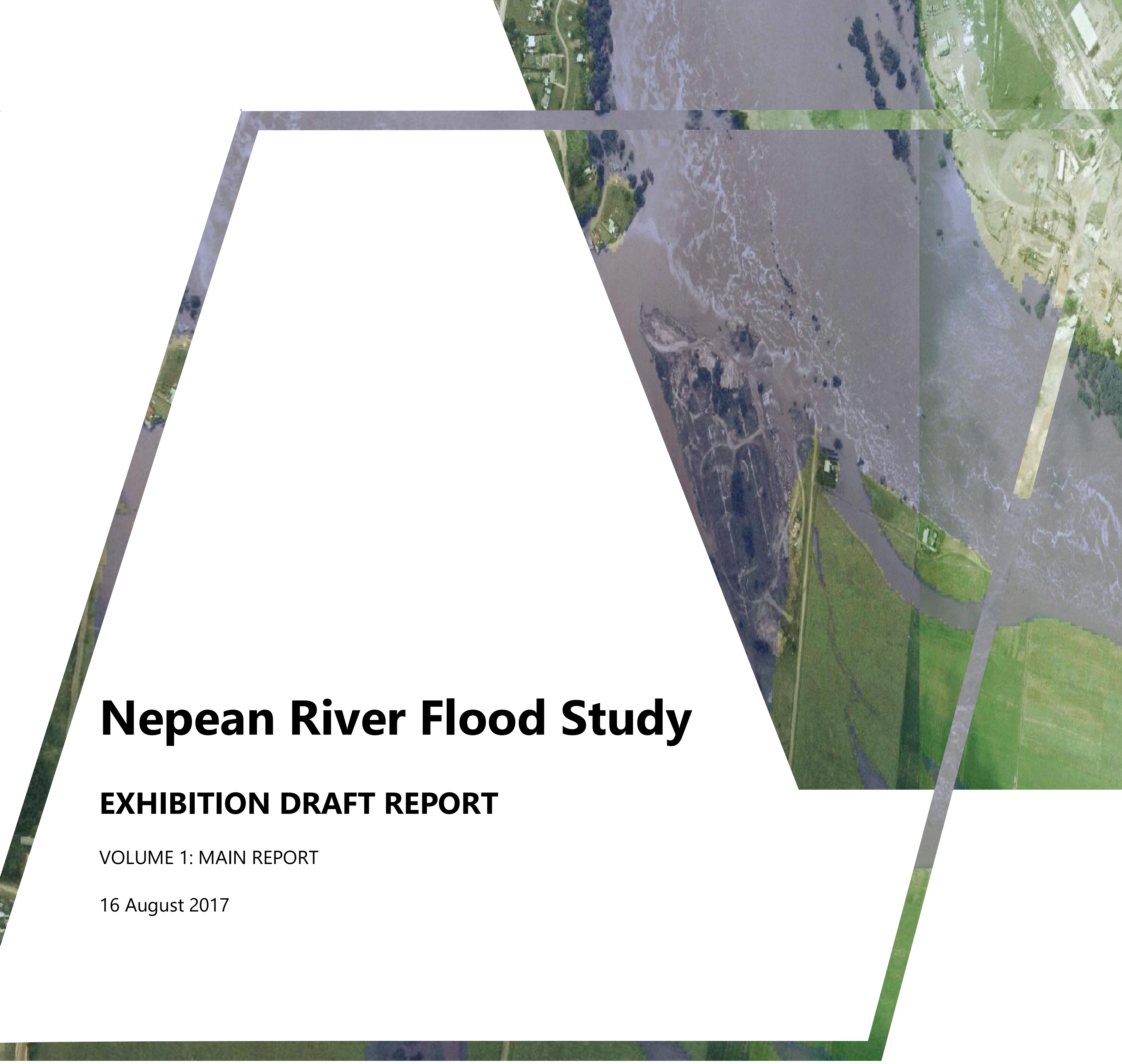

Nepean River Flood Study

EXHIBITION DRAFT REPORT

VOLUME 1: MAIN REPORT

16 August 2017

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PENRITH
CITY COUNCIL

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The Study is the culmination of many months of investigation, analysis and flood modelling, carried out in several stages over many years, and has been supported by valuable contributions from the Office of Environment & Heritage, The Department of Planning and Environment, and representatives from Penrith City Council.

Foreword

The State Government's Flood Policy is directed towards providing solutions to existing flooding problems in developed areas and ensuring that new development is compatible with the flood hazard and does not create additional flooding problems in other areas. Policy and practice are defined in the Government's Floodplain Development Manual (*2005*).

Under the Policy, the management of flood liable land remains the responsibility of Local Government. The State Government subsidises flood mitigation works to alleviate existing problems and provides specialist technical advice to assist Local Government in the discharge of their floodplain risk management responsibilities.

The Policy provides for technical and financial support by the State Government through the following four sequential stages:

Stages of Floodplain Risk Management

STAGE	DESCRIPTION
Flood Study	Determines the nature and extent of the flood problem.
Floodplain Risk Management Study	Evaluates management options for the floodplain in respect of both existing and proposed developments.
Floodplain Risk Management Plan	Involves formal adoption by Council of a plan of management for the floodplain.
Implementation of Plan	Results in construction of flood mitigation works to protect existing development and the application of environmental and planning controls to ensure that new development is compatible with the hazard.

Whilst Penrith City Council had commenced regional flood modelling prior to 2008, formalising the Flood Study only became possible with completion, within the Penrith Lakes Scheme, of the hydraulic structures and the terrain landscape surrounding the lakes. The Technical Working Group for the Nepean River Flood Study was formed with members from Penrith City Council, OEH, DPE and SES., and with the technical and financial support of the NSW Government's Floodplain Management Program, has proceeded with the floodplain management process by engaging consultants to finalise the flood modelling and prepare a Flood Study for the Nepean River within the Penrith LGA.

The Flood Study represents the first of the four stages in the process shown above. It has been prepared to assist Council and the community to understand and define the existing flood behaviour.

The modelling developed for the Flood Study will subsequently be used to assess potential flood damage reduction options and future development scenarios.

Executive Summary

This study culminates several stages in the progressive evolution of a two dimensional numerical flood model of the Nepean River through the Penrith Local Government Area. The initial flood model development commenced in 2005 by revising an earlier version with LiDAR terrain data that had been captured in 2002. The flood model then progressed in stages as more historic data was uncovered, enabling a more detailed and rigorously calibrated model to be developed. The final model awaited the completion of the lakes' terrain landscape and the hydraulic control structures within the Penrith Lakes Scheme. A new LiDAR data set was captured for the Lakes Scheme and the surrounding area in 2016, enabling completion of the study.

The flood modelling was undertaken using the RMA-2 hydrodynamic modelling package and covers the floodplain between Glenbrook Creek and Yarramundi Bridge. The calibration was greatly facilitated by a set of vertical air photos taken 3 hours after the peak of the 1978 flood, the largest flood with suitable recorded data (*the others being 1986 and 1990*). Upstream flow hydrograph and downstream stage discharge boundary condition data was sourced from the one dimensional Hawkesbury-Nepean model that had been developed for Sydney Water's Warragamba Dam studies in the mid 1990s. Eight design flood hydrographs were run through the model, including the 20yr ARI, 50yr ARI, 100yr ARI, 200yr ARI, 500yr ARI, 1000yr ARI, 2000yr ARI and the probable maximum flood.

The behaviour of the Nepean River floodplain is somewhat unique amongst the NSW coastal rivers. Typically, flood flows exceed the capacity of the main channel, inundating the floodplain for floods less than a 10yr ARI, and the probable maximum flood is less than two metres higher than the 100yr ARI flood. In contrast the main channel of the Nepean River through Penrith contains flood flows well in excess of a 50yr ARI and the probable maximum flood is five metres higher than the 100yr ARI flood.

The 100yr ARI flood, which is generally the basis for flood planning levels, just breaks out across the floodplain at two key locations, Knapsack Creek and Boundary Creek, whereas higher floods breakout along significant lengths of the river bank inundating significantly larger areas.

The Knapsack Creek breakout affects the Emu Plains residential area and backs up behind the railway embankment. Insufficient flow enters the area during the 100yr ARI flood to reach equilibrium storage levels, especially between the Great Western Highway and the railway. A slightly higher flood would see flood depths in this area rise dramatically affecting many more properties. Evacuation of the entire residential area along the eastern side would have to commence before the Knapsack Creek breakout occurs.

The Boundary Creek breakout discharges into the eastern lakes of the Penrith Lakes Scheme, which progressively fill until Duralia Lake overtops into the main lake of the Scheme. With normal operating levels in the eastern lakes, Duralia Lake does not completely fill during the 100yr ARI flood. The flooding in Cranebrook Village is directly linked to levels in Duralia Lake and is thus susceptible to antecedent levels in the eastern lakes and the total amount of flow from the breakout.

Recommendations are made for managing flood planning levels in these two areas until such time as a Flood Risk Management Study can comprehensively consider the risks and recommend a suitable outcome.

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Glossary

annual exceedance probability (AEP)	The probability of a flood event occurring in any given year expressed as a percentage
Annual return interval (ARI)	The average, or expected, value of the periods between exceedances of a given flood event. It is implicit in this definition that the periods between exceedances are generally random.
Australia Height Datum (AHD)	National altitude geodetic datum corresponding approximately to mean sea level
catchment	The catchment at a particular point is the area of land which drains to that point.
design floor level	The minimum *(lowest)* floor level specified for a building.
design flood	A hypothetical flood representing a specific likelihood of occurrence *(for example the 100 year recurrence flood or 1% annual exceedance probability flood)*. The design flood may comprise two or more single source dominated floods.
development	Existing or proposed works which may or may not impact upon flooding. Typical works are filling of land, and the construction of roads, floodways and buildings.
DLWC	Former NSW Department of Land and Water Conservation, now OEH
DPE	NSW Department of Planning and Environment
digital elevation model (DEM)	A digital model or 3D representation of a terrain's surface
discharge	The rate of flow of water measured in terms of volume over time. It is not the velocity of flow, which is a measure of how fast the water is moving. Rather, it is a measure of how much water is moving. Discharge and flow are interchangeable terms.
effective warning time	The available time that a community has from receiving a flood warning to when the flood reaches them.
flood	Above average river or creek flows which overtop banks and inundate floodplains.
flooding	The State Emergency Service uses the following definitions in flood warnings: ▪ **Minor flooding**: causes inconvenience such as closing of minor roads and the submergence of low level bridges. ▪ **Moderate flooding**: low-lying areas are inundated requiring removal of stock and/or evacuation of some houses. Main traffic bridges may be covered. ▪ **Major flooding**: extensive rural areas are flooded with properties, villages and towns isolated and/or appreciable urban areas flooded.
flood behaviour	The pattern/characteristics/nature of a flood. The flood behaviour is often presented in terms of the peak average velocity of floodwaters and the peak water level at a particular location.
flood awareness	An appreciation of the likely threats and consequences of flooding and an understanding of any flood warning and evacuation procedures.

	Communities with a high degree of flood awareness respond to flood warning promptly and efficiently, greatly reducing the potential for damage and loss of life and limb. Communities with a low degree of flood awareness may not fully appreciate the importance of flood warnings and flood preparedness and consequently suffer greater personal and economic losses.
flood frequency analysis	An analysis of historical flood records to determine estimates of design flood flows.
flood fringe	Land which may be affected by flooding but is not designated as a floodway or flood storage.
flood hazard	The potential threat to property or persons due to flooding.
flood level	The height or elevation of flood waters relative to a datum *(typically the Australian Height Datum)*. Also referred to as "stage".
floodplain	Land adjacent to a river or creek which is periodically inundated due to floods up to the Probable Maximum Flood event. Floodplains are a natural formation created by the deposition of sediment during floods.
flood planning levels (FPL)	Flood levels selected for planning purposes, as determined in floodplain management studies and incorporated in floodplain management plans. Selection should be based on an understanding of the full range of flood behaviour and the associated flood risk. It should also take into account the social, economic and ecological consequences associated with floods of different severities. Different FPL's may be appropriate for different categories of land-use and for emergency services planning. The concept of FPL's supersedes the "standard flood event" referred to in the 1986 edition of the *'Floodplain Development Manual'*. **FPL's do not define the extent of flood prone land, and floodplain management plans must always consider that there is flood prone land above the area defined by an adopted FPL.**
flood proofing	Measures taken to improve or modify the design, construction and alteration of buildings to minimise or eliminate flood damages and threats to life and limb.
floodplain management	The coordinated management of the risks associated with human activities that occur on the floodplain.
flood source	The source of the flood waters. In this study South Creek, Ropes Creek and Kemps Creek form the primary sources of floodwaters. The minor tributaries that also contribute are Thompsons, Badgerys, Cosgroves, Blaxland, Claremont and Werrington Creek. Floodwaters along each of these tributaries originates as runoff from rainfall falling over each respective catchment.
flood storages	Floodplain areas which are important for the temporary storage of flood waters during a flood.
freeboard	A factor of safety usually expressed as a height above the flood standard. Freeboard tends to compensate for factors such as wave action, localised hydraulic effects and uncertainties in the design flood levels.
high hazard	Danger to life and limb; evacuation difficult; potential for structural damage, high social disruption and economic losses.

historical flood	A flood which has actually occurred.
hydraulic	The term given to the study of water flow in rivers, estuaries and coastal systems.
hydrograph	A graph showing how a river or creek's discharge changes with time.
hydrology	The term given to the study of the rainfall-runoff process in catchments.
LiDAR	Light Detection and Ranging, is a remote sensing method using a pulsed laser light beam to measure ranges (variable distances) to the earth
low hazard	Flood depths and velocities are sufficiently low that people and their possessions can be evacuated.
management plan	A clear and concise document, normally containing diagrams and maps, describing a series of actions which will allow an area to be managed in a co-ordinated manner to achieve defined objectives.
OEH	NSW Office of Environment and Heritage
peak flood level, flow or velocity	The maximum flood level, flow or velocity occurring during a flood event.
PLDC	Penrith Lakes Development Corporation
probable maximum flood (PMF)	An extreme flood deemed to be the maximum flood likely to occur.
probability	A statistical measure of the likely frequency or occurrence of flooding.
runoff	The amount of rainfall from a catchment which actually ends up as flowing water in the river or creek.
stage	See flood level.
stage hydrograph	A graph of water level over time.
STP	Sewage treatment plant
velocity	The speed at which the flood waters are moving. Typically, modelled velocities in a river or creek are quoted as the depth and width averaged velocity, ie. the average velocity across the whole river or creek section.
WAE	Work as executed drawings or reports detailing engineering works as they have been constructed
WRL	Water Research Laboratories, a part of the engineering faculty of the University of NSW

1 Introduction

The Hawkesbury-Nepean River catchment is one of the largest coastal basins in NSW with an area of 21,400 square kilometres. The catchment at Penrith is 52% of the total area and of this portion, 80% is under the control of Warragamba Dam.

The Nepean valley within the Penrith LGA is characterised by a relatively narrow floodplain that is divided into three parts by the river channel. The northern floodplain area encompasses Penrith Lakes and the eastern side of the valley. The channel divides the valley south of this with the western side over Emu Plains and the eastern side over the Mulgoa and Central Business District (*CBD*) area.

Recent significant floods have remained in channel with only a small amount of backwater and fringe flooding of these floodplains. There is no living memory of a Nepean River flood that has affected the urban area. A flood in excess of a 50yr ARI would be required to impact urban residential properties. Even the 100yr ARI flood affects a relatively small number of properties as it only just exercises the main floodplain flowpaths. In contrast higher floods completely inundate the narrow floodplain area with significant energy.

The flood of record occurred in the Hawkesbury-Nepean River in 1867 and has been estimated as greater than the 250 year ARI flood at Penrith.

The hydrological modelling for determining rainfall runoff for the catchment was undertaken with Sydney Water's investigation of the safety of Warragamba Dam in the mid 1990's. This work was extensively peer reviewed.

Flood modelling of the Hawkesbury-Nepean River was initiated with Sydney Water's Warragamba Dam investigation. A one dimensional (*1D*) RUBICON model of the river extending from the dam to Broken Bay was developed to support the studies, and included an extensive review of the catchment hydrology and dam operation to generate design flood criteria.

Also at the time, Penrith Lakes Development Corporation (*PLDC*) had employed the Water Research Laboratories (*WRL*) from the University of NSW to build and operate a physical model to investigate options to manage Nepean River flood behaviour through the lakes scheme. This model extended from Devlin's Road up to Victoria Bridge.

Development of the current 2D hydraulic model followed several stages:

- By 2002:

  In the late 1990s a 2D RMA model was established to augment the physical model and enable PLDC to include flooding impacts in the master planning process being undertaken for future development of the site. This model extended from the Glenbrook Creek confluence to Devlin's Road and was calibrated to the physical model results.

  At this stage the river channel had been developed on the basis of twelve cross-sections used for the RUBICON model. To enhance this limited data, a field and airphoto geomorphology assessment of the river channel from Penrith Weir to Devlin's Road was used to refine the model mesh. This model was also used to assess flood impacts for several large scale developments including Waterside and Lambridge Place (*off Andrews Road*).

- By 2006:

  Penrith Council engaged Patterson Britton & Partners (*later acquired by WorleyParsons*) in late 2004 to refine the 2D RMA model using the 2002 LiDAR terrain data that had been captured. The model's mesh was significantly enhanced with the benefit of the LiDAR terrain, and was extended downstream to the LGA boundary at Yarramundi.

The Emu Plains residential area was rebuilt to better manage the breakout from Knapsack Creek, detail of the road network, the residential blocks, parks and open areas, and large buildings. The North Penrith industrial area extending to Andrews Road was also extensively refined to capture the breakout from Boundary Creek. This model was further used to asses developments such as David Road industrial (*off Old Bathurst Road*) and the Castlereagh Road upgrade.

- By 2008:

  In 2008, Council provided an earlier hydrographic survey of the river channel between the Penrith Weir and the M4 Motorway, enabling the model to be refined upstream of Victoria Bridge for the first time. At this stage, the refined model had been calibrated with the 1978, 1986 and 1990 flood hydrographs and associated flood level records. An oblique airphoto taken around the peak of the 1986 flood next to the M4 bridge was discovered in Council archives providing a key upstream reference for calibration.

  At this stage, the model mesh within the Penrith Lakes area was based on the landform used in the WRL physical model. Completion of the modelling was paused awaiting finalisation of the Penrith Lakes landform.

- By 2010:

  In late 2009, a set of airphotos flown a few hours after the peak of the 1978 flood became available from DLWC (*now OEH*). These photos enabled further fine adjustments to the mesh detail and roughness parameters within the channel so that a near perfect match was obtained between the modelled flood extents and the airphotos.

  Further refinements were applied around hydraulic structures across flood plain areas and within Penrith Lakes. An agreed landform for Penrith Lakes, derived from 2D modelling being undertaken by PLDC, was provided as a terrain model to inform the changes within the Lakes Scheme. This landform became known as the 'Alignment Scheme'.

- By 2016:

  Uncertainty as to the final landform for the Penrith Lakes scheme left the model in abeyance until the preparation of PLDC's Water Management Plan (*WMP 2012*), the development of the wildlife lake, the grading and completion of the lakes perimeters, and the construction of the hydraulic control features (*river connection weir, internal lake connecting weirs and hydraulic structures*).

  The terrain within the Lakes Scheme was captured as a detailed LiDAR DEM by Council, and together with the work as executed drawings provided by the Department of Planning and Environment, the model was re-built within the Scheme's boundary for the purpose of finalising the flood study.

Notwithstanding the limited detail available for the proposed upland development areas and the development completion of all critical hydraulic control structures within the lakes scheme, Council in consultation with the state agencies (*Office of Environment and Heritage and Department of Planning and Environment*) are in a position to complete the flood modelling and prepare a flood study for the Nepean River so that the floodplain planning process can be progressed.

2 Study Methodology

2.1 General

Floodplain risk management in New South Wales generally follows guidelines established in the NSW Government's *'Floodplain Development Manual'* (*2005*). The Manual outlines the steps involved in the process and the activities required to be undertaken to successfully develop a Floodplain Risk Management Plan for flood affected areas.

A description of the relationship between the various stages of a Floodplain Risk Management Plan is provided in the flow chart shown overleaf. This flow chart shows the link between the various outcomes of the studies involved in the floodplain risk management process and the implementation of measures to reduce flood damages (*both planning and structural*).

The formulation and implementation of floodplain risk management plans is the cornerstone of the Government's *Flood Prone Land Policy*. The primary objective of the *Flood Prone Land Policy* is to reduce the impacts of flooding on individual owners and occupiers of flood prone land, and to reduce private and public losses caused by flooding.

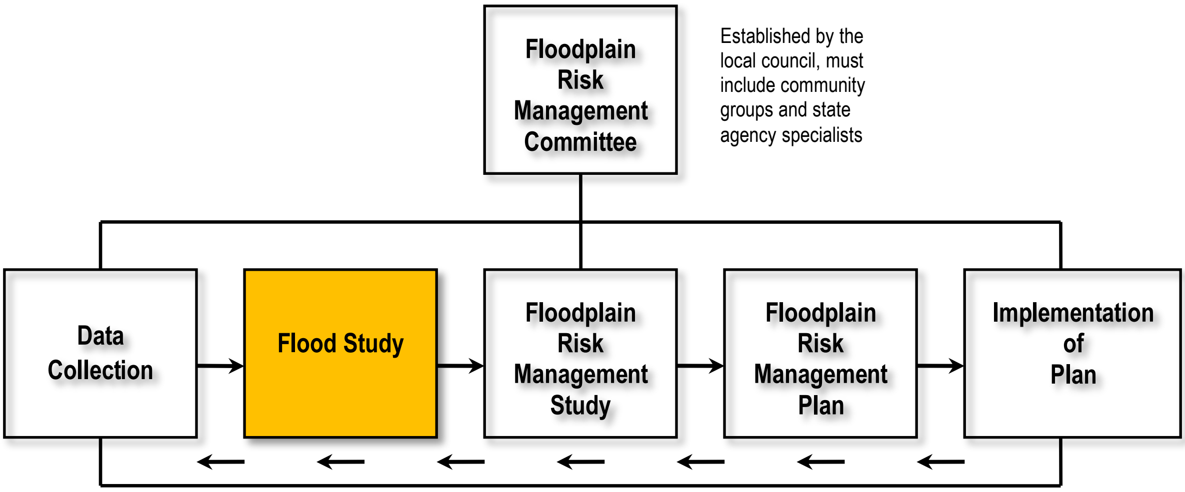
In this regard, the Policy recognises:

- that flood prone land is a valuable resource that should not be sterilised by unnecessarily precluding its development; and.
- that if all applications for development on flood prone land are assessed according to rigid and prescriptive criteria, some proposals may be unjustifiably disallowed or restricted, and equally, quite inappropriate proposals could be approved (*NSW Government, 2005*).

One of the key steps involved in formulating a floodplain risk management plan is the recognition, definition and quantification of the principal factors associated with flooding. This information is presented in a Flood Study, which becomes a baseline document summarising flood related data which can be used to resolve floodplain risk management issues.

Penrith City Council initiated the process for the Nepean River by commissioning this study.

The aim of the study is to produce information on flood flows, velocities, levels, flood extents, and hydraulic and hazard category mapping for a range of flood events under existing floodplain and catchment conditions. The study will also define and map the flood planning area for the study area, except for lands within the Penrith Lakes Scheme.



Established by the local council, must include community groups and state agency specialists

Compilation of existing data and collection of additional data. Usually undertaken by consultants appointed by the council.

Defines the nature and extent of the flood problem, in technical rather than map form. Usually undertaken by consultants appointed by the council.

Determines options in consideration of social, ecological and economic factors relating to flood risk. Usually undertaken by consultants appointed by the council.

Preferred options publicly exhibited and subject to revision in light of responses. Formally approved by the council after public exhibition and any necessary revisions due to public comments.

Flood, response and property modification measures including mitigation works, planning controls, flood warnings, flood readiness and response plans, environmental rehabilitation, ongoing data collection and monitoring.

Source: *'Floodplain Development Manual'* (*2005*)

2.2 Adopted Approach

The general approach and methodology employed to achieve the study objectives involved:

- compilation and review of available information, including previous flood modelling, digital terrain data of the floodplain, hydrographic surveys of the river channel and details of bridge crossings and culvert openings;
- site inspections to identify and categorise critical hydraulic controls such as bridges, culverts and weirs;
- the creation and merging of the 2002 and 2016 LiDAR data into a comprehensive DEM;
- the collection of historical flood information, including records of peak flood levels and airphotos for historical floods (*such as occurred in 1978, 1986 and 1990*);
- the collection of relevant boundary condition data (*inflow hydrographs and stage discharge data*) from the Sydney Water 1D model;
- the development of a computer based hydraulic model to simulate the movement of floodwaters through the floodplain within the Penrith LGA;
- calibration of the model against recorded data and flood air photos for the 1978, 1986 and 1990 floods;
- validation of headlosses through bridges and the railway openings, using empirical methods and some 1D models;
- the determination of peak water levels, flood flows, depths and flow velocities along the Nepean River and the floodplain for the 20, 50, 100, 200, 500, 1000 and 2000 year ARI floods and the Probable Maximum Flood (*PMF*); and,

- the definition of the flood planning area for the study area (*except lands within the Penrith Lakes Scheme*). The resolution of the flood planning area and level within the Penrith lakes Scheme is retained for future determination through a separate engagement by the OEH and the DPE.

2.3 Numerical Models

Computer run numerical models are the most reliable and cost-effective tools available to simulate flood behaviour in rivers and streams. Two types of computer models are commonly as part of a Flood Study. These are:

- a **hydrologic model** to simulate catchment runoff following a particular rainfall event. The main outputs from a hydrologic model are discharge hydrographs which define the quantity of runoff as well as the rate of rise, timing and magnitude of peak discharges resulting from the rainfall event. The discharge hydrographs are utilised as inputs into the hydraulic model.
- a **hydraulic model** to simulate the passage of floodwater along waterway reaches and across floodplain areas. The hydraulic model calculates key flooding characteristics such as flood levels, flow velocities, floodwater depths and flood hazard at selected points of interest throughout the study area.

For this study reference was made to the peer reviewed results from the Sydney Water hydrologic and 1D hydraulic models for boundary conditions required by the hydraulic model.

Information on the topography and characteristics of the watercourses and their floodplains, is built into the models. For each historic flood, data on flood levels and river flows can be used to simulate and validate (*calibrate and verify*) the models.

Development of the numerical model involves:

- discretisation of the river and floodplain;
- incorporation of physical characteristics (*river cross-sections, geomorphic features, hydraulic structures, etc.*);
- setting up of relevant data (*river flows, flood levels*) for historic events;
- calibration to one or more historic floods (*calibration is the adjustment of parameters within acceptable limits to reach agreement between modelled and measured values*); and,
- verification to one or more other historic floods (*verification is a check on the model's performance without adjustment of parameters*).

Once model development is complete, it may then be used for:

- establishing design flood conditions;
- setting flood standards for planning, so that future land-use is controlled to minimise potential losses/damage due to flooding;
- developing flood hazard mapping;
- hydraulic categorisation of the floodplain; that is, delineating floodway, flood storage and flood fringe;
- assessment and quantification of the impacts of climate change on design flood characteristics; and,
- the modelling of "what-if" management scenarios to assess the hydraulic impacts of structural mitigation measures; e.g., changes to a bridge structure to reduce upstream bridge afflux or the potential benefits of constructing a levee.

3 Available Data

A range of data is required to develop a flood model and for that model to be applied to simulate flood behaviour. Typically, a digital elevation model of the land surface and cross-sections of the river system are required to represent the floodplain topography and channel bathymetry. Details of critical hydraulic controls such as bridges and roadway embankments also need to be defined as they can influence flood behaviour. In addition, surface roughness parameters are required to reflect the influence that land features may have on the way floodwaters travel overland. These are usually based on consideration of vegetation density and built features.

Calibration and verification of the model requires the collection of stream flows and flood level information for a series of historic floods. Design flood simulation requires that the peak flows entering the modelled area have been established.

The data for this study has been obtained from a number of sources including:

- Penrith City Council (PCC);
- WRL physical modelling reports;
- Sydney Water model results from WMA Water;
- Recent large residential and industrial developments;
- Penrith Lakes Development Corporation;
- the NSW Office of Environment and Heritage (*OEH*) and its predecessors; and,
- river channel and floodplain feature surveys undertaken for the study.

The two primary sources of information used in creating the model were the Penrith City Council LiDAR surveys and accompanying air photos. The former was used as the primary source for elevations outside recent and proposed large development areas, whilst the latter was primarily used to assign roughness parameters. The Penrith Lakes development is yet to be completely defined, however the lakes and their hydraulic controls have been completed, and a reasonable assessment of the upland area has been created.

The following data was used in building and setting up the flood model:

- Penrith Council's LiDAR floodplain topography data, (*PCC, 2002 and 2016*);
- Penrith Council's riverbed topography survey data upstream of Victoria Bridge, (*PCC 1979*);
- Air Photos of the Penrith-Nepean Region, (*PCC, 2002 and 2016*);
- River cross-section surveys (*PLDC 1987, SWC/Webb McKeown 1988*);
- Airphoto and on-site geomorphic assessment of the river channel and it's prominent features (*PBP & DLWC 2001*);
- Site inspection and survey of built environment flow controls (*PBP 2004*);
- RUBICON modelling results (*Webb McKeown 1994 & 2005*);
- Penrith Lakes Scheme, Flood Protection Model, Recalibration of River Flood Profiles (*WRL TR2007-18, Sep 2007*);
- Digital topography data for the lake environment ('*Waterside*') development (*Stockland 2003 & 2005*);
- Digital topography data for Penrith Lakes Scheme as of 2006 (*Alignment model*);
- 1986 and 1978 airphotos captured during the flood event;
- Work as executed data from DPE for Penrith Lakes, North Penrith and Waterside. Of the 81 documents received there were 9 documents with useful data for Penrith Lakes, 2 for Waterside and 1 for North Penrith.

The WRL physical model re-calibration report (*WRL, 2007*) contains a compendium of recorded historic flood levels which are summarised in **Table 1.**

Table 1 - Recorded flood levels (WRL 2007)

Location	Distance D/S of Victoria Bridge	1978 Flood	1986 Flood	1990 Flood
Victoria Bridge U/S	-40	23.35 (WRL)	19.93 (gauge)	23.42 (gauge)
Victoria Bridge	0	24.16 (PCC)		23.65 (PCC)
Lugard Street	1330		18.99 (WRL)	23.00 (WRL)
800m D/S Lugard	2130			22.68 (WRL)
1400m D/S Lugard	2730			21.47 (WRL)
Sheens Lane	3703	21.85 (WRL)	17.00 (WRL)	21.17 (WRL)
Alma Crescent	4420	21.72 (WRL)		
500m U/S Jacksons Lane	5300			20.85 (WRL)
Jacksons Lane	5842	19.76 (PCC)	16.23 (WRL)	20.59 (WRL)
Equestrian Centre	7430		15.67 (WRL)	
Smith Street	10824		14.91 (WRL)	
Devlin Road	12937	18.36 (PWD)	14.54 (PCC)	
PWD Castlereagh	15159		13.98 (WRL)	
Yarramundi Bridge	18512	15.74 (PWD)	13.50 (BMG)	16.39 (PCC)

3.1 Data Processing

Some of the data used in building the model required some degree of processing before it could be used. The most important data set is the ground surface topography and this was generated as a digital terrain model covering the study area from all useful available data. A detailed description of this process is provided in Section 4.

Other data processing included the following:

- The 1979 bed survey contours, were digitised, georeferenced and converted into a DEM;
- Data from large scale future, recent and active development sites were converted into local DEMs using the development information provided by the developer. These sites included Penrith Lakes, Waterside, and PacLib's developments off Andrews Road and Old Bathurst Road;
- Results from the RUBICON model were used to create upstream inflow hydrographs and to determine tailwater boundary conditions, and this is discussed further in **Section 6**;
- Structures such as bridges, piers, underpasses and culverts can all significantly influence flow levels and are not accurately represented in the LiDAR data. As a result, a site survey of these structures in the Penrith-Nepean region was conducted, and approximately 20 different structures were identified as important to flows, **Appendix B**:.

4 Digital Elevation Model

The original digital elevation model (DEM) used in the creation of the RMA 2D model was created from LiDAR data flown in 2002 for Council. This data was provided as tiles of ASCII XYZ points and used to create a tiled set of triangular network (TIN) terrain surfaces. These TIN DEMs have been used as the basis in creation of the RMA model network across the majority of the floodplain areas.

Additional data was used to inform the surface below water in the river channel, and within several large development sites:

- a field and airphoto geomorphology assessment of the river channel from Penrith Weir to Devlin's Road undertaken with DLWC (*now OEH*),
- a river hydrographic survey data upstream of Penrith Weir provided by Council,
- a DEM for the Waterside development provided by Stocklands,
- a DEM for the Lambridge Place industrial development provided by PacLib, and
- a DEM for the David Road industrial development provided by PacLib.

The 'Alignment Scheme', was used for the interior of the Penrith Lakes area. A 2m gridded DEM was created from the TIN tiles for the purposes of presenting the RMA model results. This DEM covers the extent of the modelled area from Glenbrook Creek to Yarramundi.

As a precursor to completing the Flood Study, a new LiDAR point set covering Penrith Lakes and surrounding areas was captured in July 2016 for Council. The purpose for this dataset was to capture the completed parts of the Penrith Lakes area (*essentially all but the eastern upland area*) and the surrounding large developments (*Castlereagh Road upgrade*, *Waterside, Lambridge Place, and North Penrith*).

The completed works within Penrith Lakes include the landform surrounding the lakes, the main connecting weir from the river, the internal lake to lake weirs and associated hydraulic control structures (*including the Wildlife Lake*), the lake reticulation pipes, the Duralia and eastern Lakes system, the regatta lake area and the southern wetland ponds. Details of these features were provided by DPE in the form of work as executed drawings. The details included the extent of completed earthworks and grading, the crest, width and profile of the main river connecting weir, the diameters and invert levels of all pipe connections between the lakes and the river and in-between the lakes, and the crest and channel dimensions of all open channel hydraulic structures.

The objective of capturing the 2016 data was to integrate it with the 2002 data and generate a current DEM that reflects the major landform changes that have taken place over the past decade.

The unfinished terrain data within the Penrith Lakes Scheme is the upland area along the eastern side of the main lakes, **Figure 1**.

Apart from stockpiles and remnant low areas the majority of the upland area lies around RL 24m to RL 25m AHD (*2016 LiDAR survey*).

A set of contours and spot elevations were drawn to generate a reasonable representation of a finished landform with an upper level around RL24m AHD to RL 24.5m AHD. The contours and the boundary were adjusted to ensure alignment with the remainder of the 2016 DEM around the edges. Additionally, a floodway channel was included to transfer overflows from Duralia Lake into Main Lake A and avoid backwater effects on Cranebrook and Waterside, **Figure 2**. The floodway was tabled by PLDC in their deliberations for site flood management. A 300m wide channel was proposed to extend from the RL 22m AHD outlet of Duralia Lake westwards to join into the edge of Main Lake A.

