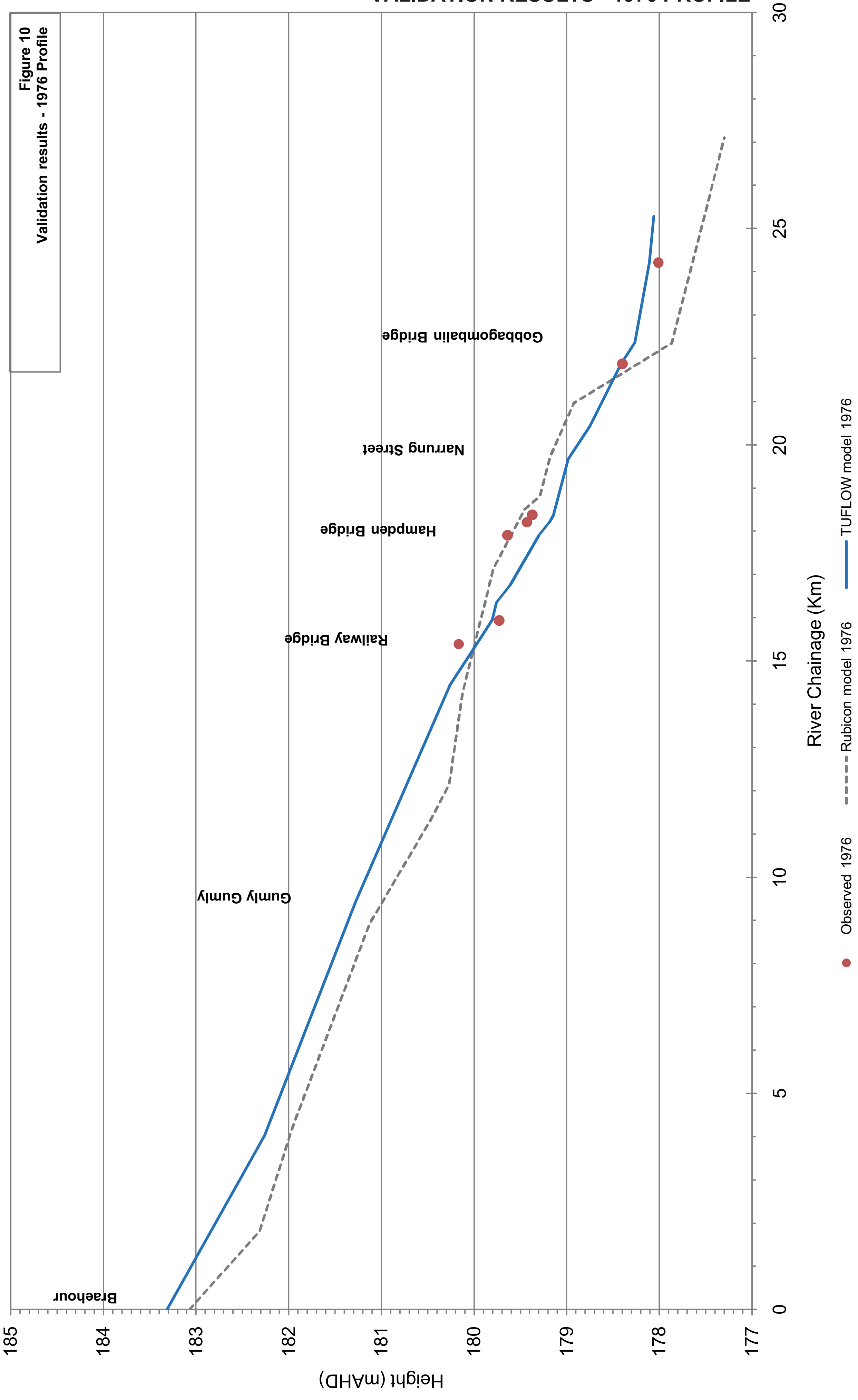
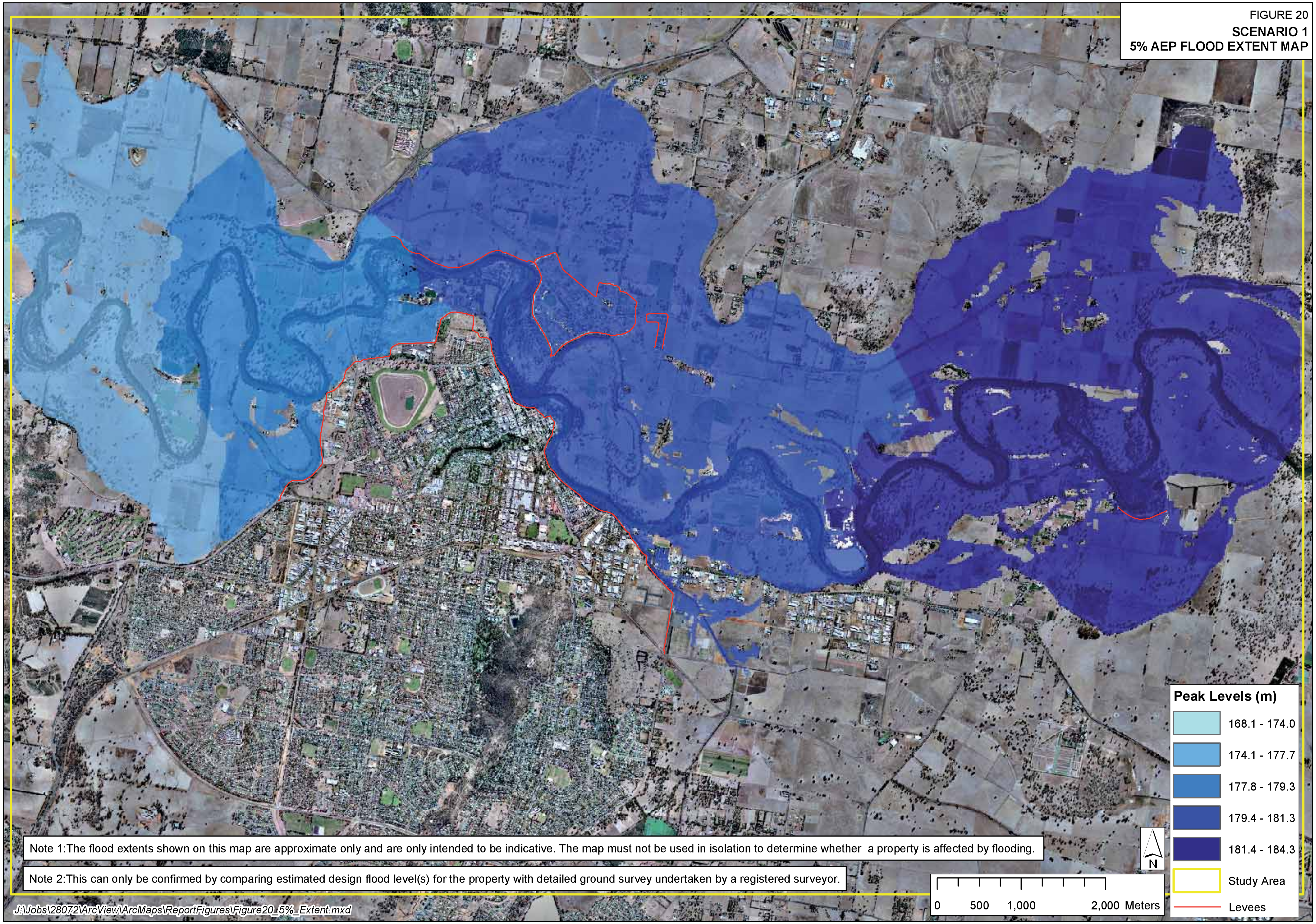


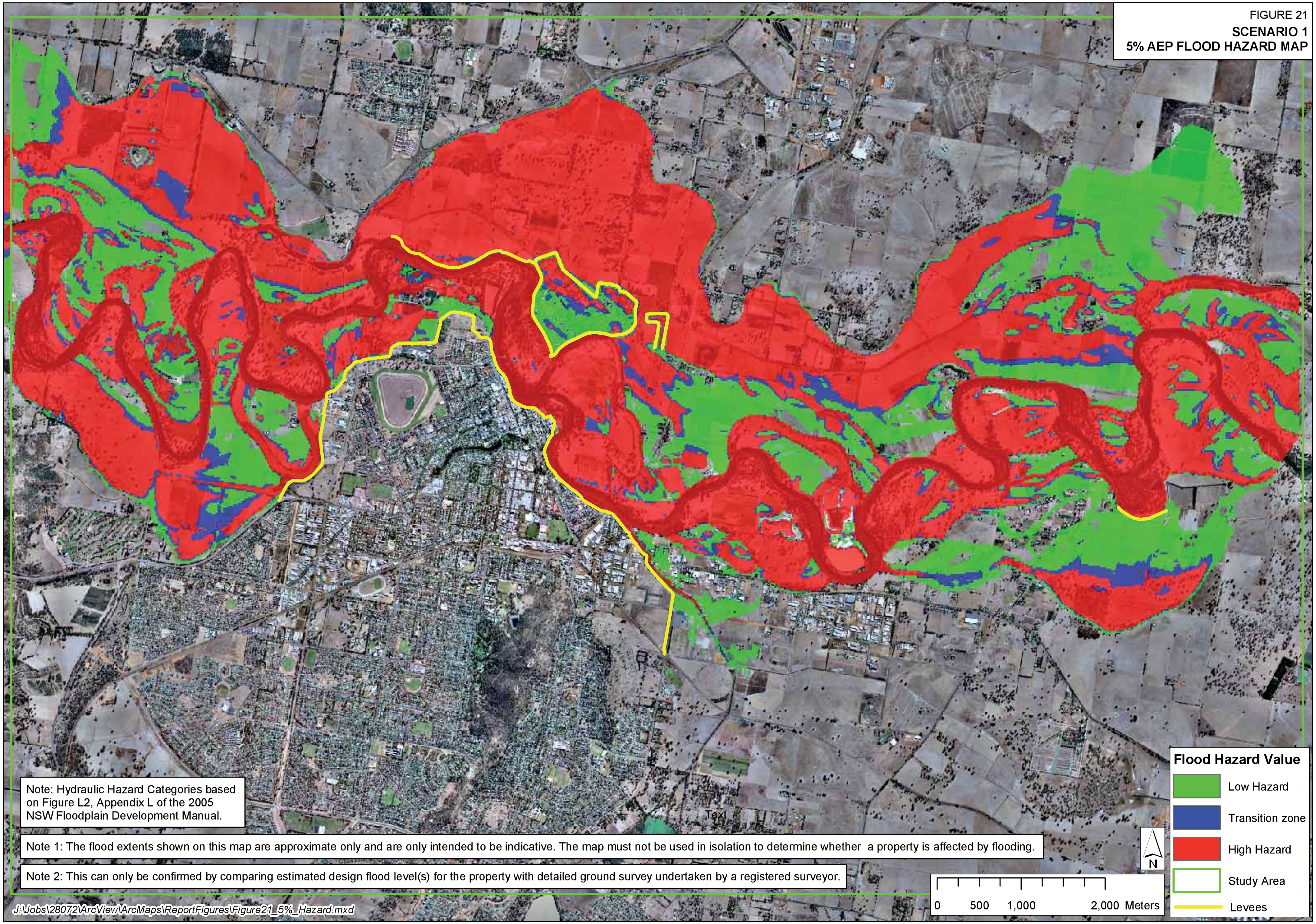
FIGURE 20
SCENARIO 1
5% AEP FLOOD EXTENT MAP



Note 1:The flood extents shown on this map are approximate only and are only intended to be indicative. The map must not be used in isolation to determine whether a property is affected by flooding.

Note 2:This can only be confirmed by comparing estimated design flood level(s) for the property with detailed ground survey undertaken by a registered surveyor.

FIGURE 21
SCENARIO 1
5% AEP FLOOD HAZARD MAP



Note: Hydraulic Hazard Categories based on Figure L2, Appendix L of the 2005 NSW Floodplain Development Manual.

Note 1: The flood extents shown on this map are approximate only and are only intended to be indicative. The map must not be used in isolation to determine whether a property is affected by flooding.

Note 2: This can only be confirmed by comparing estimated design flood level(s) for the property with detailed ground survey undertaken by a registered surveyor.