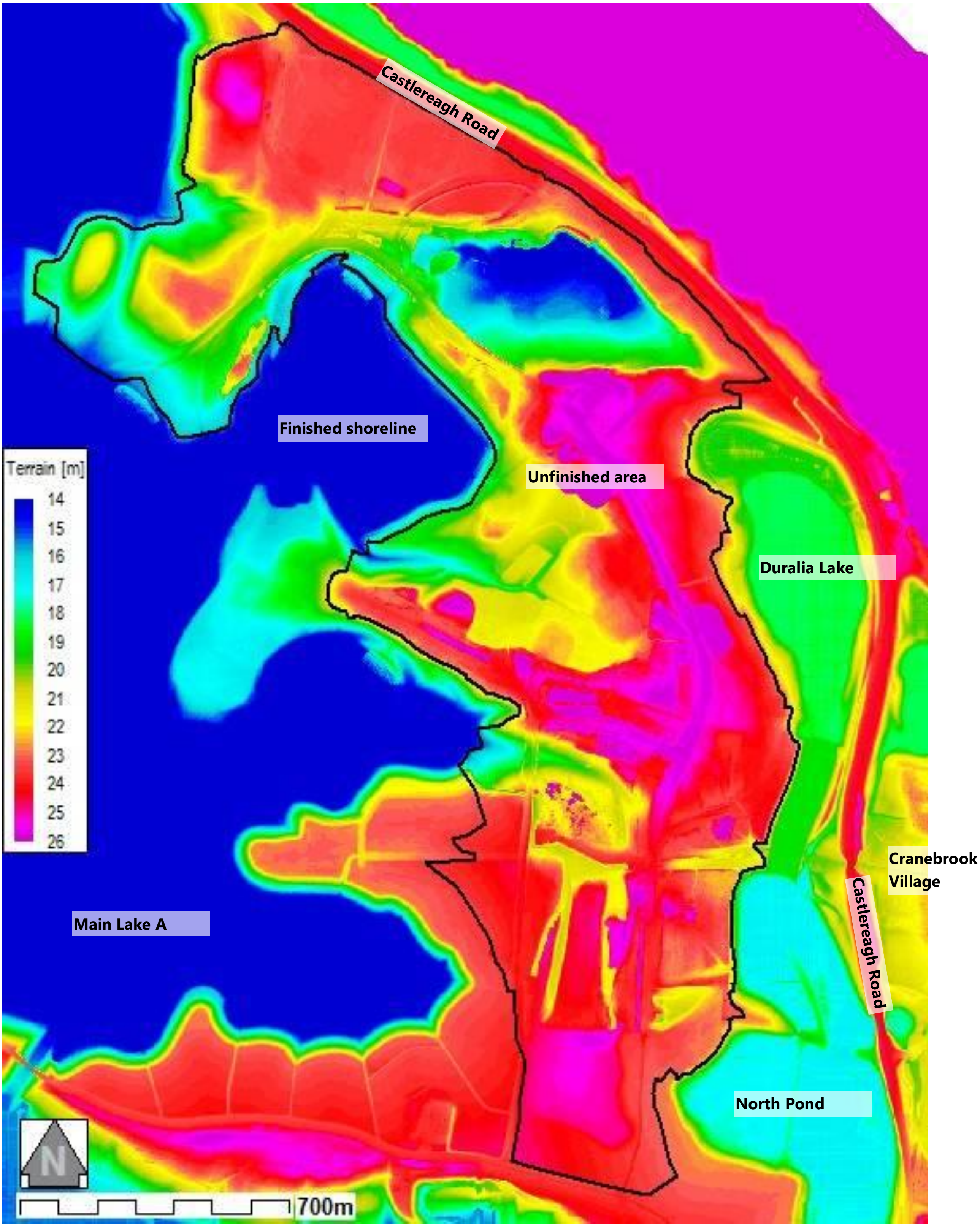


Figure 1 - Penrith Lakes Terrain (2016)

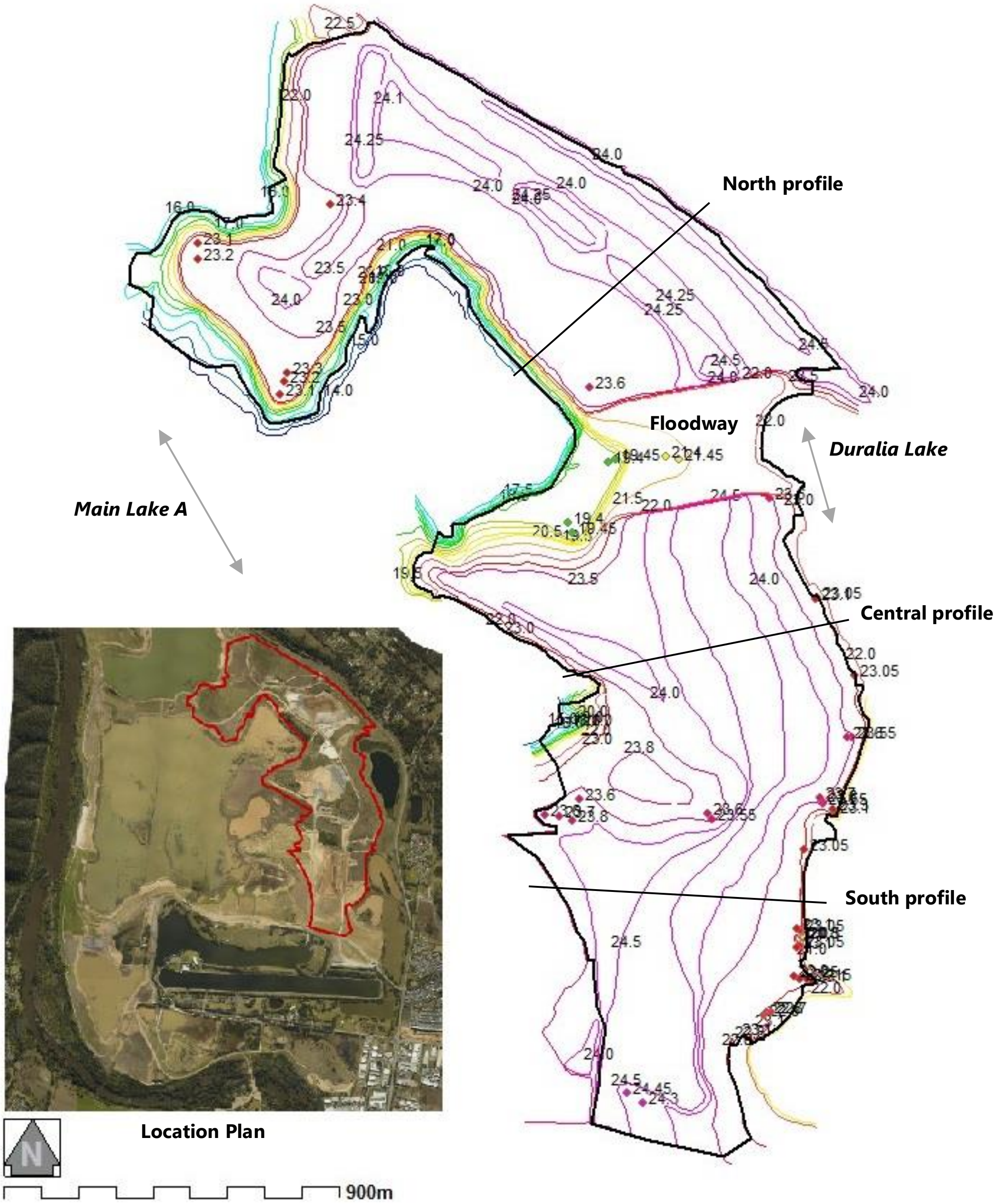


Figure 2 - Proposed contours for shaping Penrith Lakes unfinished upland area

The following three profiles show the comparison between the existing 2016 terrain and the proposed contour surface, **Figure 3, Figure 4, Figure 5**.

The process for merging the DEMs involved clipping the 2016 DEM to the boundary polygon created, similarly clipping the proposed upland surface, then overlying the upland surface onto the 2016 DEM and finally overlaying this surface onto the 2002 DEM.

The full merged DEM is shown in **Figure 6**, and in more detail in MAP 040 in **Volume 2**.

The currently proposed upland landform has assumed that the Poplars site would be filled in.

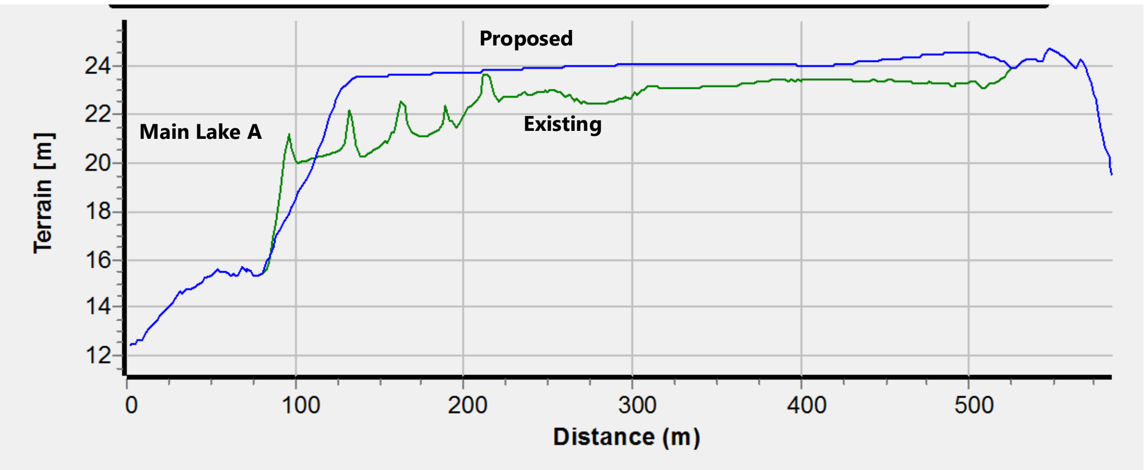


Figure 3 - North Profile. Landform across north end from Lake A to Castlereagh Rd

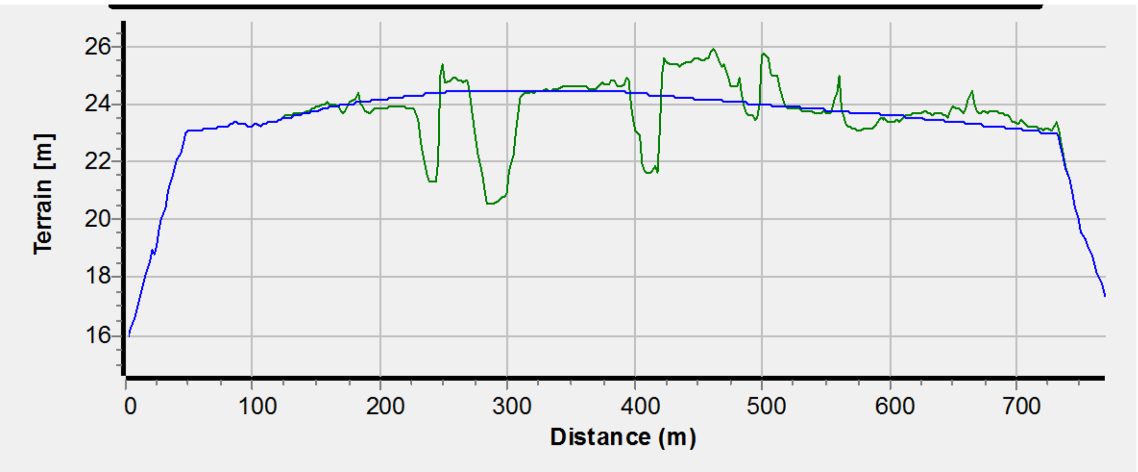


Figure 4 - Central Profile. Landform across central area from Lake A to Duralia Lake

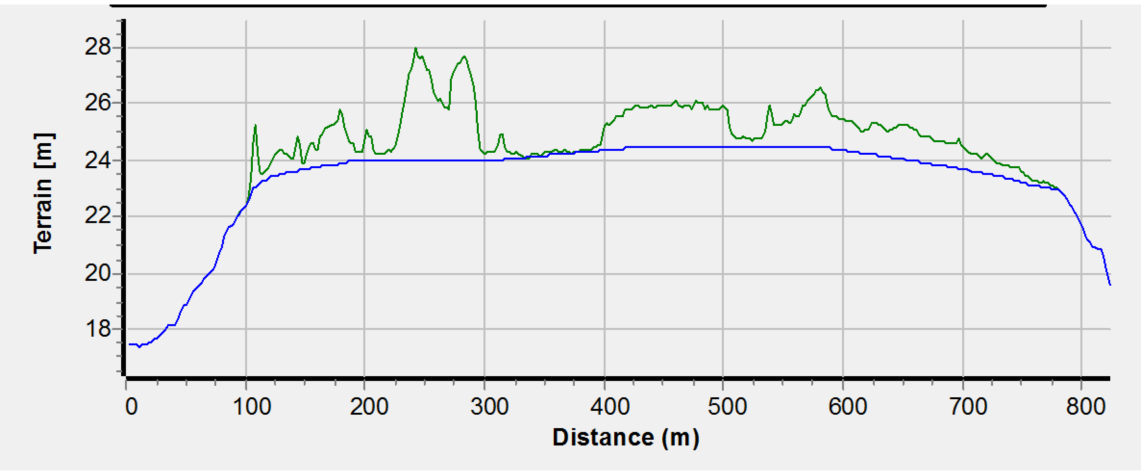


Figure 5 – South Profile. Landform across south end from Lake A to North Pond

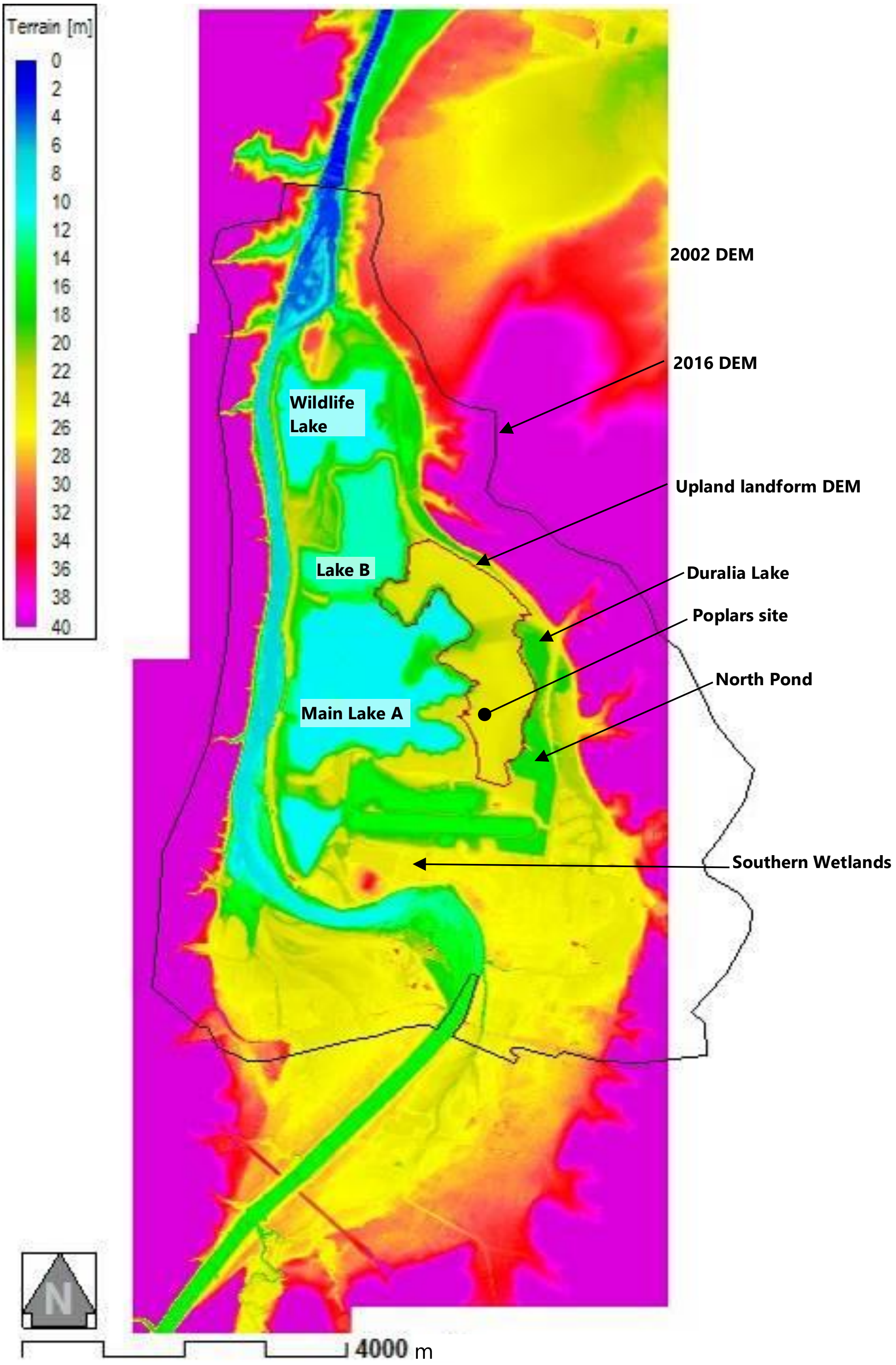


Figure 6 - Penrith Flood Study merged DEM

5 Hydraulic Model Development

5.1 Model Framework

RMA-2 is a two dimensional finite element fluid flow program which can model complex and detailed flow systems based on a network that represents a discretised version of the topography. The network itself consists of quadrilateral and triangular elements with nodes at each corner and each midside. Each node is effectively 'linked' mathematically to the surrounding nodes where each element represents a portion of the ground surface. Nodes are used to define the surface elevation at a location in 2D space, whilst elements are used to represent the average physical properties of the topography that it covers. The accuracy of a finite element analysis is a function of the degree to which the mesh network replicates the physical system. Therefore, land areas that are homogenous in elevation and physical properties require a less dense network to accurately model them than areas of rapid spatial variations. For example, if a large, level, consistent, grassy plain is modelled with 1 large element, the accuracy of the solution obtained would be essentially the same to that obtained if it was modelled with 100 smaller elements. The same would not be true if a single large element was used to model a hilly landscape that contained a creek and different types of urban or vegetative coverings.

The two primary properties that are required for nodes and elements are elevation and roughness. The flexible nature of the network permits complex changes in topography, built environment and hydraulic conditions to be modelled effectively.

As mentioned, the resolution of the RMA model is generally related to the density of elements; however, it depends on the change in topography and physical parameters compared to the density of elements used. In other words, the accuracy is only improved by increasing the density of elements up to a certain extent. The computational time increases with an increase in the density of elements. Therefore an optimisation of the network was undertaken to ensure that, whilst accuracy was maintained, computational time was not excessive. Large buildings and complexes that did not permit much room for flow, such as the main Penrith Panthers buildings, were completely eliminated from the model. Sparsely built areas such as residential and commercial estates were represented with large elements with high roughness values and largely homogenous areas were represented with larger elements.

Figure 7 shows the Penrith-Nepean region of interest. To optimise the computational time, the model was simplified for the calibration flood networks by reducing the size of the network to match with the predicted flood extents (*based on preliminary analyses*). This technique assisted in speeding the solution time without compromising on the accuracy of the model.

Two networks were created, one for the calibration, and one for the design flood events (**Figure 8**).

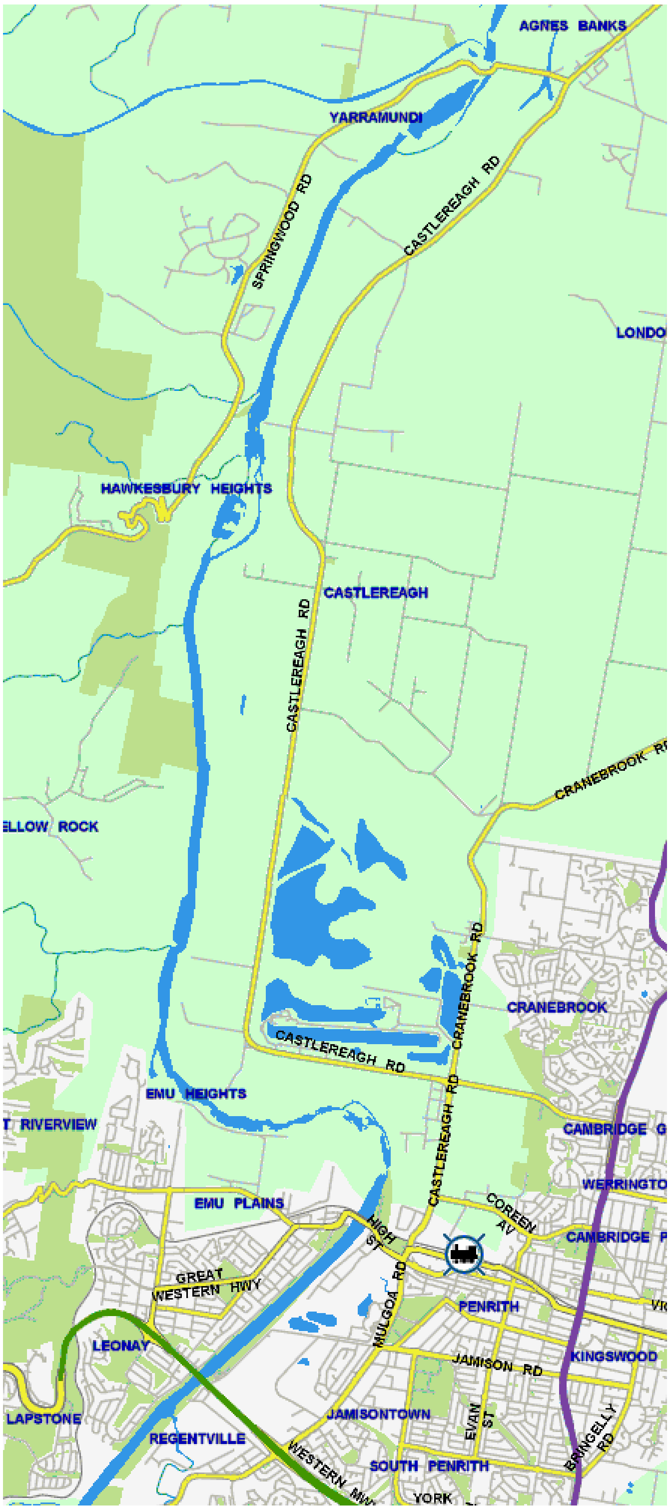


Figure 7: Region of Interest (Whereis, 2004)

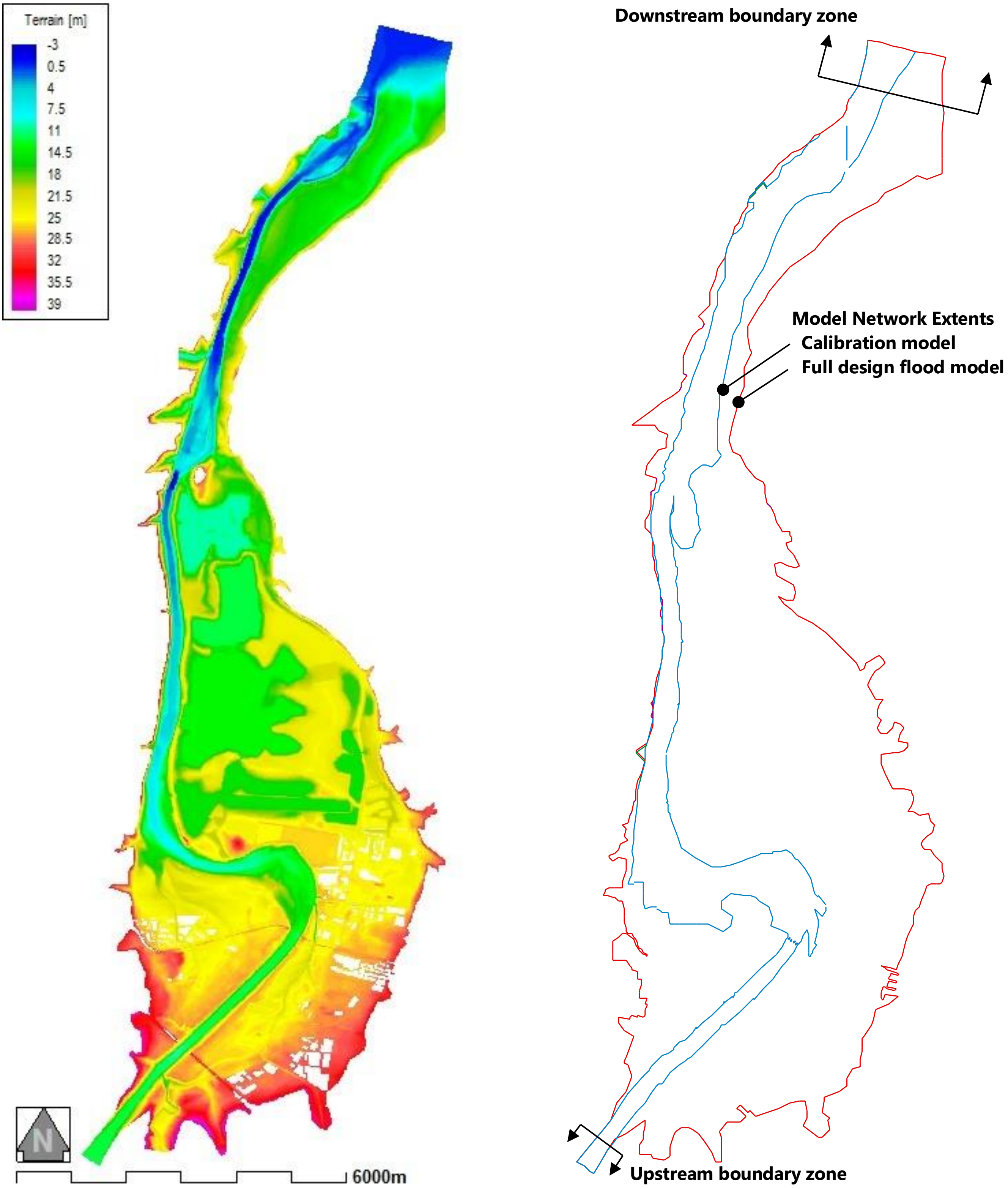


Figure 8: Full network terrain and partial network extents for various ARI floods

5.2 General Model Setup

The review of existing reports, models and spatial data ensured the best available information was applied in creating a model that effectively represents the Nepean floodplain.

The updated composite DEM (*2002 and 2016 LiDAR, and schematised Penrith Lakes upland*) was used as a basis for development of the general model mesh.

The river channel in the model upstream of Victoria Bridge was developed in reference to the DEM created from the 1979 bed survey contours, whilst downstream, the channel was developed with reference to the surveyed cross-sections and the geomorphic assessment.

Key structures such as bridges, piers, underpasses and culverts were incorporated into the RMA-2 model with reference to the site survey data.

The model network for Waterside, and PacLib's developments off Andrews Road and Old Bathurst Road were referenced to their local DEMs.

The network across the Penrith Lakes area was prepared in reference to the refined DEM, **Section 4**. The lakes themselves were allocated elevations based on normal water levels, not their bed height, to prevent inaccuracy associated with the lakes filling during modelling. The lake weirs were included in the RMA 2 model in order to replicate floodwaters entering and leaving the lakes, and individual weir lengths and crest elevations were extracted from the PLDC WAE drawings and confirmed by the 2016 LiDAR. The initial lake levels within Penrith Lakes are as follows:

Regatta Centre lakes	RL 15m
the North Pond	RL 15m
Duralia Lake	RL 17m
Main Lake A	RL 13.5m
Lake B	RL 12.0m
Wildlife Lake	RL 10.0m

Roughness, in the form of Manning's 'n' values, was defined on an element by element basis, so care was taken to ensure elements covered a surface area that appeared homogenous. Roughness parameters were gauged from aerial photos, site surveys, CAD drawings and literature. The air photos were taken in conjunction with the LiDAR capture and once again, the primary limitation of this data was in areas covered by water. All other areas could be accurately estimated based on the type of vegetative or urban covering visible (*or proposed*).

The riverbed areas unseen in the air photos were the primary variable of interest when calibrating the model as discussed in **Section 6**. This section of the model is critical as velocities are high, causing roughness to have a significant effect on water levels. Floodplain areas where velocities are low are less sensitive to the selection of a roughness coefficient and conservative values were adopted, **Table** 2. No allowance was made for changes to roughness over time.

Table 2 Adopted Roughness Values

Area	Adopted Manning's n Value
Residential	0.055
Industrial	0.070
Roads	0.030
Park, open field, grassland	0.035 & 0.040
Bushland	0.050
Lakes	0.030
Core River Bed	0.030 initially, calibrated to 0.023 U/S of Penrith Weir and 0.027 D/S

Large individual buildings and building complexes were blocked out of the model network and small buildings such as residential areas were separated from the road network and assigned a high roughness.

The following sections give a brief overview of the main areas within the model that have been constructed from the data currently available. A significant amount of detail has been included in the Emu Plains area, and the recent developments such as Waterside and the PacLib industrial areas on Andrews Road and Old Bathurst Road have been incorporated.

5.3 The River Channel & Victoria Bridge

Modelling of the river channel was the most important and most difficult component of the study, because the limitations of the LiDAR data in not penetrating water. Although some areas of the riverbed were not covered by water when the LiDAR was taken, a significant amount was, and the following information was used to create the riverbed surface:

- Upstream of Penrith Weir – 1979 contour plans (*PCC*)
- Areas Around the S-bend - LiDAR DEM (*PCC*) and geomorphic assessment (*PBP, DLWC*)
- Downstream of the S-bend – cross-sections (*SW, PLDC*), LiDAR DEM and geomorphic assessment

Victoria Bridge was modelled according to onsite photographs and measurements. It has eight piers that affect the flow of the Nepean River, causing a backwater affect (Section 6.5). These piers are approximately 4.5 metres wide and 15 metres long and are constructed of large rough stone blocks, **Figure 9.** Measurements were made of the right bank piers which are accessible by land, and confirmed from airphotos. The piers were modelled as a series of blank elements, effectively forcing flow to divide around them. Although there are two rows of four piers (**Figure 10** *left*), for modelling purposes, they were amalgamated into one row of four longer piers (**Figure 10** *right*). This does not affect results as the distance between the two rows of piers is negligible with respect to the flow resolution.

Figure 9 - Photographs of Victoria Bridge piers

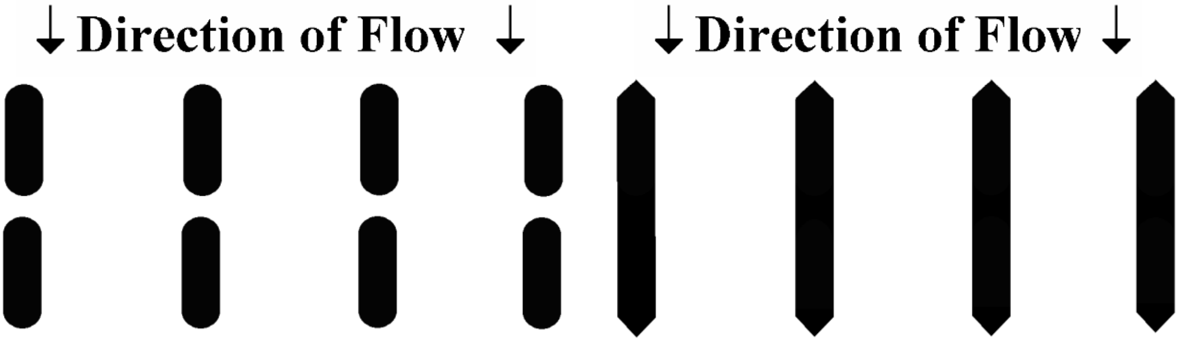


Figure 10: Victoria Bridge Piers and Model Representation

5.4 The Areas Around the M4 Motorway

The M4 motorway crosses the floodplain and river near the upstream end of the model and consists of approximately a 5 m high embankment with a bridge over the river. The bridge has a wider opening than Victoria Bridge with 4 slender piers, (*refer photos in* **Appendix B**:), and these were included in the model in a similar fashion to Victoria Bridge. The left floodplain is relatively narrow and the road embankment across the wider right floodplain includes three culverts that align with a series of small relict back channels. These culverts are particularly important for the early stages of flooding and significantly affect local flow paths as well as the surrounding water levels. These culverts were examined in the field, (*refer photos in* **Appendix B**:) and accommodated appropriately into the model. North of the M4, School House Creek was inspected, (*refer photos in* **Appendix B**:) and detail on the bed shape was included.

5.5 The Residential Areas of Emu Plains

The residential area of Emu Plains consists of parks, streets, and housing areas, which all vary significantly in terms of flow roughness. Large parks were modelled with single elements, streets were all modelled as routes of low roughness and housing areas were modelled together with large roughness values. Other significant features which were included in the Emu Plains residential area included the central storm water channel, the Nepean High School and the Lennox Village shops.

The Emu Plains residential area south of the railway is situated on the left floodplain of the river upstream of the large S bend. Knapsack Creek crosses this floodplain at its southern end cutting a channel through the river's alluvial sediments. Rising river levels backup through this channel and eventually break out across the left bank of Knapsack Creek and onto the floodplain. The initial breakout area is approximately 200m upstream from the mouth of the creek. Attention was applied to this area in the model to ensure the initiation of these overflows was correctly captured.

5.6 Peachtree Creek and Surrounding Areas

Peachtree Creek carries water from the Nepean River past Penrith, Jamisontown and South Penrith and plays a significant role in the early stages of flooding. Peachtree Creek carries water around the main channel bank allowing flow to move to the low level areas well before the flood waters from the Nepean River overtop their banks.

Furthermore, the structures which Peachtree Creek passes through were also surveyed and included in the model. These include the bridge piers under the railroad, the bridge piers under the Great Western Highway, the culvert under Jamison Road, and the concrete channel along Peachtree Creek and Surveyors Creek.

Penrith Panthers is a large complex close to Peachtree Creek. Although its buildings are not completely water tight, it is assumed that they would exclude most of any through flow in a flood event. Therefore these buildings were removed from the network, thus forcing flow in the model to pass around them.

5.7 Railroads

The railroad is constructed similar to the M4 motorway as it is elevated above ground level. In the smaller floods the railroad does not overtop, and a number of openings through the embankment ensure continuous flow of water through the structure.

Site inspections located the following features that were added to the RMA-2 model:

- Underpass at Castlereagh Road (*also an attached underpass for pedestrians*)
- Bridge at Peachtree Creek
- Underpass at Bruce Neale Drive
- Underpass at Old Bathurst Road (*also an attached underpass for pedestrians*)
- Opening west of Old Bathurst Road adjacent to school yard
- Stormwater channel opening near Hartigan Avenue
- Underpass at Russell Street

5.8 Industrial Areas of Emu Plains

Large industrial buildings that block significant flow conveyance were not included in the RMA-2 network. This has the effect in the model of forcing flow to pass around the blocked out areas. The PacLib Industrial site located between Old Bathurst Road and David Road has been included in the model network in accordance with a site layout provided by the developer. All roads were modelled as low roughness flow routes.

The floodplain on the inside of the river bend downstream of Victoria Bridge has been used for quarrying operations and includes artificial structures, such as mounds of sand and gravel which have been picked up by the LiDAR. They are subject to change and will not remain as permanent features. Additionally, in the interim they would most likely be eroded during the early stages of a flood, and thus they have not been included in the model.

Figure 11: Example area west of Victoria Bridge accounting for structures impeding flow

5.9 Boundary Creek to Andrews Road

Boundary Creek and the surrounding areas were built in detail accounting for the sewage treatment plant and the significant buildings in the area.

Boundary Creek itself is important in the early stages of flooding, as well as affecting peak water levels and velocities in the surrounding areas. The creek passes underneath Castlereagh Road through culverts, and these were incorporated into the RMA-2 model in reference to the site visit information **Appendix B**:.

The sewage plant and some of the industrial area comprises buildings with openings that would not totally prevent flow, but would constrict any through-flows significantly. These areas were modelled with high roughness or partially excluded from the mesh as appropriate.

The PacLib industrial development on the southern side of Andrews Road has also been included within the model.

5.10 Waterside Development

The Stockland 'Waterside' development located between Andrews Road and the Cranebrook residential area has been incorporated into the RMA 2 network. The basis for incorporating this development was provided as a built environment DEM and site layout details for the lakes, roads and residential areas. An earlier RMA model was used to assess the 'Waterside' development as the layout evolved and the current model includes the final revision of site topography and layout.

5.11 Penrith Lakes

The Penrith Lakes area is a significant feature of the landscape as it occupies the majority of the right floodplain north of the S-bend in the river, and is likely to significantly affect flood behaviour. The lakes landscape, that has evolved from the mining operation, has now been graded and finalised around the perimeter of the lakes. The river connection weir has been constructed and internal lakes connections have also been graded and finalised, and some of these include hydraulic structures, **Figure 12**.

Work as executed drawings and reports were provided by DPE for the completed works as PDF files. Of the 64 files relevant to Penrith Lakes, 9 had useful data pertaining to the hydraulic structures incorporated in the model.

The upland area along the eastern side of Main Lake A is unfinished with the majority of the terrain around RL 24m to RL 25m AHD. A schematised landscape across this area was generated for the model with a central north-south ridge at RL 24m to RL 25m AHD sloping away to align with the surrounding finished terrain.

Overflows from Duralia Lake need to be channelled into Lake A. There have been several approaches identified by PLDC and the latest, involving a floodway, was tabled by PLDC in their deliberations for site flood management. A 300m wide channel was proposed to extend from the RL 22m AHD outlet of Duralia Lake westwards to join into the edge of Main Lake A.

Details of the upland terrain and the floodway are discussed in **Section 4**.

Although this upland area has an assumed landform, it fits reasonably into the current unfinished topography and lies above 100yr ARI flood levels, so will only have the potential to influence larger floods.

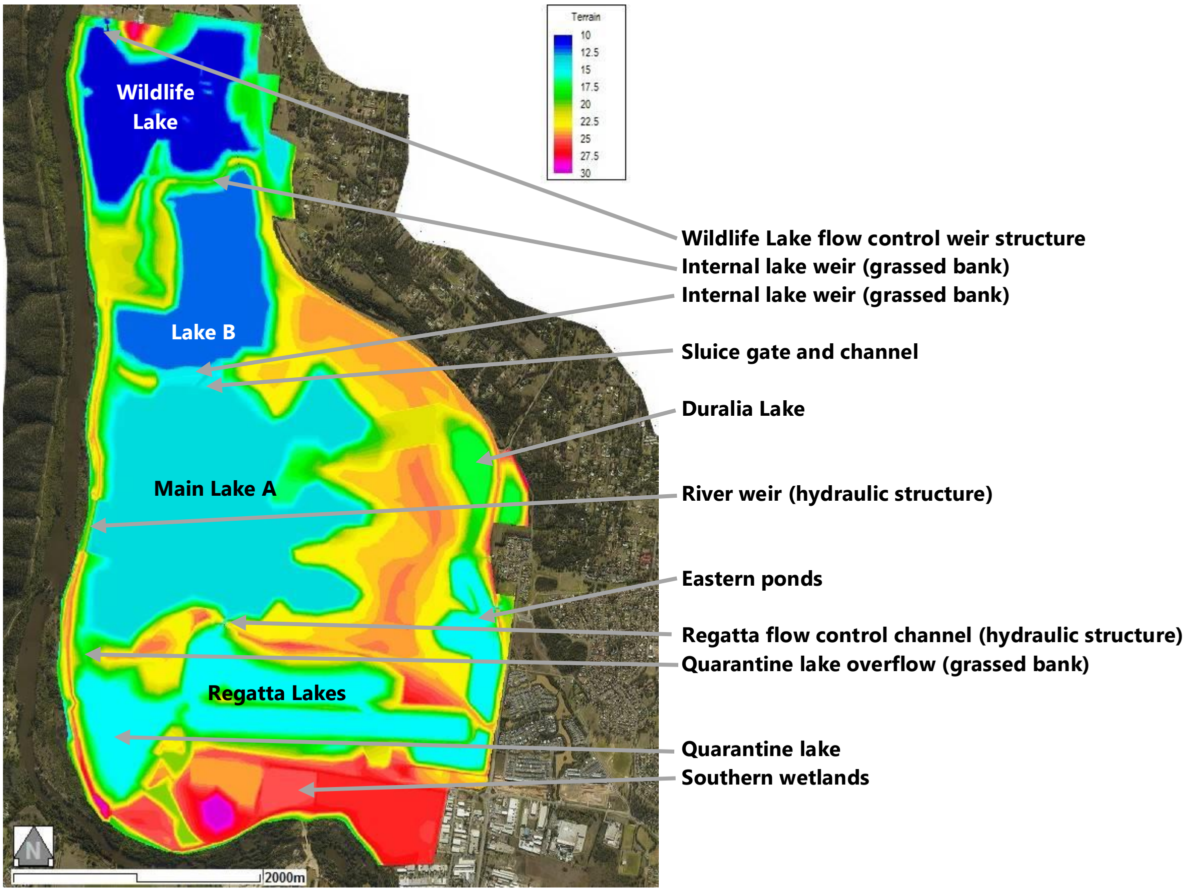


Figure 12 - Penrith Lakes features

The connections and hydraulic structures include:

- The Wildlife Lake flow control weir: hydraulic structure, width 66m, crest RL 14m AHD (*GroupDLA_13-12-2013_Penrith Lakes Development - Wildlife Lake Weir & Outlet Pipeline_.pdf*);
- Internal weir between Lake B and the Wildlife Lake: grassed bank capped by asphalt road, width 450m, crest RL 20m AHD (*140630 Lake B Submission Report (PLDC).pdf & 140630_SCCS_Lake B Landform WAE signed.pdf*);
- Internal weir between Lake A and the Lake B: grassed bank, width 550m, crest RL 15m AHD (*140630_SCCS_Lake B Landform WAE signed.pdf & 150701 Lake A Submission Report (PLDC).pdf*);
- Sluice gate and channel embedded in the internal weir between Lake A and the Lake B: channel structure, width 10 to 30m, crest RL 13.5m AHD (*140630_SCCS_Lake B Landform WAE signed.pdf & 150701 Lake A Submission Report (PLDC).pdf*);
- River weir: hydraulic structure with stepped spillway, width 420m, crest RL 20.9m AHD (*131218 Stamped Plans for Weir 3 CC.pdf*);
- Regatta flow control channel: earth and rock structure, base width 25m, crest RL 16.5m AHD (*150629_TPK_Landform WAE Signed by Surveyor.pdf & 150701 Lake A Submission Report (PLDC).pdf*);
- Quarantine Lake overflow: grassed bank, vee shaped cross-section, top width 300m, crest RL 18.5m AHD (*2016 LiDAR & 160517_cj_southern wetlands details.pdf*).

There is also a collection basin and large diameter culvert on the east side under Castlereagh Road feeding overland flow into the Eastern ponds.

The lakes have interconnecting reticulation culverts to control normal operating levels and these have been set as follows:

- Regatta Lakes: 1.5m diam. pipe at RL 14m AHD connecting to Lake A (*150701 Lake A Submission Report (PLDC).pdf*);
- Lake A is controlled by the sluice gate channel at RL 13.5m AHD connecting to Lake B (*140630_SCCS_Lake B Landform WAE signed.pdf & 150701 Lake A Submission Report (PLDC).pdf*);
- Lake B: 0.9m diam. pipe at RL 10.5m AHD connecting to the Wildlife lake and 2x1.35m diam. pipes at RL 11m connecting to the river(*140630 Lake B Submission Report (PLDC).pdf & 140630_SCCS_Lake B Landform WAE signed.pdf*);
- Wildlife Lake: 1.35m diam. pipe at RL 10m AHD connecting to the river(*GroupDLA_13-12-2013_Penrith Lakes Development - Wildlife Lake Weir & Outlet Pipeline_.pdf*).

The final proposed landscape is to consist of extensive parkland surrounding the lakes, and some, as yet undecided development across the eastern upland area between the main lakes and the eastern lakes. This is likely to consist of residential, commercial and industrial development.

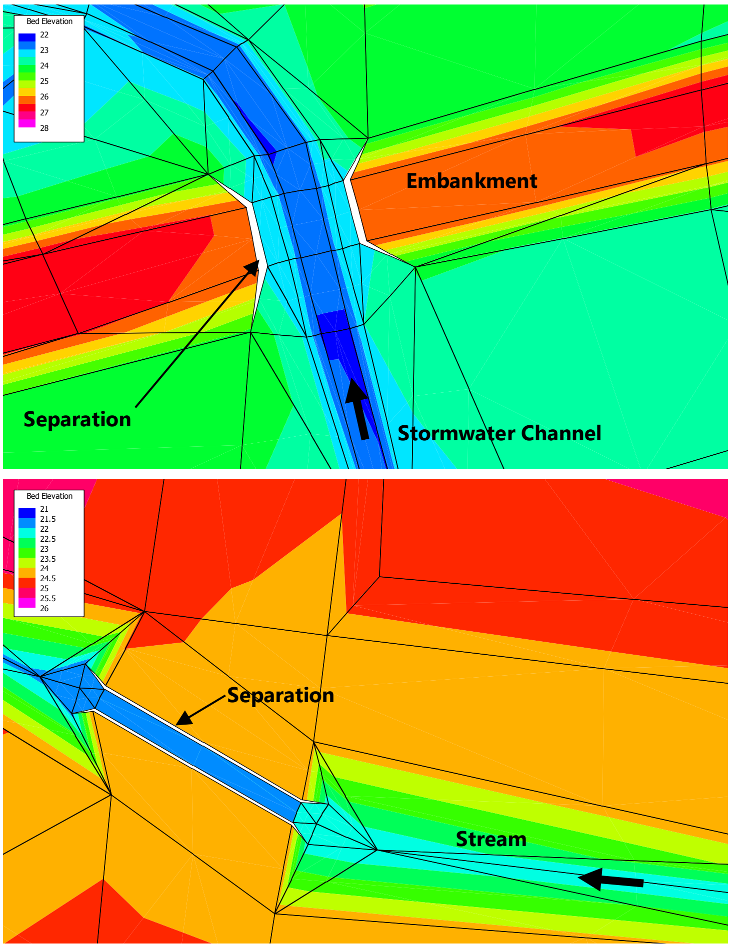
5.12 Yarramundi Lagoon Floodplain

Yarramundi Lagoon is located at the downstream end of the model and runs parallel with the main river channel. The lagoon starts from approximately 750 metres north of Devlin Road and extends all the way to the downstream end of the model. In the early stages of flooding the water level from the Nepean River cannot overtop the bank, and Yarramundi Lagoon initially backs up from its downstream end before overtopping occurs and it becomes a secondary flow path.

The terrain for Yarramundi Lagoon and the associated right floodplain was developed in the RMA network from the LiDAR DEM.

5.13 Culverts and Bridges

Culverts and bridge openings have been built into the model network as gaps in the road or embankment that crosses the waterway. Sloping bridge abutments are included in the network but vertical bridge abutments and culverts have the gap representing the opening width separated from the road or embankment by a wingwall shape that is not a part of the network, **Figure 13**. Large bridges with obstructing piers, such as Victoria Bridge have the piers also excluded from the network. Entrance and exit losses are automatically accommodated by the 2D hydraulic solution, but roughness values for smaller openings are often increased to accommodate obstructions.



RMA network configuration for bridge in railway embankment over stormwater channel.

Note pseudo abutments and wingwalls separating the flow opening from the embankment.

RMA network configuration for culvert through road.

Note network exclusion separating the flow opening from the road.

Figure 13 Network representation of bridges and culverts

5.14 Embankment Overflows

The RMA-2 model includes a wetting and drying process coupled with subsurface or marsh flow. The model's solution employs an implicit scheme where the previous timestep results (*depth and velocity*) are used to seed the next timstep solution. There is an initial determination to eliminate elements that are not wet, to improve processing efficiency. The determination to include an element is based on a threshold difference between the current water level and the elevation of the lowest node in the element as the level is rising, and likewise, the element is eliminated when the level falls below the threshold.

When an element is deemed to become wet on a rising water surface, the element will not yet be truly wet (*depth > 0*), but may become wet during the timestep solution. To accommodate these marsh elements, subsurface flow is modelled through a reduced cross-sectional area or slot. The surface area of the element transitions to the equivalent area of the slot over a short depth. For the current Nepean River hydraulic model, the transition has been set to 0.1m and the slot area is 1% of the element area.

Furthermore, when marsh flow is active and the water surface is within the marsh slot, a factor is applied to increase the friction to minimise the subsurface flow. Too high a friction enhancement factor can lead to numerical instabilities and poor convergence. For the current Nepean River hydraulic model, a factor of 50 has been used, and this increases friction by 8 to 25 times in the 15m to 28m elevation range where the majority of the embankment overflows occur.

Finally, to optimise control of marsh flow at critical breakout and embankment overflow areas, the mesh has been constructed with horizontal elements forming the crest, so that the subsurface flows are not activated any earlier than necessary, **Figure 14.** The distribution of these control elements is shown in **Figure 15**.

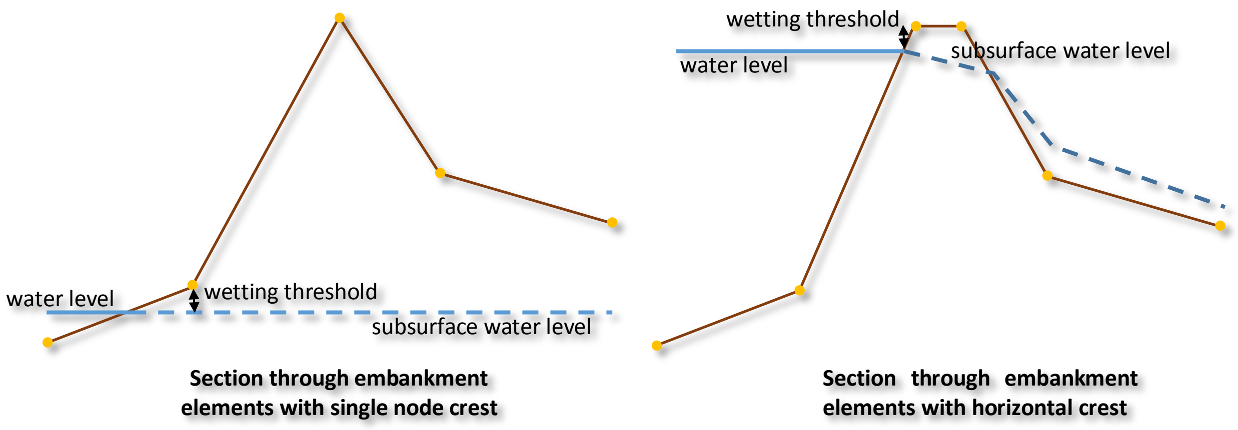


Figure 14 - Embankment subsurface flow control

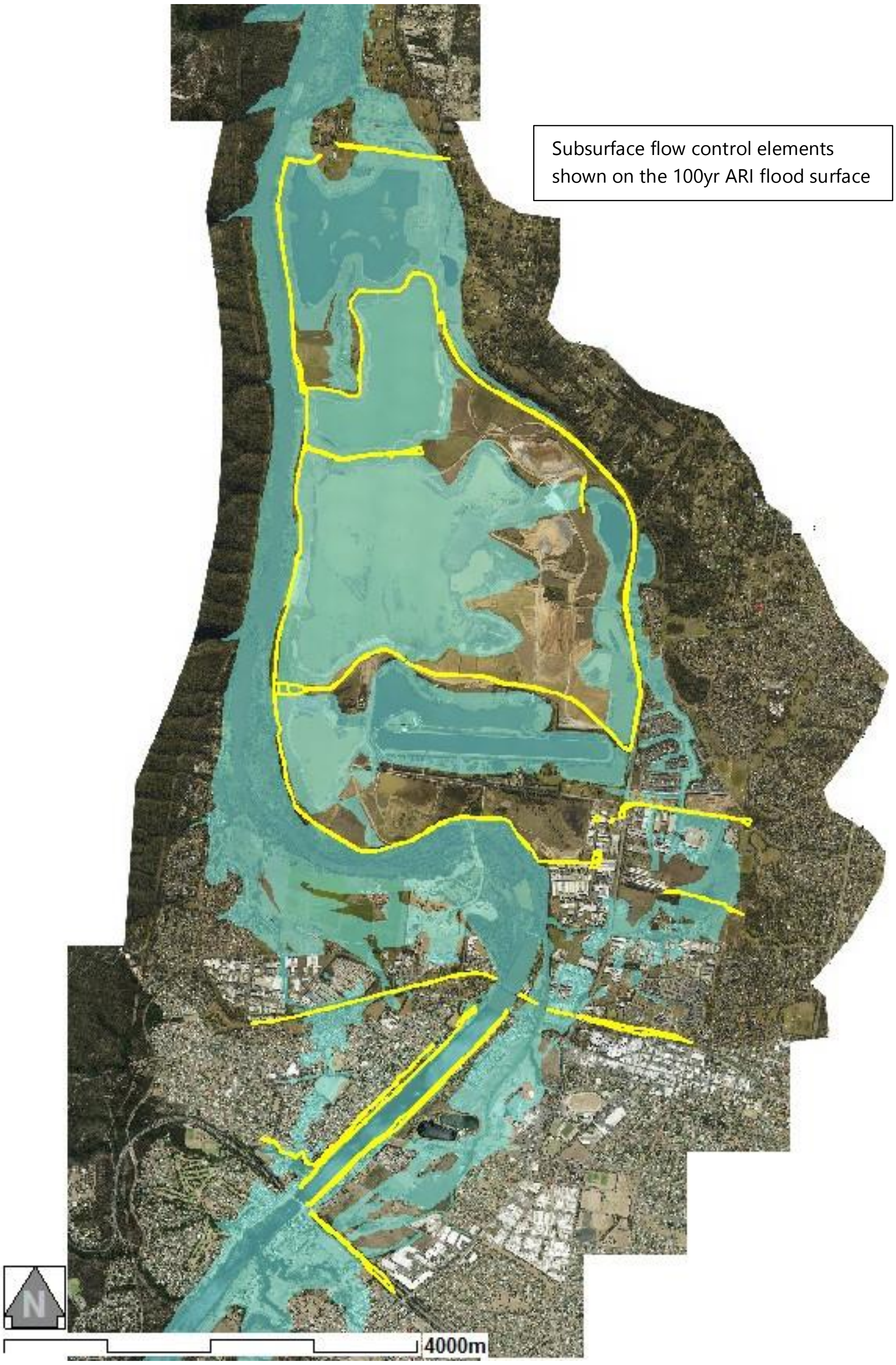


Figure 15 - Embankment overflow control elements

5.15 Boundary Conditions

Like any numerical hydrodynamic model, RMA-2 requires a set of boundary conditions placed on the model in order to solve the governing equations. The upstream boundary condition is simply the input hydrograph and it governs a primary variable of the system – the flow with respect to time. The downstream boundary condition also needs to control a variable of the system, and a stage-discharge relationship was chosen as the best way to do this from the data available. This controls the relationship between tailwater level and discharge at the downstream boundary.

The most applicable data available based on best practice analysis that could be used for the boundary conditions is the RUBICON 1D model results (*Webb McKeown 1994*) undertaken for the upgrade analysis of Warragamba Dam.

Tributary inflows have not been included as they are not likely to coincide with the main river flows and are of little consequence in comparison to the magnitude of the main channel flow. The Grose River is the only significant tributary within the scope of the model and the tailwater relationship has been purposefully referenced upstream of the Grose so that its flows will have no influence.

5.15.1 Inflow Hydrographs

The M4 cross-section for the main channel in the RUBICON provides a suitable inflow location for the RMA model, which commences just downstream from the Glenbrook Creek confluence. Inflow hydrographs were provided for the 20yr ARI, 50yr ARI, 100yr ARI, 200yr ARI, 500yr ARI, 1000yr ARI, 2000 ARI and the probable maximum flood (*PMF*), **Figure 16.**

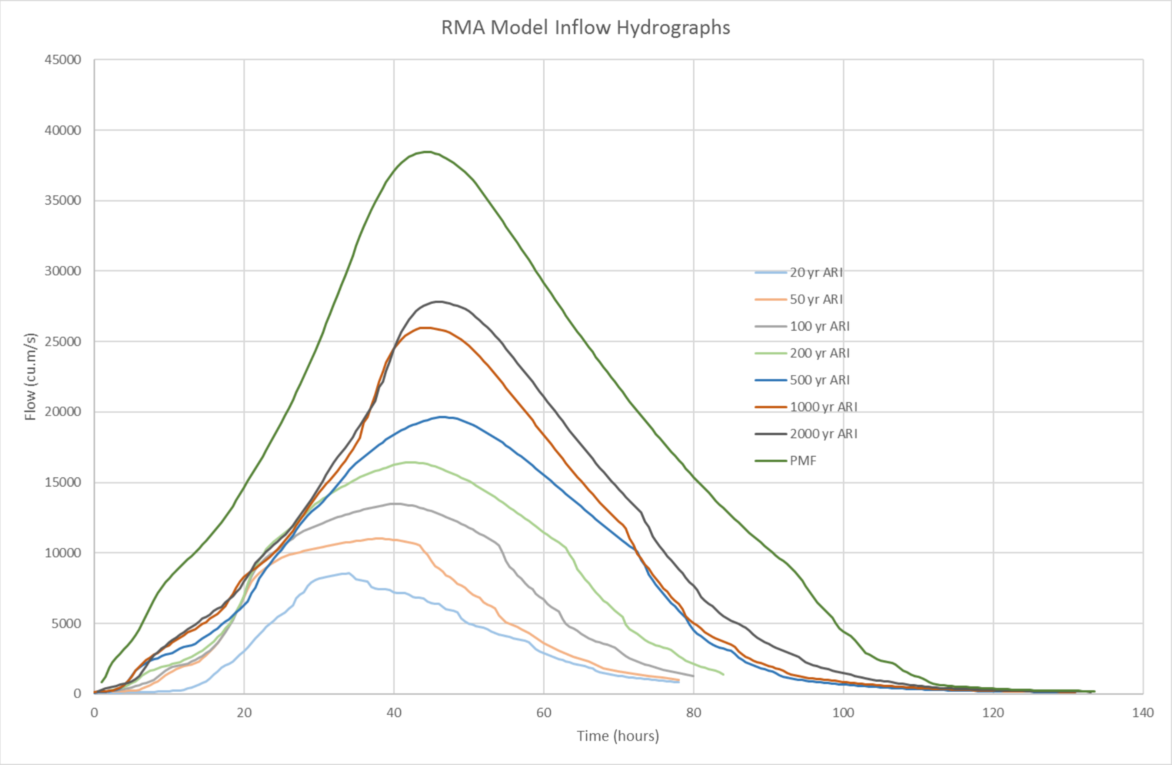


Figure 16 - RMA model inflow hydrographs extracted from the RUBICON model

The RUBICON hydrographs were discretised at 2 hourly intervals for input into the RMA boundary conditions file. These are represented in **Appendix C**:.

5.15.2 Tailwater Control

The closest complete cross-section of the main channel and floodplain in the RUBICON network that matches the downstream end of the RMA model is at Shaws Island and Yarramundi Lagoon (*SHAWSIS & YARLAGOON*).

This RUBICON stage-discharge data for all historic and design floods was assessed and it was found that a line of best fit to the data would not be a simple mathematical relationship. Instead, the data was graphed and visually, a line of best fit was applied to the rising limb of the design flood data so that a table of stage vs discharge could be created. Backwater conditions within the Windsor-Richmond basin downstream have an obvious effect on the falling limb of the hydrograph, and since the focus of the study is on planning (*ie. peak values*) and emergency response (*rising stages*), only the rising limb of the stage-discharge data was used. A plot showing the RUBICON design flood data and the line of best fit digitised at 1m stage increments is shown in **Figure 17**.

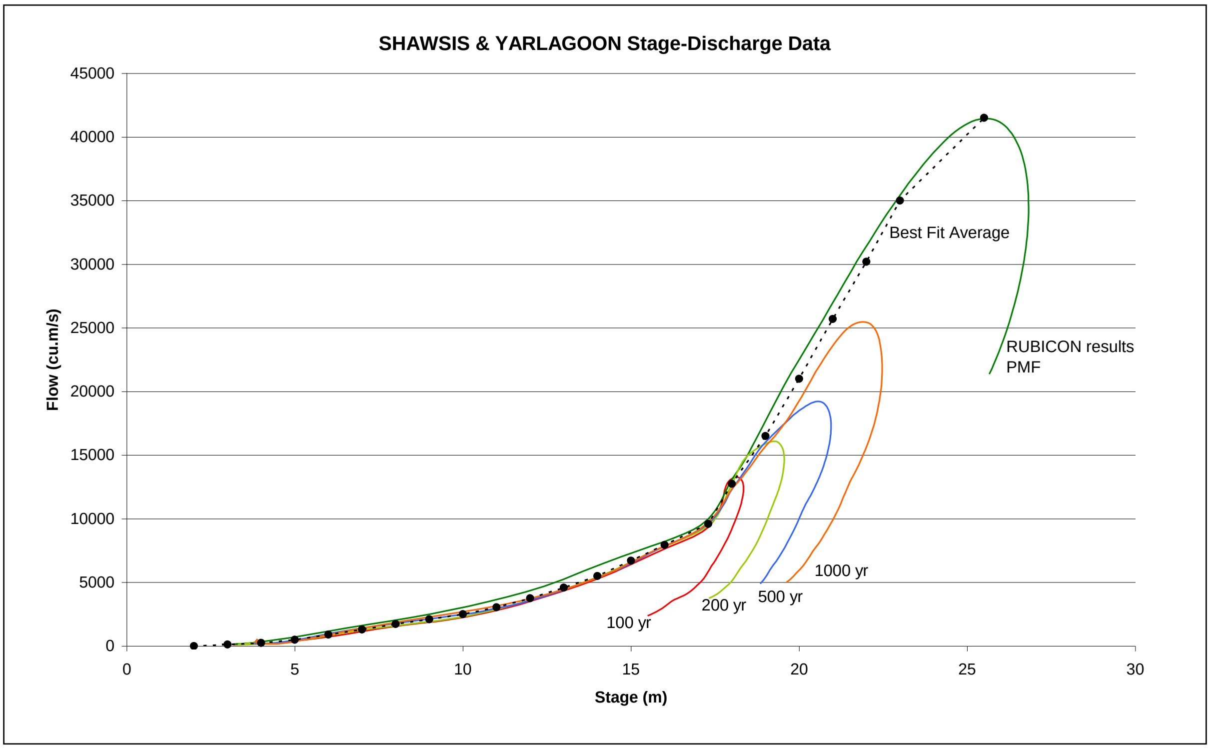


Figure 17 - Tailwater stage discharge data

The RUBICON stage-discharge trend of the design floods, does not match the trend of the historical floods. As the objective of the study is a design flood assessment, only the design flood data was used to establish the tailwater stage-discharge table for the design runs, whilst the specific data for the historic floods was used for calibration. These discrepancies are discussed in detail in **Section 6**.

Earlier modelling at the initiation of the study indicated a discrepancy in predicted water surface profiles between the RMA and the RUBICON results along the reach between Devlin Road and Shaws Island. The RUBICON model was revised with additional cross-sections extracted from the DTM, which led to a better agreement with the RMA-2 preliminary results. The final stage-discharge relations used to control the tailwater of the RMA-2 model were derived from the results of the updated RUBICON model (*Webb McKeown 2005*).

6 Model Calibration and Verification

A major portion in the development of the Nepean RMA-2 model was the calibration phase. The model roughness in the river channel where velocities are very high was treated as the primary variable of interest and was initially estimated before being adjusted to meet historical flood data and results from other numerical modelling and the physical model. Calibration of the RMA-2 model yielded good agreement with available data.

6.1 Methodology

Calibration of the RMA-2 Penrith-Nepean network was performed using all available data, which included:

- Penrith Council's LiDAR floodplain topography survey data
- Penrith Council's riverbed topography survey data upstream of Victoria Bridge
- Air Photos
- An on-site geomorphic analysis of the river channel and it's prominent features
- RUBICON Stage-Discharge data and hydrographs
- Historic flood levels for 1978, 1986 and 1990 as detailed in the WRL physical model calibration report
- Historic flood levels estimated from aerial photos of the 1978 flood (*taken near the peak*)
- Historic flood levels estimated from aerial photos of the 1986 flood (*taken near the peak*)
- The WRL physical model re-calibration report (*WRL, 2007*)

After the model network was created and initial estimates had been made for the model's physical parameters, historic flood analyses were performed and the results were compared with flood extents in the historic airphotos and with the recorded levels as tabled in the WRL Re-calibration Report, **Table 1**. This process led to iteration in the model's physical parameters, and continued, until results satisfactorily matched historic flood data.

Once the channel roughness had been established the model was run for the 100yr and 200yr ARI design floods for comparison with the RUBICON and the WRL physical model results. These model results also assisted the hand calculations and HEC-RAS modelling used to verify the RMA-2 model head losses through Victoria Bridge, and other openings through the railway embankment.

The extent of the network used to calibrate the model with the historic floods included the reach of the Nepean River from the Glenbrook Creek confluence to the Yarramundi Bridge, including portions of minor tributaries in this region. The model was essentially cut-down to match with the extents of the historic floods in order to minimise computation time. As a result, the model consisted of the river channel with some minor but relevant floodplain areas, **Figure 8**. The Victoria and M4 Motorway Bridge piers were modelled based on photos and site visits as discussed above.

For each historical flood, an initial steady state analysis was performed in order to establish a stable water level within the model. This was undertaken withinin the first 24 hour period with zero in-flow and a constant downstream tail water level.

Input RUBICON hydrographs for the 1990, 1986 and 1978 floods were used as the upstream boundary conditions, which were input as tabular data in two hourly increments and applied at the upstream boundary. Hydrographs of these inflow boundary conditions are presented in **Figure 18** and **Appendix C:**. These floods are the most significant recent events where recorded data is available. Their peak flows of 4500 to 9600 m^3/s compare to design flood peak flows varying from 8570 m^3/s for the 20yr ARI flood to 11015 m^3/s for the 50yr ARI flood.

The downstream boundary condition consisted of a stage-discharge curve derived from updated RUBICON results at Shaw's Island and Yarramundi Lagoon, as discussed above, and applied downstream of the Yarramundi Bridge. The RUBICON stage-discharge curve for the 1990 flood has a similar characteristic to the best fit curve derived from the design floods, however the curve for the 1978 flood has a significantly different characteristic, and the 1986 curve roughly follows the 1978 curve, **Figure 19**. The appropriate curves were used for each of the calibration floods. Data was input in approximately 1 m intervals

All boundary condition data was linearly interpolated between increments.

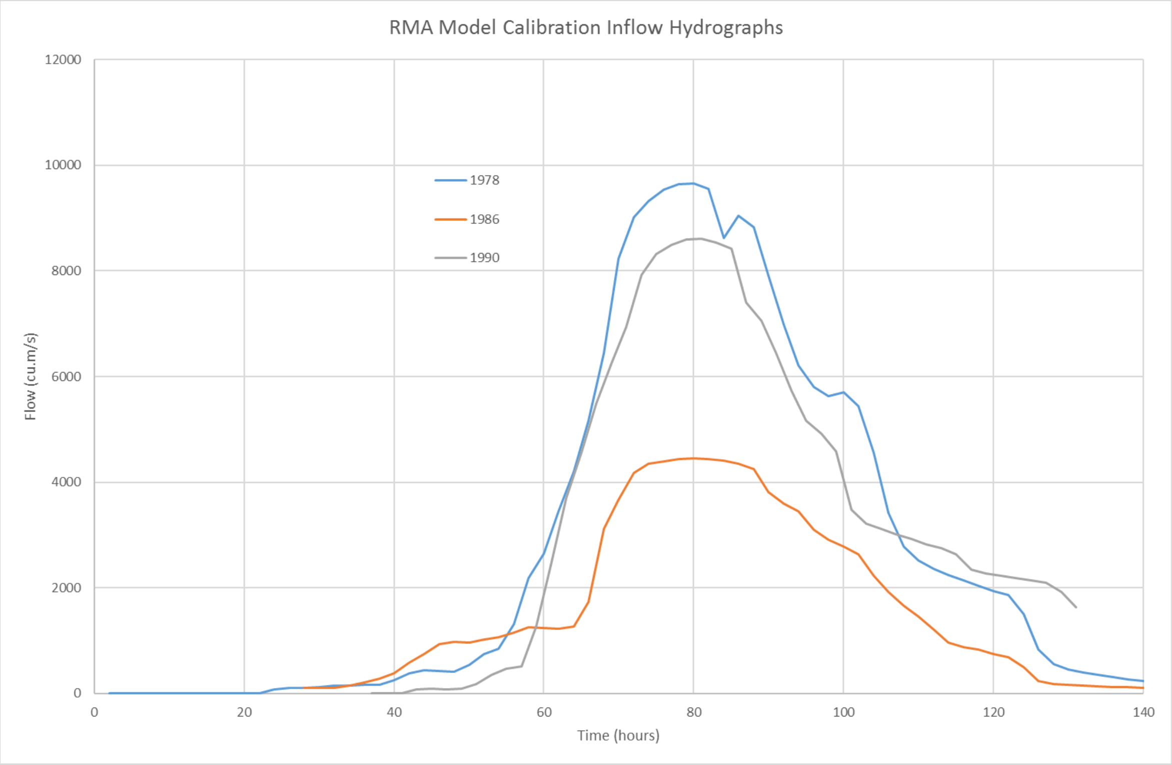


Figure 18: Inflow Hydrographs used to model historic floods (WRL Recalibration Report)

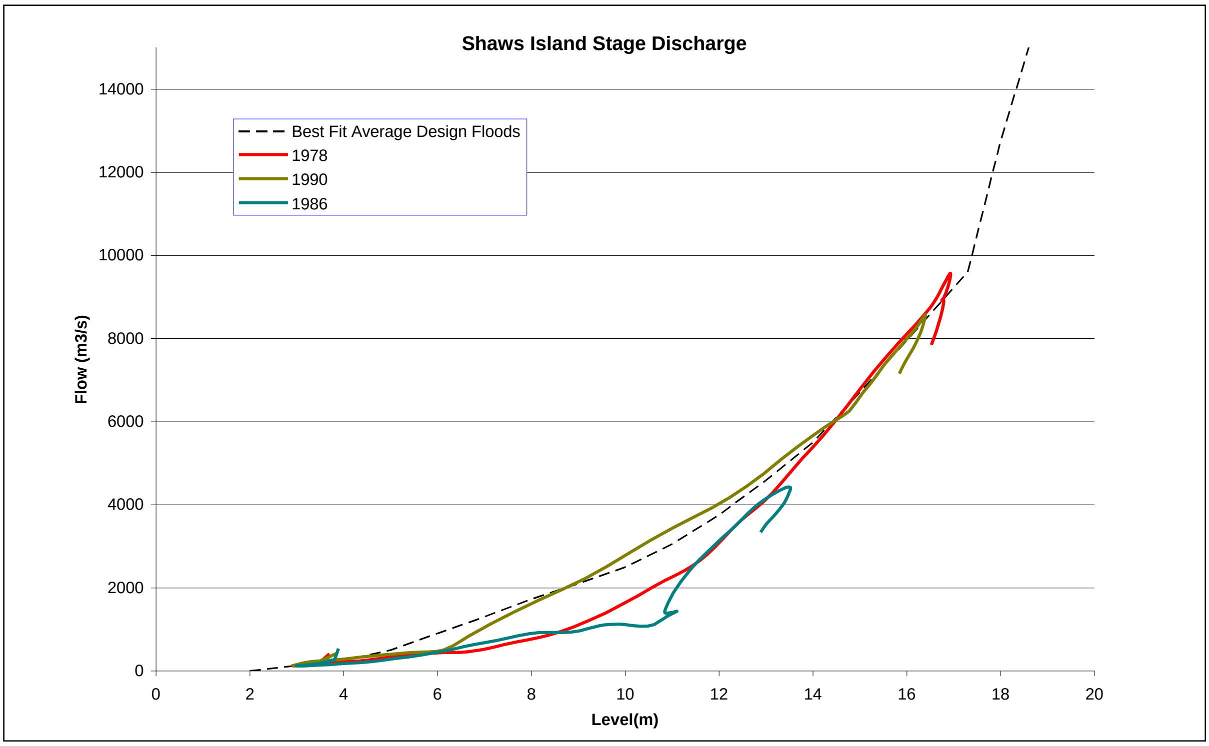


Figure 19 - Downstream Boundary : Stage-Discharge

Table 3- Best-Fit Stage-Discharge Data

Stage	Discharge	Stage	Discharge	Stage	Discharge
2	0	10	2500	18	12750
3	125	11	3050	19	16500
4	250	12	3750	20	21000
5	500	13	4585	21	25700
6	900	14	5500	22	30200
7	1300	15	6700	23	35000
8	1725	16	7950	25.5	41500
9	2100	17.3	9600		

The primary component in calibration of a 2D model is matching the terrain geometry, and as detailed above significant effort has been invested in achieving a match between the model and the captured landscape.

The next component of interest, especially where velocities are high is the Manning’s ‘n’ roughness parameter. Assessments were initially based on aerial photographs and site visit exploration, with estimates having to be made for the ponded sections of the river channel. Values across the floodplain areas and dry portions of the channel were generally gauged as good and were only varied slightly throughout the calibration process. A minimum roughness parameter of 0.030 was initially assigned to the in-channel areas covered by water, with a maximum roughness of 0.080

assigned in areas of extremely dense foliage. The distribution of roughness within the river channel was skewed towards the minimum value as the majority of the channel bed is not highly vegetated.

The 1978 flood was used as the primary test case for calibrating the RMA-2 model as it has a significant flow with excellent historic data derived from airphotos taken at 3:30pm, 10 hours after the peak of the flood. The model roughness, primarily along the bed of the river channel was adjusted until an acceptable fit was achieved with the historic data. After the model had been calibrated to the 1978 flood, the 1986 and 1990 floods were used as verification test cases. Some further adjustments to the river bed roughness using the 1986 flood were made upstream of Victoria Bridge to achieve calibration with the only recorded data in this reach.

6.2 Calibration Analyses

The 1978 flood hydrograph consists of a 124 hour period with a maximum inflow of 9650 m^3/s after 78 hours. A limitation with the 1978 flood is that changes to the river structure are thought to have resulted in 1986, meaning that results with post-1986 conditions (*i.e. those that exist currently*) may not be directly comparable with 1978 recorded levels. Initial analyses predicted results that were generally above recorded levels downstream of Victoria Bridge and above most of the RUBICON results, especially upstream of Victoria Bridge.