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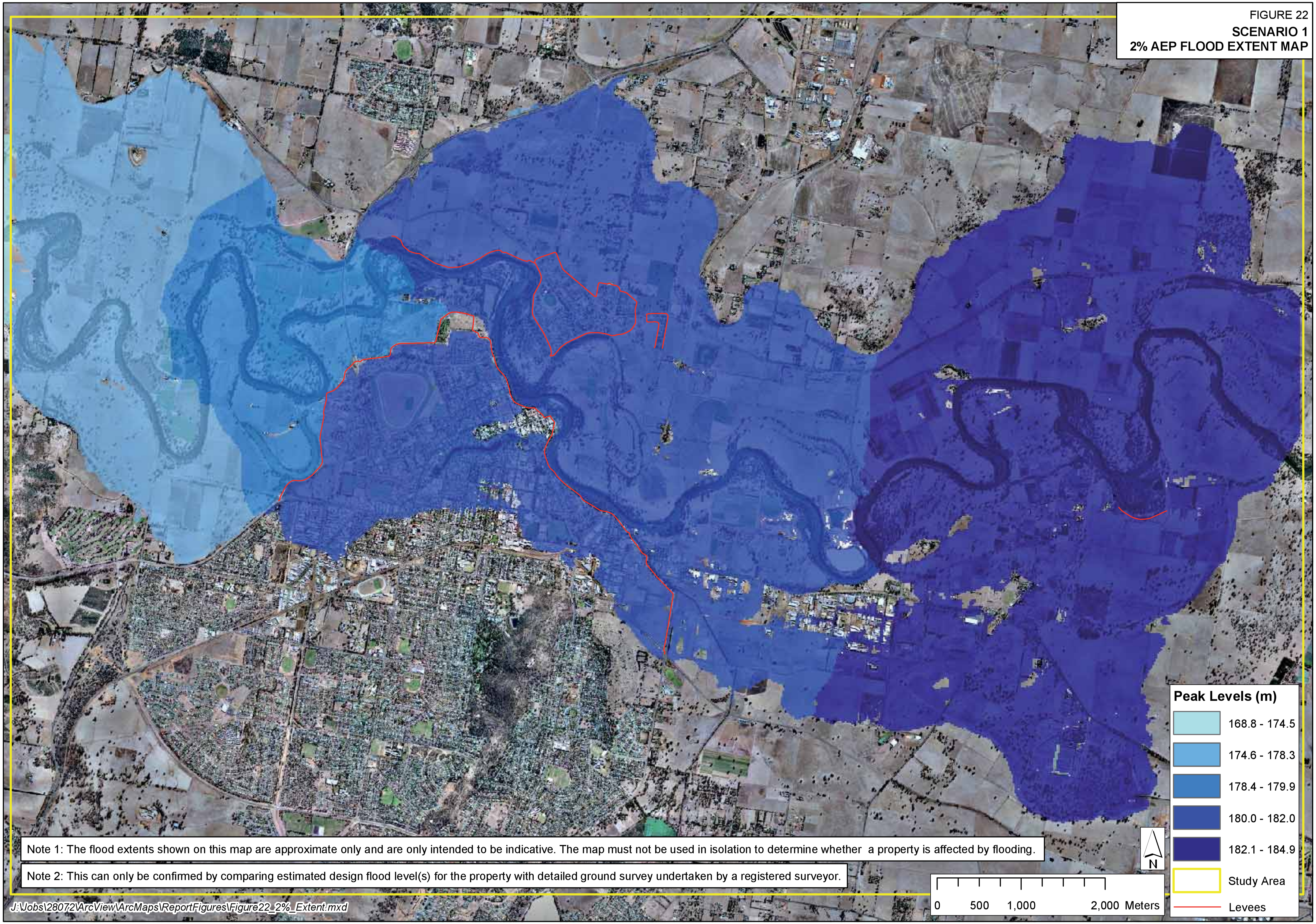
FIGURE 22
SCENARIO 1
2% AEP FLOOD EXTENT MAP



Note 1: The flood extents shown on this map are approximate only and are only intended to be indicative. The map must not be used in isolation to determine whether a property is affected by flooding.

Note 2: This can only be confirmed by comparing estimated design flood level(s) for the property with detailed ground survey undertaken by a registered surveyor.

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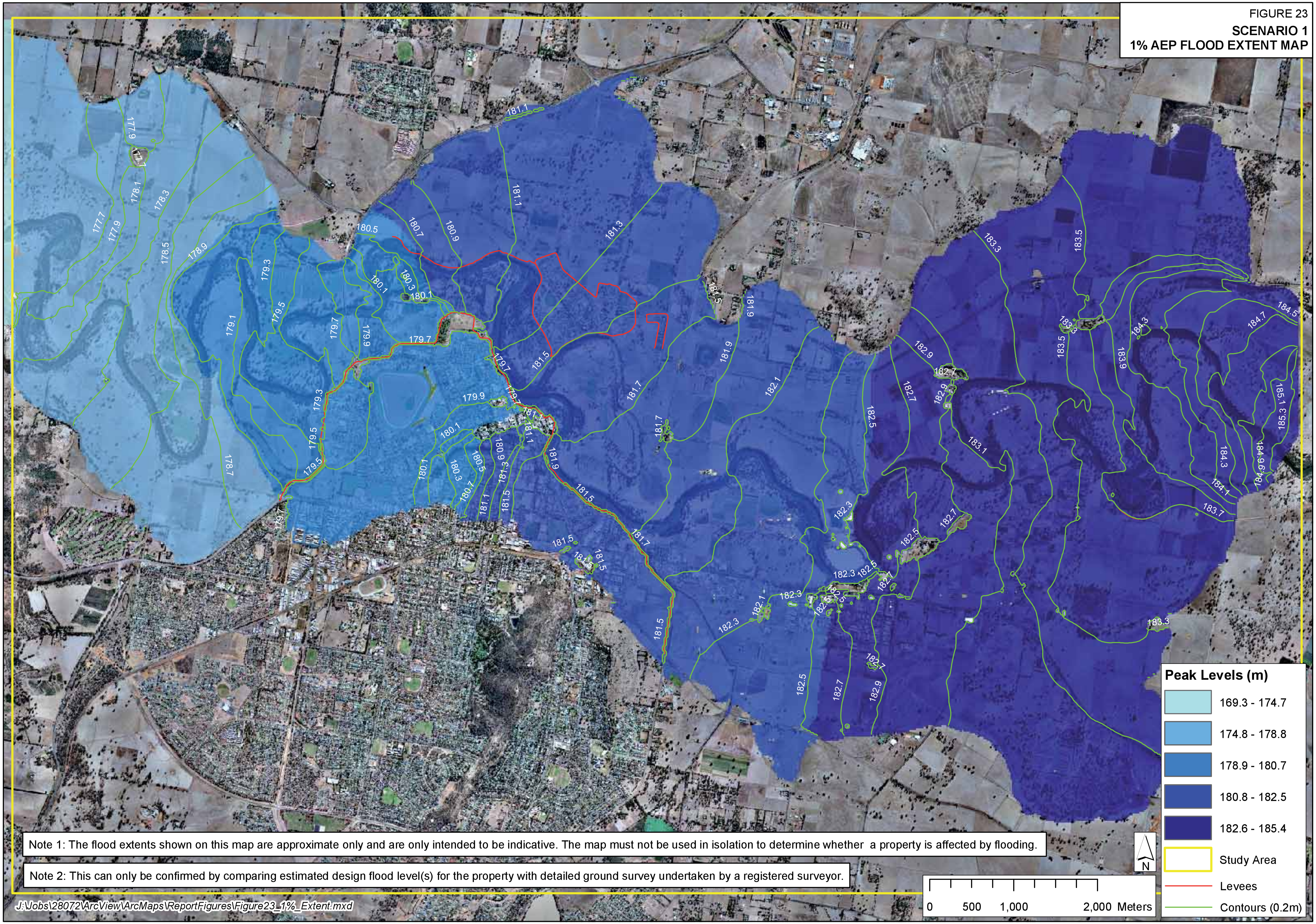
FIGURE 23
SCENARIO 1
1% AEP FLOOD EXTENT MAP



Note 1: The flood extents shown on this map are approximate only and are only intended to be indicative. The map must not be used in isolation to determine whether a property is affected by flooding.

Note 2: This can only be confirmed by comparing estimated design flood level(s) for the property with detailed ground survey undertaken by a registered surveyor.

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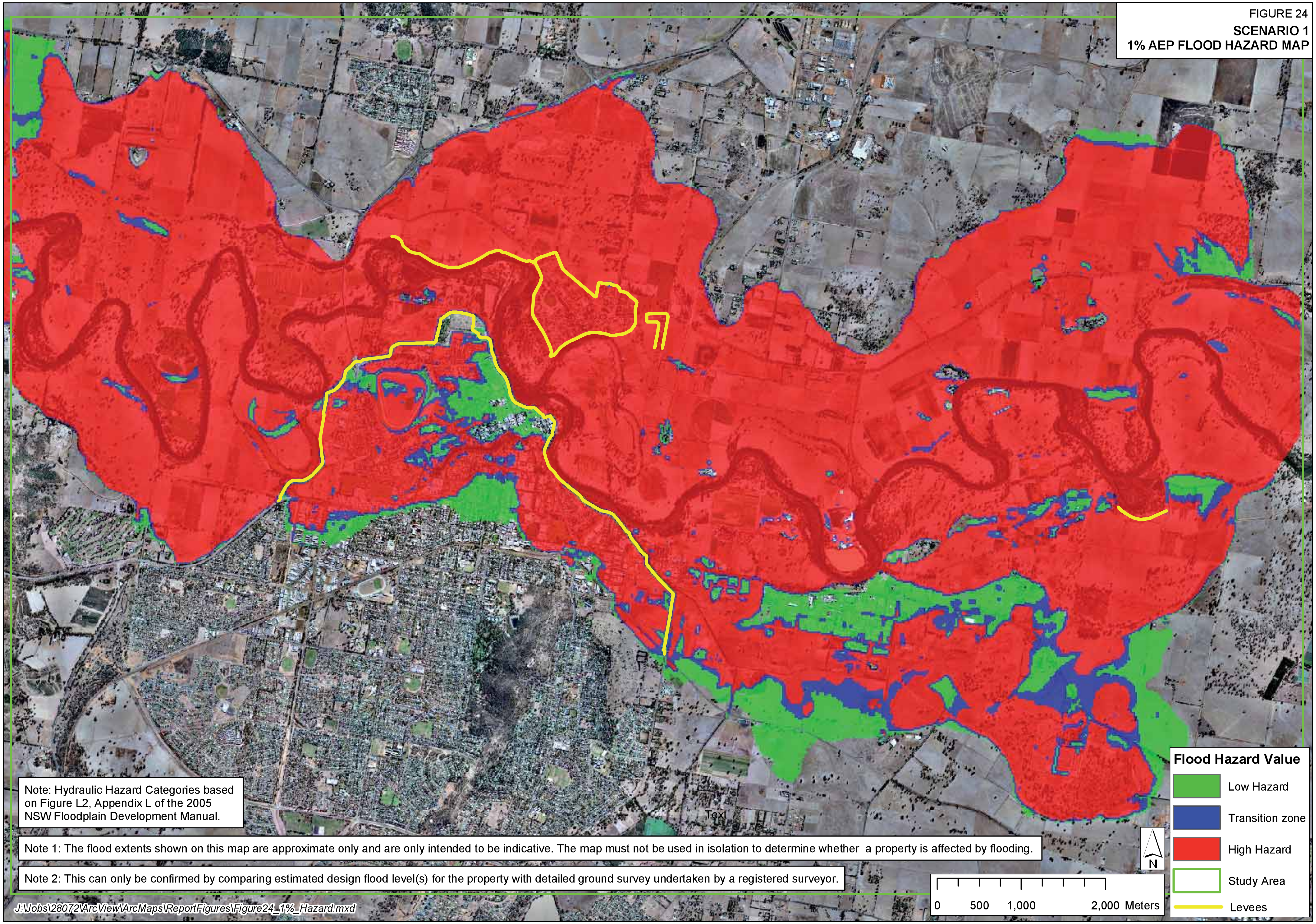
FIGURE 24
SCENARIO 1
1% AEP FLOOD HAZARD MAP
Flood Hazard Value
Low Hazard
Transition zone
High Hazard
Study Area
Levees
N
0
500
1,000
2,000 Meters
Text
Note: Hydraulic Hazard Categories based on Figure L2, Appendix L of the 2005 NSW Floodplain Development Manual.
Note 1: The flood extents shown on this map are approximate only and are only intended to be indicative. The map must not be used in isolation to determine whether a property is affected by flooding.
Note 2: This can only be confirmed by comparing estimated design flood level(s) for the property with detailed ground survey undertaken by a registered surveyor.
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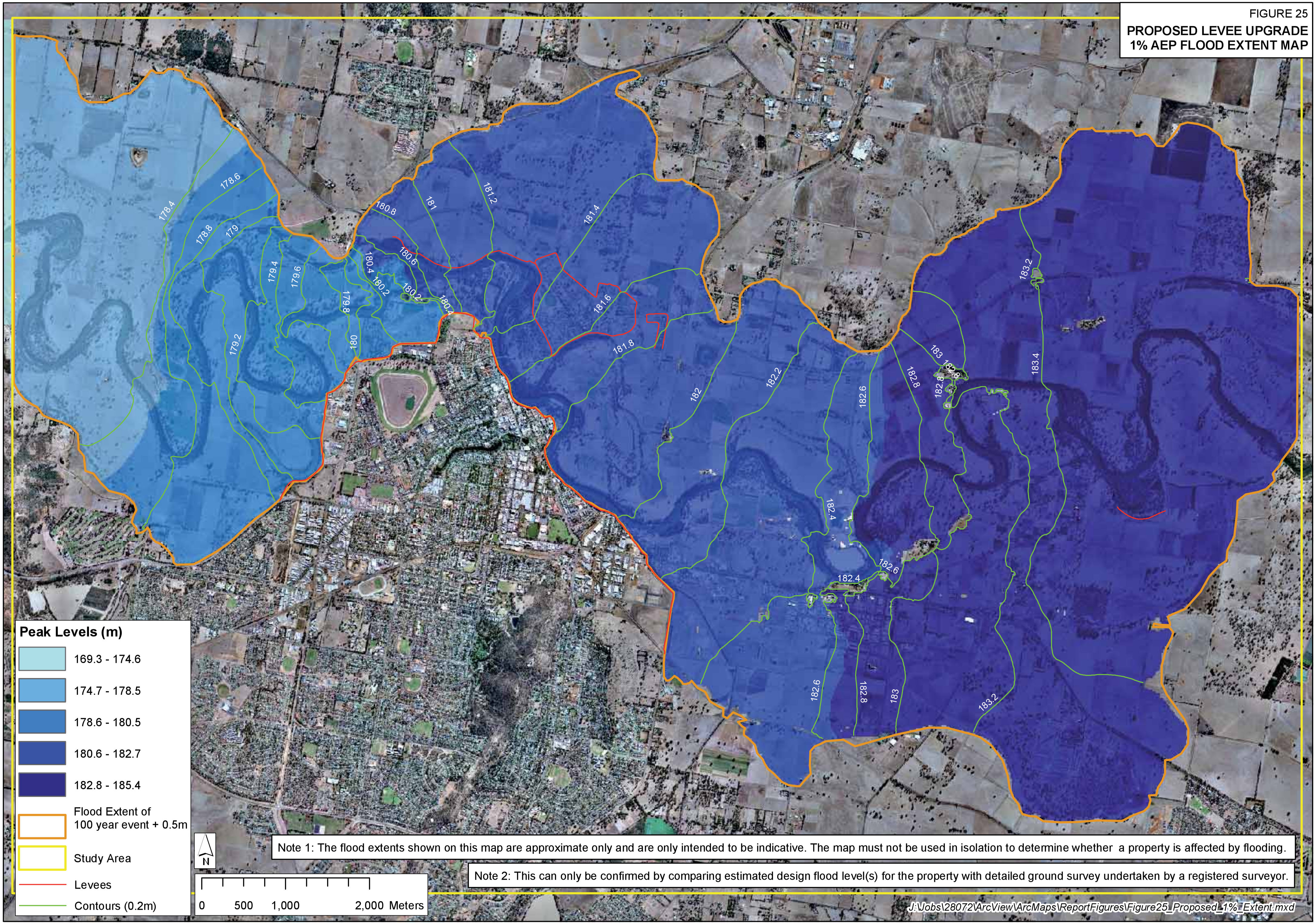
FIGURE 25

PROPOSED LEVEE UPGRADE
1% AEP FLOOD EXTENT MAP



Note 1: The flood extents shown on this map are approximate only and are only intended to be indicative. The map must not be used in isolation to determine whether a property is affected by flooding.