The 1990 flood hydrograph consists of a 90 hour period with a maximum inflow of 8606 m^3/s after 40 hours.

The 1986 flood hydrograph consists of a 122 hour period with a maximum inflow of 4450 m^3/s after 52 hours. Initial analyses showed water levels that were above recorded levels upstream of Victoria Bridge.

River channel roughness was adjusted until good agreement was achieved with the recorded data downstream of Victoria Bridge for the 1978 flood, and then further adjusted upstream of Victoria Bridge to match recorded data from the 1986 flood. The results were then compared to the downstream data of the1986 flood and all of the 1990 flood data.

6.3 Calibration Results

The calibrated distribution of Manning's roughness is illustrated in **Figure 20**, where a value of 0.027 was used for the majority of the water-covered riverbed (*in normal flow conditions*) downstream of Penrith Weir with a value of 0.023 being used upstream of the weir. This difference is justified in a comparison of river bed gradients. Upstream of the weir the bed is relatively flat whereas downstream it has a gradient of approximately 0.12%. The average water surface slope, on the other hand is relatively constant with a slope of 0.04%, and thus there would be a propensity for finer sediments to remain stable under the deeper flows on the upstream bed, with coarser and thus rougher armouring to be typical downstream. Small adjustments were also made to the nominal 0.035 and 0.040 sections along the edge of the channel, with the 0.035 being reduced to 0.033 and the 0.040 raised to 0.041.

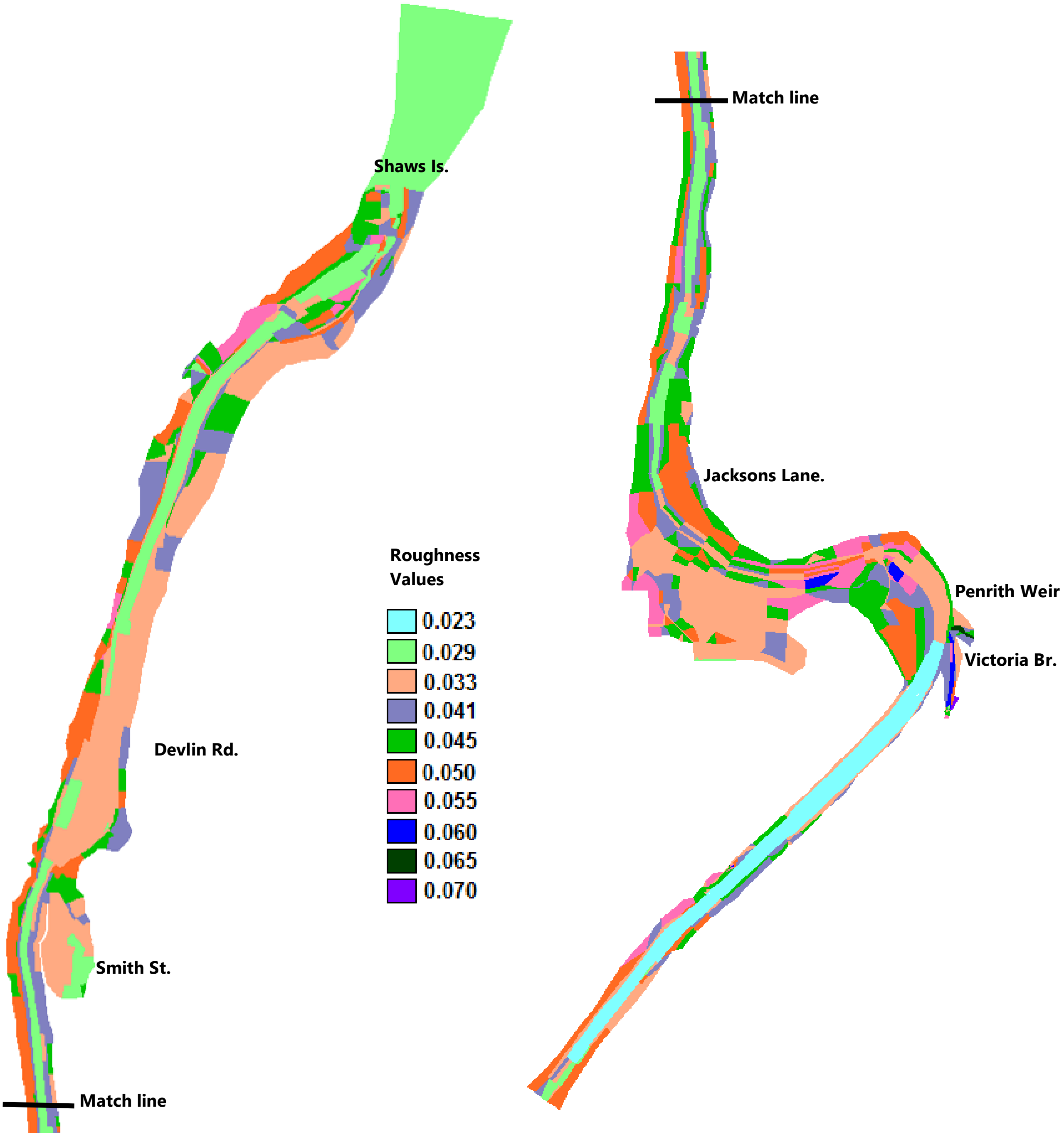


Figure 20 - River channel roughness zones in the calibration model

The sequence of vertical airphotos taken during the 1978 flood extends from the downstream half of the S-bend to Yarramundi. The photos are known to have been taken at 3:30 pm, March 21, 1978, some 10 hours after the peak at 5:30am (*Hawkesbury River Basin, Flood March 1978, Recorded heights, PWD*).

A methodology was adopted to extract the best possible flood levels from these airphotos by overlaying the initial 1978 model surface on the airphotos and selecting a model timestep where the modelled flood extent matches the airphoto flood extent, **Figure 21** and **Figure 22**. The mid-channel flood level can then be read from the model surface and factored up to account for the drop in levels between the peak and the time of the airphotos. The initial model surface indicated this relative difference to be 0.62 m at Victoria Bridge.

Each photo had to be rotated digitally and geo-referenced to MGA94 coordinates. The RMA model surface had to be matched at an appropriate timestep to each airphoto making sure that there was a consistency in the time increasing with downstream points, both because of the floodwave travelling downstream and the initial RMA surface being high. Some of the photos had distinctive flood extents on relatively flat floodplain areas, thus providing good anchor points for the full airphoto set.

The initial calibration run indicated that the shape of the hydrograph flattened as it progressed downstream from Victoria Bridge, thus gradually reducing the difference between the level at the time of the photos and the peak level in a downstream direction. Several iterations were required with small adjustments to the roughness values to achieve a best fit between the adjusted airphoto levels and the peak of the model run. The final differences varied from 0.62m at the S bend to 0.46m at Smith Road and 0.29m at Kooringal.

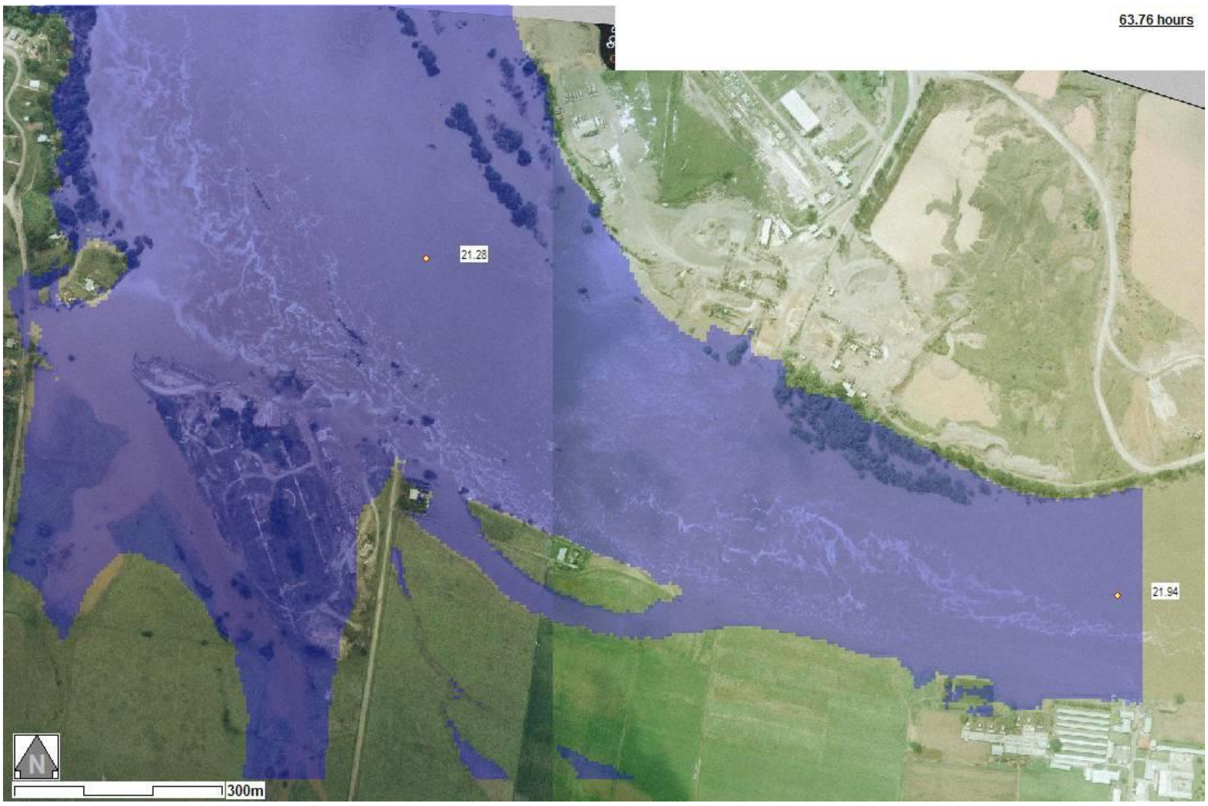


Figure 21 - 1978 airphoto water level registration at upstream end

Figure 22 - 1978 airphoto water level registration through mid section

The calibrated model results for the 1978 flood are shown in **Figure 23**. Results for the 1986 and 1990 events are shown in **Figure 25**and **Figure 26** respectively.

Sensitivity to roughness was also checked on the 1978 flood with all roughness values being increased and decreased by 0.001. The results indicate a uniformly increasing variation with distance upstream from the same tailwater level, **Table 4**.

Table 4 - Sensitivity of channel roughness on water levels

	Roughness increased by 0.001	Roughness decreased by 0.001
M4 Bridge	+0.12 m	-0.13 m
Victoria Bridge	+0.06 m	-0.14 m
Devlin Road	+0.12 m	-0.02 m

The calibrated model results for the 1978 flood fit the airphoto levels to better than 0.11m (*average of 0.02m*). The reliable recorded levels also show a good match and the RUBICON results show a variability that likely relates to the differences between the 1D and 2D modelling approaches.

The calibrated model results for the 1986 flood fit the airphoto levels well and show a good agreement with recorded levels and RUBICON results. The RUBICON results for the 1986 event are from the old model that did not have additional cross-sections.

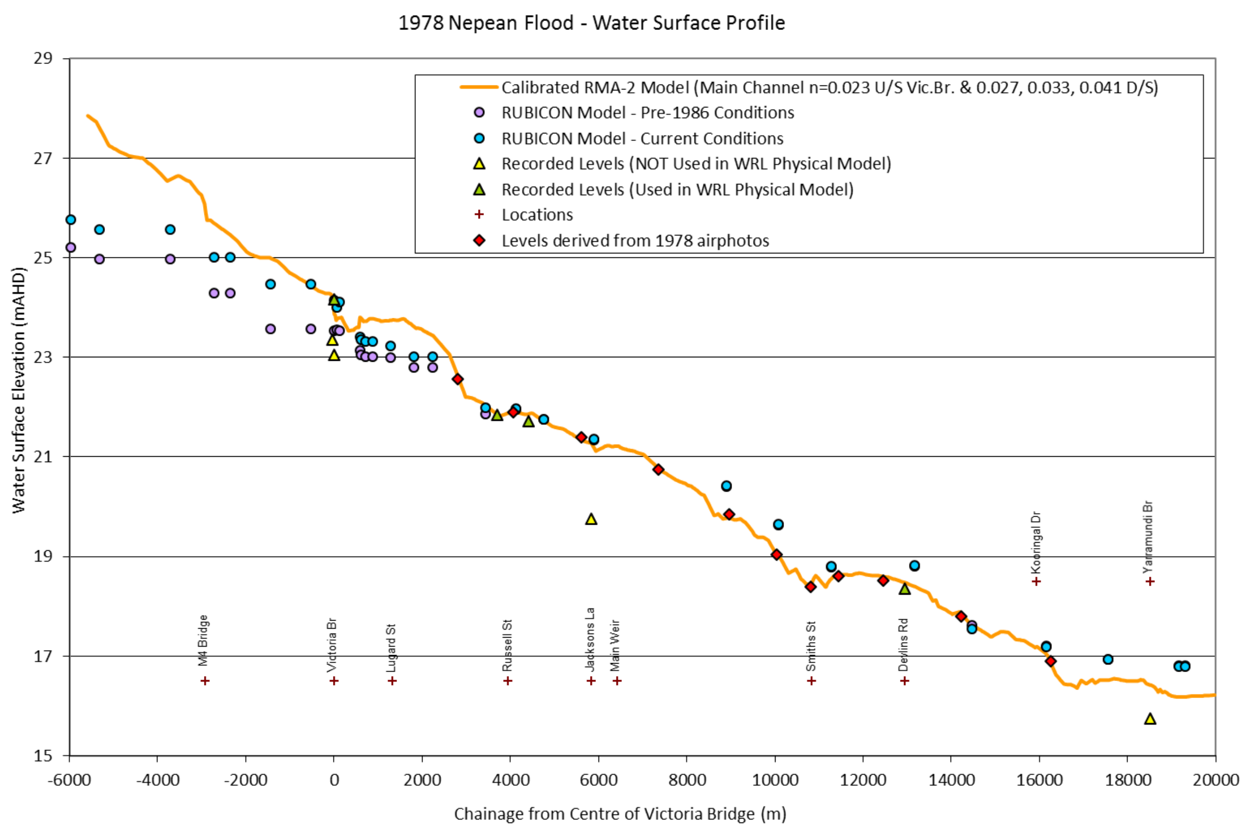


Figure 23: Summary of 1978 Historic Flood Results showing fully calibrated model, airphoto levels, recorded levels and RUBICON data

Air photo assessment data was estimated by Penrith Council from oblique air photos taken during the 1986 event. The levels shown in the air photos were also assessed by WorleyParsons using waterRIDE tools and the LiDAR DEM with some refinements being apparent. Close examination of the photos together with the 1986 flood surface in waterRIDE indicates that the timing of the photos would likely have been on the upward limb of the flood near to the peak.

Whilst there are discrepancies in the PCC estimates, the refinements made in the further analysis show a reasonable fit between the model and the flood levels estimated from these air photos. In fact, the photos in the vicinity of the M4 Bridge provide the only recorded data upstream of Victoria Bridge and this data was used to calibrate the model's river bed roughness upstream of Penrith Weir as discussed above. The middle recording of these three levels is shown without an error band as the level is distinctively clear on a section of asphalted road, **Figure 24**.

Figure 24 - Example calibration of 1986 Flood air photos with ALS DTM (WP)

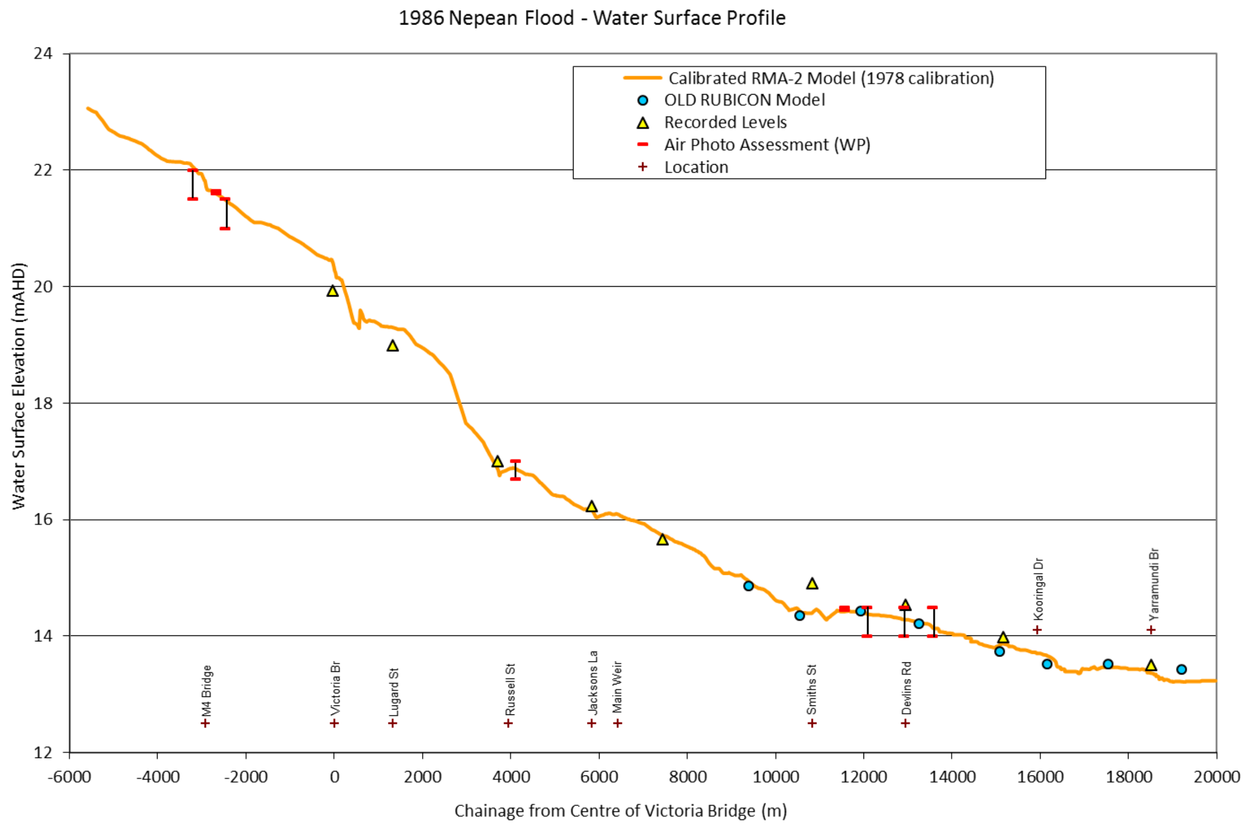


Figure 25: Summary of 1986 Historic Flood Results showing fully calibrated model, airphoto levels, recorded levels and (old) RUBICON data

From Victoria Bridge to the upstream end of the RMA model, the RUBICON results (1978 & 1990) indicate a flattening of the water surface gradient in comparison to the RMA model, **Figure 23** and **Figure 26**. The reported RUBICON profile extending further upstream shows an increasing gradient in concert with the bed profile and this local flattening is not representative of the overall water surface profile. (*Warragamba Dam Auxiliary Spillway Environmental Impact Study – Flood Study, Part C – Hydraulic Modelling, WMA, 1996*).

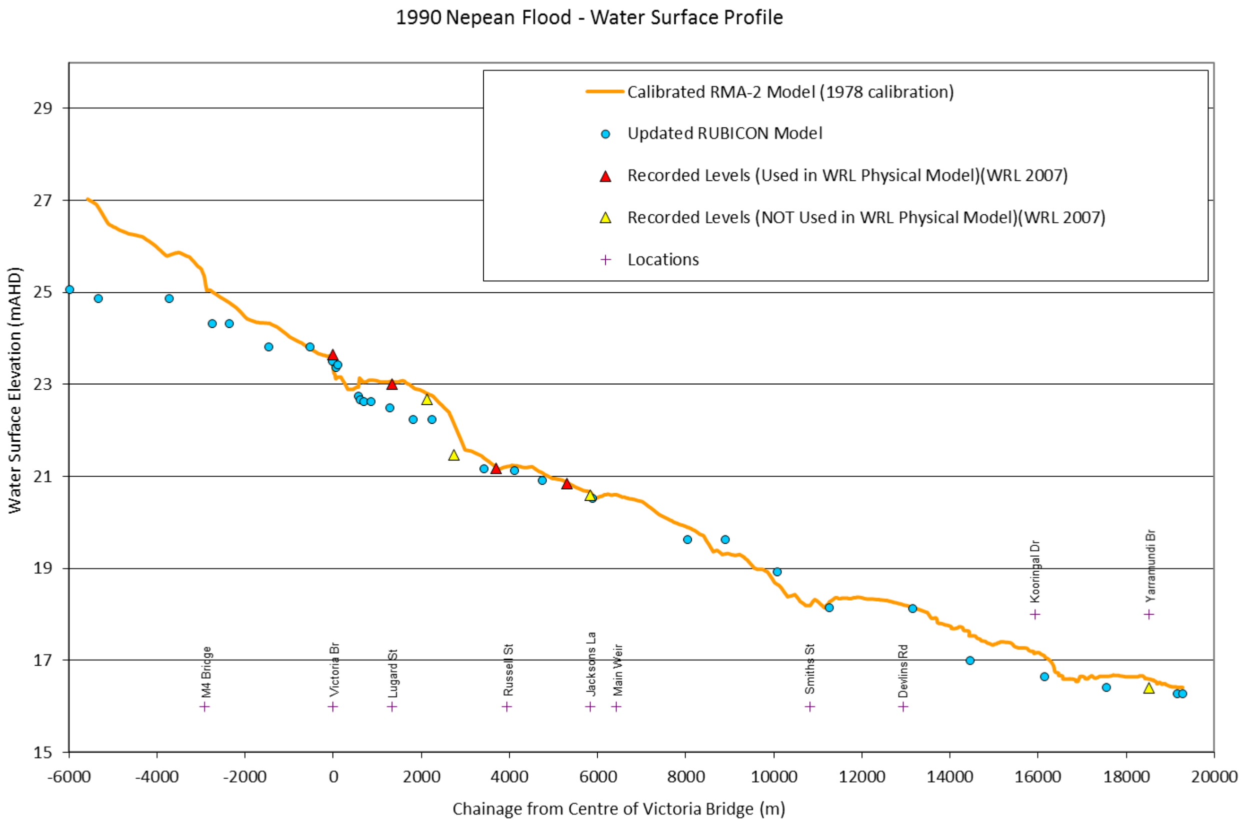


Figure 26: Summary of 1990 Historic Flood Results showing fully calibrated model, recorded levels and RUBICON data

6.4 Tree Regrowth Downstream of Victoria Bridge

Concern has been raised regarding the impact of the regrowth of tree vegetation across the floodplain on the inside of the bend downstream of Victoria Bridge. Notwithstanding the drought conditions in the mid 2000s, there has been extensive growth in this area since the last significant flow in 1990 when floodplain depths peaked at 5m to 9m coupled with velocities of 0.5 m/s to 2 m/s.

Field experience along the floodplain and along the Woronora River (*similar rocky substrate with gravel deposits*) would indicate that this vegetation (*typically casuarinas and melaleucas*) bends readily with flows resulting in low roughness impacts at high depths. However, should the vegetation establish itself as mature trees after a long spell with few freshes, it may have a greater impact until it is removed or defoliated by the deep and high velocity flows of a large flood.

As an upper bound case, the 1990 model was run with this area set to a roughness of 0.08 and the results indicated an increase in peak flood levels of 0.2m upstream of Victoria Bridge. Significant floods would be expected to remove or destroy much of the vegetation as has occurred in the past, reducing the roughness to something less than 0.04 as a lower bound. In consideration for the planning perspectives of the modelling, the current network employs roughness values between 0.04 and 0.05 within this area as a slightly conservative compromise between the two bounds.

Another concern lies with the potential for the loss of such vegetation to create impacts downstream through debris jams. Consideration of the limited sizes of the trees and the magnitude of the vegetation compared to the size of the channel and the high energy of the flow would suggest that debris jams or constrictions other than small amounts of debris lodging against trees and fences on the upper banks and floodplain would be most unlikely. The effects of such debris on flood performance have not been considered in the model parameters, but can be inferred where there are local areas of concern.

6.5 Validation of Victoria Bridge Levels and Railway Openings

One of the primary outcomes of the RMA-2 model results for the historic flood events is the apparent head loss and apparent backwater effect of Victoria Bridge.

In the 1990 historic case, the RMA-2 model predicts a backwater effect of approximately 0.5 metres over 100 metres (*from 60 metres upstream to 40 metres downstream of the bridge*). The 1D RUBICON results do not show this affect.

The RUBICON model only has three cross-sections at the bridge, the first being in the centre of the bridge and the two others being approximately 50 metres sequentially downstream. The next nearest cross-section upstream of the bridge is approximately 500 metres away. The RMA-2 model captures a significantly greater terrain and structure detail with mesh elements around and through the bridge opening in the order of 3 to 10 metres. The bridge piers have also been included as cutout sections in the mesh to ensure 2D flow inducing approach and exit losses are considered.

The recorded levels are unreliable in verifying the backwater effect because there are simply not enough data. Not only is there only a handful of recorded readings at Victoria Bridge, in all historic cases it is not clear whether recorded levels were taken upstream, downstream or directly at the bridge. The localised effect of the backwater would also prove difficult to resolve with the eye.

Since RUBICON does not show a backwater effect due to its network limitations, and the recorded data is spatially uncertain, verification of the backwater effect required alternative methods - two methods were performed:

1. A HEC-RAS Model was created and analysed for a reach of the Nepean around Victoria Bridge.
2. Hand Calculations based on Bradley’s Method were carried out.

The results verify that there is a backwater effect and the RMA-2 model successfully resolves this effect and models its influence on water levels upstream of Victoria Bridge.

6.5.1 HEC-RAS Model (Victoria Bridge)

HEC-RAS version 4.0 was used to model the stretch of the Nepean from 5 km upstream to 6 km downstream of Victoria Bridge. The model consisted of 20 cross-sections and included a special cross-section detailing the Victoria Bridge and its piers, **Figure 27**.

The 1990 peak flow as shown in **Figure 18** was used as the upstream boundary condition and a water level from the RMA-2 results for 6 km's downstream of Victoria Bridge was used as the downstream boundary condition in HEC-RAS.

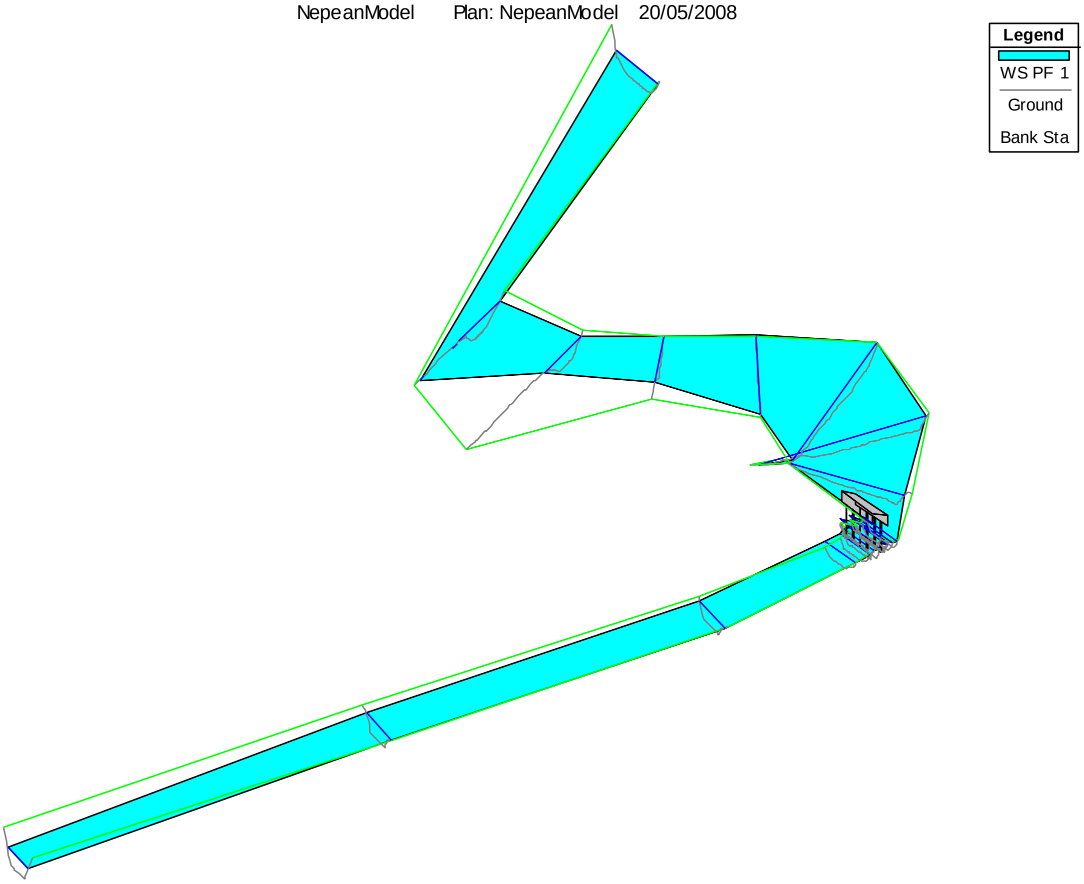


Figure 27: HEC-RAS Model

Manning roughness parameters were assigned in accordance with the calibrated RMA 2 model and default recommended values for expansion and contraction losses were used.

A steady state flow analysis was performed with results indicating a headloss of approximately 0.5 metres across the bridge structure, **Figure 28**. This agrees with the loss predicted by RMA-2. It must be emphasised that the recorded data point location is unknown so it was placed directly in the centre of Victoria Bridge.

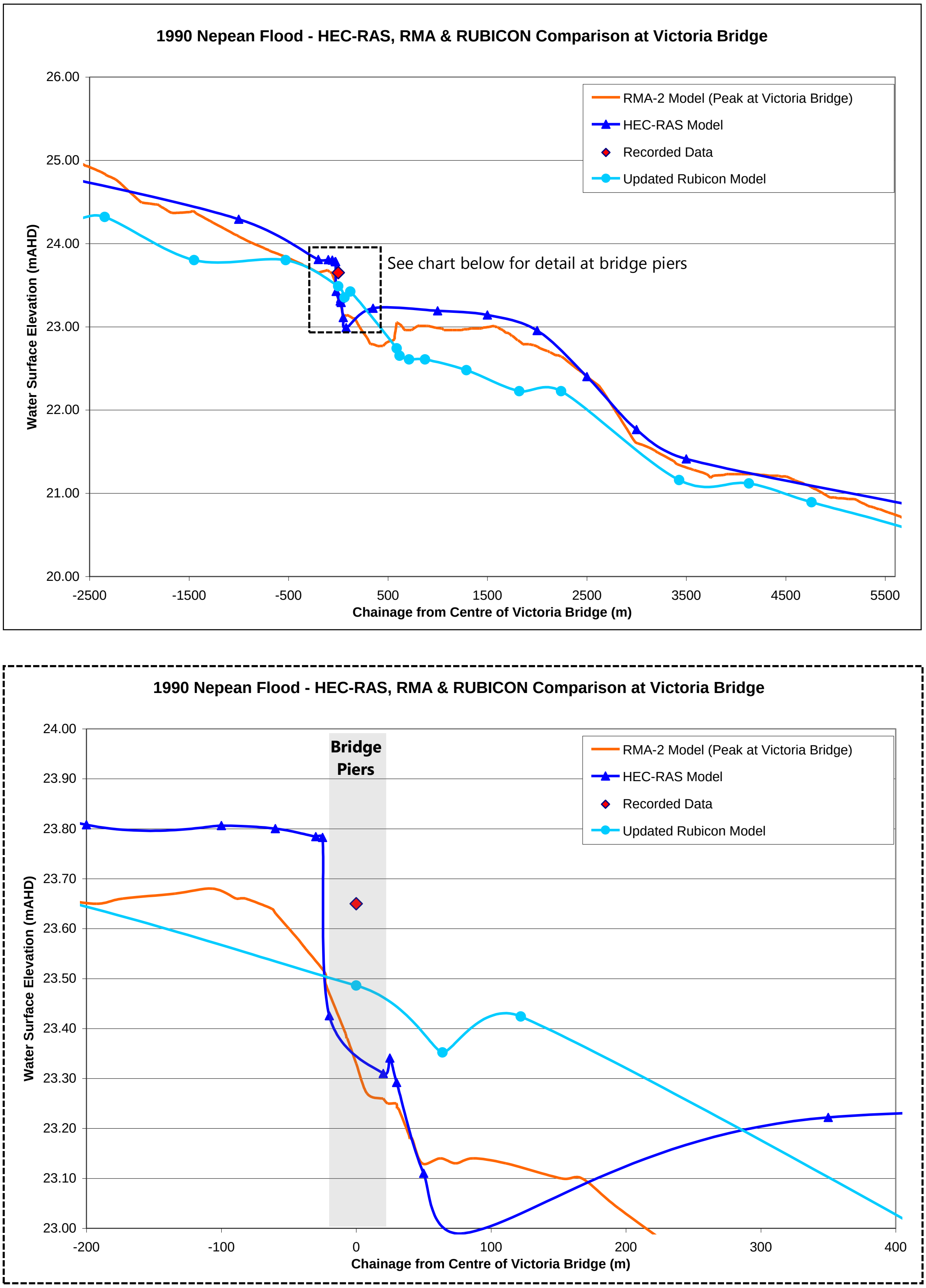


Figure 28 - HEC-RAS, RMA 2 and RUBICON comparison, overview and Victoria Bridge detail

6.5.2 Bradley's Method (Victoria Bridge)

In order to further verify that there is a backwater effect at Victoria Bridge, Bradley's Method was applied to estimate the headloss using the flow characteristics from the initial 100yr ARI design flood model run. All variables were conservatively approximated from RMA-2 and HEC-RAS. To calculate the total backwater, the following formula is applied:

$$h^* = K^*\alpha_2 \frac{V_{n2}^2}{2g} + \alpha_1\left[\left[\frac{A_{n2}}{A_4}\right]^2 - \left[\frac{A_{n2}}{A_1}\right]^2\right]\frac{V_{n2}^2}{2g} \qquad (1)$$

The value of K^* (*the total backwater coefficient*) is calculated using the bridge opening ratio M, the base coefficient, K_b, and the number, size and shape of piers in the constriction, K_p.

$$K^* = K_b + K_p \qquad (2)$$

1. The Bridge Opening Ratio, M, defines the degree of stream constriction. It is defined as the ratio of the flow which can pass unimpeded thought the bridge constriction, to the total flow of the river:

$$M = \frac{q_b}{Q} \qquad (3)$$

Where: $q_b \approx 11545$ m^3/s

$Q \approx 13935$ m^3/s

$\therefore M \approx 0.83$

2. The base coefficient is an empirical value dependant on the value of M. From Figure 29, using an M value of 0.89:

$K_b \approx 0.30$

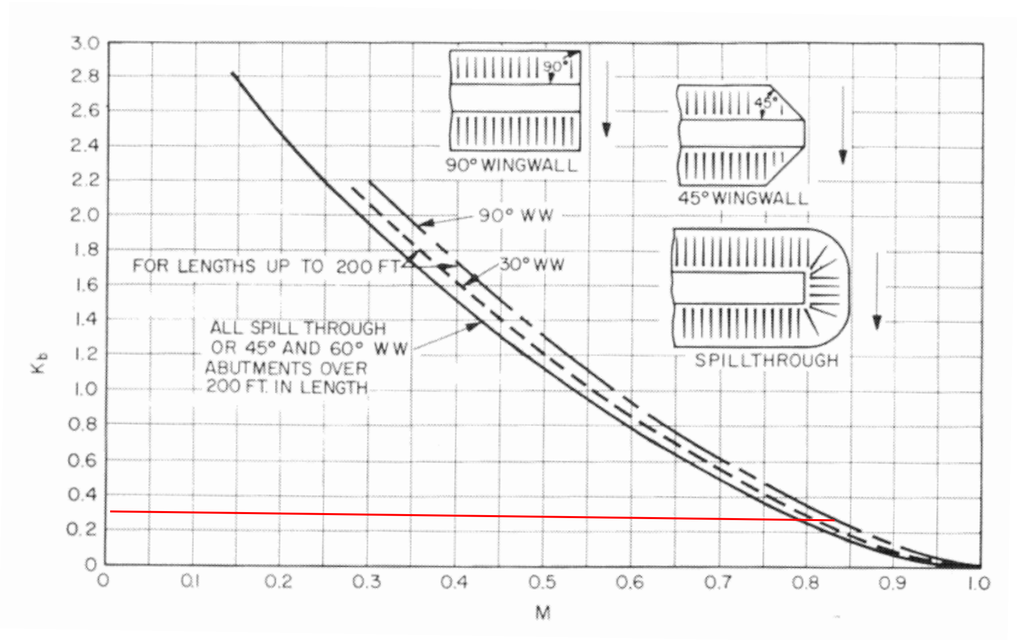


Figure 29: Backwater coefficient base curves

3. The backwater effect of the piers is empirically dependant on J, which is the ratio of the total area of the piers normal to the flow, to the total cross-sectional flow area:

$$J = \frac{A_p}{A_{n2}} \tag{4}$$

$A_p \approx 234\ m^2$

$A_{n2} \approx 2741\ m^2$

$\therefore J \approx 0.09$

Then, from Figure 30, $\Delta K \approx 0.18$ and $\sigma \approx 0.96$ so:

$K_p = \Delta K \sigma$

$K_p \approx 0.17$

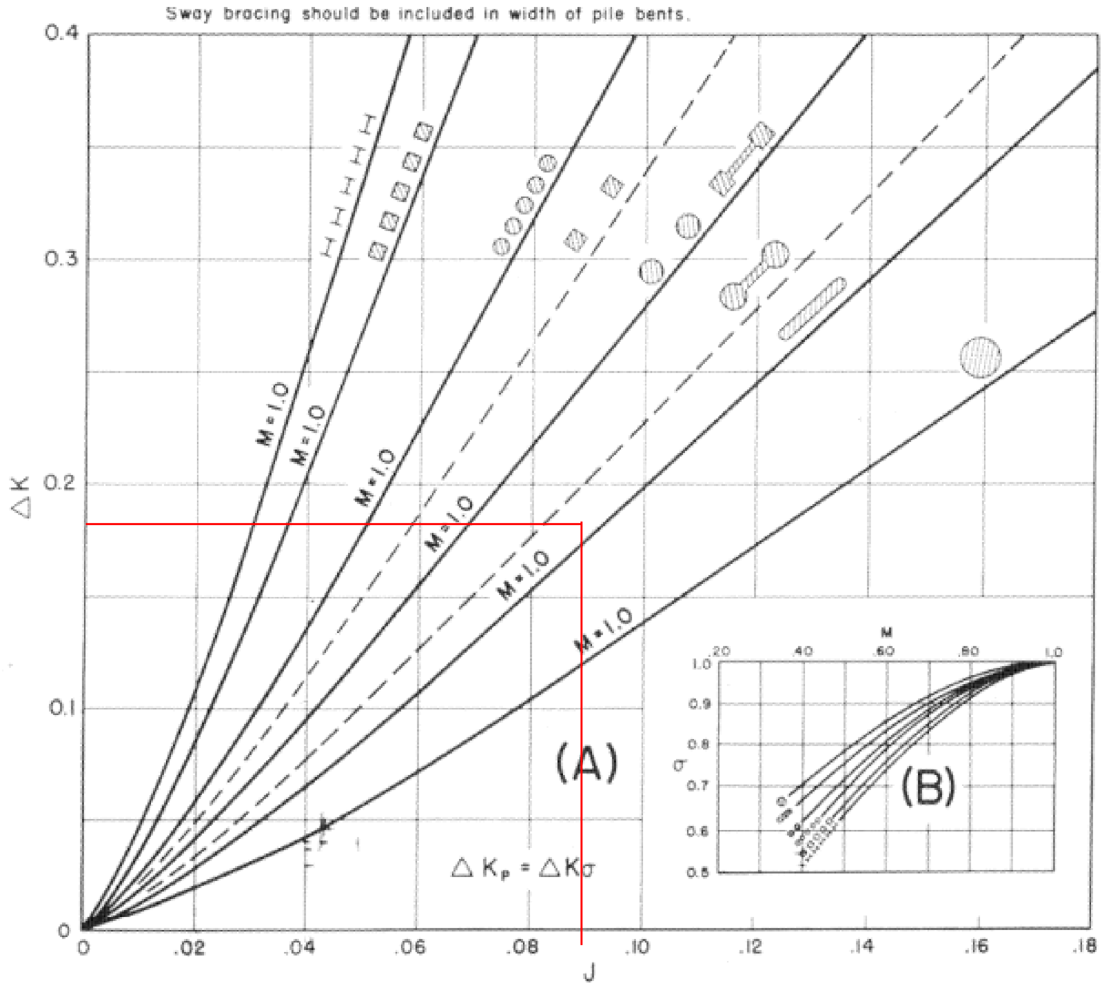


Figure 30: Incremental backwater coefficient for piers

Then the total backwater coefficient is, using equation (2):

$K^* \approx 0.30 + 0.17$

$K^* \approx 0.47$

The kinetic energy coefficient, α_1, is obtained from the following:

$$\alpha_1 = \frac{\sum qv^2}{QV^2} \qquad (5)$$

Where:

LOB	$q \approx 1727\ m^3/s$	$v \approx 6.03\ m/s$
Main Channel	$q \approx 11545\ m^3/s$	$v \approx 5.75\ m/s$
ROB	$q \approx 271\ m^3/s$	$v \approx 2.86\ m/s$
Whole Cross-section	$Q \approx 13935\ m^3/s$	$V \approx 5.09\ m/s$

$$\therefore\ \alpha_1 \approx 1.24$$

Then α_2, the velocity head correction coefficient, is empirically related to α_1 and M. From Figure 31:

$$\therefore\ \alpha_2 \approx 1.20$$

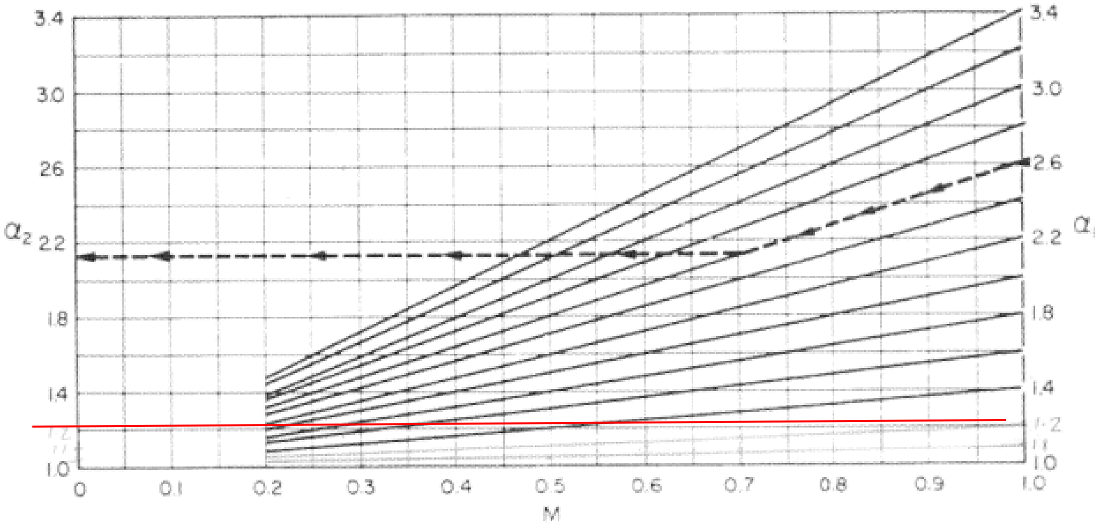


Figure 31: Aid for estimating α_2

Calculating the backwater, h^*:

Using equation (1), we have:

$K^* \approx 0.47$	(Total Backwater Coefficient)
$\alpha_1 \approx 1.24$	(Kinetic Energy Coefficient)
$\alpha_2 \approx 1.20$	(Velocity Head Correction Coefficient)
$V_{n2} \approx 5.09\ m/s$	(Bridge Section Average Flow Velocity)
$A_{n2} \approx 2741\ m^2$	(Water Area at Bridge)
$A_4 \approx 2850\ m^2$	(Water Area DS of Bridge)
$A_1 \approx 2820\ m^2$	(Water Area UP of Bridge)
$g \approx 9.81\ m/s^2$	(acceleration due to gravity)

$$\therefore\ h^* \approx \mathbf{0.72\ metres}$$

6.5.3 Hydraulic Structures Headloss Validation

Bradleys method for bridge and culvert opening headlosses as detailed above for Victoria Bridge was applied to the M4 bridge and other railway openings, **Figure 32**. The initial design flood modelling showed the openings on the west side of the river experienced adequate flows at the peak of the100yr ARI flood whereas the openings on the east side remained in a backwater. It is not until the right bank of the river overtops into Peachtree Creek that significant flow passes through these eastern openings. Consequently 200yr ARI flow characteristics were used to assess these two openings. The sequence of analysis for each of the openings including the M4 and Victoria bridges is summarised below, **Table 5**.

Table 5 - Bridge and railway opening headloss analysis summary

Parameter	M4 bridge	Victoria bridge	Hartigan Avenue railway culvert	Nepean High School railway opening	Old Bathurst Road railway underpass	Castlereagh Road railway underpass	Peachtree Creek railway bridge
Flood	100yr	100 yr	100 yr	100 yr	100 yr	200 yr	200 yr
V_{n2}	3.48	5.09	3.38	1.88	0.46	1.42	2.04
q_b	11659	11545	60.0	17.7	19.8	127.4	425.0
Q	13027	13935	78.0	17.7	22.7	142.2	723.0
M	0.89	0.83	0.77	1.00	0.87	0.90	0.59
K_b	0.12	0.30	0.38	0.10	0.20	0.18	0.90
A_p	78.0	234.0	6.3	4.0	5.0	4.1	32.0
A_{n2}	3294	2741	25.4	9.2	45.0	95.4	376.2
A_1 (u/s)	3900	2820	55.0	12.0	70.0	115.0	460.0
A_4 (d/s)	3300	2850	30.0	10.0	55.0	90.0	380.0
J (A_p/A_{n2})	0.02	0.09	0.25	0.43	0.11	0.04	0.09
ΔK	0.04	0.18	0.50	0.95	0.30	0.07	0.17
σ	0.99	0.96	0.48	0.97	0.98	0.98	0.75
K_p	0.04	0.17	0.24	0.92	0.29	0.07	0.13
Σqv^2	236033	446718	927.5	64.0	5.9	312.7	3050.2
QV^2	157762	361029	891.1	62.6	4.8	286.7	3008.8
α_1	1.50	1.24	1.04	1.02	1.23	1.09	1.01
α_2	1.46	1.20	1.00	1.00	1.18	1.08	1.01
Headloss	**0.41**	**0.72**	**0.67**	**0.23**	**0.01**	**0.08**	**0.29**
Model H/L	**0.58**	**0.82**	**0.70**	**0.35**	**0.04**	**0.10**	**0.25**

Considering the accuracy of Bradley’s empirical method and the accuracy of 2D modelling, the RMA model is faithfully reproducing acceptable headloss values through all these openings.

The Great Western Highway crossing of Peachtree Creek has very little effect on headloss values for regional flooding. As indicated above, it is not until the 200yr ARI design flood and larger that significant flow crosses over the highway, and because of backwater effects, with sufficient depth to drown any potential effect of the bridge.

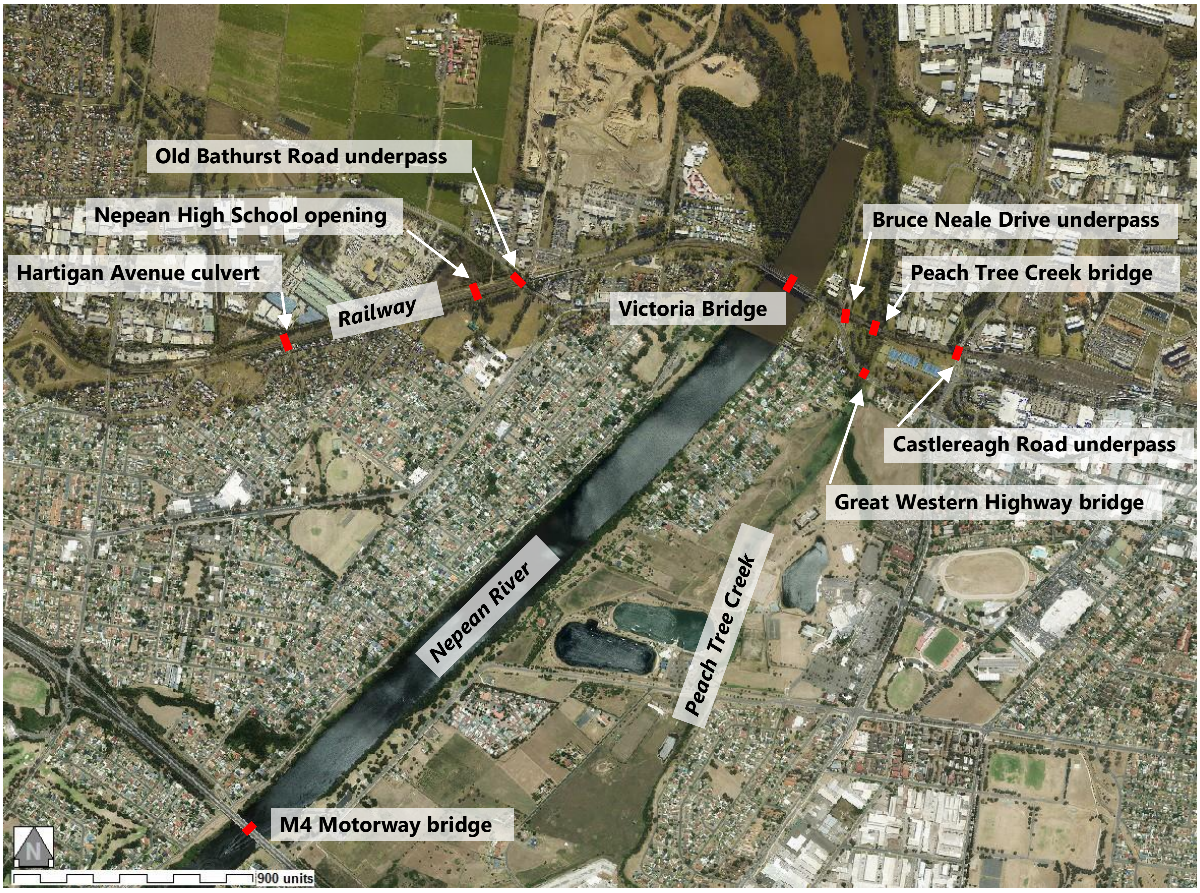


Figure 32 - Hydraulic structure headloss locations

6.6 Knapsack Creek Breakout, Flow Validation

The Emu Plains residential area is initially inundated by backwater from the main channel breaking out over the north bank of Knapsack Creek at a low area in the terrain. A review of the initial model results run following the calibration, indicated that this breakout is activated for a short period at the peak of the 100yr ARI flood without sufficient time for the storage upstream of the railway embankment to be fully realised. The model mesh in this area was refined with a line of subsurface flow control elements to improve the control of breakout flows into Emu Plains under initial wetting and drying conditions, **Section 5.14**.

Subsequent model runs, showed that these changes reduced the volume of water entering Emu Plains for the 100yr ARI flood and consequently the peak level was reduced in comparison to the previous 'Alignment' model results.

Table 6 - Knapsack Creek breakout changes

Location / Item	Previous Value	Updated Value
South of railway	Peak wl = 25.30	Peak wl = 24.75
Gt. Western Highway.	Peak wl = 26.17	Peak wl = 25.92
Forbes Street	Peak Q = 59 cu.m/s	Peak Q = 18 cu.m/s
Water volume at peak	353000 cu.m	126000 cu.m

To confirm the validity of these results, a 1D steady state HEC-RAS model was constructed and used to establish flow vs headloss relationship for the Knapsack Creek breakout flows.

Nine cross-sections were extracted from the LiDAR terrain between the north bank of Knapsack Creek and the Great Western Highway. A selection of flows and tailwater levels (*at the highway*) were extracted from the RMA model results (*100yr and 200yr ARI*) and the HEC-RAS model was run with these values to determine upstream levels in Knapsack Creek, and then to establish a flow vs depth relationship for the Knapsack Creek breakout, **Figure 33**.

The purpose of the HEC-RAS 1D model was to validate the performance of the RMA model at this location, and to confirm the reduction in breakout flows when compared to the earlier modelling (*2010 & 2008*). The two models differ in their representation of the landscape, in their numerical solution for the water surface and flow distribution. The HEC-RAS model has discrete cross-sections extracted from the 2m DEM while the RMA model has a triangulated 2D mesh with a coarser discretisation than the 2m grid. An illustration of these differences can be seen in a typical cross-section comparison, **Figure 35**. Flows in the 2D RMA model are represented across the mesh by the mass and momentum of the water, whilst the 1D HEC-RAS model has a constant flow through all the cross-sections. Comparisons between the two models are at best an approximation within the accuracy limitations of each model.

A comparison between flows extracted from the RMA model (*100yr and 200yr ARI across Forbes St.*) and the HEC-RAS results, indicates the RMA model has slightly higher flows than the HEC-RAS model for an equivalent level upstream in Knapsack Creek, **Figure 34**. Given the relative accuracies of the two models, these differences are considered reasonable and the HEC-RAS model has validated the reduced flows breaking out from Knapsack Creek as a result of the sub-surface flow control refinements made to the RMA mesh.

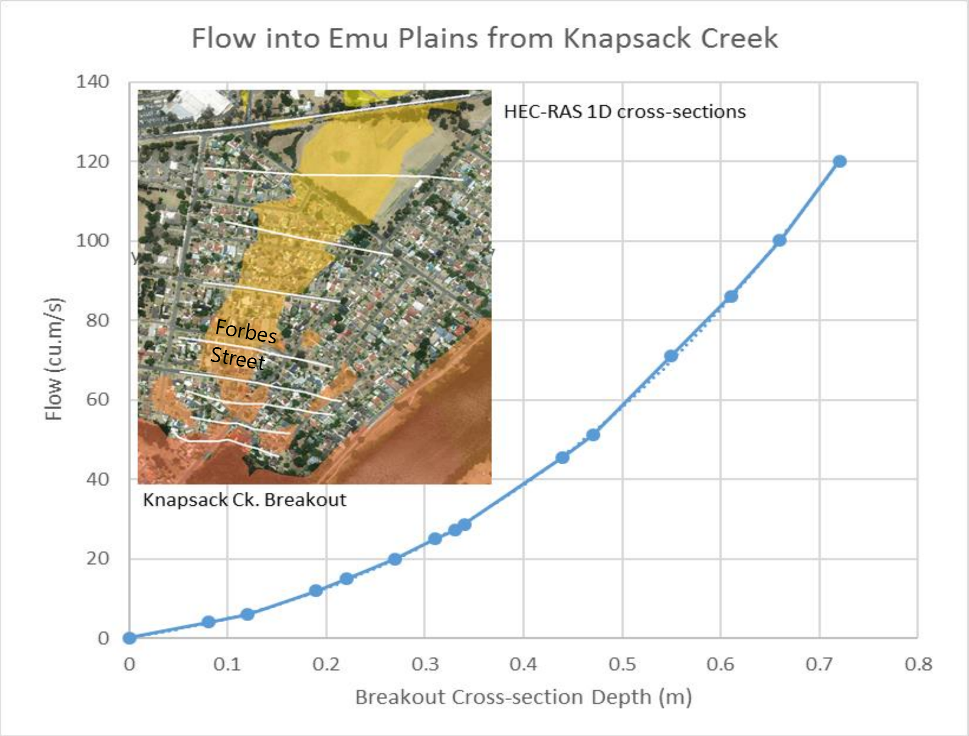


Figure 33 - Knapsack Creek breakout flow vs depth relationship

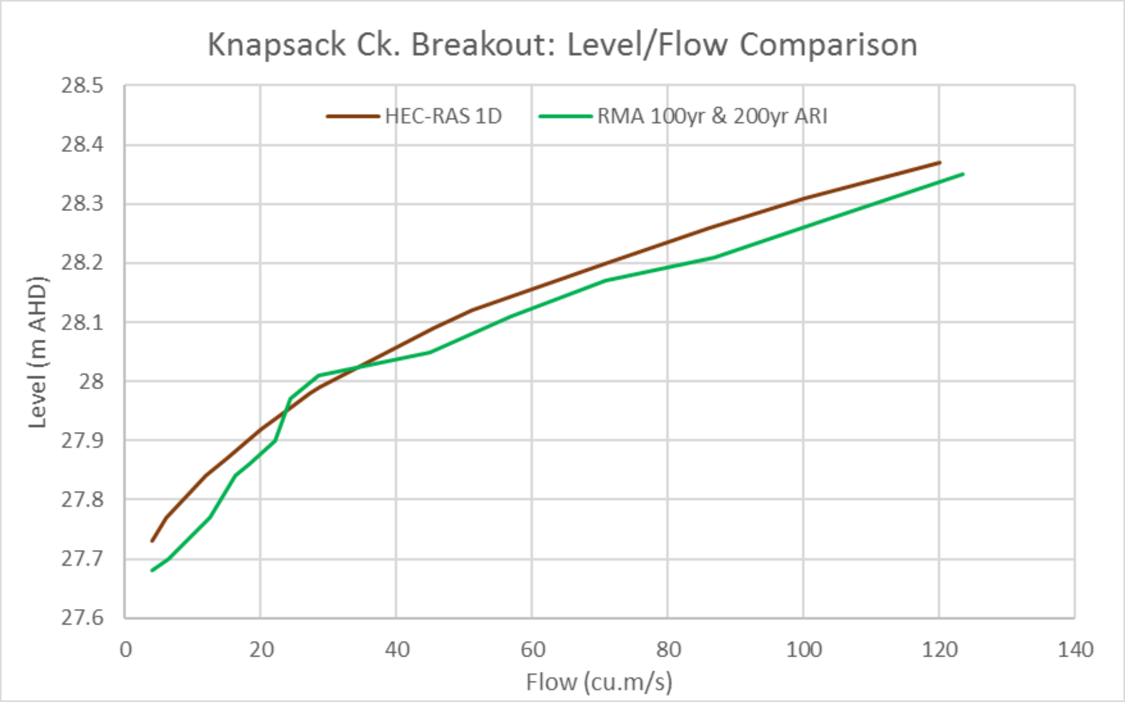


Figure 34 - Knapsack Ck. breakout flow comparison

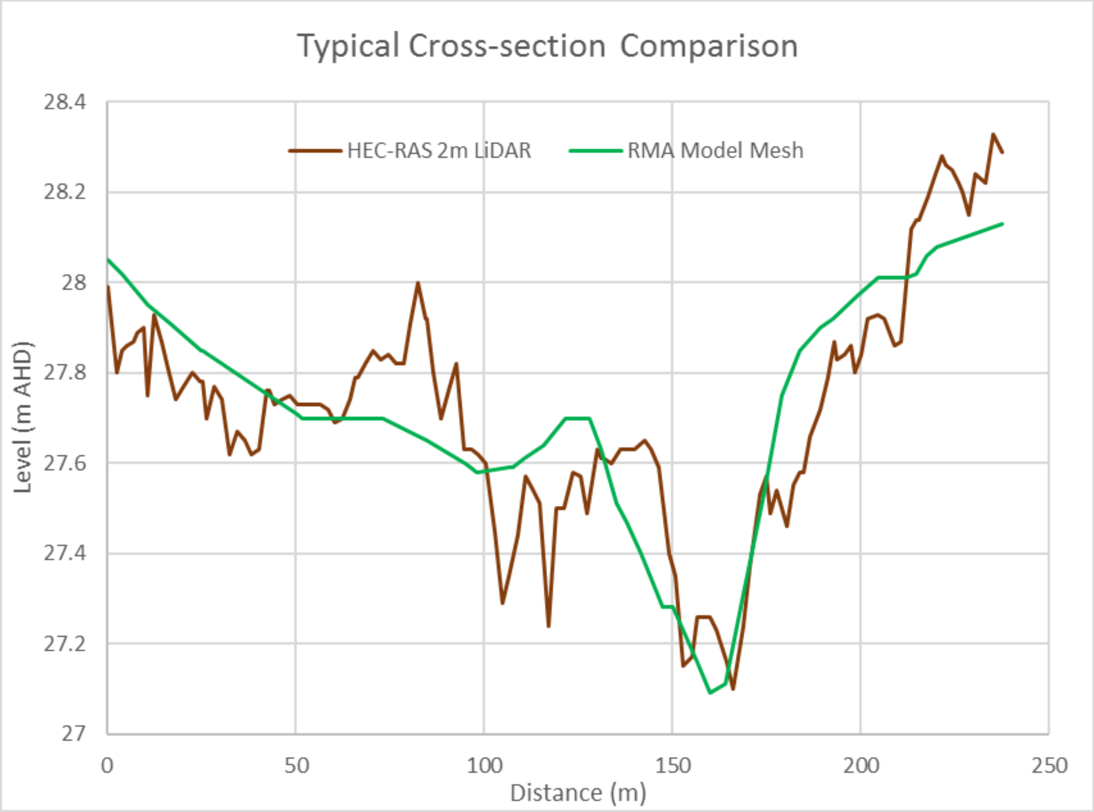


Figure 35 - Typical cross-section comparison for Knapsack Ck. breakout analysis

7 Design Flood Model Results

7.1 Data Processing

The model result files were converted into waterRIDE™ time series files to facilitate visualisation and assessment for the Flood Study and to facilitate further analysis for future floodplain management studies. The conversions included the full hydrographs captured at 15 minute intervals.

The 100yr ARI design flood shows incipient flow through the Emu Plains floodplain and the Andrews Road flow corridor. The wetting and drying routine in RMA-2 has left some isolated elements in these areas with remnant shallow depths outside the core inundated area. These areas require some cleaning to avoid misinterpretation of the results. During the early stages of flow overtopping embankments, the water surface, although hydraulically correct, may be just below ground on the downstream face. This issue can also be cleaned using waterRIDE™ tools.

For the larger floods, 200yr ARI and up, the wetting/drying issue only appears for a short period on the rising limb, but the embankment overflow issue occurs at several locations and has been cleaned in a similar fashion.

A peaks surface set was extracted from each time series flood result file and mapped to the 2m grid DEM, **Section 4**. Once mapped, the blocked out building areas within the model were filled by stretching the mapped result files to generate continuous surfaces.

7.2 Overview of Results

An overview of the results from the modelling are presented in the following figures and tables including a composite flood coverage map, a map of the flood affected area, river profiles, and peak flood parameters (*level, depth, velocity & flow distribution*) at selected locations. A full set of flood result maps is included in **Appendix A, Volume 2**.

The locations selected for the flood parameters cover the river channel, floodplain breakouts and critical road low points, **Figure 36**.

A comparison of the range of design floods is provided as a set of flood surface profiles along the river channel where the risk from rarer floods is obvious in the larger relative increase in flood levels, **Figure 37**.

The entire flood affected area is shown as flood depths for the PMF flood where the significant depths of 4 to 5m of flooding over the urban areas can be seen, **Figure 38**.

The initial limited inundation of the floodplain by the 100yr ARI flood, the significant expansion of floodplain inundation by the 200yr ARI and the extended coverage by the rarer floods is shown in a composite map of all flood extents, **Figure 39**.

Table 7 - Design floods peak levels, depths, velocities and flow distribution

Location	20yr ARI	50yr ARI	100yr ARI	200yr ARI	500yr ARI	1000yr ARI	2000yr ARI	PMF
M4 Bridge	w 25.01 d 14.49 v 4.45 q 100%	w 26.75 d 16.22 v 4.88 q 99.8%	w 28.22 d 17.69 v 5.22 q 99.4%	w 29.25 d 18.73 v 5.82 q 99.0%	w 29.78 d 19.25 v 6.62 q 98.7%	w 30.77 d 20.24 v 7.55 q 95.8%	w 31.05 d 20.52 v 7.69 q 92.8%	w 32.54 d 22.01 v 8.40 q 84.3%
Victoria Bridge (*Penrith Gauge*)	w 23.36 d 10.32 v 3.55 q 100%	w 24.97 d 11.93 v 3.86 q 99.6%	w 26.30 d 13.25 v 4.13 q 99%	w 27.32 d 14.28 v 4.26 q 91.6%	w 28.06 d 15.02 v 4.28 q 79.1%	w 29.28 d 16.24 v 4.29 q 72.2%	w 29.56 d 16.53 v 4.30 q 70.1%	w 31.13 d 18.11 v 4.30 q 57.8%
Boundary Creek (*mouth*)	w 22.78 d 9.56 v 2.32 q 100%	w 24.38 d 11.16 v 2.37 q 100%	w 25.63 d 12.41 v 2.58 q 99.3%	w 26.58 d 13.36 v 2.67 q 94.7%	w 27.22 d 14.01 v 2.67 q 86.9%	w 28.16 d 14.94 v 2.71 q 79.7%	w 28.41 d 15.19 v 2.71 q 77.5%	w 30.15 d 16.93 v 2.72 q 65.7%
Penrith Lakes (*Main Lake A*)	na	w 20.30 d 6.80 v 0.39 q 4.7%	w 21.97 d 8.47 v 0.50 q 14.0%	w 22.78 d 9.28 v 0.67 q 25.0%	w 23.77 d 10.27 v 0.72 q 35.6%	w 25.71 d 12.21 v 0.77 q 50%	w 26.24 d 12.74 v 0.76 q 52%	w 29.02 d 15.52 v 0.70 q 69%
Devlin Road	w 17.64 d 16.34 v 1.96 q 100%	w 19.25 d 17.96 v 2.17 q 100%	w 20.43 d 19.13 v 2.55 q 100%	w 21.50 d 20.20 v 2.86 q 100%	w 22.43 d 21.14 v 3.17 q 100%	w 24.09 d 22.79 v 3.63 q 100%	w 24.55 d 23.25 v 3.75 q 100%	w 27.02 d 25.72 v 4.34 q 100%
Kooringal Drive	w 16.01 d 1.78 v 0.21 q 0.7%	w 17.57 d 3.34 v 0.83 q 5.3%	w 18.41 d 4.18 v 1.27 q 9.8%	w 19.29 d 5.07 v 1.64 q 12.8%	w 20.07 d 5.84 v 1.79 q 26.4%	w 21.43 d 7.20 v 1.93 q 30.4%	w 21.83 d 7.60 v 1.95 q 34.4%	w 24.02 d 9.79 v 1.98 q 41.7%
Yarramundi Bridge (*lagoon low point*)	w 15.98 d 2.73 v 0.15 q 1.9%	w 17.40 d 4.15 v 0.51 q 11.4%	w 18.09 d 4.84 v 0.79 q 14.2%	w 18.90 d 5.65 v 1.06 q 17.0%	w 19.63 d 6.38 v 1.26 q 30.7%	w 20.95 d 7.70 v 1.49 q22.7%	w 21.36 d 8.11 v 1.53 q 26.2%	w 23.60 d 10.35 v 1.70 q 27.8%
Knapsack Creek breakout	na	na	w 27.71 d 0.55 v 0.54 q 0.15%	w 28.55 d 1.38 v 1.30 q 1.8%	w 28.94 d 1.66 v 1.20 q 4.3%	w 29.79 d 2.51 v 1.38 q 4.8%	w 30.04 d 2.76 v 1.53 q 5.6%	w 31.31 d 4.03 v 2.24 q 8.2%
Great Western Highway Emu Plains	na	na	w 26.13 d 0.32 v 1.66 q 0.23%	w 27.21 d 1.40 v 1.74 q 2.3%	w 28.12 d 2.31 v 1.78 q 6.7%	w 29.29 d 3.48 v 1.82 q 10.1%	w 29.54 d 3.73 v 1.83 q 11.4%	w 30.90 d 5.09 v 1.86 q 17.7%
Emu Plains upstream of railway	na	na	w 24.75 d 0.64 v 0.08 q 0.38%	w 27.21 d 3.09 v 0.12 q 3.5%	w 28.10 d 3.98 v 0.32 q 9.6%	w 29.25 d 5.13 v 0.53 q 15.3%	w 29.49 d 5.37 v 0.60 q 17.1%	w 30.82 d 5.09 v 1.86 q 27.1%
Old Bathurst Road (*Lapstone Creek*)	na	na	w 23.81 d 0.48 v 0.40 q 0.4%	w 25.02 d 1.69 v 1.01 q 1.2%	w 25.89 d 2.56 v 1.54 q 2.2%	w 27.09 d 3.76 v 1.74 q 3.7%	w 27.40 d 4.07 v 1.73 q 3.8%	w 29.46 d 6.12 v 1.73 q 4.8%

w=water level (m AHD), d=depth (m), v=velocity (m/s), q=% of total flow

Location	**20yr ARI**	**50yr ARI**	**100yr ARI**	**200yr ARI**	**500yr ARI**	**1000yr ARI**	**2000yr ARI**	**PMF**
Jamison Road (*Peachtree Creek*)	na	w 24.43 d 0.73 v 0.50 q 0.4%	w 25.63 d 1.93 v 0.44 q 0.6%	w 27.23 d 3.52 v 0.43 q 3.2%	w 28.37 d 4.67 v 0.41 q 6.3%	w 29.68 d 5.97 v 0.53 q 8.3%	w 29.95 d 6.25 v 0.58 q 10.0%	w 31.43 d 7.73 v 0.82 q 14.7%
Great Western Highway (*Peachtree Creek*)	na	w 24.36 d 0.62 v 0.35 q 0.4%	w 25.62 d 1.87 v 0.42 q 0.7%	w 27.10 d 3.36 v 0.87 q 5.0%	w 28.17 d 4.43 v 1.16 q 12.6%	w 29.39 d 5.65 v 1.42 q 12.3%	w 19.65 d 5.91 v 1.46 q 12.8%	w 31.12 d 7.38 v 1.58 q 15.1%
Castlereagh Road (*North Penrith*)	na	na	w 25.33 d 0.94 v 0.29 q 0.3%	w 26.23 d 1.84 v 0.34 q 0.8%	w 26.86 d 2.47 v 0.35 q 1.2%	w 27.79 d 3.40 v 0.36 q 1.6%	w 28.04 d 3.66 v 0.36 q 1.7%	w 29.86 d 5.48 v 0.36 q 1.9%
Andrews Road	na	na	w 24.95 d 0.27 v 1.07 q 0.3%	w 25.14 d 0.46 v 1.69 q 1.9%	w 25.35 d 0.67 v 2.28 q 3.4%	w 26.44 d 1.76 v 2.59 q 5.0%	w 26.87 d 2.19 v 2.59 q 5.3%	w 29.33 d 4.65 v 2.59 q 7.2%
Nepean Street	na	na	w 22.09 d 0.29 v 0.10 q 0.3%	w 23.27 d 1.47 v 1.29 q 1.9%	w 24.11 d 2.31 v 1.43 q 3.4%	w 25.80 d 4.00 v 1.57 q 5.0%	w 26.32 d 4.52 v 1.61 q 5.3%	w 29.09 d 7.29 v 1.68 q 7.2%
Farrells Lane Cranebrook	na	na	w 21.50 d 0.39 v 0.17 q 0.3%	w 23.24 d 2.13 v 0.57 q 1.9%	w 24.10 d 3.00 v 0.64 q 3.4%	w 25.78 d 4.68 v 0.76 q 5.0%	w 26.30 d 5.20 v 0.74 q 5.3%	w 29.06 d 7.96 v 0.78 q 7.2%

w=water level (m AHD), d=depth (m), v=velocity (m/s), q=% of total flow

Figure 36 - Key flood parameter locations (south right, north above left)