Note 2: This can only be confirmed by comparing estimated design flood level(s) for the property with detailed ground survey undertaken by a registered surveyor.

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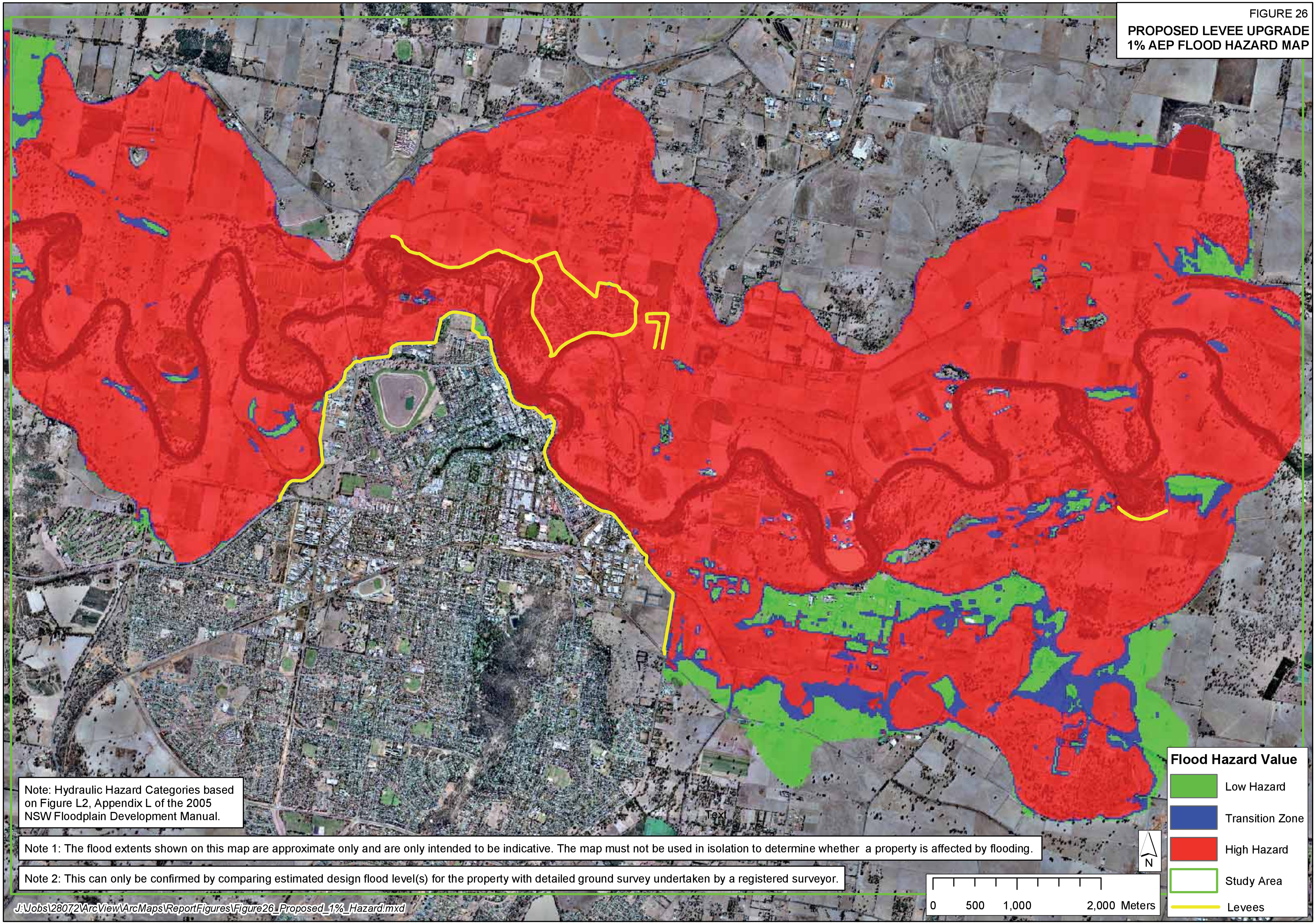
FIGURE 26

PROPOSED LEVEE UPGRADE
1% AEP FLOOD HAZARD MAP



Note: Hydraulic Hazard Categories based on Figure L2, Appendix L of the 2005 NSW Floodplain Development Manual.

Note 1: The flood extents shown on this map are approximate only and are only intended to be indicative. The map must not be used in isolation to determine whether a property is affected by flooding.

Note 2: This can only be confirmed by comparing estimated design flood level(s) for the property with detailed ground survey undertaken by a registered surveyor.

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FIGURE 27

PROPOSED LEVEE UPGRADE

1% AEP PEAK HEIGHT PROFILE D PROFILE

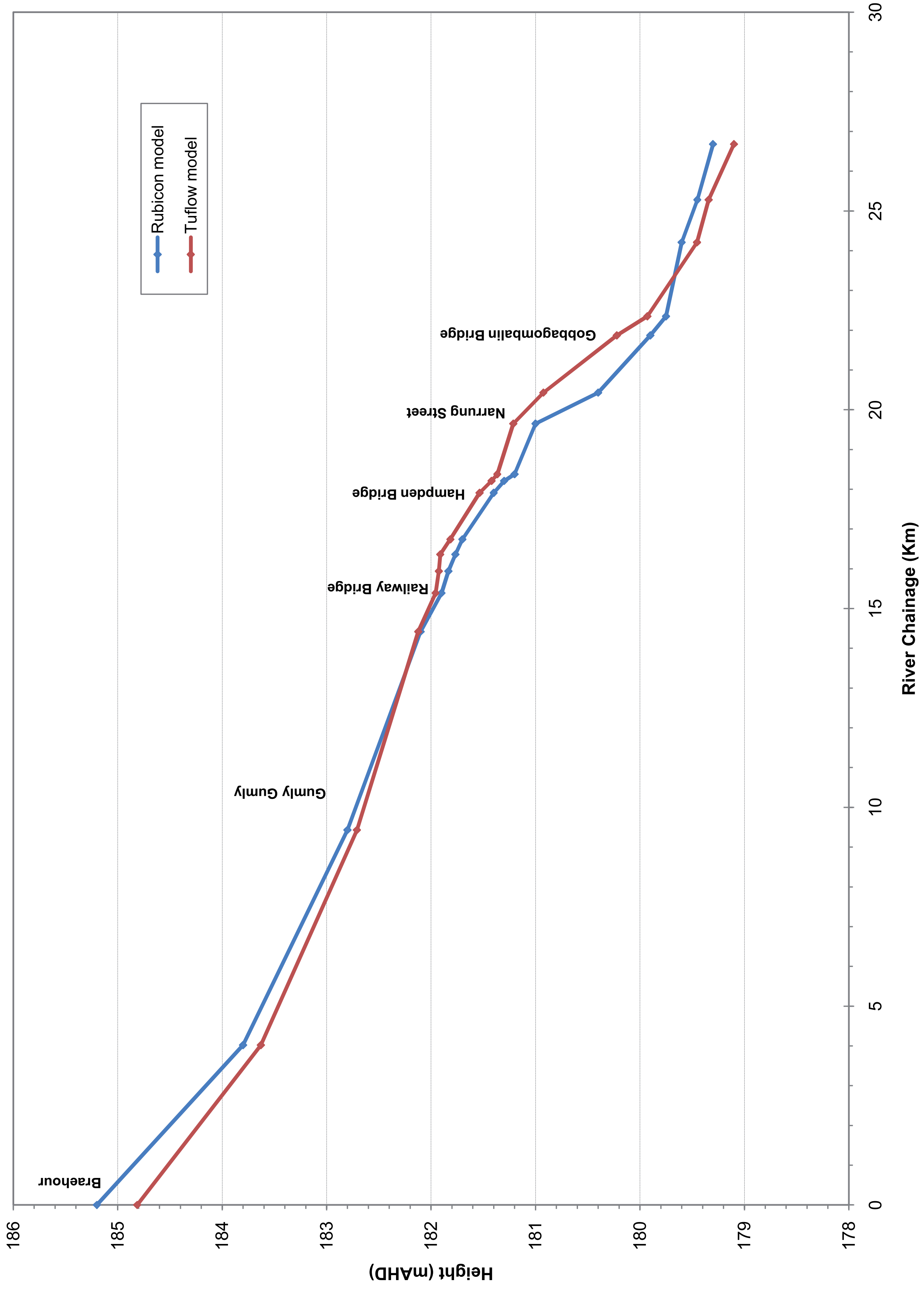

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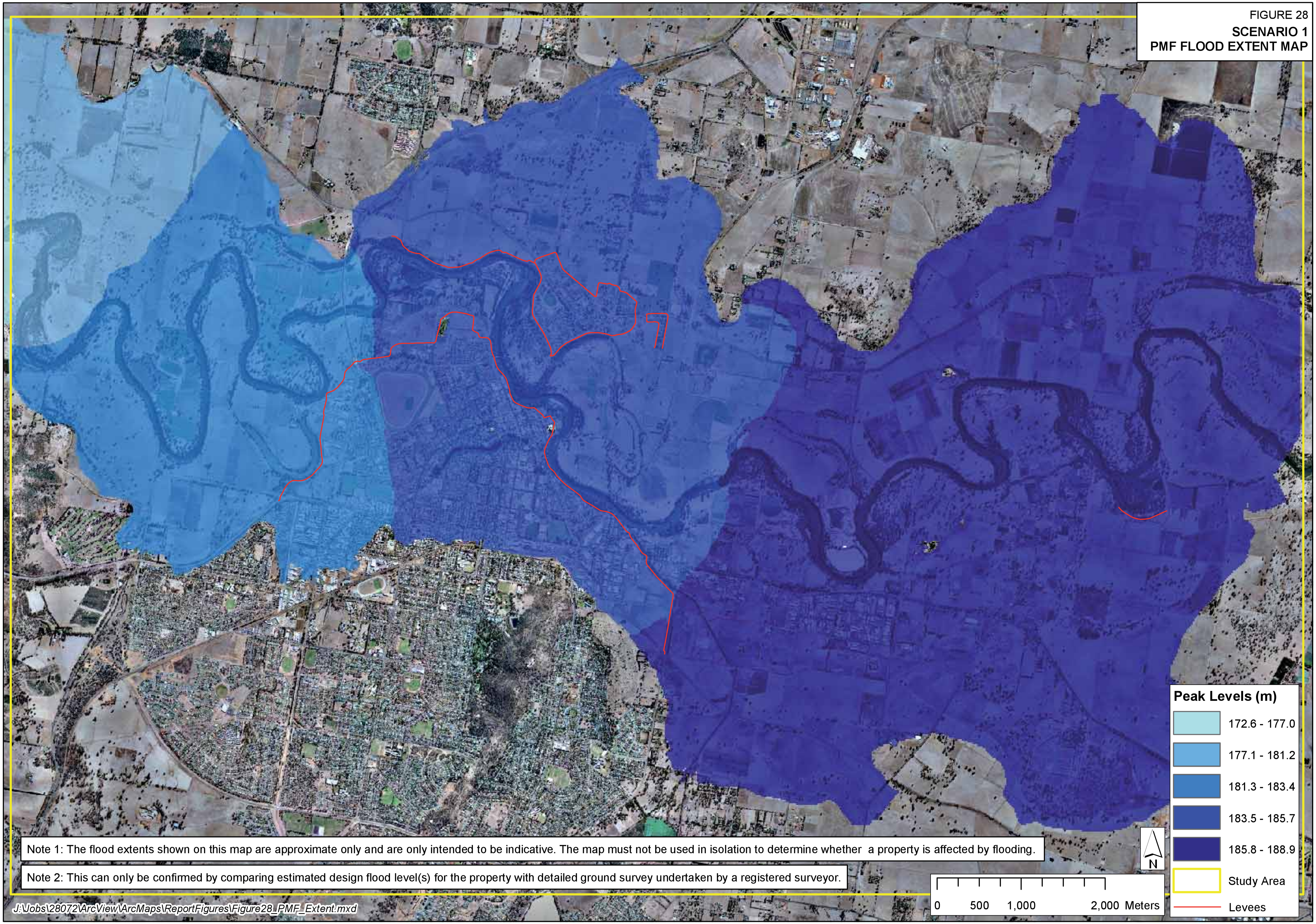
FIGURE 28
SCENARIO 1
PMF FLOOD EXTENT MAP



Note 1: The flood extents shown on this map are approximate only and are only intended to be indicative. The map must not be used in isolation to determine whether a property is affected by flooding.