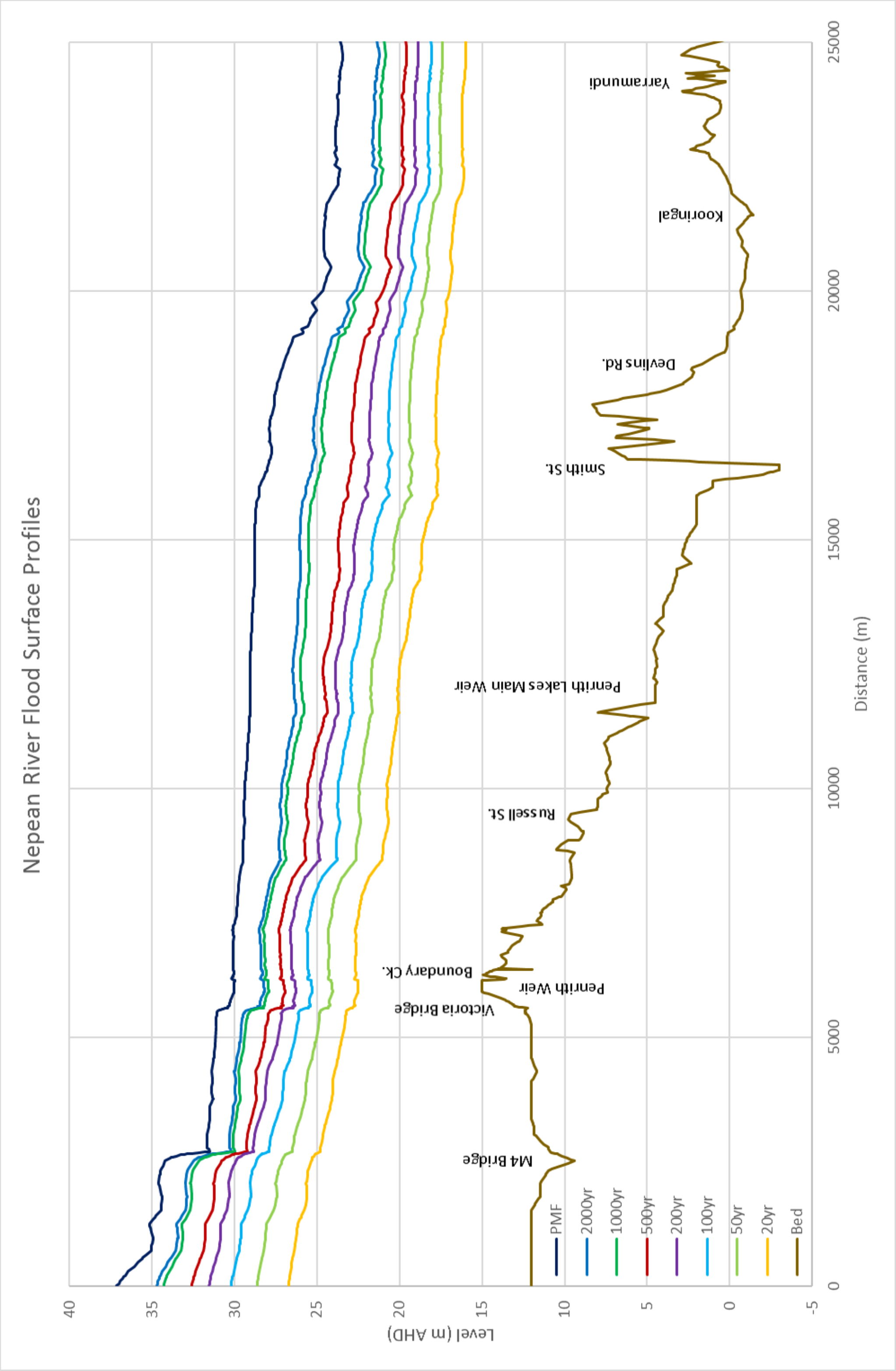


Figure 37 - Design floods river surface profiles A3 version included in Appendices

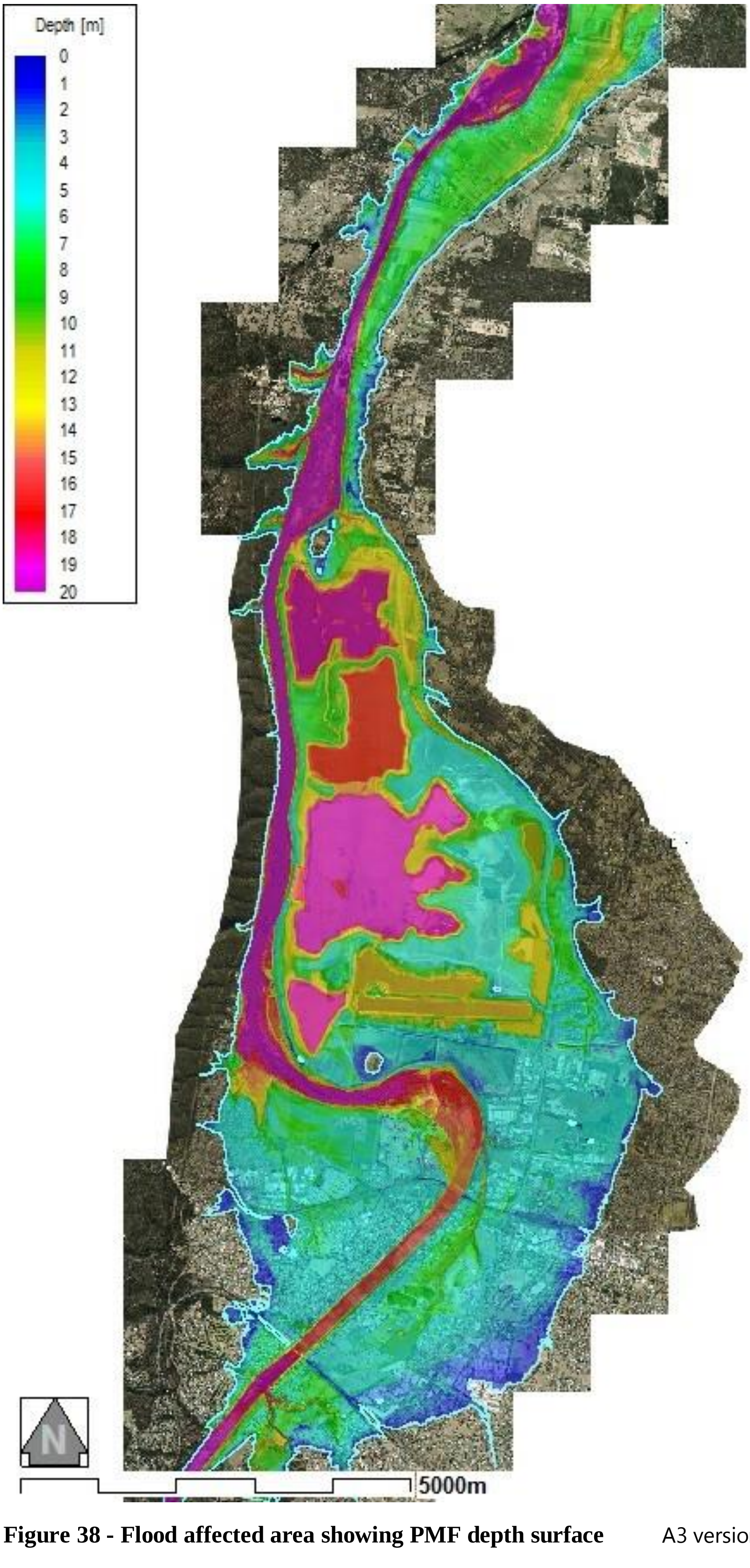


Figure 38 - Flood affected area showing PMF depth surface A3 version included in Appendices

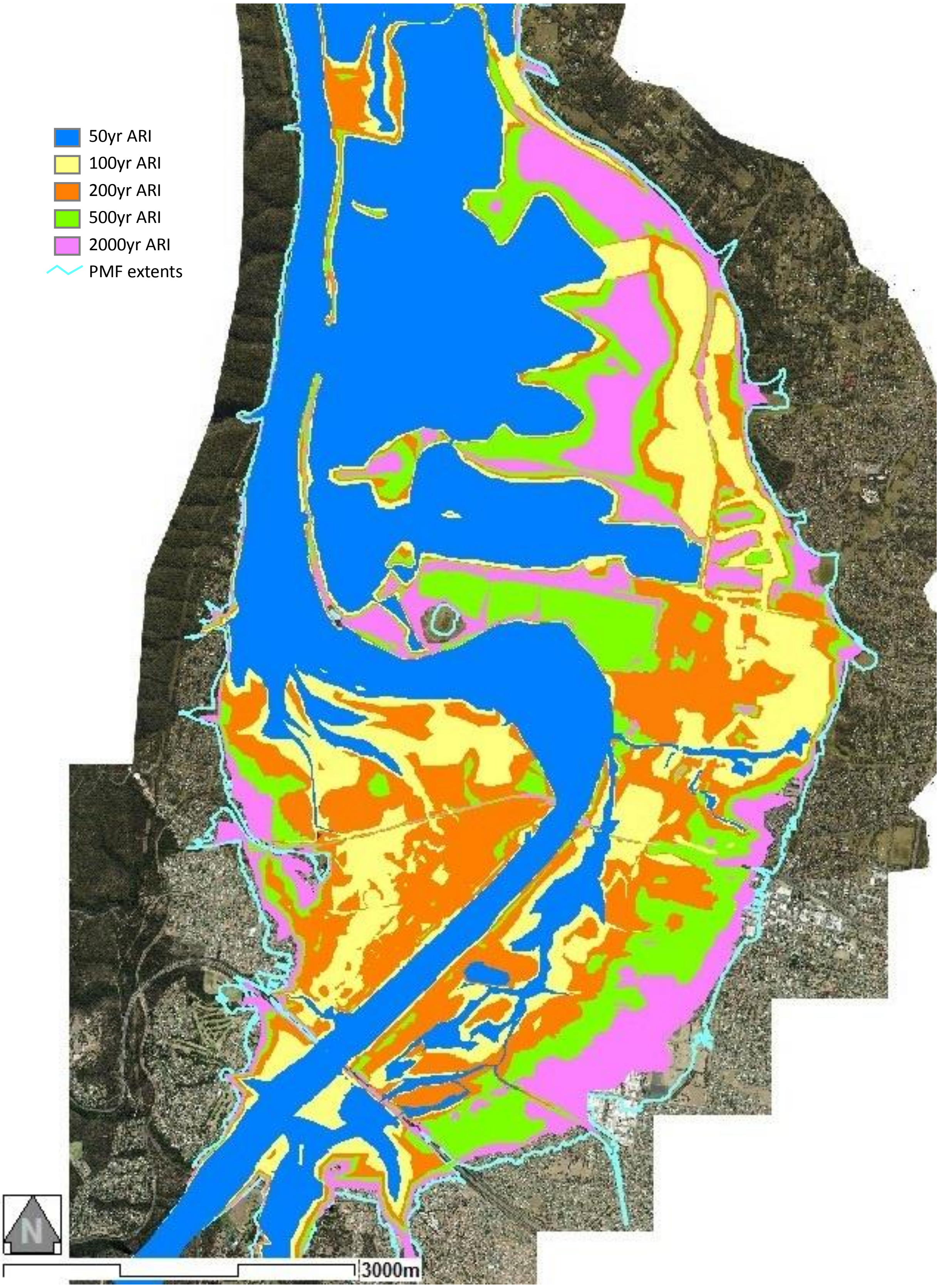


Figure 39 - Composite overlay of design flood extents, Penrith Lakes and urban areas

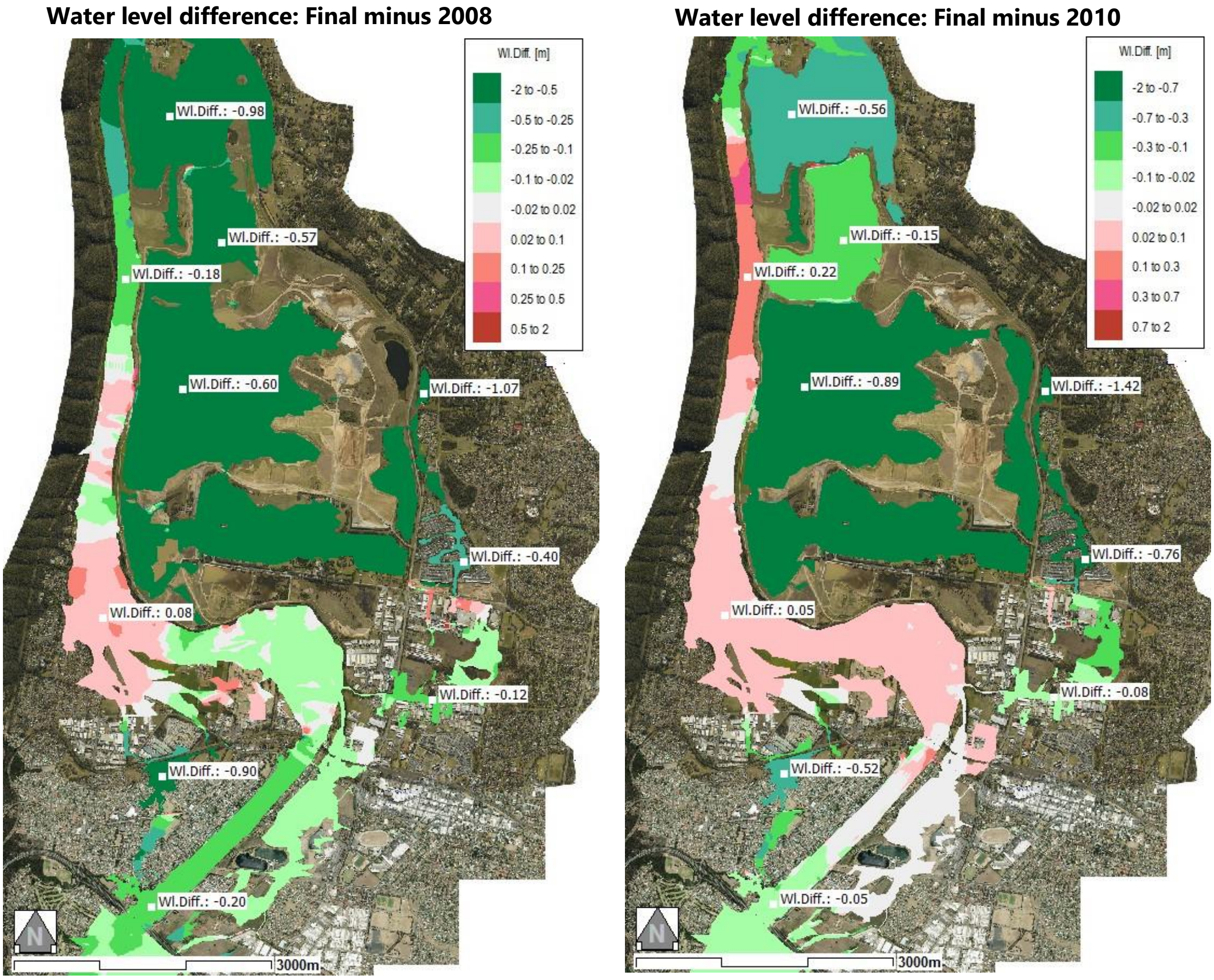
7.3 Model Comparison

Some assessments have been undertaken over the past several years on the basis of the ‘Alignment Scheme’ (2008 & *2010*) model results as discussed above in **Section 1**. Additionally, flood planning levels within the Emu Plains residential area have been based on the 2008 model.

Compared to the 2010 model, the final model has slightly higher river levels upstream of Devlin Rd, except for the upstream end where the reverse is the case. The Penrith Lakes levels are considerably lower as a result of the difference in hydraulic connections to the river. This difference is reflected in much lower levels in Cranebrook village and through the Waterside development, **Figure 40**.

Compared to the 2008 model, the final model has lower levels throughout the river channel except for a small increase through the downstream end of the S bend. The Penrith Lakes, Cranebrook Village and Waterside levels are, like the 2010 model comparison, also considerably lower, **Figure 40**.

The overflow from Knapsack Creek across the Emu Plains residential area is lower when compared to the 2010 model and more so when compared to the 2008 model



Water level difference: Final minus 2008

Water level difference: Final minus 2010

Figure 40 - 100yr ARI flood level comparison between the 2008, 2010 and final models

The Emu Plains residential area floodplain and the Andrews Rd corridor floodplain are only just activated for the 100yr ARI flood.

In the case of the Andrews Road corridor the final model for the 100yr ARI flood does not see Duralia Lake overtopping into the Main Lake A. The model results indicate a storage volume of 3.57M cu.m and an inflow volume of 3.21M cu.m. In contrast the 'Alignment' model results for the 100yr ARI flood saw flow initially entering Duralia Lake from the Main Lake before Duralia Lake filled and the flow reversed. The model results indicate a storage volume of 3.93M cu.m and a net inflow of 3.34M cu.m. These volumes are higher but somewhat similar to the final model and the differences in flood behaviour along the Andrews Road corridor between the two models can be explained by the different configuration of the Penrith Lakes Scheme.

The short duration of overtopping from Knapsack Creek into the Emu Plains residential area south of the railway for the 100yr ARI flood, results in a peak volume of flood storage of 0.13M m^3 with 1.1M m^3 having passed through the area. The 2010 'Alignment' model results indicate a peak storage volume of 0.35M m^3 with 1.7M m^3 passing through and likewise for the 2008 model results, the storage is 0.55M m^3 and the through flow is 3.3M m^3. These variations can be explained by the improvements made to the model mesh and the improved calibration with successive iterations of the model.

7.4 Detailed Model Results

The results for each design flood have been converted into a useful digital format then mapped to the 2m grid study DEM to provide Council with a resource to access the spatial and temporal data generated by the model. These data sets have been used to generate the summary data in **Table 7** and to produce a series of detailed model result maps, **Appendix A: Volume2**.

The maps present the following datasets:

Flood Surface Profiles: showing a comparison of each design flood river channel profile from the M4 Bridge downstream to Yarramundi Bridge.
Appendix A, Volume2, MAP 002.

Provisional Flood Hazards and Hydraulic Categories: as described in Section 8 below for the 100yr ARI, 200yr ARI and PMF design floods.
Appendix A, Volume2, MAP 004, MAP 005, MAP 006 & MAP 007.

Extent of Inundation: showing the flooded area for each design flood (*20yr, 50yr, 100yr, 200yr, 500yr, 1000yr and 2000yr ARI and the PMF*).
Appendix A, Volume2, MAP 008 to MAP 015.

Flood Levels: showing a thematically mapped and contoured surface of flood levels to AHD for each design flood (*20yr, 50yr, 100yr, 200yr, 500yr, 1000yr and 2000yr ARI and the PMF*).
Appendix A, Volume2, MAP 016 to MAP 023.

Floodwater Depths: showing a thematically mapped surface of flood depths in metres for each design flood (*20yr, 50yr, 100yr, 200yr, 500yr, 1000yr and 2000yr ARI and the PMF*).
Appendix A, Volume2, MAP 024 to MAP 031.

Flow Velocities: showing the floodwater flow velocity surface thematically mapped with flow direction arrows for each design flood (*20yr, 50yr, 100yr, 200yr, 500yr, 1000yr and 2000yr ARI and the PMF*).

Appendix A, Volume2, MAP 032 to MAP 039.

There are a significant number of properties affected by Nepean River flooding within the Penrith LGA, ranging from under 500 for a 20yr ARI flood to over 7000 for a PMF. The property count was based on the maximum depth of flood waters around the perimeter of each property parcel for each design flood. The Penrith Lakes Scheme area was excluded in the assessment.

Table 8 - Numbers of properties affected by flooding

Flood	Depth > 0m	Depth > 1m	Depth > 2m	Depth > 5m
20yr ARI	455	384	333	259
50yr ARI	742	530	444	296
100yr ARI	2305	1182	619	331
200yr ARI	4440	2793	1552	401
500yr ARI	5608	4314	2374	500
1000yr ARI	6576	5871	4686	868
2000yr ARI	6772	6123	5124	1194
PMF	7433	7084	6502	2964

8 Hazard and Hydraulic Categories

8.1 Provisional Flood Hazard Categories

Penrith City Council have adopted the Australian Rainfall and Runoff hazard categories (*AR&R 2016, Book 6, Chapter 7*) as provisional flood hazard categories for regional flooding from the Hawkesbury-Nepean River throughout the Penrith LGA. Details of the classification are presented in **Table 9** and **Figure 41**.

Table 9 - Hydraulic Hazard Classification (*AR&R 2016, Book 6, Chapter 7*)

Hazard Classification	Description
H1	Generally safe for vehicles, people and buildings
H2	Unsafe for small vehicles
H3	Unsafe for vehicles, children and the elderly
H4	Unsafe for vehicles and people
H5	Unsafe for vehicles and people. All building types vulnerable to structural damage. Some less robust building types vulnerable to failure
H6	Unsafe for vehicles and people. All building types considered vulnerable to failure

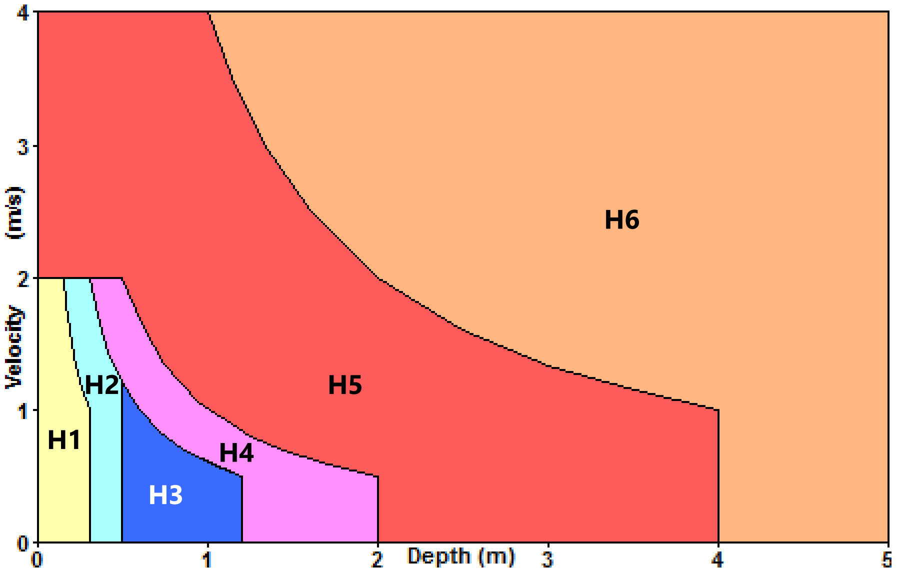


Figure 41 - AR&R 2016 hazard categories chart

For all design floods the hazard category along the entire river channel is H6. The 100yr ARI flood commences to breakout across the floodplain generating hazards across Emu Plains residential area, the Peachtree Creek residential area, some of the North Penrith industrial area, and some the Kooringal properties. As the floods become progressively larger, more properties are affected across the floodplain areas with increasing hazard. A summary of these progressive impacts for selected floodplain areas is given below, **Table 10**.

Table 10 - Progressive flood hazard impacts across selected areas

Location	Flood Hazards
Emu Plains residential	100yr – H1 to H3 for some properties 200yr – H1 to H5 for all east side properties 500yr – H3 to H6 for all east side properties 1000yr – H5 to H6 for all east side properties
Peachtree Creek residential	100yr – H3 to H4 for the west side properties 200yr – H4 to H5 for most of the residential properties 500yr – H5 to H6 for the west side properties
Emu Plains industrial	200yr – H1 to H4 for a third of the properties 500yr – H2 to H6 for half the properties 1000yr – H2 to H6 for all properties
Emu Plains north residential	100yr – up to H4 for a small number of properties 200yr – H1 to H5 for ¾ of the affected properties 500yr – H3 to H6 for most of the affected properties 1000yr – H4 to H6 for the affected properties
North Penrith industrial	100yr – H1 to H3 for several properties 200yr – H1 to H5 for most of the properties 500yr – H3 to H5 for most of the properties 1000yr – H4 to H5 across all properties
Waterside residential	200yr – H2 for a small number of properties 500yr – H1 to H3 for about a fifth of the properties 1000yr – H3 to H5 for most of the properties
Cranebrook Village	100yr – up to H3 for a few properties 200yr – H3 to H5 for half the properties 500yr – H4 to H5 for most of the properties 1000yr – H4 to H6 for all the properties
Kooringal Drive	100yr – up to H5 for some properties 200yr – H4 to H6 for all properties 500yr – H5 to H6 for all properties 1000yr - H6 for all properties

8.2 Hydraulic Classification

The NSW Government's *'Floodplain Development Manual'* (*2005*) also characterises flood prone areas according to the hydraulic categories presented in **Table 11**. The hydraulic categories provide an indication of the potential for development across different sections of the floodplain to impact on existing flood behaviour.

Table 11 - Hydraulic Category Criteria

HYDRAULIC CATEGORY	DESCRIPTION
FLOODWAY	• those areas where a significant volume of water flows during floods • often aligned with obvious natural channels • they are areas that, even if only partially blocked, would cause a significant increase in flood levels and/or a significant redistribution of flood flow, which may in turn adversely affect other areas • they are often, but not necessarily, areas with deeper flow or areas where higher velocities occur.
FLOOD STORAGE	• those parts of the floodplain that are important for the temporary storage of floodwaters during the passage of a flood • If the capacity of a flood storage area is substantially reduced by, for example, the construction of levees or by landfill, flood levels in nearby areas may rise and the peak discharge downstream may be increased. • Substantial reduction of the capacity of a flood storage area can also cause a significant redistribution of flood flows.
FLOOD FRINGE	▪ the remaining area of land affected by flooding, after floodway and flood storage areas have been defined. ▪ Development in flood fringe areas would not have any significant effect on the pattern of flood flows and/or flood levels.

Unlike for the hazard categorisation outlined above, the *'Floodplain Development Manual'* (*2005*) does not provide explicit quantitative criteria for defining hydraulic categories. This is because the extent of floodway, flood storage and flood fringe areas is largely dependent on the geomorphic characteristics of the floodplain in question.

The geomorphic evolution of the Hawkesbury-Nepean valley within the Penrith LGA includes a relatively narrow floodplain situated between the Glenbrook gorge and the Castlereagh constriction, before expanding into the Richmond lowlands. The narrow floodplain is divided into three parts by the river which crosses the floodplain at the S-bend, creating a northern part across Penrith Lakes and the eastern side of the valley, and two southern parts, the western side over Emu Plains and the eastern side over the Mulgoa and Central Business District (*CBD*) area. The gravel and cobble deposits extracted from the northern part of the floodplain are evidence of a high energy flow regime. The modelling confirms this situation in regard to the higher floods where the entire valley floor is inundated to considerable depth and essentially becomes one floodway.

The lower floods are essentially representative of in-channel flows where velocity times depth values range from 20 to over 60. The 50yr ARI flood also overtops the river weir into Penrith Lakes initiating a through flow, which is fully activated in the 100yr ARI flood. Velocity times depth values across the floodplain areas for the 100yr ARI flood are typically less than 1.

Setting a velocity times depth (*V*D*) threshold to estimate the floodway from the 100yr ARI extents will eliminate the emergent floodplain flowpaths but at the same time eliminate a large portion of the Penrith lakes area. Adding in a depth criteria as well as the V*D threshold will also include large sections of the floodplain flowpaths which do not convey significant flows until greater than a 500yr ARI flood.

In consideration of these circumstances, it would be prudent to consider the river channel and Penrith Lakes as a floodway (*similar to the extent of the 50yr ARI flood)*), the floodplain areas as storage, and no flood fringe areas.

The floodway extents made use of the 50yr ARI flood extents with backwater areas excluded. These backwater areas include the tributaries of Peachtree Creek, Schoolhouse Creek, Mulgoa Creek, Tunnel Gully, Knapsack Creek, Lapstone Creek, Boundary Creek, and the gullies along the western side of the river downstream of the S-bend, **Figure 42**. The probable maximum flood extents were used to define the flood storage area outside of the floodway.

Further to this general hydraulic classification of the Nepean floodplain through the Penrith LGA, hydraulic categories were identified for the 100yr ARI, the 200yr ARI and the PMF flood. These categorisations show the floodway in relation to the flood extents for each of these three design floods, **Appendix A, Volume 2, Map 004**.

These maps demonstrate the significance of the channel capacity for containing floods up to the 200yr ARI and the spread of floodway characteristics across much of the floodplain for a PMF. The maps were generated using hydraulic parameters to replicate the geomorphic appreciation of the floodplain. The same hydraulic parameters were used for each of the three floods allowing the floodway area to be determined by velocity and depth relationships. The parameters involved (Velocity times Depth > 4) AND (Velocity > 0.5) OR (Depth > 5).

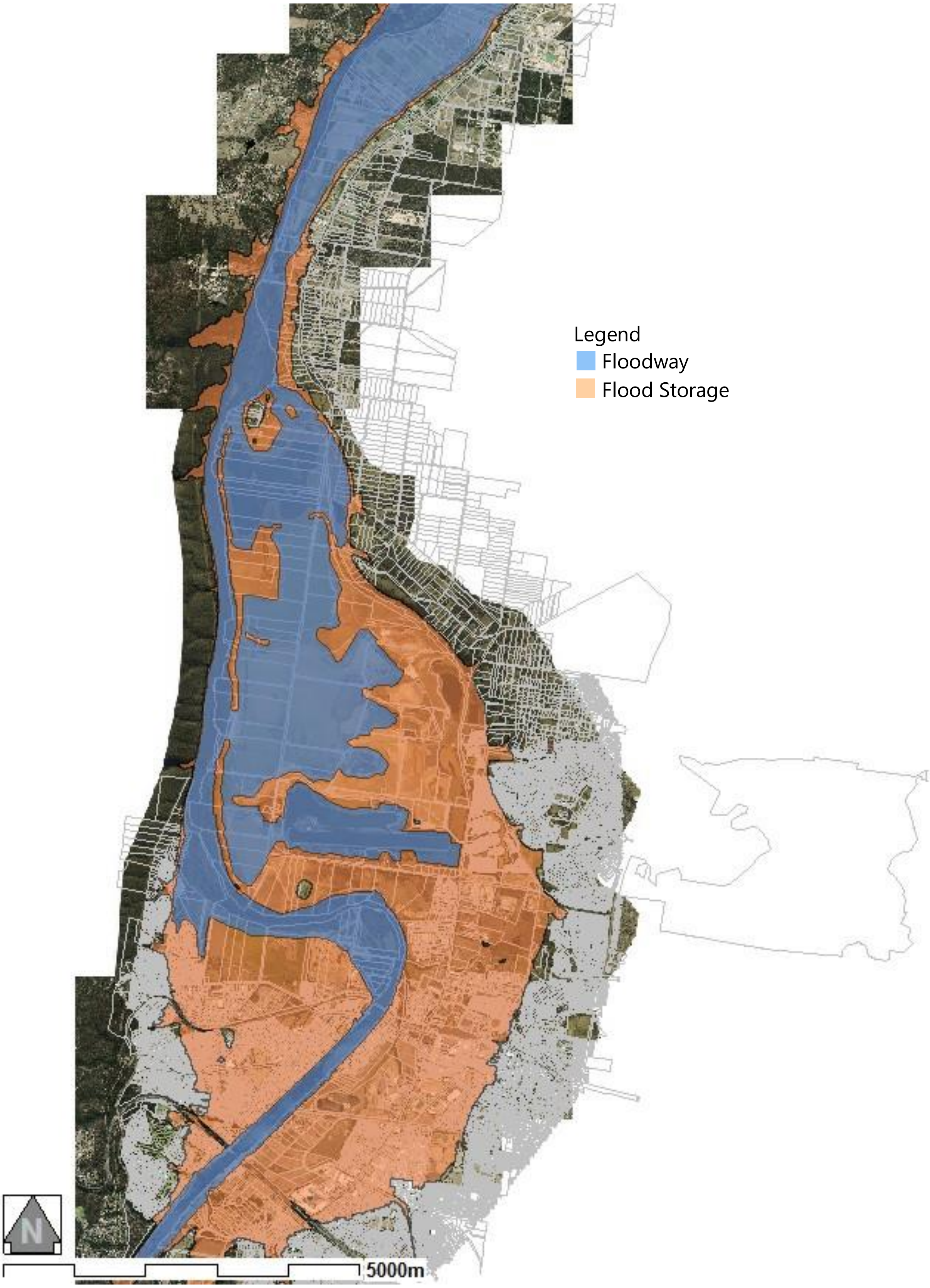


Figure 42 – Hydraulic Classification

9 Hot Spots Analysis

The following flood behaviour analyses have been undertaken using the design flood hydrographs as a reference for timings. The times shown are indicative only and may vary under real flood conditions.

9.1.1 Flood Behaviour – Emu Plains Residential

The Emu Plains residential area encompasses the flood affected area between the railway line and M4 embankments west of the river and covers approximately 1900 dwellings. More importantly, however are the dwellings situated between the central drainage path and the river plus the small enclave between the M4 and Knapsack Creek. There are almost 1200 residences in these two areas that will require evacuation before rising flood levels break out of Knapsack Creek and eventually engulf these properties, **Figure 43.**

Apart from a small number of local streets on the west side, the Great Western Highway would act as the central evacuation route. Highway access over Victoria Bridge to the east is cut by water backing up Peachtree Creek some 5 hours prior to the breakout at Knapsack Creek and hence evacuation would likely have to proceed to the west.

At 600 vehicles per hour (*HNFMAC 1997*), evacuation would thus need to commence in earnest at least 2 hours before the Knapsack Creek breakout occurs. This time is equivalent to RL 25.5m AHD at the Penrith gauge (*Victoria Bridge*), which is approximately a 65yr ARI flood. Likewise, the Highway crossing over Peachtree creek is affected at approximately a 45yr ARI flood.

The Knapsack Creek breakout is not activated for floods smaller than the 100yr ARI, and at the peak of the 100yr ARI flood the majority of the residential area east of the central drainage path is not affected. Hence the 200yr ARI flood is considered more appropriate for identifying the impacts on the community for severe floods. Likewise the 2000yr ARI flood is suitable for assessing the impacts of extreme floods with a higher rate of rise. The rate of rise of flood waters at the time of the Knapsack Creek breakout is 0.3 m/hr for the 200yr and 500yr ARI floods and rises to 0.4 m/hr for the 2000yr ARI and to 0.5 m/hr for the PMF.

The following table provides a sequential breakdown of flood behaviour during the rising stages of severe and extreme floods, where evacuation prior to egress being cut is essential.

Table 12 - Emu Plains Residential, flood evacuation constraints

Time after Knapsack Ck. Breakout	Situation
0 hours (creek level RL 27.65m)	A third of the properties between Knapsack Creek. and the M4 Motorway will be inundated and all will have lost egress
+ ½ hour (27.77m)	150 properties adjacent to the Railway will be inundated by 0.2 to 0.4m, the Great Western (*GW*) Highway will be passable
+ 1 hour (27.86m)	Some properties adjacent to the Railway at Hartigan Avenue will be affected to H3 hazard, the GW Highway will be affected to H1 hazard
+ 2 hrs severe flood (28.05m)	More properties affected to H3 hazard, GW Highway passable for trucks
+ 2 hrs extreme flood (28.32m)	Some properties have increased to H4 hazard, the GW Highway has increased to H5 with high velocities

+ 3 hours severe flood (28.21m)	Several properties have increased to H4 hazard and the GW Highway has increased to H2
+ 3 hrs extreme flood (28.54m)	Some properties and the GW Highway have increased to H5 hazard
+ 6 hrs severe flood (28.49m)	Several properties have increased to H4 hazard where floodwaters are > 2m deep
+ 6 hrs extreme flood (28.93m)	A large number of properties are H5 hazard, where floodwaters are > 3m deep, all properties are flooded on the east side
+ 14 hrs (28.74m)	Peak of the 200yr ARI flood, only a few properties within the east side along the river's natural levee have some dry land

Figure 43 - Emu Plains residential area flood related characteristics

9.1.2 Flood Behaviour – Penrith and Jamisontown

The Penrith and Jamisontown area encompasses the flood affected area between the Railway Line and M4 embankments east of the river up to Mulgoa Road and covers approximately 650 dwellings, including an aged care facility. There are also a number of industrial and commercial facilities including the Panthers football club. More importantly, however are the dwellings situated between the central drainage path and the river. There are 220 residences in this area, including semi-rural, that will require evacuation before rising flood levels remove egress to the east. The entire area is flood affected.

Flooding of the area from the Nepean River is initially caused by waters backing up Peachtree Creek from the main channel, **Figure 44**. There are a number of low point constraints affecting evacuation of the various areas within the precinct, **Table 13**.

Some 10 hours after the initial inundation of the area (*loss of Jamison Rd*), the river bank commences to overtop its natural levee around Nepean Shores and just north of Jamison Rd, **Figure 44**. Some minor flow from the river occurs at the northern end of the precinct, close to the railway at the bend in Memorial Avenue, where the Old Ferry Road cuts through the natural levee. This inflow commences before the main levee overtopping and flows along Memorial Avenue into the backwater pond.

At the peak of the 100yr ARI flood, the river is overflowing through the Old Ferry Road cutting, however there is no overflow across any of the natural levee along the right bank of the Nepean River. At the peak of the 200yr ARI flood, a significant length of the levee would just be overtopping with the majority of the area between the river and Mulgoa Road inundated. Exceptions are the Jamisontown industrial block and half the adjacent residential area to the north.

The area only becomes a major flowpath during the extreme floods, 1000yr ARI and greater. As a result 200yr ARI velocities across the residential areas are less than 0.2m/s, and hazards are H5 across the western residential area, where depths are up to 3m.Likewise, hazards are H4 over the eastern residential area and H3 over the aged care facility.

At the peak of the 2000yr ARI flood, the level is more than 2m over the top of the river bank levee and the gradients across the length of the precinct and the river are equal.

A description of the key egress control points and their time of inundation relative to backwater in Peachtree Creek inundating the Jamison Road crossing is provided in **Table 13**.

Table 13 – Jamisontown and Penrith evacuation constraints

Location	Elevation	Usage	Rel. Time
Jamison Road at Peachtree Creek crossing	22.0m	primary egress route for the rural residential dwellings and the Nepean Shores	0 hours
Blaikie Road at drainage crossing	25.8m	alternate egress route for the rural residential dwellings, usage controlled by access to the road at RL 25.3m	+ 3.8 hrs
Tench Road at M4 underpass	25.6m	alternate egress route for the Tench Road dwellings and Nepean Shores	+ 2.5 hrs
Great Western Highway	24.1m	only egress for western residential area	+ 4.3 hrs
Area east of central drainage	various	residential dwellings, the aged care facility and industrial/commercial areas have a number of local roads providing access to flood free land	+ 7.5 hrs

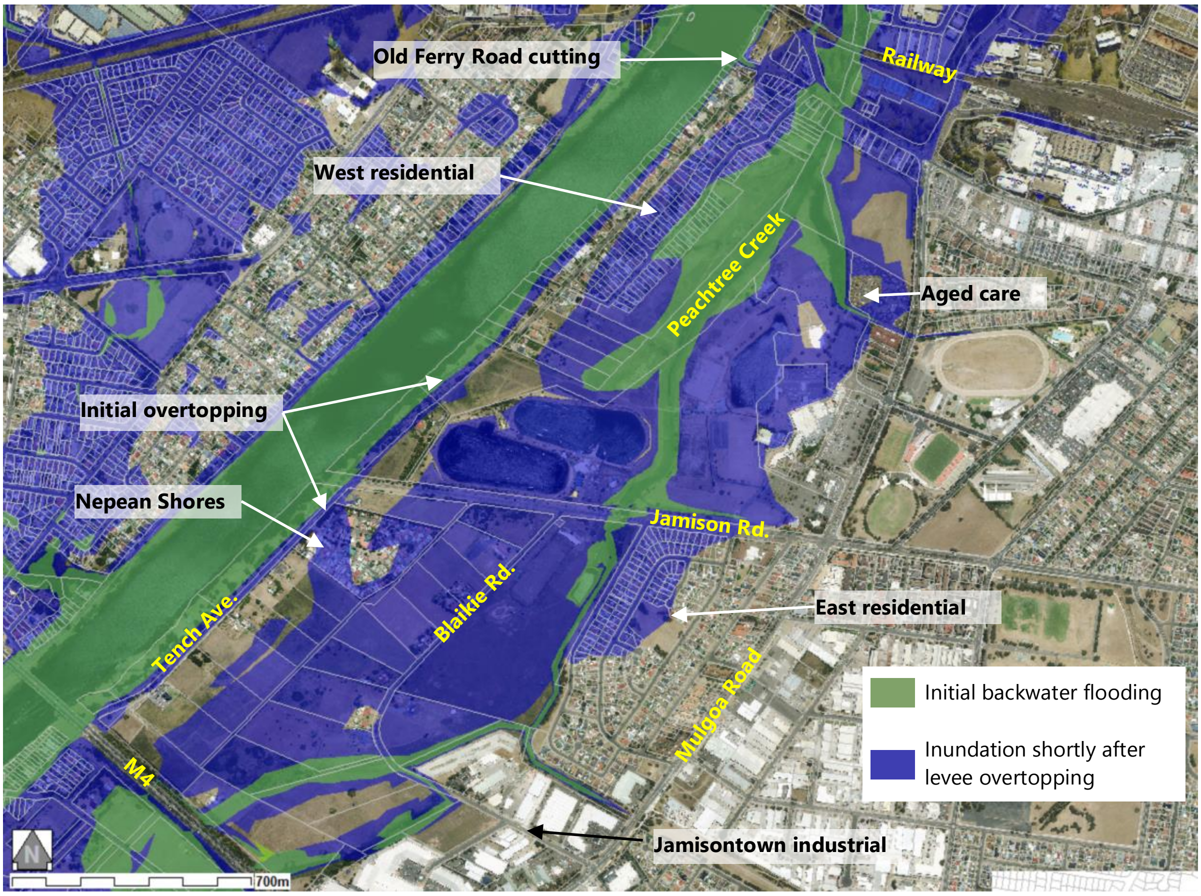


Figure 44 – Jamisontown and Penrith flood characteristics

9.1.3 Flood Behaviour – Emu Plains North

The Emu Plains north area encompasses the area between the railway embankment and the S-bend in the river. The flood affected area includes a band of residential properties to the north alongside the river, two residential blocks separated by a drainage path along the west side, a correctional facility around the centre of the area, industrial development alongside the railway, and a college and holiday facility at the eastern edge, **Figure 45**.

The band of properties to the north is the first area to become affected across Emu Plains north. The 100 or so properties become isolated when Wedmore Road is cut at a Penrith gauge level of RL 23.9m. Property inundation occurs shortly thereafter along Alma Crescent, and a total of 40 dwellings are flood affected.

The north residential block has a direct connection to Wedmore Road and is progressively flooded over about 5 hours commencing at a Penrith gauge level of RL 27.1m. Wedmore Road remains open during this time but is cut shortly after all the properties have been affected.

The south residential block only has a footpath connection to Wedmore Road. The main access to the area is at the eastern edge onto Russell Street. Egress along Russell Street is cut at around the same time that flooding of the north block commences. This is about 9 hours after the band of properties to the north is isolated.

The correctional facility becomes isolated where its access road joins Old Bathurst Road. This occurs at a Penrith gauge level of RL 26.05m or about 6 hours after the band of properties to the north is isolated. The facility is completely inundated some 4 hours later.

The industrial properties east of Lapstone Creek plus the holiday centre and McCarthy College become isolated when Old Bathurst Road is cut at Lapstone Creek and to the east around the same time that the correctional facility access is cut. Depending on the magnitude of the flood and the rate of rise, flow through the railway opening 200m to the west of the Old Bathurst Road underpass may result in the road being cut earlier.

The industrial area west of Lapstone Creek becomes progressively inundated but access to high ground along Bromley Road remains open as the flooding progresses westwards.

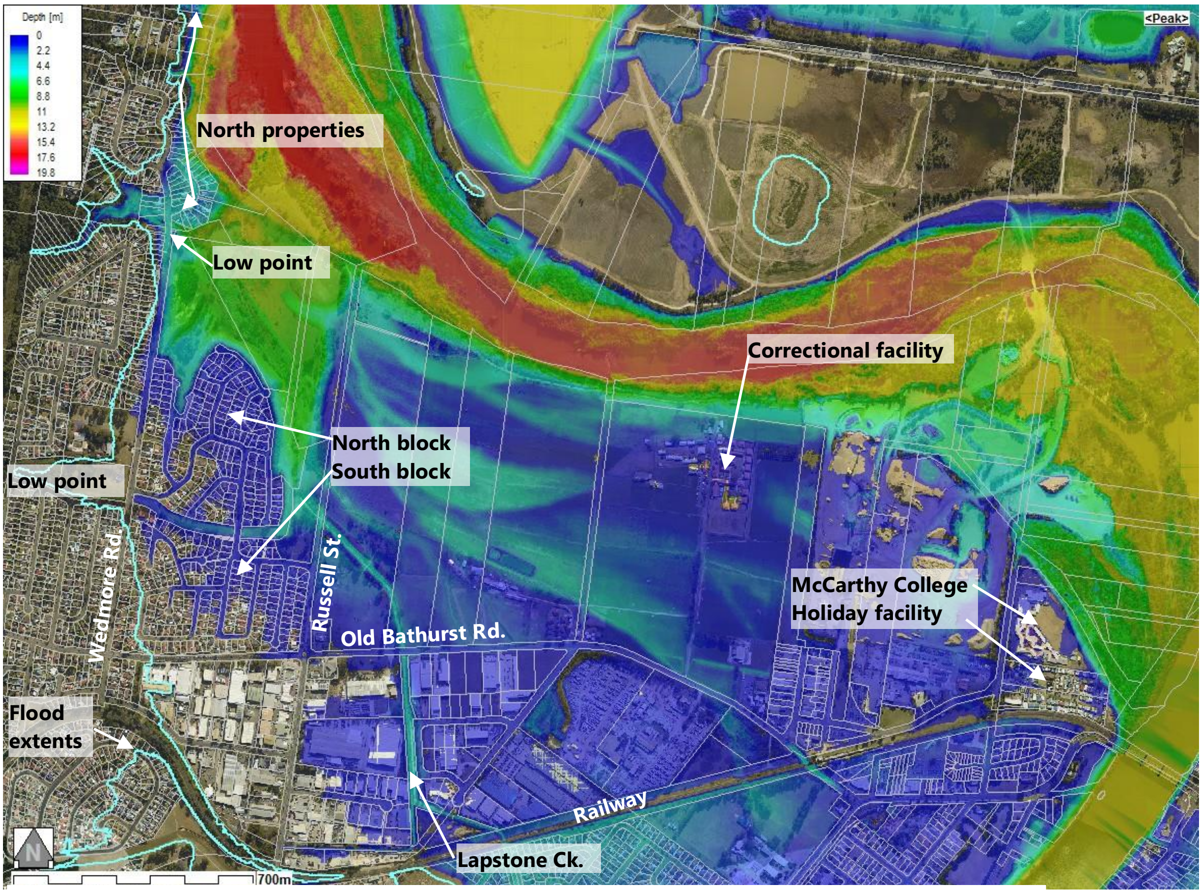


Figure 45 - Emu Plains North, peak 200yr ARI depth surface and PMF flood extents

9.1.4 Flood Behaviour – Andrews Road Corridor

The Andrews Road corridor follows a relict flowpath along the eastern edge of the valley running northwards from Boundary Creek. It currently emanates as a backwater breakout from the creek at the rear of the Penrith Sewerage Treatment Plant (*STP*) and traverses across Andrews Road, through the Waterside lakes, under Castlereagh Road just south of Cranebrook, then through the North Pond and Duralia Lake, and eventually draining into Penrith Lakes Main Lake A, **Figure 47**.

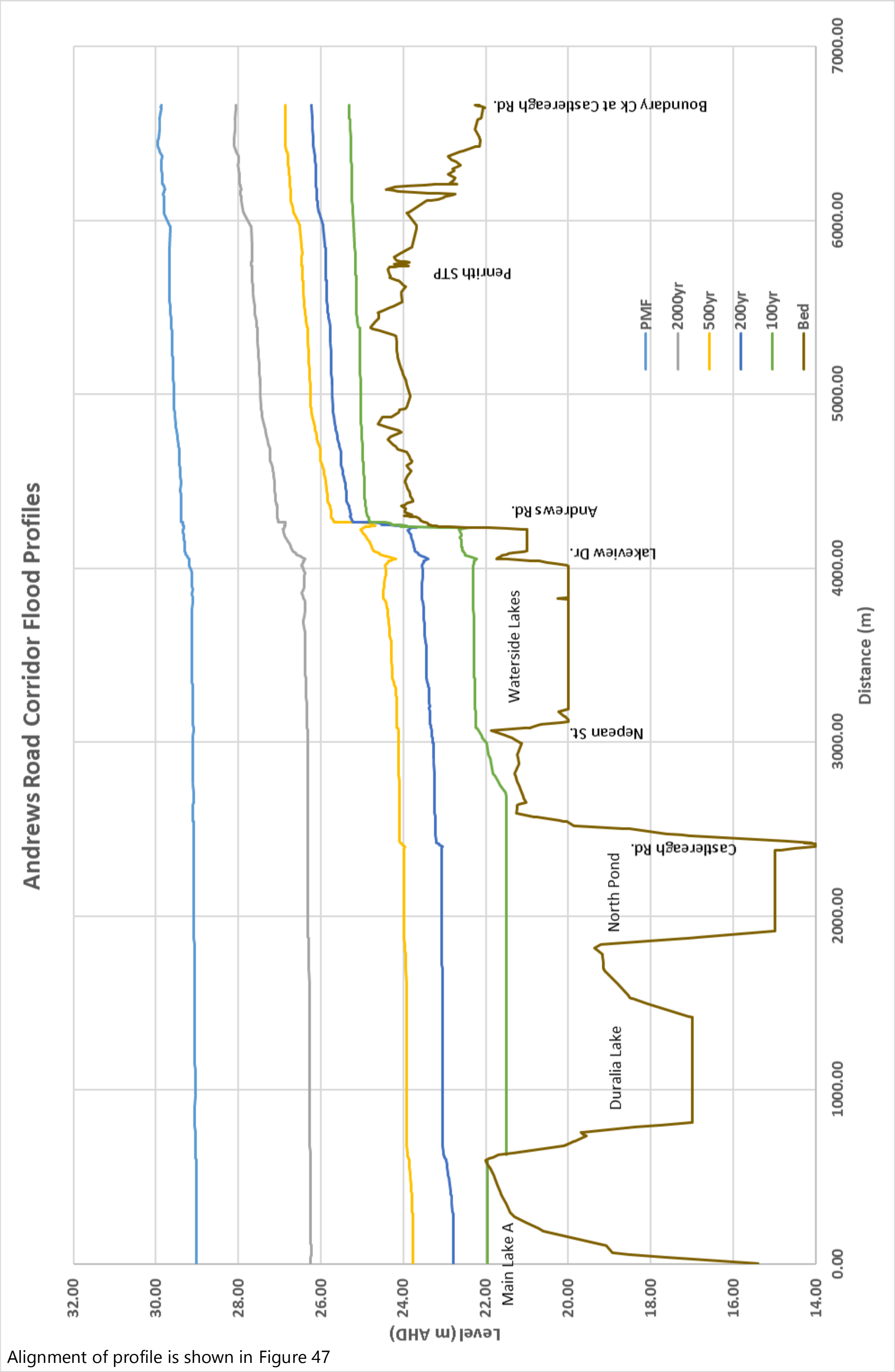
Under the normal operating levels of the eastern lakes within the Penrith Lakes Scheme, there is insufficient volume of overflow along the Andrews Road corridor for the 100yr ARI flood to completely fill Duralia Lake, and thus the peak 100yr ARI level in Cranebrook village and Waterside is sensitive to both the volume and the initial level of the lakes. The 200yr ARI and higher floods experience a fully connected flowpath between Boundary Creek and Main Lake A, **Figure 46**.

The Boundary Creek breakout occurs at a Penrith gauge level of RL 25.5m and subsequent behaviour is detailed as follows, **Table 14**.

Table 14 - Andrews Road flow corridor, flood behaviour

Time Relative to Breakout	Flood Behaviour
0 hours (breakout level RL 24.7m)	Some industrial properties along the creek are affected
+ 2.8 hrs (25.01m)	Flow has expanded across the flowpath, connected through to Lambridge Place, overtopped Andrews Road and extended up Castlereagh Road while the Waterside lakes have been filling
+ 3.5 hrs (25.15m)	The Waterside lakes have filled and flow has crossed Nepean Street.
+ 5.8 hrs (25.58m)	Flow has connected through the Bebo arch culvert under Castlereagh Road into the North Pond within Penrith Lakes. Peachtree Creek, and the river north of Boundary Creek Have overtopped, inundating more of the industrial properties
+ 6.3 hrs (25.71m)	The North Pond has overflowed into Duralia Lake and Cranebrook Village has become affected
+ 7.0 hrs (25.89m)	Main Lake A overtops into Duralia Lake
+ 8.3 hrs (26.17m)	Access to Andrews Road from Waterside has been cut along Laycock Street.
+ 8.5 hrs (26.22m)	Main Lake A and Duralia Lake levels equalise, after which Duralia Lake remains slightly higher.

Note: Thea above times and levels at the breakout are based on the PMF design flood which has the fastest rate of rise.



Alignment of profile is shown in Figure 47

Figure 46 - Andrews Road flow corridor flood profiles

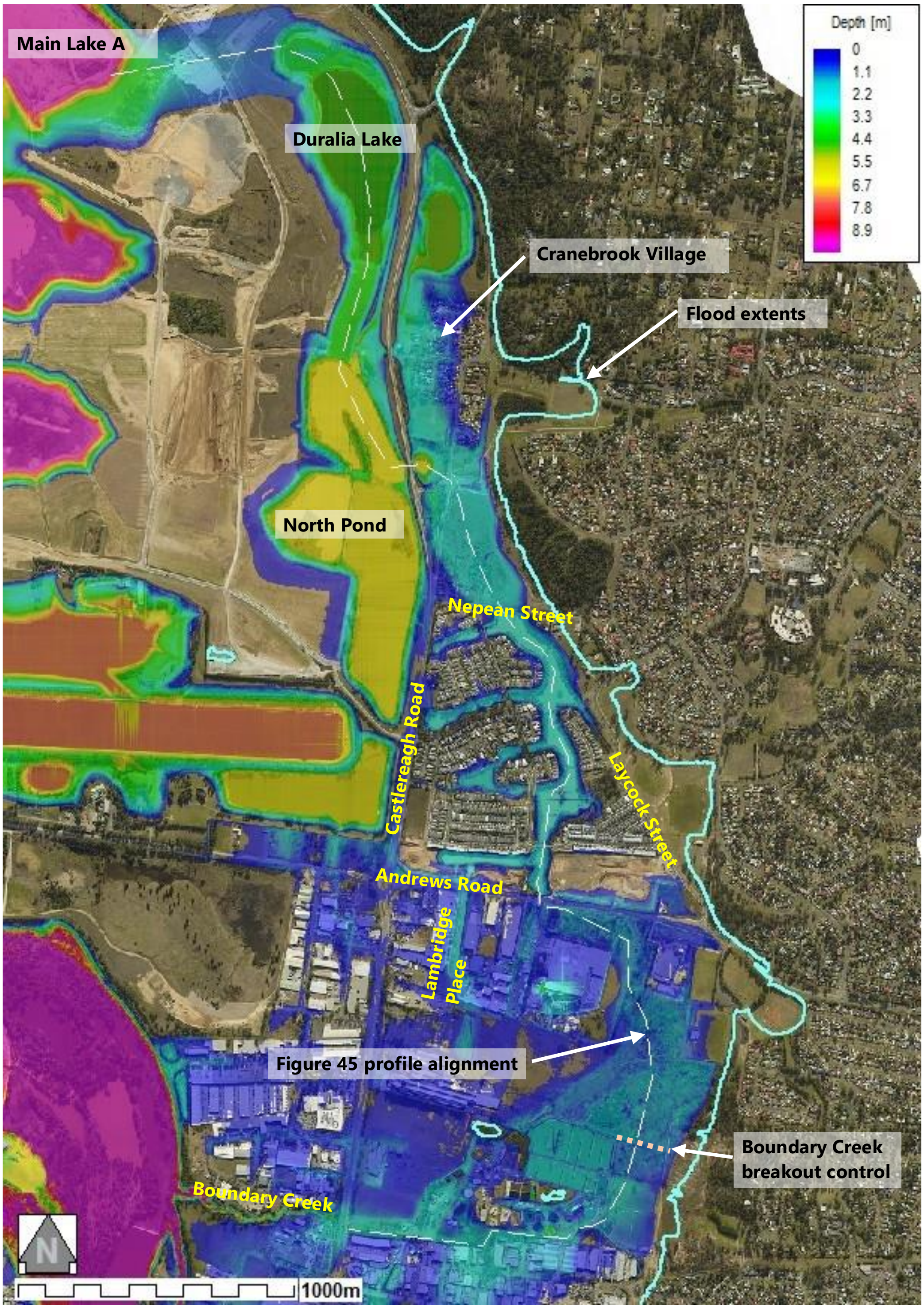


Figure 47 - Andrews Road flow corridor showing peak 200yr ARI depth and PMF extents

10 Flood Planning Area

The flood planning area is defined by the terrain and the flood planning level (*FPL*). Flood planning levels are related to flood levels from significant historical flood events and to floods of specific ARIs combined with freeboards selected for floodplain risk management purposes. Selecting appropriate flood planning levels for the construction of new development is fundamental to managing the risk to buildings on floodplains and is an integral part of the local floodplain risk management process.

The 100yr ARI flood is widely used in Australia as the basis for the FPL for residential development, and generally within NSW a freeboard of 0.5m is added to the 100yr ARI flood level to obtain the FPL for a property. Special circumstances can arise when the consequences of higher floods can result in significant losses.

Penrith City Council has adopted a FPL that is generally based on the 100yr ARI level with a freeboard of 0.5m. It is recommended that this definition of the FPL be adopted for the study area with two exceptions. The State Government has recognised the risks associated with development within the Penrith Lakes area and has established an increased freeboard of 1.0m. It is recommended that residential land that is affected by backwater flooding from Penrith Lakes but outside of the Penrith Lakes boundary also have a freeboard of 1.0m applied. Cranebrook Village would be affected by this condition. The other area is the Emu Plains residential area between the Great Western Highway and the railway embankment. This area has much lower 100yr ARI flood levels than the adjacent area south of the highway and will experiences a dramatic increase in depth for floods just above the 100yr ARI.

There are two floodplain flowpaths that have a significant impact on property. These are the overflow from Knapsack Creek onto the Emu Plains floodplain, and the relict flowpath along the eastern side of the valley emanating as backwater overflow from Boundary Creek (*Andrews Road corridor*). Flow initiates across both these flowpaths a few hours prior to the peak of the 100yr ARI flood and lasts for a period of about 10 hours.

The Andrews Road corridor terminates initially into the eastern lakes within the Penrith Lakes scheme and through flow is not established until the lakes have filled. The 100yr ARI model results indicate there is enough storage to accommodate the overflow volume from Boundary Creek and Duralia Lake does not overtop, **Figure 46**. Further details for Cranebrook village are discussed below.

The railway embankment creates a storage area within the Emu Plains residential floodplain with limited capacity for flow to pass through culverts and openings until the railway is overtopped. For the 100yr ARI flood, the limited duration of overflow from Knapsack Creek provides insufficient volume to fill this storage, whereas for the 200yr ARI the storage is filled and in the 500yr ARI flood, the railway is overtopped, **Figure 48**.

Flood levels within both these floodplain areas for the 100yr ARI flood are sensitive to the duration and volume of overtopping flows. In recognition of the inherent risk to lives and property in these two sensitive areas, an alternate approach to establishing the flood planning level is recommended.

In all other areas, apart from the Penrith Lakes Scheme, the flood planning level (*FPL*) is defined by the 100yr ARI flood surface plus 0.5m freeboard. The flood planning area is then determined by stretching this FPL surface to its intersection with the terrain surface, **Figure 50**.

Penrith Lakes Scheme

Flood planning levels within the bounds of the Penrith Lakes Scheme are under consideration by the NSW State Government as a part of SEPP 1989. As a result, the Penrith Lakes Scheme area has been excluded from the Flood Planning Area map, **Figure 50**.

Emu Plains Residential

The short duration of overtopping from Knapsack Creek into the Emu Plains residential area south of the railway for the 100yr ARI flood, results in a peak volume of flood storage of 0.13M m^3 with 1.1M m^3 having passed through the area. In contrast, the 200yr ARI flood has a storage volume of 2.1M m^3 and a throughput of 25M m^3. These results reflect the level pond extending from the railway embankment to south of the Great Western Highway for the 200yr ARI surface compared to the sharp drop over the Great Western Highway for the 100yr ARI surface, **Figure 48**, resulting in a difference of 2.4m in flood level. The difference in the river channel is only 1m.

Flooding in Emu Plains is highly sensitive to the river level at the mouth of Knapsack Creek and the duration the river level remains above the breakout level. The risk associated in using the 100yr ARI flood as a basis for flood planning levels within the Emu Plains residential area, especially between the railway and the Great Western Highway can be further expressed in the excessive increase in depth for the 200yr ARI flood, in comparison to other areas, **Table 15**.

In recognition of the risk that this local flood behaviour poses, three options are suggested for consideration:

1. Extend the FPL of 100yr ARI plus 0.5m freeboard (*RL of 26.44m AHD*) that exists just south of the Great Western Highway northwards until it meets the railway embankment.
2. Base the FPL for the area between the Great Western Highway and the railway embankment on the 200yr ARI surface.
3. Retain the FPL for the area which is based on the 2008 100yr ARI flood model results (*in reference to the 1st option, the current FPL has an effective freeboard of 0.2m*).

Option 1 is recommended as an interim measure until a Flood Risk Management Study and Plan is prepared and a suitable FPL for this area is adopted by Council.

This area has been included as per option 1 in the Flood Planning Area map, **Figure 50**.

Table 15 - 100yr to 200yr ARI flood level differences

Location	100yr ARI Level (m AHD)	200yr ARI Level (m AHD)	Increase (m)
Emu Plains (south of railway)	24.75	27.23	2.48
Mulgoa residential area	25.62	27.17	1.55
Emu Plains (north of railway)	23.82	25.04	1.22
North Penrith	25.25	26.12	0.87
Kooringal area (downstream)	18.48	19.38	0.90

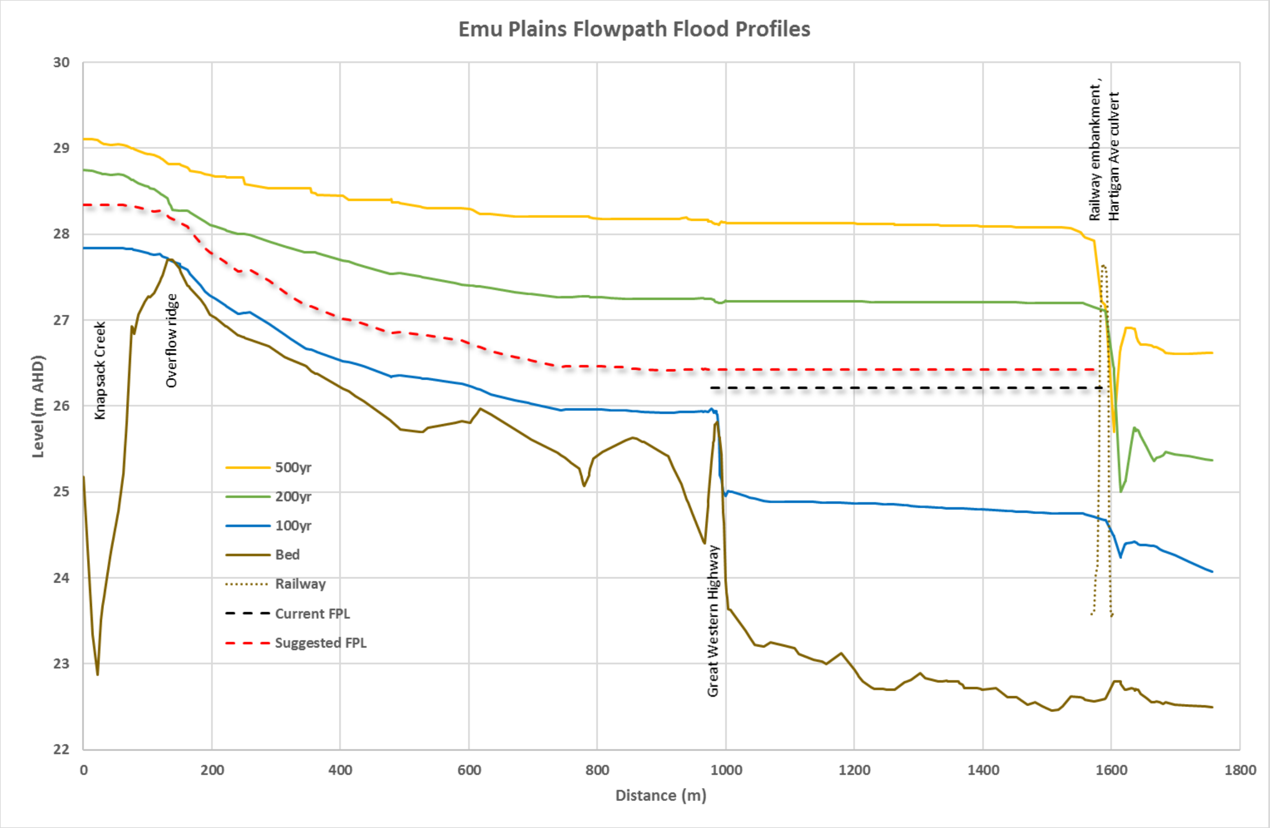


Figure 48 - Emu Plains floodplain flood profiles

Cranebrook Village

The Andrews Road corridor conveys flood flows backing up Boundary Creek and overflowing across the floodplain to the north, where they pass through the Waterside development, through the Bebo arch under Castlereagh Road, into the eastern lakes and finally, when Duralia Lake has filled into Main Lake A of the Penrith Lakes Scheme.. There is a large headloss across Andrews Road for the 100yr and 200yr ARI floods which isolates the industrial area south of Andrews Road from downstream backwater effects. An additional headloss across Nepean Street somewhat isolates Waterside from downstream levels, which are initially governed by the level in the eastern lakes until Duralia Lake joins with the level in Main Lake A. The results of the 100yr ARI flood model indicate that Duralia Lake does not completely fill, whereas for the 200yr ARI flood, Duralia Lake overflows into the Main Lake A, **Figure 46**.

Up until a point when Duralia Lake has filled and there is sufficient flow to cause a headloss through the Bebo arch, the flood level in Cranebrook Village is governed by the level in Duralia Lake. Although the modelling shows that Duralia Lake does not overtop for100yr ARI design flood, it is based on the assumption that the eastern lakes will start at their normal operating level.

Flood levels in Cranebrook Village are thus sensitive to the available storage in the eastern lakes and to the volume of flood waters flowing through the corridor. The overflow from Duralia Lake has been set at RL 22m AHD to exclude the 100yr ARI flood level in Main Lake A from backing up into Duralia Lake, whilst at the same time optimising the flow characteristics of the corridor for larger floods.

Antecedent rainfall may well lessen the available storage in the lakes, or a variation on the shape of the flood hydrograph, increasing the duration of corridor flows, may well lead to raised 100yr ARI flood levels in a real event. The risks associated with these outcomes need to be accommodated in the setting of a flood planning level for Cranebrook Village. The State Government has applied an increased freeboard of 1.0m for establishing flood planning levels across the Penrith Lakes Scheme (*SEPP 1989, Part 6 Clause 33, Part 1 Clause 5*), and it is recommended that flood planning levels for Cranebrook Village be consistent with this approach, by applying a 1.0m freeboard to the 100yr ARI level in Duralia Lake. This area has been included with the 1m freeboard in the Flood Planning Area map, **Figure 50**.

The flood planning area mapping is presented in **Appendix A, Volume 2, MAP 003**

Figure 49 - 100yr Flood extents map

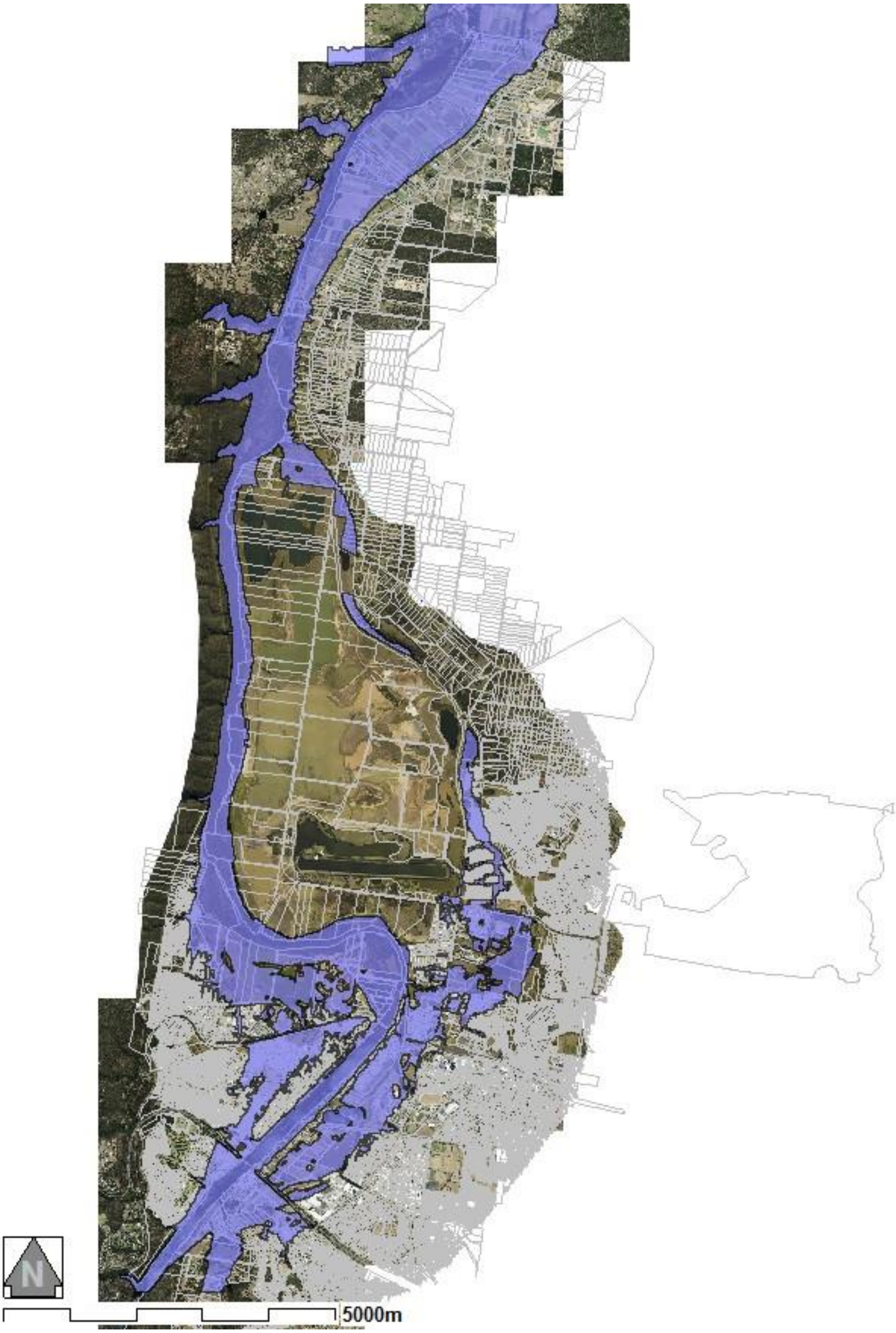


Figure 50 - Flood planning area map including above recommendations

11 References

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Appendix A:

Flood Modelling Results

The detailed flood modelling maps are located in volume 2 of the report.