Note 2: This can only be confirmed by comparing estimated design flood level(s) for the property with detailed ground survey undertaken by a registered surveyor.

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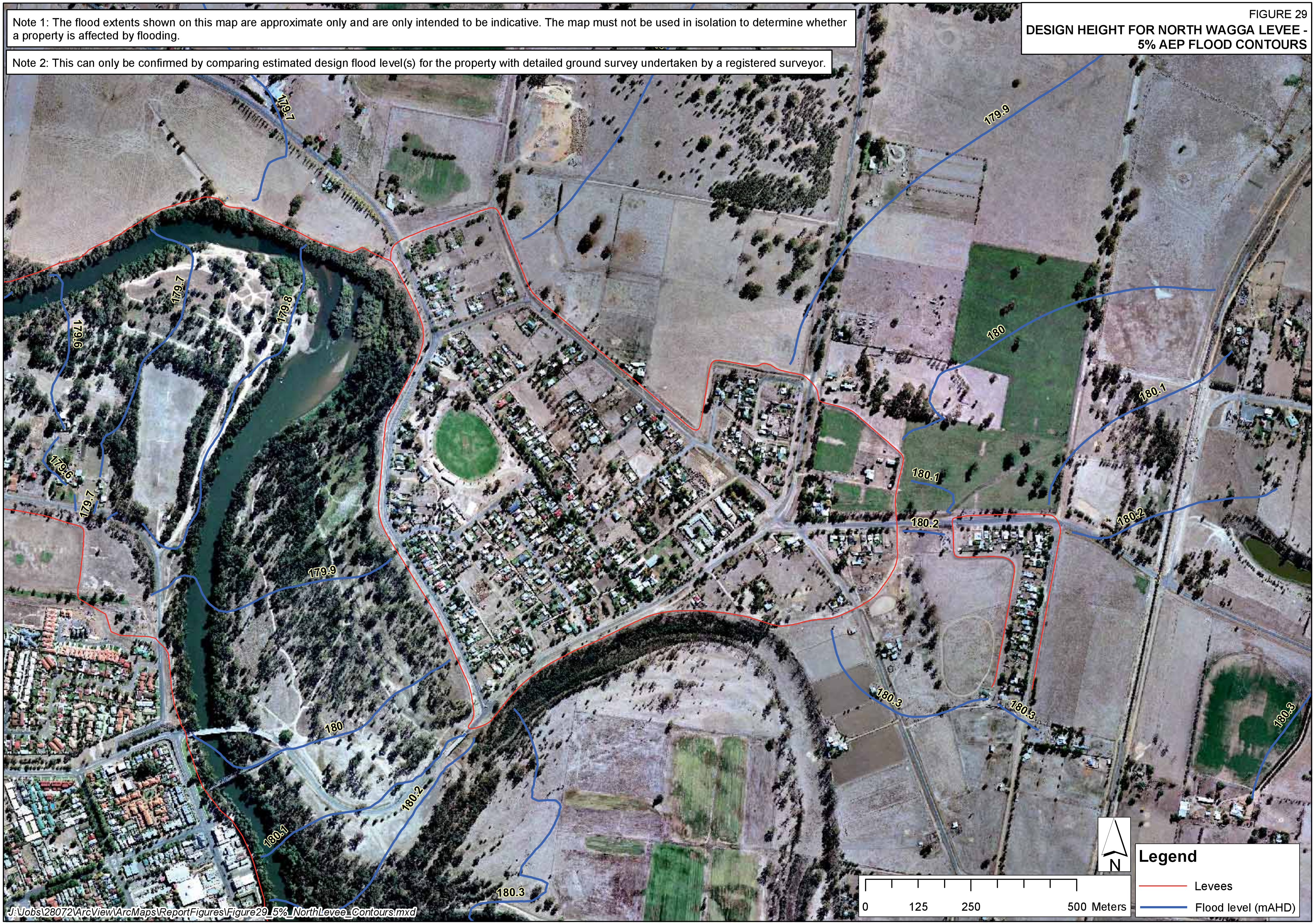
FIGURE 29

DESIGN HEIGHT FOR NORTH WAGGA LEVEE - 5% AEP FLOOD CONTOURS

Note 1: The flood extents shown on this map are approximate only and are only intended to be indicative. The map must not be used in isolation to determine whether a property is affected by flooding.

Note 2: This can only be confirmed by comparing estimated design flood level(s) for the property with detailed ground survey undertaken by a registered surveyor.



J:\Jobs\28072\ArcView\ArcMaps\ReportFigures\Figure29_5%_NorthLevee_Contours.mxd

FIGURE 30

DESIGN HEIGHT FOR NORTH WAGGA LEVEE

5% AEP FLOOD PROFILE

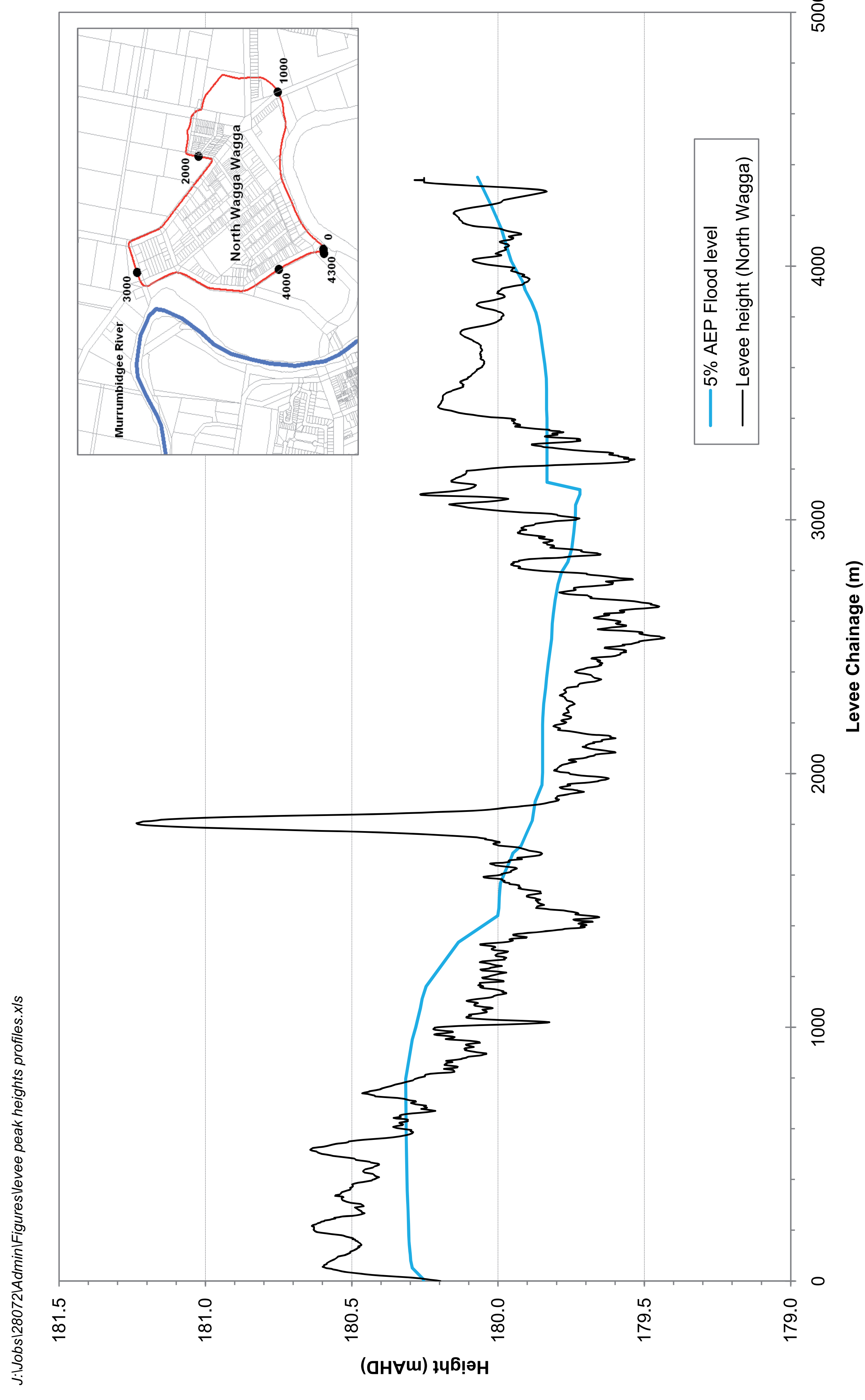


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FIGURE 31

DESIGN HEIGHT FOR MAIN CIYY LEVEE
1% AEP FLOOD PROFILE

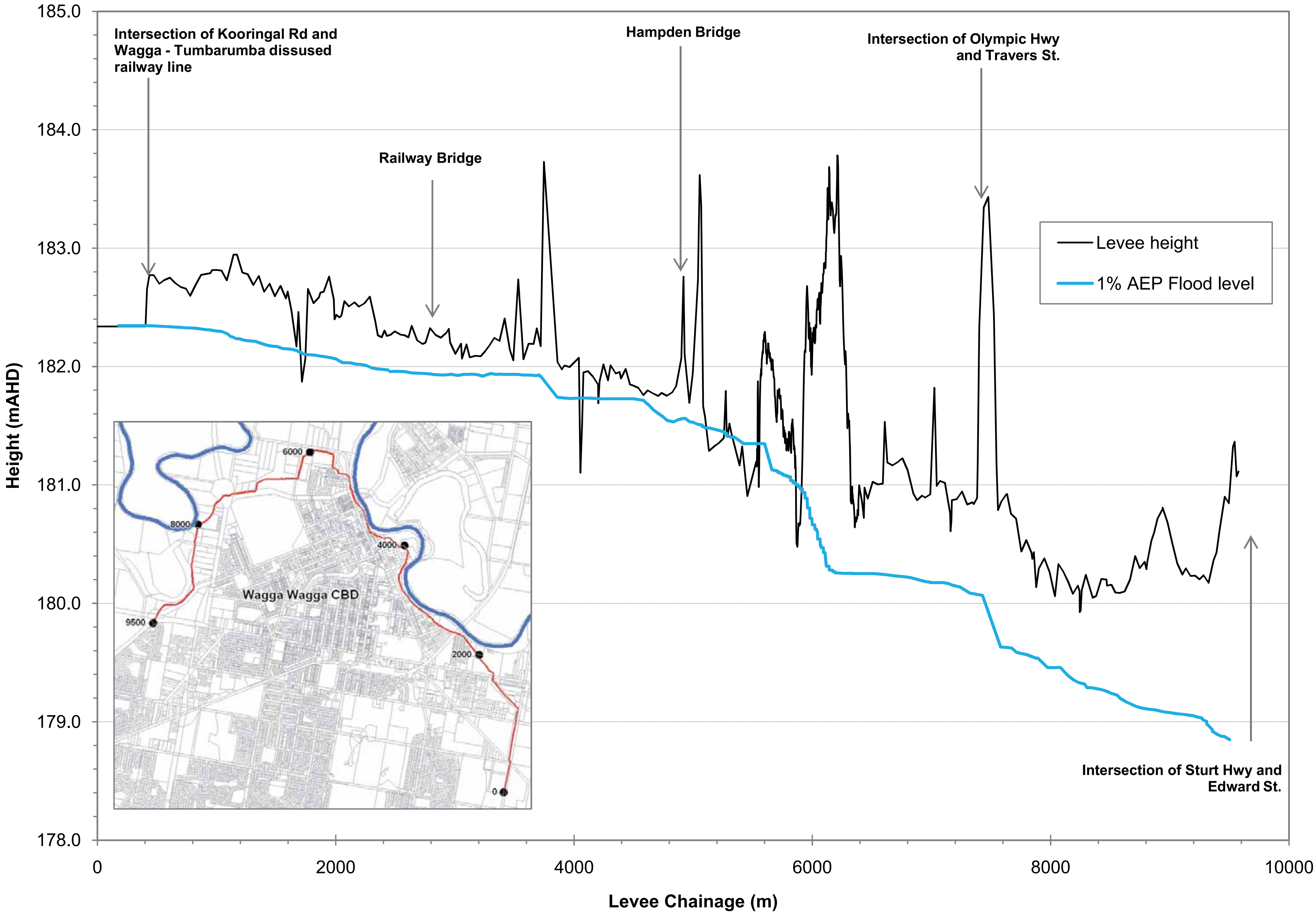


FIGURE 32

KEY LOCATIONS FOR VEGETATION MANAGEMENT RUNS

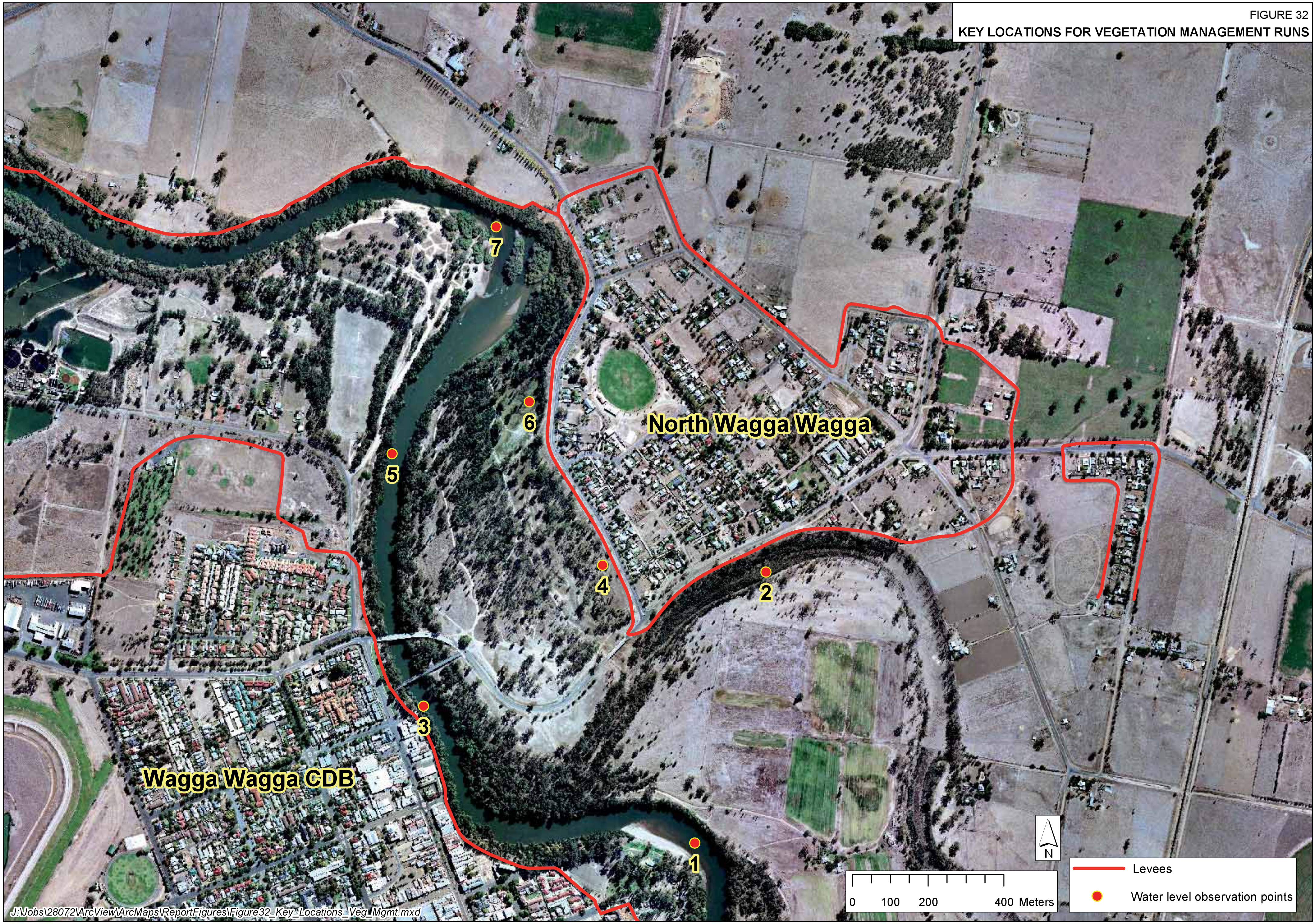
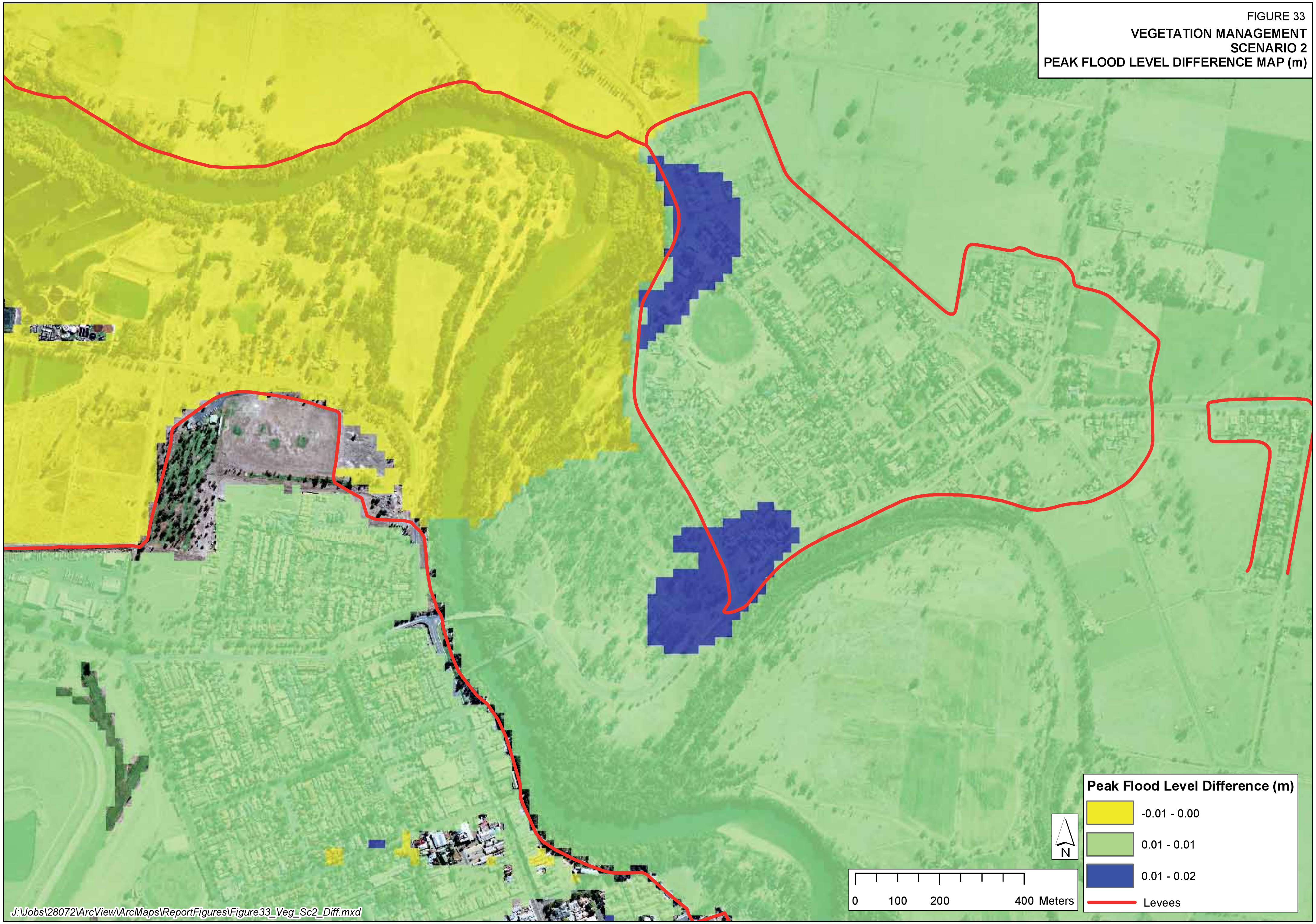


FIGURE 33
VEGETATION MANAGEMENT
SCENARIO 2
PEAK FLOOD LEVEL DIFFERENCE MAP (m)



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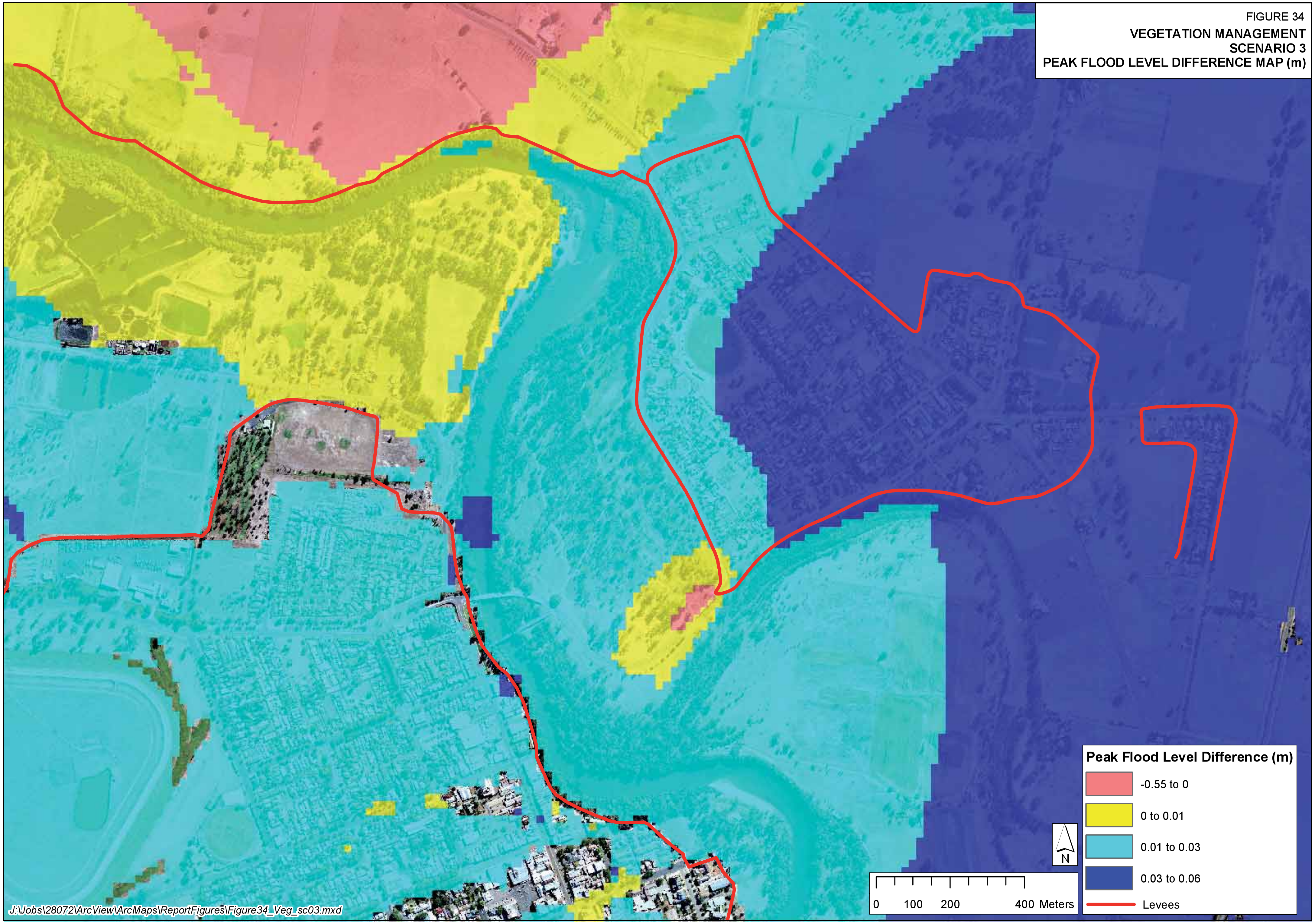


FIGURE 34
VEGETATION MANAGEMENT
SCENARIO 3
PEAK FLOOD LEVEL DIFFERENCE MAP (m)
Peak Flood Level Difference (m)
-0.55 to 0
0 to 0.01
0.01 to 0.03
0.03 to 0.06
Levees
N
0
100
200
400 Meters
J:\Jobs\28072\ArcView\ArcMaps\ReportFigures\Figure34_Veg_sc03.mxd

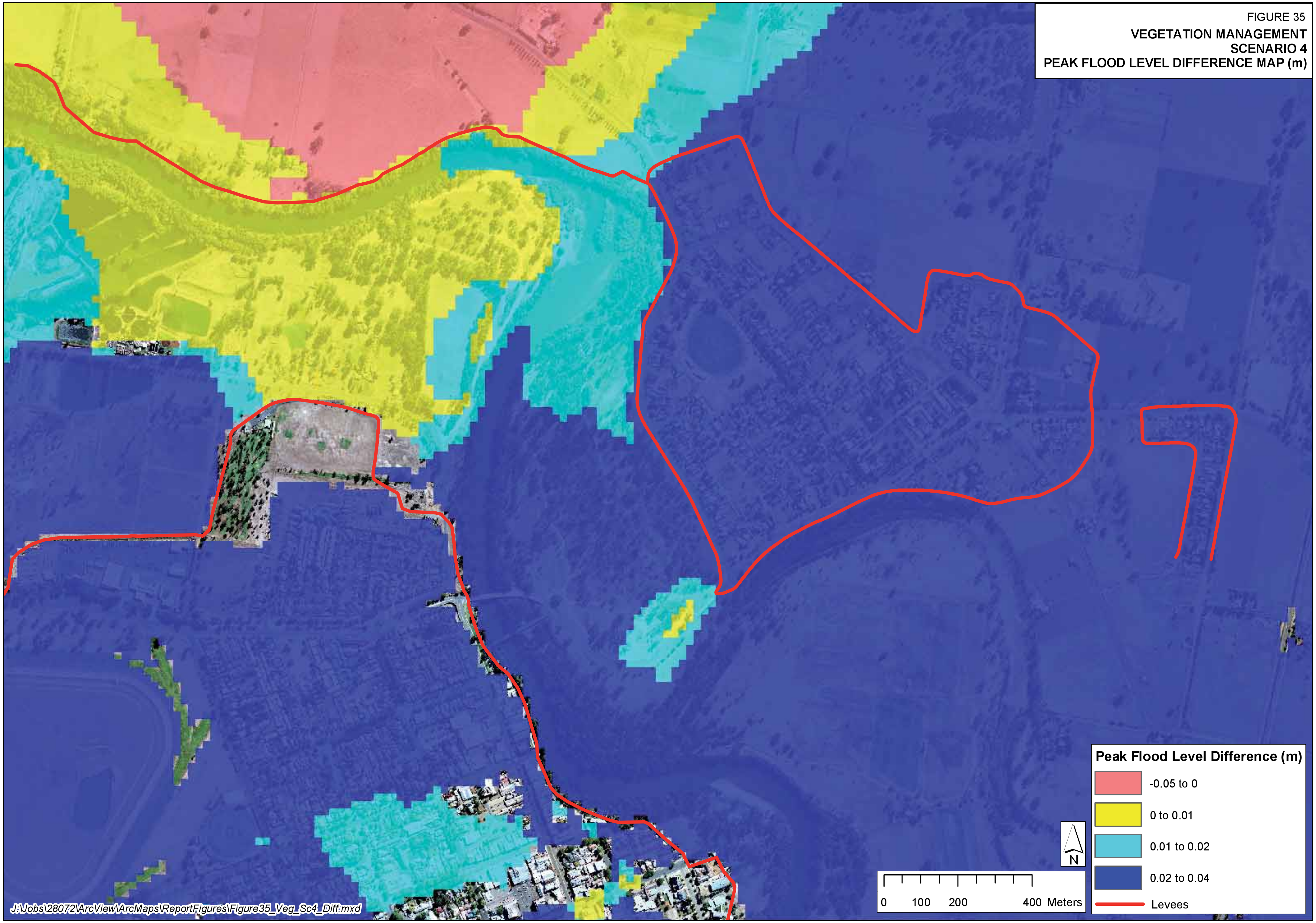


FIGURE 35
VEGETATION MANAGEMENT
SCENARIO 4
PEAK FLOOD LEVEL DIFFERENCE MAP (m)
Peak Flood Level Difference (m)
-0.05 to 0
0 to 0.01
0.01 to 0.02
0.02 to 0.04
Levees
N
0
100
200
400 Meters
J:\Jobs\28072\ArcView\ArcMaps\ReportFigures\Figure35_Veg_Sc4_Diff.mxd

FIGURE 36
VEGETATION MANAGEMENT
SCENARIO 5
PEAK FLOOD LEVEL DIFFERENCE MAP (m)

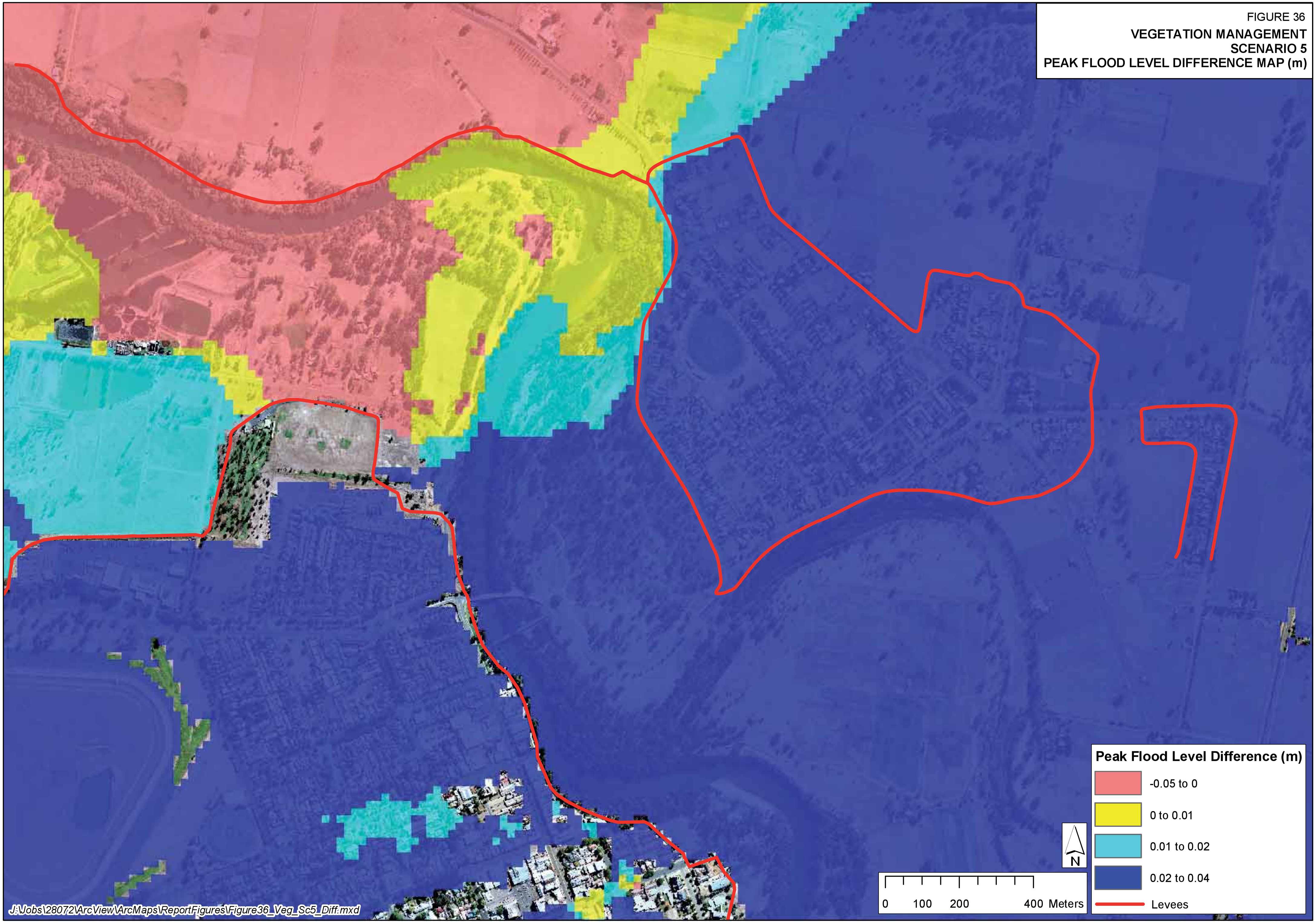
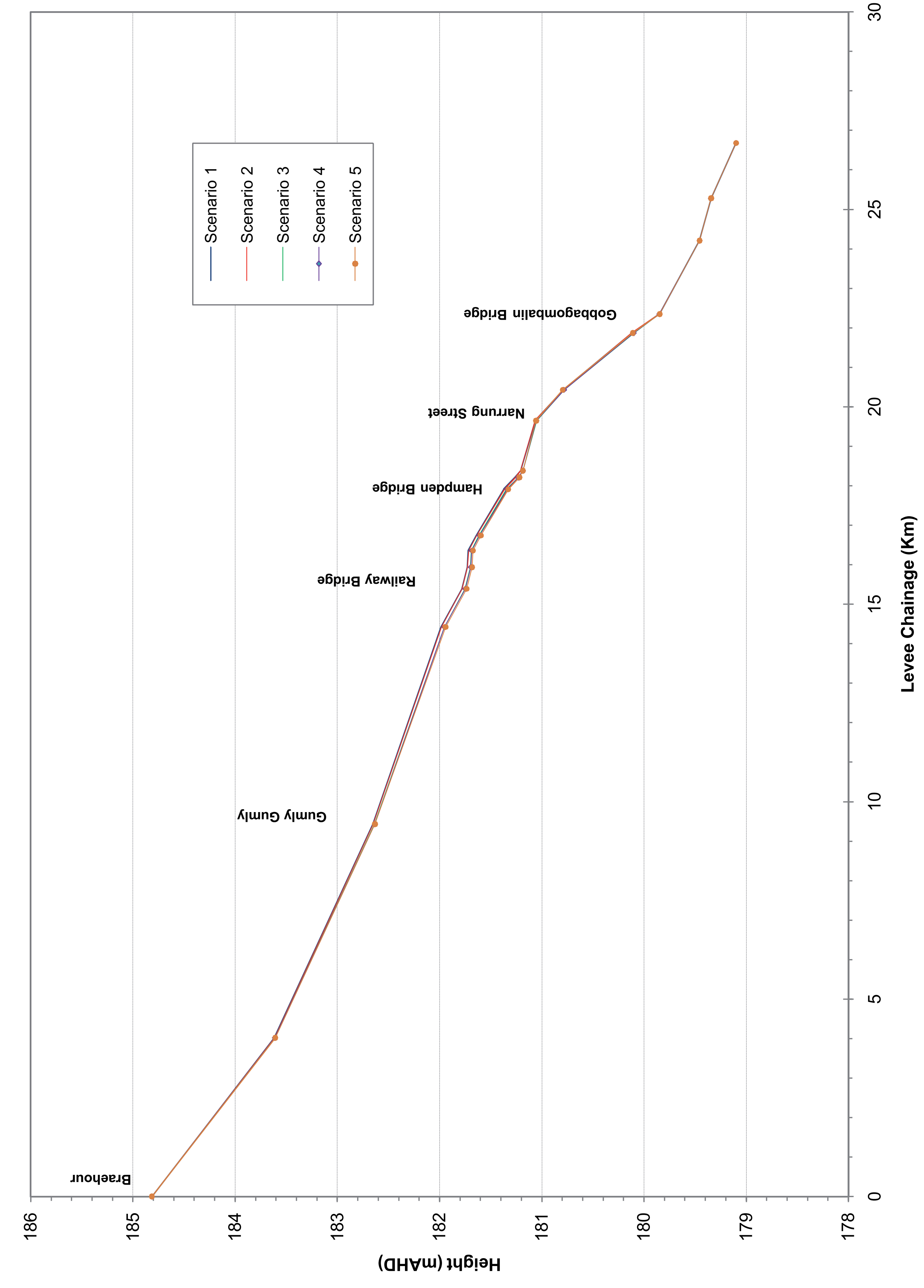


FIGURE 37
VEGETATION MANAGEMENT
COMPILED PEAK FLOOD LEVEL PROFILES



J:\Jobs\28072\Admin\Figures\peak heights profiles - design runs.xls

Appendix A

APPENDIX A: GLOSSARY

Taken from the Floodplain Development Manual (April 2005 edition)

acid sulfate soils	Are sediments which contain sulfidic mineral pyrite which may become extremely acid following disturbance or drainage as sulfur compounds react when exposed to oxygen to form sulfuric acid. More detailed explanation and definition can be found in the NSW Government Acid Sulfate Soil Manual published by Acid Sulfate Soil Management Advisory Committee.
Annual Exceedance Probability (AEP)	The chance of a flood of a given or larger size occurring in any one year, usually expressed as a percentage. For example, if a peak flood discharge of 500 m^3/s has an AEP of 5%, it means that there is a 5% chance (that is one-in-20 chance) of a 500 m^3/s or larger event occurring in any one year (see ARI).
Australian Height Datum (AHD)	A common national surface level datum approximately corresponding to mean sea level.
Average Annual Damage (AAD)	Depending on its size (or severity), each flood will cause a different amount of flood damage to a flood prone area. AAD is the average damage per year that would occur in a nominated development situation from flooding over a very long period of time.
Airborne Laser Scanning (ALS)	A terrain definition process which utilises and airborne laser source to accurately measure the earth surface from computation of laser range and return signal intensity measurements recorded in-flight along with position and altitude data derived from airborne GPS and inertial subsystems. Falls into the category of airborne instrumentation known as LIDAR (Light Detection and Ranging).
Average Recurrence Interval (ARI)	The long term average number of years between the occurrence of a flood as big as, or larger than, the selected event. For example, floods with a discharge as great as, or greater than, the 20 year ARI flood event will occur on average once every 20 years. ARI is another way of expressing the likelihood of occurrence of a flood event.
American Standard Code for Information Interchange file (ASCII)	A file whose data is in ASCII characters and does not include formatting such as bold, italic, centred text, etc.
caravan and moveable home parks	Caravans and moveable dwellings are being increasingly used for long-term and permanent accommodation purposes. Standards relating to their siting, design, construction and management can be found in the Regulations under the LG Act.
catchment	The land area draining through the main stream, as well as tributary streams, to a particular site. It always relates to an area above a specific location.
Canopy Elevation Model (CEM)	CEM is a grid that represents the mean canopy height above the ground surface. The CEM is generally derived from the first return LiDAR data. The CEM therefore represents the highest derived vegetation surface.
Colour digital aerial photography (RGB)	Digital photographic images captured by a digital sensor off an airborne platform such as a plane. Colour aerial photography includes red, green and blue wavelengths. To be acquired for the primary purpose of providing qualitative information of on-ground features, which will be used the development of the digital terrain model. However this could be used for other applications such as mapping broadly defined vegetation types.

consent authority — The Council, government agency or person having the function to determine a development application for land use under the EP&A Act. The consent authority is most often the Council, however legislation or an EPI may specify a Minister or public authority (other than a Council), or the Director General of DIPNR, as having the function to determine an application.

Digital Elevation Model (DEM) — The representation of continuous elevation values over a topographic surface by a regular array of sampled z-values, referenced to a common datum. To be expressed as a grid for the purposes of this tender process. The DEM excludes vegetation such as trees and shrubs, but includes bare ground and human constructed features such as shed and houses that are detectable within the accuracy of the Digital Elevation Model. The DEM is used for visualisation purposes and is not suitable for hydraulic modelling.

development — Is defined in Part 4 of the Environmental Planning and Assessment Act (EP&A Act).

infill development: refers to the development of vacant blocks of land that are generally surrounded by developed properties and is permissible under the current zoning of the land. Conditions such as minimum floor levels may be imposed on infill development.

new development: refers to development of a completely different nature to that associated with the former land use. For example, the urban subdivision of an area previously used for rural purposes. New developments involve rezoning and typically require major extensions of existing urban services, such as roads, water supply, sewerage and electric power.

redevelopment: refers to rebuilding in an area. For example, as urban areas age, it may become necessary to demolish and reconstruct buildings on a relatively large scale. Redevelopment generally does not require either rezoning or major extensions to urban services.

disaster plan (DISPLAN) — A step by step sequence of previously agreed roles, responsibilities, functions, actions and management arrangements for the conduct of a single or series of connected emergency operations, with the object of ensuring the coordinated response by all agencies having responsibilities and functions in emergencies.

discharge — The rate of flow of water measured in terms of volume per unit time, for example, cubic metres per second (m^3/s). Discharge is different from the speed or velocity of flow, which is a measure of how fast the water is moving for example, metres per second (m/s).

Digital photography — A type of imagery that, in contrast to wet film photography, uses electronic devices to record and capture the image as binary or digital data that can be readily stored and edited on a computer. Aerial digital photography is digital photography taken from the vantage of a flighted vehicle such as a helicopter or aeroplane.

Digital Terrain Model (DTM) — A topographic model of the earth's surface in digital format as elevation data related to a rectangular grid and referenced to the Australian Height Datum. The DTM is a filtered version of the DEM that represents only bare earth surfaces. The DTM representation of ground includes works such as levees, banks and roads because this is the surface over which floods will flow.

ecologically sustainable development (ESD) — Using, conserving and enhancing natural resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future, can be maintained or increased. A more detailed definition is included in

	the Local Government Act 1993. The use of sustainability and sustainable in this manual relate to ESD.
effective warning time	The time available after receiving advice of an impending flood and before the floodwaters prevent appropriate flood response actions being undertaken. The effective warning time is typically used to move farm equipment, move stock, raise furniture, evacuate people and transport their possessions.
emergency management	A range of measures to manage risks to communities and the environment. In the flood context it may include measures to prevent, prepare for, respond to and recover from flooding.
ESRI	Environmental Systems Research Institute.
flash flooding	Flooding which is sudden and unexpected. It is often caused by sudden local or nearby heavy rainfall. Often defined as flooding which peaks within six hours of the causative rain.
flood	Relatively high stream flow which overtops the natural or artificial banks in any part of a stream, river, estuary, lake or dam, and/or local overland flooding associated with major drainage before entering a watercourse, and/or coastal inundation resulting from super-elevated sea levels and/or waves overtopping coastline defences excluding tsunami.
flood awareness	Flood awareness is an appreciation of the likely effects of flooding and a knowledge of the relevant flood warning, response and evacuation procedures.
flood education	Flood education seeks to provide information to raise awareness of the flood problem so as to enable individuals to understand how to manage themselves an their property in response to flood warnings and in a flood event. It invokes a state of flood readiness.
flood fringe areas	The remaining area of flood prone land after floodway and flood storage areas have been defined.
flood liable land	Is synonymous with flood prone land (i.e. land susceptible to flooding by the probable maximum flood (PMF) event). Note that the term flood liable land covers the whole of the floodplain, not just that part below the flood planning level (see flood planning area).
flood mitigation standard	The average recurrence interval of the flood, selected as part of the floodplain risk management process that forms the basis for physical works to modify the impacts of flooding.
floodplain	Area of land which is subject to inundation by floods up to and including the probable maximum flood event, that is, flood prone land.
floodplain risk management options	The measures that might be feasible for the management of a particular area of the floodplain. Preparation of a floodplain risk management plan requires a detailed evaluation of floodplain risk management options.
floodplain risk management plan	A management plan developed in accordance with the principles and guidelines in this manual. Usually includes both written and diagrammetic information describing how particular areas of flood prone land are to be used and managed to achieve defined objectives.
flood plan (local)	A sub-plan of a disaster plan that deals specifically with flooding. They can exist

at State, Division and local levels. Local flood plans are prepared under the leadership of the State Emergency Service.

flood planning area
The area of land below the flood planning level and thus subject to flood related development controls. The concept of flood planning area generally supersedes the Aflood liable land@ concept in the 1986 Manual.

Flood Planning Levels (FPLs)
FPL=s are the combinations of flood levels (derived from significant historical flood events or floods of specific AEPs) and freeboards selected for floodplain risk management purposes, as determined in management studies and incorporated in management plans. FPLs supersede the Astandard flood event@ in the 1986 manual.

flood proofing
A combination of measures incorporated in the design, construction and alteration of individual buildings or structures subject to flooding, to reduce or eliminate flood damages.

flood prone land
Is land susceptible to flooding by the Probable Maximum Flood (PMF) event. Flood prone land is synonymous with flood liable land.

flood readiness
Flood readiness is an ability to react within the effective warning time.

flood risk
Potential danger to personal safety and potential damage to property resulting from flooding. The degree of risk varies with circumstances across the full range of floods. Flood risk in this manual is divided into 3 types, existing, future and continuing risks. They are described below.

existing flood risk: the risk a community is exposed to as a result of its location on the floodplain.

future flood risk: the risk a community may be exposed to as a result of new development on the floodplain.

continuing flood risk: the risk a community is exposed to after floodplain risk management measures have been implemented. For a town protected by levees, the continuing flood risk is the consequences of the levees being overtopped. For an area without any floodplain risk management measures, the continuing flood risk is simply the existence of its flood exposure.

flood storage areas
Those parts of the floodplain that are important for the temporary storage of floodwaters during the passage of a flood. The extent and behaviour of flood storage areas may change with flood severity, and loss of flood storage can increase the severity of flood impacts by reducing natural flood attenuation. Hence, it is necessary to investigate a range of flood sizes before defining flood storage areas.

floodway areas
Those areas of the floodplain where a significant discharge of water occurs during floods. They are often aligned with naturally defined channels. Floodways are areas that, even if only partially blocked, would cause a significant redistribution of flood flows, or a significant increase in flood levels.

Focus Area
Priority areas identified within the NSW Wetlands Study Areas (comprising 1. Gwydir wetlands; 2. Macquarie Marshes; and 3. Murrumbidgee Floodplain/Great Cumbung Swamp) where a higher quality data is required, including a greater density of LiDAR points. The location of these areas is defined on the maps in Attachment 2 and the ESRI shape files of these areas provided to the tenderer are provided at Attachment 4.

freeboard	Freeboard provides reasonable certainty that the risk exposure selected in deciding on a particular flood chosen as the basis for the FPL is actually provided. It is a factor of safety typically used in relation to the setting of floor levels, levee crest levels, etc. Freeboard is included in the flood planning level.
Ground Sample Distance (GSD)	Ground resolution of airborne or satellite imagery, e.g. 30 cm GSD
habitable room	**in a residential situation:** a living or working area, such as a lounge room, dining room, rumpus room, kitchen, bedroom or workroom. **in an industrial or commercial situation:** an area used for offices or to store valuable possessions susceptible to flood damage in the event of a flood.
hazard	A source of potential harm or a situation with a potential to cause loss. In relation to this manual the hazard is flooding which has the potential to cause damage to the community. Definitions of high and low hazard categories are provided in the Manual.
hydraulics	Term given to the study of water flow in waterways; in particular, the evaluation of flow parameters such as water level and velocity.
hydrograph	A graph which shows how the discharge or stage/flood level at any particular location varies with time during a flood.
hydrology	Term given to the study of the rainfall and runoff process; in particular, the evaluation of peak flows, flow volumes and the derivation of hydrographs for a range of floods.
Image block file	Strip of digital imagery captured from a plane (or similar airborne platform) along a section of a flight run.
ICSM	Inter-Governmental Committee on Surveying and Mapping
LAS v1.1	LAS version 1.1 is a standard LiDAR file format, defined by The American Society of Photogrammetry and Remote Sensing's (ASPRS). LAS v1.1 defines, amongst other things, mandatory data fields and point categories. This includes mandatory metadata documentation. See full description at: http://www.lasformat.org/
LiDAR	Light Detection and Ranging (LiDAR). A technology that determines distance to a surface using laser pulses. Distance is computed by measuring the time delay between transmission and detection of the reflected signal.
local overland flooding	Inundation by local runoff rather than overbank discharge from a stream, river, estuary, lake or dam.
local drainage	Are smaller scale problems in urban areas. They are outside the definition of major drainage in this glossary.
Local Site Datum	Established network of state survey control marks in close proximity to each project area.
mainstream flooding	Inundation of normally dry land occurring when water overflows the natural or artificial banks of a stream, river, estuary, lake or dam.

Councils have discretion in determining whether urban drainage problems are

major drainage associated with major or local drainage. For the purpose of this manual major drainage involves:

$ the floodplains of original watercourses (which may now be piped, channelised or diverted), or sloping areas where overland flows develop along alternative paths once system capacity is exceeded; and/or

$ water depths generally in excess of 0.3 m (in the major system design storm as defined in the current version of Australian Rainfall and Runoff). These conditions may result in danger to personal safety and property damage to both premises and vehicles; and/or

$ major overland flow paths through developed areas outside of defined drainage reserves; and/or

$ the potential to affect a number of buildings along the major flow path.

mathematical/computer models The mathematical representation of the physical processes involved in runoff generation and stream flow. These models are often run on computers due to the complexity of the mathematical relationships between runoff, stream flow and the distribution of flows across the floodplain.

merit approach The merit approach weighs social, economic, ecological and cultural impacts of land use options for different flood prone areas together with flood damage, hazard and behaviour implications, and environmental protection and well being of the State=s rivers and floodplains.

The merit approach operates at two levels. At the strategic level it allows for the consideration of social, economic, ecological, cultural and flooding issues to determine strategies for the management of future flood risk which are formulated into Council plans, policy and EPIs. At a site specific level, it involves consideration of the best way of conditioning development allowable under the floodplain risk management plan, local floodplain risk management policy and EPIs.

minor, moderate and major flooding Both the State Emergency Service and the Bureau of Meteorology use the following definitions in flood warnings to give a general indication of the types of problems expected with a flood:

minor flooding: causes inconvenience such as closing of minor roads and the submergence of low level bridges. The lower limit of this class of flooding on the reference gauge is the initial flood level at which landholders and townspeople begin to be flooded.

moderate flooding: low-lying areas are inundated requiring removal of stock and/or evacuation of some houses. Main traffic routes may be covered.

major flooding: appreciable urban areas are flooded and/or extensive rural areas are flooded. Properties, villages and towns can be isolated.

modification measures Measures that modify either the flood, the property or the response to flooding. Examples are indicated in Table 2.1 with further discussion in the Manual.

Near-Infrared digital aerial photography (NIR) Digital near-infrared imagery captured by a digital sensor from an airborne platform such as a plane.

To be gained for the primary purpose of providing information of the distribution of standing and flowing water, which will be used the development of the digital terrain model

NSW Government — Means in general, entities which: a) have some form of public sector ownership; b) are engaged in trading goods and/or services; c) have a large measure of self sufficiency; and d) are subject to Executive control. In this context, the term NSW Government includes NSW Government Departments, Agencies, Statutory Authorities, Trusts, Public Trading Enterprises, and State Owned Corporations and General Government Businesses. NSW Government includes Catchment Management Authorities.

peak discharge — The maximum discharge occurring during a flood event.

Probable Maximum Flood (PMF) — The PMF is the largest flood that could conceivably occur at a particular location, usually estimated from probable maximum precipitation, and where applicable, snow melt, coupled with the worst flood producing catchment conditions. Generally, it is not physically or economically possible to provide complete protection against this event. The PMF defines the extent of flood prone land, that is, the floodplain. The extent, nature and potential consequences of flooding associated with a range of events rarer than the flood used for designing mitigation works and controlling development, up to and including the PMF event should be addressed in a floodplain risk management study.

Probable Maximum Precipitation (PMP) — The PMP is the greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends (World Meteorological Organisation, 1986). It is the primary input to PMF estimation.

probability — A statistical measure of the expected chance of flooding (see AEP).

Raw digital aerial photography — Digital aerial photography that has not been colour balanced, orthorectified or converted into a mosaic, and which still contains redundant imagery such as overlapping images.

Raw LiDAR survey data — Unprocessed LiDAR data that has been processed to correct for in flight error (such as roll, yaw, pitch), is georeferenced and contains x, y and z and intensity values for each point. No points are removed. That is, it includes all returns (1^{st}, 2^{nd} *etc.* up to the last return) and data still contains random or systematic errors, as well as redundant data on overlapping edges of LiDAR acquisition runs. The data is, however, *georeferenced*. The data includes the intensity of the 1^{st}, 2^{nd} *etc.* and last return for each point.

risk — Chance of something happening that will have an impact. It is measured in terms of consequences and likelihood. In the context of the manual it is the likelihood of consequences arising from the interaction of floods, communities and the environment.

runoff — The amount of rainfall which actually ends up as streamflow, also known as rainfall excess.

SCIMS — The Survey Control Information Management System managed by NSW Department of Lands

SP1 — ICSM Special Publication No.1 - Standards and Practices for Control Surveys

stage — Equivalent to Awater level@. Both are measured with reference to a specified datum.

stage hydrograph — A graph that shows how the water level at a particular location changes with time during a flood. It must be referenced to a particular datum.

Study Area	The area that is comprised of four wetlands: 1. Gwydir wetlands; 2. Macquarie Marshes; and 3. Murrumbidgee Floodplain/Great Cumbung Swamp, 4. Narrandra Forests, with the spatial extents of these areas defined according to total area represented by the maps in Attachment 2 and the ESRI shape files of these areas provided to the tenderer.
Surveyor General Directions	The directions detailed within the following website: http://www.lands.nsw.gov.au/publications/guidelines/surveyor_generals_directions
survey plan	A plan prepared by a registered surveyor.
water surface profile	A graph showing the flood stage at any given location along a watercourse at a particular time.
wind fetch	The horizontal distance in the direction of wind over which wind waves are generated.

Appendix B

Wagga Wagga City Council
P.O. Box 20
WAGGA WAGGA NSW 2650

28072/P090506_WWCC

6 May 2009

Attention: Brad Jeffrey

Dear Brad,

Re: Check on Accuracy of 1m Raster DTM Product

Following receipt of ALS data Wagga Wagga City Council (WWCC) have asked WMAwater (previously trading as Webb, McKeown and Associates Pty Ltd) to carry out an assessment of the accuracy of the 1 m Digital Terrain Model (DTM) (Data item 21) portion of the overall data product delivered by FUGRO. The following is then a brief report which provides the background to this task, presents the method by which the check was undertaken and also the results of that check.

Executive Summary

In April 2009 WWCC began to receive elements of its overall data package from FUGRO. This data included DTM raster surfaces (ground terrain) suitable for utilisation in the 2D flood model that WWCC had requested WMAwater build (using the original Rubicon model as the basis). WWCC sought to ensure the validity of the DTM prior to its utilisation in various critical end uses and as such requested that WMAwater carry out a check of the data.

Using spot heights provided by WWCC, WMAwater have undertaken a check of the vertical accuracy of the 1m DTM raster product provided to WWCC by FUGRO. What has been found is that providing that those points without decimals are removed, as well as those points that exhibit gross error, mean error for the remaining point set achieves the typical accuracy specifications for low level ALS data, i.e. 67% percent of points lie within +/- 0.15 m of “real” elevation (as indicated in this case by the survey points supplied by WWCC).

Webb, McKeown & Associates Pty Ltd (trading as WMAwater) **ABN 50 366 075 980**

DIRECTORS
M K Babister BE(Hons), MEngSc, GradDipMgt, MIEAust
G L Hurrell BSc, BE(Hons), MIEAust
R W Dewar BSc(Hons), MEngSc, MAIG, MIEAust

ASSOCIATES
M J Chadwick BE(Hons), MEngSc
E J Askew BE(Hons), MIEAust
S D Gray BE, MEng

Level 2, 160 Clarence St, SYDNEY NSW 2000
Phone: 02 9299 2855 Fax: 02 9262 6208
Email: enquiry@wmawater.com.au
Website: wmawater.com.au

Methodology

The calculation of the mean elevation error and standard deviation error in the WWCC supplied point data set was carried out by comparing the actual heights in the point data set to the Digital Terrain Model (DTM) in the Wagga Wagga floodplain area. The total number of marks in the point database supplied by WWCC was 1406.

Cleaning the point database

Prior to being compared to the 1 m DTM raster the WWCC point data set was edited substantially. This editing process consisted of eliminating:

- All points falling outside the study area,
- points with elevations equal to zero, and
- points with integer elevation values.

Following this process the number of points had been reduced from 1406 to 896. These 896 points were then used in the subsequent analysis which is detailed below. It was considered likely that further points which showed up as being grossly at odds with the DTM would be needed to be removed from the point database. Such points could not be identified however until the elevations of the point database were compared with the elevations sourced from the DTM.

Analysis

Using the cleaned point database a Geographical Information System (GIS) was then used in order to make a point inspection of the 1 m DTM surface. That is, the at the x,y location where the points within the point database intersect the raster, an elevation is sampled from the raster. The raster sampled elevation is then compared to the point database elevation which is typically land survey based. Subsequent analysis was based on the following defined equations.

Equation 1 calculates the difference between the elevation of the SCIMS mark and the elevation in the DTM:

$$Herror_i = H_{SCIMS_i} - H_{DTM_i}$$

Equation 1: Elevation error in mark

The mean elevation error is given by the equation:

$$MEE = \frac{\sum_i^n Herror_i}{n}$$

Equation 2: Mean elevation error

The standard deviation error is given by the equation:

$$\sigma_{MEE} = \sqrt{\frac{\sum_i^n (MEE - Herror_i)^2}{n}}$$

Equation 3: Standard deviation of the elevation error

Results for the 896 points found that the standard deviation was well in excess of the target of +/- 0.15 m. As such the process became one of eliminating the truly erroneous errors and seeing how the error distribution changed. First those points greater than +/- 10 m difference were eliminated. This reduced the point database by six points only to 890 points and barely improved results. Results are shown in Figure 1.

Those points with an error greater than +/- 1 m were then eliminated and this gave the result shown in Figure 2. Although this result was very close to achieving the accuracy criteria of the contract, a final run was done using a tolerance of +/- 0.5 m to weed out errant points. This left a total of 790 points from the original total of 896 cleaned points and gave results that well and truly met the accuracy criteria for the data project. Results are shown in Figure 3.

Results

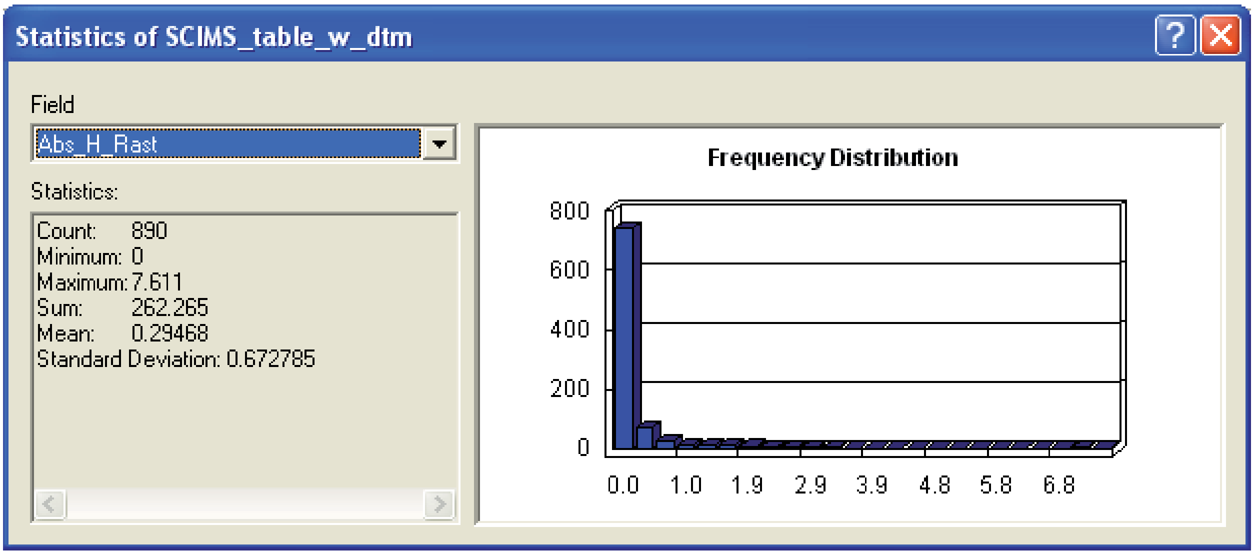


Figure 1: Analysis for Cleaned Points minus those > +/- 10 m difference to grid

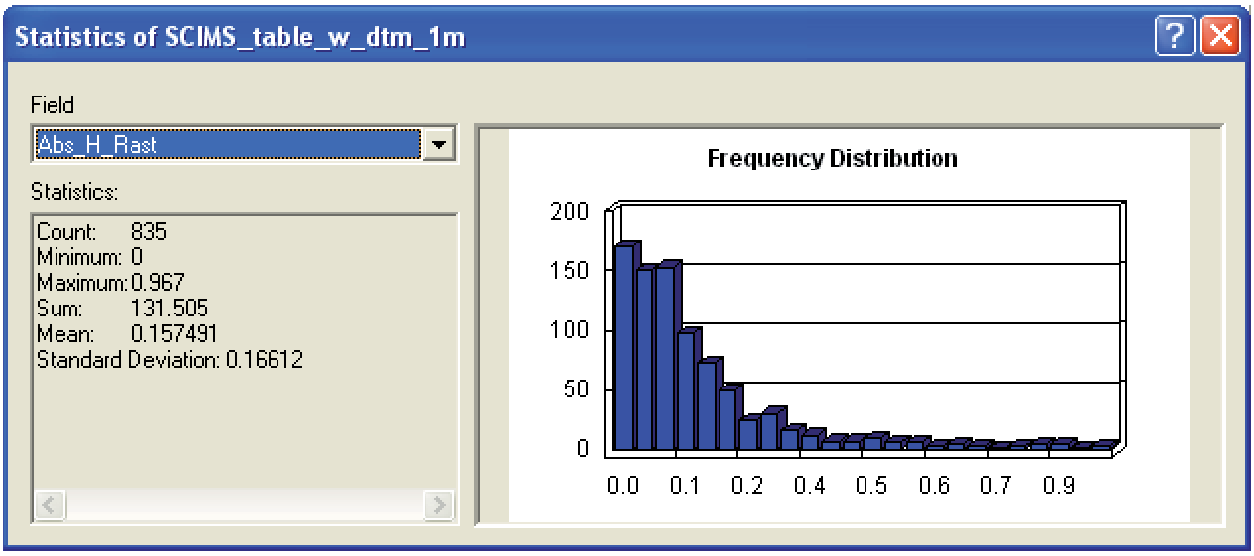


Figure 2: Analysis for Cleaned Points minus those > +/- 1 m difference to grid

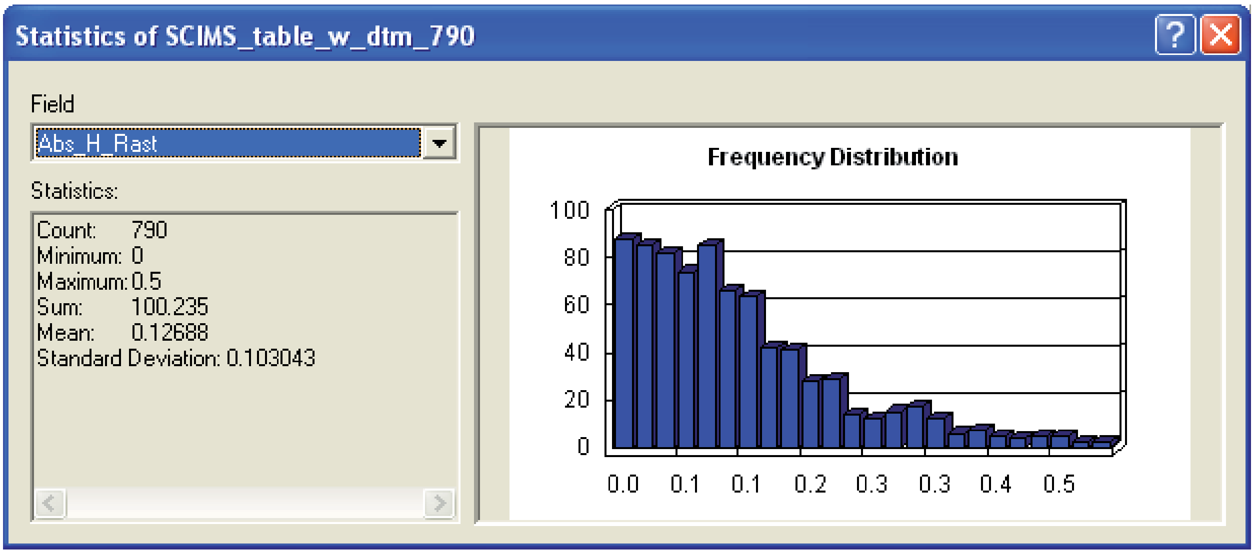


Figure 3: Analysis for Cleaned Points minus those > +/- 0.5 m difference to grid

Figure 4: Map of check points with compliance with error criteria indicated by colour

Discussion

Results indicate that as long as "gross" errors are eliminated from the point comparison data set provided by WWCC, that a reasonable match is made between the test points and the 1m raster DTM provided to WWCC by FUGRO. Furthermore Figure 4 shows that where points do not meet the criteria, there is no particular trend. Those points outside of the error tolerance appear to be fairly well spread throughout the wider dataset.

The only potential issue is in the definition of "gross" error. If points with an absolute error greater than 1.0 m are excluded the criteria is very nearly met (standard deviation 0.17 as opposed to target of 0.15) for the data set and this retains 835 of the original 896 points (93%). If the "gross" error tolerance is adjusted to 0.5 m then 790 points only remain (88%) and the criteria is well and truly achieved (standard deviation of 0.1).

Gross errors are expected to occur when one of two situations arises:

- the DTM includes a value from an object which is non-ground, for example a fence post, a telephone exchange, sub-grid station, parked car etc and then compares this non-ground strike with a survey mark which is ground based; or
- the survey marker is non-ground based.

Further complicating the work is that whilst survey markers typically have established vertical elevations accurate to within millimetres, the horizontal accuracy can be such that when comparing point heights to those extracted from a 1 m raster, the "wrong" raster cell height is being utilised in the comparison.

In order to establish which mechanism is leading to error in those points that do not meet the accuracy criteria further detailed ground truthing work would be required which is outside the scope of this work.

Conclusion

A sub-set comprising approximately 90% of the original 896 points utilised in the analysis do meet the accuracy criteria for the 1 m DTM product in that 67% of the points are accurate to within +/- 0.15 m. This indicates that the DTM product is conforming to specification and should be endorsed for use by Council.

Yours faithfully,

WMAwater

Stephen Gray

Associate