Appendix B:

Site Photos of Hydraulic Structures

A – M4 MOTORWAY BRIDGE

B – TENCH RESERVE

C – PEACHTREE CK, JAMISON RD

C – PEACHTREE CK, JAMISON RD


16. 11. 2004


16. 11. 2004


16. 11. 2004

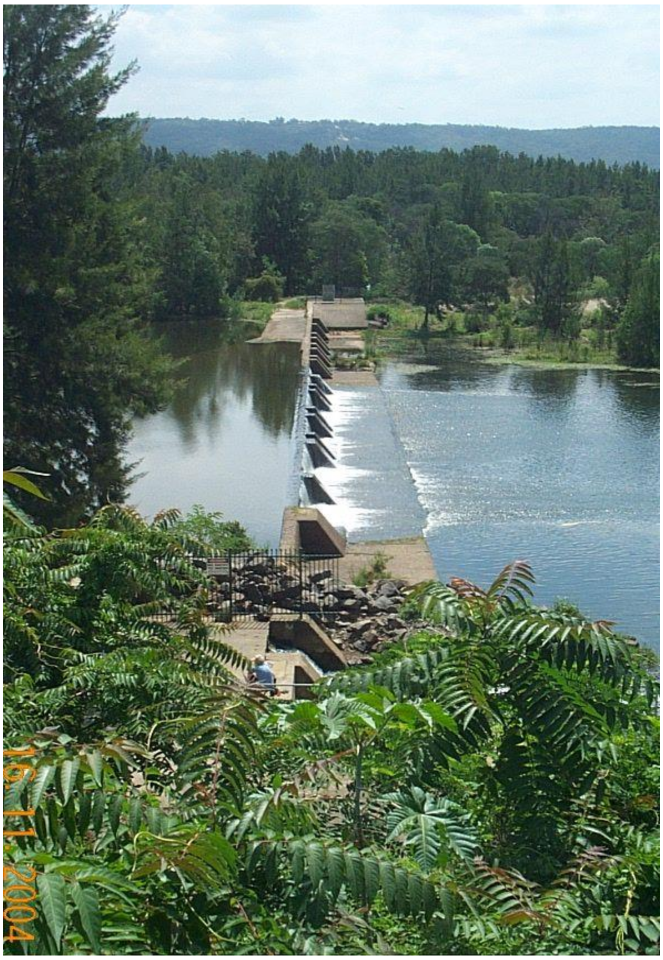

16. 11. 2004

D – PEACHTREE CK/SURVEYORS CK

E – BOUNDARY CK, CASTLEREAGH RD

F – CASTLEREAGH RD RAILWAY UNDERPASS

G NEPEAN RIVER WEIR



H – WEIR RESERVE & PEACH TREE CREEK RAIL UNDERPASS

H – PEACH TREE CREEK RAIL UNDERPASS

16. 11. 2004

16. 11. 2004

16. 11. 2004

H – PEACH TREE CK, GREAT WESTERN HIGHWAY BRIDGE & WEIR

H – PEACH TREE CK, GREAT WESTERN HIGHWAY BRIDGE

H – BRUCE NEALE DRIVE RAILWAY UNDERPASS

I – VICTORIA BRIDGE

16.11.2004

16.11.2004

16.11.2004

16.11.2004

16.11.2004

16.11.2004

I – VICTORIA BRIDGE

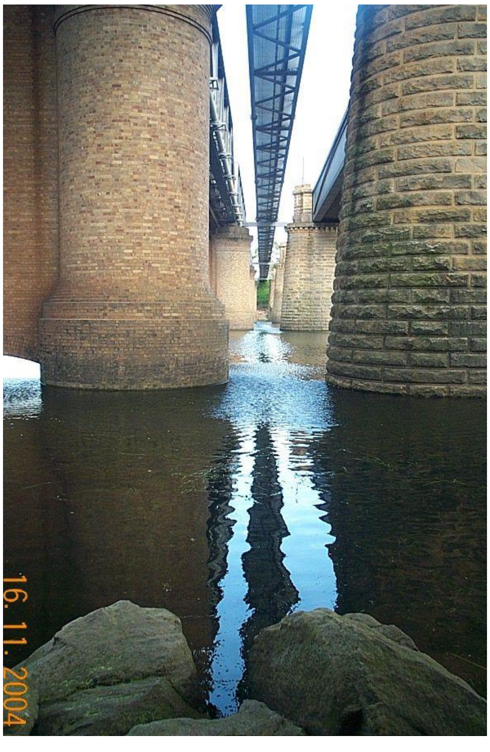
I – VICTORIA BRIDGE


16. 11. 2004


16. 11. 2004


16. 11. 2004


16. 11. 2004


16. 11. 2004


16. 11. 2004

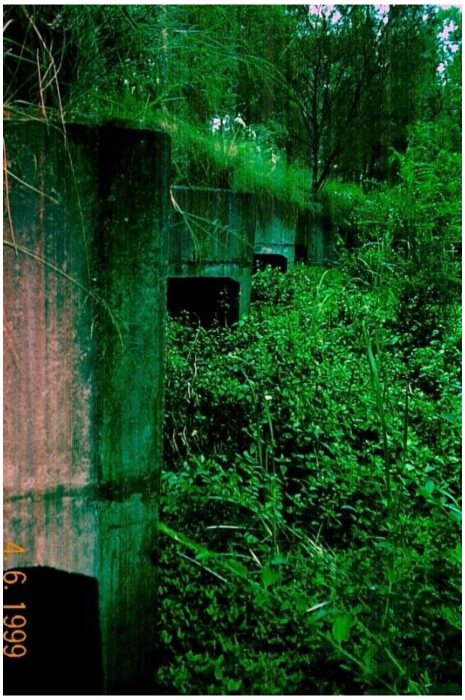
J – M4 MOTORWAY BRIDGE (WEST BANK)

K – FACTORY ROAD (M4 CULVERTS)

L – FACTORY ROAD (M4 CULVERTS)

M – RIGHT BANK LEVEE

N – KNAPSACK CK LEONAY PDE CULVERTS



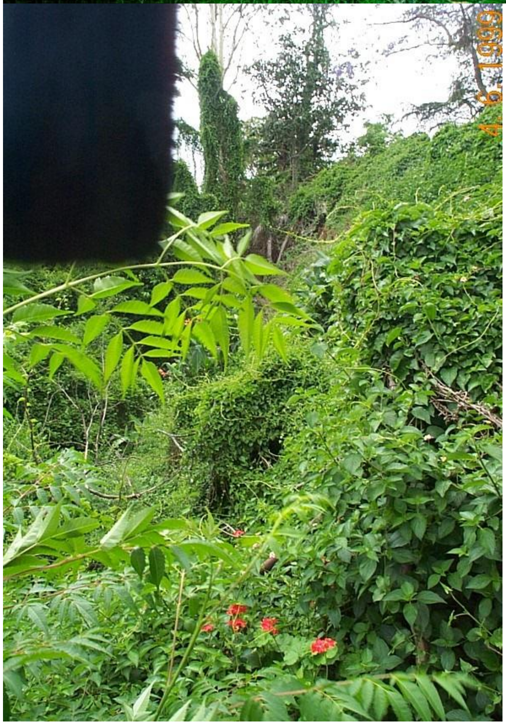
O – KNAPSACK CK RIVER RD CULVERT

4. 6. 1999

4. 6. 1999

4. 6. 1999

4. 6. 1999



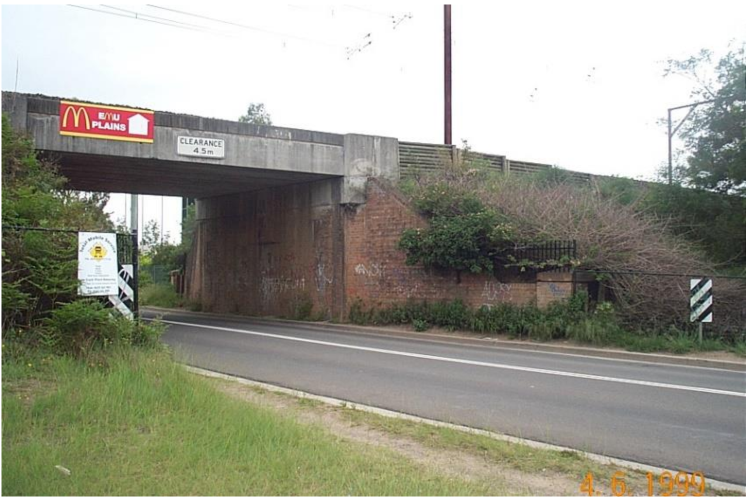
4. 6. 1999

4. 6. 1999

P – OPEN AREA AND EMBANKMENT NEAR

P – KNAPSACK CK OPEN AREA & NEPEAN ST BRIDGE

Q – RUSSELL ST & CONCRETE CHANNEL RAILWAY UNDERPASSES



R – CHANNEL UNDER RAILWAY NR NIXON ST (HARTIGAN AVE)


4. 6. 1999


4. 6. 1999


4. 6. 1999

S – OLD BATHURST ROAD RAILWAY UNDERPASS

S – OLD BATHURST ROAD RAILWAY UNDERPASS & OPENING NEAR NEPEAN HGH

T – YARRAMUNDI LAGOON & CROSSING


4. 6. 1999


4. 6. 1999


4. 6. 1999


4. 6. 1999


4. 6. 1999


4. 6. 1999

U – YARRAMUNDI BRIDGE

U – YARRAMUNDI BRIDGE

V – LOW GROUND NEAR YARRAMUNDI LAGOON

Appendix C:

RUBICON Model Inflow Hydrographs

RUBICON Model Design & Historic Flood Flow Hydrograph Data at F4BRDG (flow m^3/s)

Time (hours)	20yr ARI	50yr ARI	100yr ARI	200yr ARI	500yr ARI	1000yr ARI	2000yr ARI	PMF	1978	1986	1990
1.1	105.2									104.5	
1.6	93.9									103.6	
2.1	83.1									102.8	
2.6	92.2									101.5	
3.1	94.8									100.7	
3.6	91.3									104.0	
4.1	88.5									106.0	
4.6	86.7									108.6	
5.1	85.0									110.6	106.7
5.6	83.5									119.8	90.9
6.1	82.4									128.9	82.3
6.6	81.7									137.9	92.9
7.1	81.4									147.3	94.8
7.6	81.4									163.0	91.2
8.1	81.7									178.7	88.9
8.6	82.3									193.9	86.9
9.1	83.4									209.7	85.2
9.6	84.4									228.4	83.6
10.1	85.5					105.2	106.7	115.1		247.1	82.6
10.6	86.7					94.8	113.5	219.2		266.5	81.8
11.1	87.8					85.6	195.0	812.4		284.9	82.1
11.6	88.8					103.7	272.6	1225.7		311.2	83.6
12.1	89.9				105.2	119.3	386.3	1892.3		337.3	87.3
12.6	90.8				94.1	136.8	455.3	2252.5		362.8	102.1
13.1	91.7				83.5	159.7	522.1	2567.2		389.0	121.0
13.6	92.5				95.0	181.6	586.9	2873.7		438.3	149.9
14.1	93.3				101.2	202.8	649.7	3170.9		488.9	185.0
14.6	94.0				106.4	223.4	708.6	3446.4		537.8	221.7
15.1	94.6				115.8	245.9	777.9	3779.2		588.3	263.0
15.6	95.2				143.0	321.9	900.1	4163.0		627.3	309.2
16.1	95.7				179.0	448.0	1069.9	4578.6		667.4	356.0
16.6	96.2				231.1	628.8	1291.0	5027.1		707.7	394.0
17.1	96.6			105.2	294.8	867.2	1575.1	5569.1		746.9	422.7
17.6	97.0			96.3	389.0	1235.9	1974.8	6143.9		794.8	446.7
18.1	97.3			89.2	606.6	1656.4	2410.2	6663.5		842.0	469.8
18.6	97.6			108.8	873.5	1948.7	2730.5	7141.7		889.4	488.1
19.1	97.9	105.2	105.3	127.4	1285.7	2146.0	2958.9	7545.3		937.1	501.5
19.6	98.1	93.9	99.2	148.6	1645.8	2393.7	3222.8	7900.7		948.3	510.6
20.1	98.4	83.1	94.5	176.2	1880.7	2566.3	3416.2	8211.5		959.9	518.3
20.6	98.5	93.5	115.9	210.3	2017.5	2791.1	3649.4	8492.4		971.6	533.6

Time (hours)	20yr ARI	50yr ARI	100yr ARI	200yr ARI	500yr ARI	1000yr ARI	2000yr ARI	PMF	1978	1986	1990
21.1	98.7	97.9	135.7	246.2	2174.8	2932.3	3809.4	8757.9	105.5	983.2	649.6
21.6	98.9	99.1	154.2	282.9	2350.4	3128.0	4014.1	9013.7	95.8	977.0	902.5
22.1	99.0	103.4	176.0	323.7	2457.4	3334.0	4228.0	9272.6	86.9	971.4	1263.2
22.6	99.1	110.7	196.1	399.5	2527.4	3456.8	4371.5	9532.3	97.7	964.7	1652.2
23.1	99.2	119.9	215.9	510.0	2680.7	3654.6	4578.9	9794.3	102.7	959.0	1969.0
23.6	99.5	131.6	234.8	635.6	2801.1	3851.6	4785.7	10056.4	102.5	974.7	2243.7
24.1	99.8	143.9	256.5	769.6	2881.3	3981.0	4935.0	10317.6	103.1	989.7	2485.3
24.6	100.7	155.4	277.2	904.6	2934.7	4182.9	5148.4	10596.4	105.5	1005.6	2684.9
25.1	101.8	166.7	331.0	1119.3	3076.4	4362.5	5344.4	10884.4	108.0	1020.5	2928.6
25.6	102.8	175.8	397.8	1336.9	3244.7	4478.0	5487.9	11186.0	105.9	1034.2	3283.4
26.1	104.0	184.3	470.4	1504.8	3343.5	4612.3	5650.4	11507.4	104.6	1046.3	3696.6
26.6	105.5	192.1	547.1	1632.6	3408.8	4828.0	5882.7	11833.4	106.7	1059.1	3980.3
27.1	107.2	199.9	622.3	1731.1	3456.4	4958.0	6044.5	12174.8	109.4	1072.3	4187.8
27.6	112.5	212.9	702.6	1817.4	3553.3	5079.1	6202.4	12540.6	113.7	1091.1	4406.0
28.1	119.6	229.1	786.6	1909.4	3790.5	5342.5	6484.8	12929.6	118.6	1110.9	4567.7
28.6	131.6	254.7	884.5	1989.6	3953.5	5539.5	6712.7	13332.2	124.3	1129.6	4809.6
29.1	146.7	316.0	1004.8	2061.1	4087.3	5706.8	6918.2	13753.6	134.9	1149.1	4996.8
29.6	162.3	401.2	1243.5	2123.2	4249.2	5986.6	7220.8	14184.6	144.7	1175.0	5230.8
30.1	178.6	506.9	1464.2	2179.9	4509.3	6219.8	7489.0	14650.1	154.2	1201.5	5492.3
30.6	193.4	628.9	1660.3	2245.8	4676.4	6726.2	7985.6	15091.7	158.0	1227.3	5759.7
31.1	207.7	758.6	1824.0	2417.9	4933.2	7091.5	8362.2	15531.7	155.5	1252.6	5981.8
31.6	220.4	889.3	1932.0	2535.5	5150.3	7538.7	8807.5	15966.4	153.5	1251.5	6136.3
32.1	233.3	1096.6	2008.6	2622.9	5314.0	8000.6	9266.1	16406.4	151.7	1250.1	6259.7
32.6	258.6	1310.0	2060.4	2800.2	5598.7	8291.1	9581.4	16861.4	154.6	1248.8	6323.4
33.1	315.3	1479.2	2099.4	2939.1	5787.9	8515.0	9841.3	17324.4	157.3	1247.1	6345.1
33.6	381.8	1621.4	2142.2	3053.2	6016.1	8722.4	10089.0	17799.6	159.9	1242.5	6576.8
34.1	458.0	1748.5	2293.5	3316.5	6306.9	8920.9	10330.1	18281.5	163.2	1236.8	6932.2
34.6	549.6	1867.8	2438.3	3532.2	6560.3	9123.8	10576.5	18773.0	160.2	1232.2	7208.8
35.1	653.3	1970.6	2557.6	3708.2	7156.7	9331.0	10827.8	19273.3	157.4	1227.3	7346.1
35.6	766.6	2050.3	2675.9	4027.0	7548.9	9531.0	11074.8	19784.8	164.7	1238.8	7677.7
36.1	889.9	2115.6	2887.4	4272.2	8181.3	9733.7	11324.3	20298.6	172.0	1251.7	7927.1
36.6	1109.0	2188.7	3057.9	4640.8	8581.1	9980.7	11614.9	20835.4	188.1	1264.1	8065.5
37.1	1358.7	2334.1	3323.5	4942.1	8920.0	10258.6	11932.8	21379.3	213.1	1276.4	8166.6
37.6	1604.6	2550.2	3631.8	5378.4	9257.0	10575.7	12287.8	21947.9	228.2	1392.4	8248.4
38.1	1847.4	2736.6	4011.1	5863.1	9598.2	10919.6	12666.8	22524.8	256.5	1509.0	8316.7
38.6	2017.3	3005.0	4368.2	6318.7	9920.2	11256.1	13041.7	23116.2	288.8	1624.5	8373.2
39.1	2156.7	3265.7	4794.8	6946.9	10236.8	11595.1	13420.4	23719.1	331.5	1741.2	8419.1
39.6	2330.7	3631.4	5247.5	7799.0	10567.4	11951.8	13817.2	24342.1	367.3	2083.5	8459.3
40.1	2545.0	4017.7	5758.6	8508.9	10909.1	12322.3	14228.1	24980.7	389.1	2426.7	8495.2
40.6	2775.1	4416.4	6231.8	9033.7	11264.6	12727.1	14670.2	25633.8	404.7	2769.1	8527.0
41.1	3020.0	4848.5	6867.0	9479.5	11634.1	13138.7	15119.7	26296.9	422.2	3112.5	8554.2
41.6	3306.6	5317.4	7694.5	9876.3	11996.2	13536.6	15559.0	26969.8	431.0	3249.9	8575.8

Time (hours)	20yr ARI	50yr ARI	100yr ARI	200yr ARI	500yr ARI	1000yr ARI	2000yr ARI	PMF	1978	1986	1990
42.1	3595.0	5805.8	8379.2	10248.9	12354.4	13937.1	16002.4	27655.6	444.4	3387.2	8591.8
42.6	3937.2	6244.8	8856.3	10549.2	12661.9	14288.8	16402.6	28328.8	455.0	3524.2	8603.4
43.1	4207.4	6858.8	9199.5	10816.8	12937.4	14628.8	16792.4	29000.2	455.8	3661.7	8611.6
43.6	4491.7	7449.5	9454.7	11042.6	13167.8	14917.1	17141.5	29692.0	448.7	3791.6	8612.7
44.1	4771.9	7961.0	9659.4	11244.0	13386.2	15193.6	17482.2	30394.6	432.3	3921.8	8606.1
44.6	4995.8	8328.9	9858.4	11460.6	13642.8	15509.2	17857.1	31104.6	418.7	4052.0	8595.6
45.1	5203.0	8584.9	10044.0	11679.4	13914.6	15834.8	18242.0	31824.1	408.2	4182.4	8581.9
45.6	5460.9	8793.6	10237.7	11913.2	14215.2	16190.7	18645.9	32498.8	405.6	4222.5	8564.4
46.1	5627.0	8976.3	10434.2	12155.6	14523.4	16557.2	19054.8	33147.2	408.1	4263.5	8543.4
46.6	5824.6	9152.6	10637.7	12421.4	14848.0	16944.5	19475.1	33753.6	422.9	4304.4	8519.5
47.1	6076.4	9325.3	10842.3	12689.9	15181.0	17342.3	19900.7	34335.7	449.0	4344.8	8491.9
47.6	6275.9	9494.3	11053.5	12960.3	15521.1	17747.7	20328.0	34886.7	485.9	4358.0	8461.1
48.1	6796.1	9658.0	11267.5	13236.3	15865.4	18176.4	20771.1	35411.0	546.2	4371.0	8425.2
48.6	7067.1	9784.3	11435.8	13460.2	16142.4	19244.7	21750.1	35885.9	608.0	4382.8	8332.3
49.1	7234.5	9889.7	11578.3	13665.8	16397.6	19664.8	22174.1	36332.0	671.3	4395.8	8000.4
49.6	7677.8	9964.7	11690.9	13840.9	16610.5	20478.7	22924.4	36723.8	721.5	4405.1	7604.8
50.1	7925.0	10016.8	11784.2	13994.8	16801.6	21221.1	23608.7	37079.9	754.0	4414.3	7399.6
50.6	8077.5	10076.2	11893.7	14165.5	17020.7	22154.3	24449.2	37396.8	781.1	4424.2	7276.4
51.1	8180.6	10134.9	12002.5	14333.3	17237.0	22874.2	25102.7	37676.5	805.3	4433.5	7190.9
51.6	8261.6	10197.1	12114.1	14499.7	17452.8	23500.1	25669.0	37906.3	827.4	4437.3	7121.6
52.1	8325.0	10257.7	12224.2	14658.2	17658.5	24025.7	26144.6	38099.5	849.5	4441.6	7058.2
52.6	8380.1	10318.9	12330.5	14813.3	17856.8	24468.7	26542.5	38243.2	910.7	4445.5	6980.4
53.1	8427.4	10376.9	12430.2	14956.8	18043.2	24836.5	26871.1	38350.2	998.7	4449.6	6799.7
53.6	8469.9	10435.9	12529.7	15100.2	18225.8	25149.6	27147.4	38419.2	1147.9	4448.1	6583.9
54.1	8506.7	10492.5	12623.8	15235.6	18395.6	25403.2	27368.1	38454.0	1338.6	4446.5	6449.6
54.6	8541.0	10547.6	12715.1	15367.4	18557.5	25610.4	27544.0	38453.3	1542.4	4444.2	6274.4
55.1	8572.5	10599.3	12799.7	15489.6	18706.1	25766.0	27671.4	38421.9	1796.6	4441.9	5992.7
55.6	8365.5	10647.5	12879.8	15605.7	18844.7	25881.9	27760.2	38358.0	2019.1	4434.5	5828.4
56.1	8128.9	10690.8	12952.4	15711.8	18967.9	25955.2	27808.7	38266.3	2223.6	4426.9	5728.9
56.6	8065.1	10730.4	13018.2	15807.4	19075.2	25988.8	27819.3	38147.0	2360.9	4418.8	5637.5
57.1	8044.5	10765.6	13075.7	15890.4	19165.1	25981.9	27792.0	38004.5	2452.1	4411.1	5414.4
57.6	7988.6	10804.3	13138.6	15977.8	19258.9	25962.3	27750.7	37841.3	2545.8	4394.5	5265.9
58.1	7596.5	10842.6	13199.3	16063.3	19343.8	25919.7	27687.1	37659.3	2666.9	4377.4	5167.8
58.6	7477.8	10884.7	13265.2	16154.2	19433.3	25873.3	27617.5	37459.0	2817.7	4360.6	5093.7
59.1	7441.9	10926.8	13330.1	16242.6	19517.0	25814.6	27535.2	37243.0	2999.6	4344.3	5032.5
59.6	7434.9	10963.3	13385.6	16316.2	19580.7	25729.9	27428.5	37012.1	3206.4	4320.8	4978.3
60.1	7439.8	10994.1	13434.0	16378.8	19630.1	25628.1	27305.1	36767.1	3467.7	4297.3	4924.7
60.6	7352.3	11009.9	13462.8	16415.6	19647.2	25490.1	27147.4	36498.3	3768.2	4273.5	4872.1
61.1	7226.9	11015.1	13478.4	16435.9	19644.7	25330.1	26968.9	36215.6	3975.2	4250.0	4827.6
61.6	7182.1	11006.2	13475.6	16433.0	19614.7	25138.3	26751.3	35852.0	4115.2	4139.2	4770.9
62.1	7160.8	10986.1	13459.4	16414.3	19565.6	24925.1	26507.3	35434.6	4223.4	4028.6	4580.8
62.6	7147.9	10962.9	13434.5	16387.1	19506.4	24701.4	26259.4	35050.2	4342.0	3917.4	4378.6

Time (hours)	20yr ARI	50yr ARI	100yr ARI	200yr ARI	500yr ARI	1000yr ARI	2000yr ARI	PMF	1978	1986	1990
63.1	7047.7	10935.0	13401.1	16349.5	19434.1	24464.8	26002.3	34677.3	4551.7	3806.5	3917.5
63.6	6904.8	10899.9	13355.1	16294.2	19340.3	24205.3	25725.7	34304.2	4832.1	3754.2	3643.4
64.1	6846.6	10858.3	13298.5	16225.0	19230.3	23930.2	25435.7	33930.3	5183.2	3700.7	3478.5
64.6	6814.1	10808.8	13230.4	16140.3	19103.5	23635.8	25128.5	33550.5	5551.1	3648.4	3372.6
65.1	6771.0	10752.7	13153.0	16043.2	18962.9	23326.3	24807.8	33166.8	5845.2	3595.3	3302.9
65.6	6562.0	10690.7	13069.6	15939.5	18815.3	23011.8	24482.8	32782.3	6102.7	3560.0	3254.5
66.1	6465.3	10622.9	12978.6	15828.7	18658.0	22686.9	24148.2	32393.6	6462.0	3524.4	3218.2
66.6	6411.7	10550.3	12884.2	15716.7	18499.3	22365.0	23815.6	32000.3	6885.0	3488.7	3188.6
67.1	6372.2	10176.1	12784.4	15599.9	18335.4	22040.2	23480.0	31603.3	7378.9	3452.8	3161.8
67.6	6177.8	9865.4	12681.3	15481.6	18169.3	21718.6	23146.7	31204.6	7885.1	3365.7	3136.9
68.1	6042.6	9445.3	12573.6	15359.1	17998.9	21397.7	22813.8	30803.6	8265.4	3278.0	3112.7
68.6	5963.0	9079.0	12460.3	15230.9	17821.9	21075.6	22480.2	30405.2	8566.0	3190.2	3088.8
69.1	5906.0	8906.4	12341.7	15097.9	17640.7	20752.4	22145.7	30006.8	8775.3	3103.0	3065.0
69.6	5823.4	8668.0	12216.4	14953.8	17450.7	20421.9	21804.5	29605.5	8924.5	3055.6	3041.1
70.1	5362.8	8436.4	12084.8	14802.8	17253.9	20088.8	21460.9	29202.6	9032.6	3008.1	3016.8
70.6	5127.8	8293.1	11947.3	14643.3	17048.6	19748.3	21110.8	28798.2	9123.6	2961.0	2992.3
71.1	4996.7	8071.1	11804.7	14477.6	16837.7	19403.6	20757.0	28393.0	9199.2	2913.0	2967.4
71.6	4909.8	7835.5	11660.4	14309.0	16625.2	19061.0	20405.7	27992.6	9269.0	2881.3	2943.0
72.1	4841.0	7688.8	11517.9	14136.8	16409.5	18719.4	20055.5	27593.8	9334.9	2849.3	2920.0
72.6	4780.0	7544.7	11373.5	13959.1	16191.7	18380.4	19708.8	27203.8	9397.9	2816.7	2898.1
73.1	4722.8	7246.5	11226.4	13777.4	15974.1	18043.5	19365.0	26821.0	9451.9	2785.3	2876.1
73.6	4615.9	7076.2	11077.6	13592.5	15755.7	17709.7	19024.8	26445.0	9500.2	2746.1	2853.8
74.1	4432.6	6947.4	10926.6	13405.4	15536.2	17377.9	18687.4	26075.9	9540.7	2707.1	2831.5
74.6	4319.5	6815.4	10774.2	13216.8	15315.8	17046.3	18350.8	25710.7	9575.6	2667.8	2809.6
75.1	4234.4	6524.4	10534.2	13027.2	15094.6	16713.8	18013.8	25348.5	9603.1	2629.1	2789.5
75.6	4161.9	6351.0	9980.1	12838.3	14872.5	16384.5	17679.4	24985.3	9625.5	2530.3	2771.0
76.1	4095.7	6224.4	9465.3	12650.9	14649.9	16058.2	17347.3	24620.8	9641.9	2431.7	2753.1
76.6	4032.9	6079.4	9031.0	12459.9	14427.3	15734.5	17018.0	24260.2	9652.9	2333.3	2735.6
77.1	3971.2	5562.0	8769.3	12266.7	14205.1	15416.0	16693.7	23902.4	9655.8	2235.5	2718.0
77.6	3909.9	5282.2	8408.9	12072.3	13982.4	15103.4	16374.6	23547.0	9654.4	2158.8	2698.0
78.1	3848.3	5109.0	8194.3	11876.7	13755.7	14795.5	16059.8	23193.1	9651.3	2082.2	2631.0
78.6	3772.5	4979.5	7854.3	11680.5	13528.3	14490.5	15747.7	22840.6	9641.6	2005.9	2524.7
79.1	3651.5	4870.4	7617.8	11483.8	13300.4	14189.7	15439.2	22489.1	9617.0	1929.8	2440.9
79.6	3394.0	4770.6	7439.0	11292.4	13073.7	13894.8	15136.2	22140.4	9586.0	1864.3	2386.1
80.1	3196.9	4624.2	7114.9	11105.6	12847.9	13604.3	14837.0	21792.4	9552.0	1799.6	2348.7
80.6	3042.4		6881.9	10919.9	12624.4	13315.8	14539.6	21444.2	9443.9	1734.0	2321.5
81.1	2912.4		6709.7	10735.5	12405.8	13036.9	14250.2	21095.7	9108.8	1669.0	2301.0
81.6	2797.4		6401.1	10553.1	12186.8	12766.5	13968.9	20752.8	8762.3	1615.3	2284.9
82.1	2691.4		6173.0	10371.9	11966.6	12501.2	13692.6	20414.9	8617.7	1561.6	2271.4
82.6	2592.1		6006.6	9902.9	11746.5	12239.4	13419.7	20079.0	8591.5	1507.6	2259.3
83.1	2499.2		5831.0	9488.8	11527.7	11988.4	13156.3	19745.6	8787.9	1454.5	2247.4
83.6	2411.7		5287.8	8856.5	11309.8	11729.8	12887.5	19419.4	9002.1	1392.3	2235.3

Time (hours)	20yr ARI	50yr ARI	100yr ARI	200yr ARI	500yr ARI	1000yr ARI	2000yr ARI	PMF	1978	1986	1990
84.1	2328.0		4981.0	8511.2	11096.6	11038.9	12252.5	19100.0	9042.5	1331.0	2224.0
84.6	2248.1		4782.8	8117.6	10890.9	10608.0	11838.7	18782.6	9022.5	1269.3	2213.6
85.1	2171.3		4632.0	7852.3	10690.0	9934.4	11219.0	18466.4	8965.9	1207.7	2202.7
85.6	2097.5		4505.2	7486.5	10492.8	9587.1	10876.6	18152.0	8898.3	1147.7	2191.1
86.1	2027.0		4283.3	7234.2	10297.4	9157.3	10464.2	17838.3	8832.2	1086.6	2179.8
86.6	1959.9		4088.5	6947.1	10097.5	8877.6	10179.7	17526.2	8763.0	1025.4	2169.0
87.1	1895.9		3947.0	6638.8	9494.8	8472.8	9789.1	17215.9	8686.9	965.1	2158.2
87.6	1832.8		3835.1	6436.8	9105.6	8187.1	9500.1	16908.0	8491.0	943.8	2147.3
88.1	1672.4		3739.1	6182.1	8477.9	7843.4	9162.1	16602.8	7879.1	922.6	2137.6
88.6	1552.1		3652.1	5880.6	8072.3	7506.2	8830.4	16301.4	7240.0	902.4	2128.9
89.1	1471.2		3572.1	5681.3	7733.5	7270.7	8585.5	16004.1	7098.7	880.7	2119.8
89.6	1411.3		3495.7	5486.5	7408.5	6896.4	8223.2	15709.3	7125.1	869.1	2109.7
90.1	1361.5		3419.3	4931.4	7087.8	6626.7	7950.1	15417.2	6973.2	858.4	2095.2
90.6	1320.7		3305.3	4615.8	6774.2	6421.3	7731.8	15125.6	6766.4	846.5	2076.0
91.1	1285.0		3079.3	4410.9	6445.7	6035.5	7360.4	14836.0	6560.1	834.8	2039.9
91.6	1252.5		2851.6	4254.2	6227.1	5528.2	6886.6	14551.0	6327.0	812.7	1987.6
92.1	1221.5		2678.2	4079.7	5884.0	5252.5	6610.6	14273.3	6197.1	791.5	1930.6
92.6	1191.3		2536.0	3839.7	5620.9	5049.5	6396.9	13999.3	6096.3	768.7	1872.5
93.1	1161.8		2413.4	3683.2	5424.9	4880.1	6211.8	13725.5	5990.1	746.9	1804.0
93.6	1132.8		2304.6	3563.6	4915.9	4673.0	5995.1	13454.8	5889.5	732.2	1724.8
94.1	1104.4		2206.6	3464.3	4533.4	4405.3	5727.7	13189.3	5791.6	716.8	1638.1
94.6	1076.0		2116.4	3379.2	4292.7	4225.3	5535.3	12927.0	5709.9	701.5	1551.4
95.1	1047.4			3302.9	4116.4	4078.8	5372.0	12668.0	5678.3	686.0	1475.2
95.6	1018.9			3231.3	3870.2	3950.1	5224.3	12413.1	5668.7	637.9	1408.6
96.1	991.4			3125.6	3657.3	3835.3	5089.0	12162.5	5629.5	590.0	
96.6	963.5			2903.7	3508.1	3730.0	4962.3	11915.1	5594.0	541.3	
97.1	935.9			2674.1	3393.1	3632.1	4842.7	11673.0	5630.7	492.9	
97.6	909.5			2501.1	3297.3	3515.5	4708.3	11438.3	5695.5	428.7	
98.1	882.6			2359.6	3214.4	3318.5	4505.4	11202.7	5703.1	364.8	
98.6	856.4			2238.4	3140.5	3028.0	4223.5	10968.3	5676.2	300.8	
99.1	830.9			2130.9	3048.2	2824.5	4015.8	10737.2	5643.3	236.8	
99.6	805.7			2033.1	2828.3	2658.3	3840.3	10509.0	5589.1	222.5	
100.1	781.1			1943.3	2595.1	2515.6	3685.6	10287.0	5433.5	207.6	
100.6	757.0			1859.8	2417.5	2389.7	3545.7	10068.1	5226.4	193.4	
101.1	733.2			1782.1	2269.9	2277.1	3417.7	9853.0	4987.9	179.0	
101.6	709.8			1708.9	2142.5	2175.3	3299.0	9639.2	4740.9	173.7	
102.1	686.8			1640.1	2029.6	2081.1	3187.1	9427.7	4538.7	168.5	
102.6	664.4			1563.7	1928.4	1993.9	3080.4	9210.9	4345.3	162.8	
103.1	642.9			1393.9	1836.3	1912.3	2974.9	8970.4	4023.4	158.0	
103.6	621.9			1285.9	1751.4	1835.6	2869.3	8701.2	3646.0	154.1	
104.1	601.8			1209.0	1672.7	1763.1	2757.4	8367.9	3399.4	151.2	
104.6	582.4			1150.3	1599.2	1678.4	2632.3	8014.4	3240.7	147.5	

Time (hours)	20yr ARI	50yr ARI	100yr ARI	200yr ARI	500yr ARI	1000yr ARI	2000yr ARI	PMF	1978	1986	1990
105.1	563.3			1109.7	1478.1	1496.0	2422.8	7652.1	3070.9	144.4	
105.6	544.9			1066.3	1320.6	1387.4	2274.7	7280.4	2890.5	141.2	
106.1	527.2				1223.3	1313.0	2152.5	6889.1	2760.6	138.0	
106.6	510.2				1153.2	1256.1	2046.6	6506.5	2671.6	136.2	
107.1	493.2				1098.1	1209.9	1963.9	6218.2	2605.5	132.7	
107.6	476.6				1052.1	1170.5	1891.6	5960.1	2551.9	131.3	
108.1	460.8				1012.1	1135.7	1820.1	5682.0	2505.7	128.5	
108.6	445.0				976.4	1102.7	1748.1	5389.7	2464.8	126.6	
109.1	429.9				943.2	1070.9	1666.7	5028.2	2427.4	125.0	
109.6	415.4				911.6	1040.1	1585.4	4662.2	2392.7	123.3	
110.1	401.3				886.3	1009.7	1526.0	4439.4	2360.2	121.6	
110.6	387.5				855.3	979.6	1476.6	4280.8	2328.8	119.8	
111.1	374.5				826.2	949.8	1421.6	4084.1	2298.5	117.8	
111.6	362.0				798.4	920.4	1362.0	3854.0	2269.3	117.2	
112.1	350.1				771.7	891.3	1287.6	3523.6	2240.7	115.1	
112.6	338.6				745.7	861.9	1207.7	3158.4	2213.0	114.6	
113.1	327.8				720.1	837.5	1153.1	2933.8	2186.0	112.7	
113.6	317.4				696.2	807.5	1106.4	2792.9	2159.4	112.2	
114.1	307.5				672.8	779.1	1059.0	2638.5	2133.7	111.1	
114.6	297.8				649.5	751.4	1011.3	2477.8	2108.4	111.2	
115.1	288.8				627.3	724.6	972.6	2371.7	2082.0	109.7	
115.6	280.3				606.1	698.4	940.3	2305.0	2060.0	109.2	
116.1	272.0				586.0	673.9	912.5	2258.3	2032.2	109.2	
116.6	264.2				566.3	650.4	885.8	2214.3	2007.4	108.6	
117.1	256.7				547.3	627.3	844.2	2068.5	1984.3	107.5	
117.6	249.3				528.6	605.1	792.5	1850.2	1962.0	107.8	
118.1	242.2				510.4	583.8	747.0	1667.7	1940.4	106.6	
118.6	235.6				492.6	563.5	708.1	1524.4	1923.9	106.9	
119.1	229.3				475.2	543.8	673.3	1403.9	1901.4	106.2	
119.6	223.3				458.6	524.9	641.6	1299.6	1880.6	105.7	
120.1	217.7				442.8	506.4	612.0	1208.2	1860.9	105.8	
120.6	212.0				427.5	488.2	583.7	1122.7	1838.9	104.8	
121.1	206.6				412.4	470.6	551.2	1005.7	1763.8	104.9	
121.6	201.6				398.1	453.8	514.9	859.9	1636.2	104.8	
122.1	196.7				384.5	437.8	484.9	750.5	1481.0	104.5	
122.6	192.4				371.5	422.8	461.7	681.0	1312.3	103.9	
123.1	187.9				358.9	407.9	441.6	631.9	1135.4	104.4	
123.6	183.5				347.0	393.5	424.2	597.2	953.4		
124.1	179.5				335.9	380.1	409.0	572.1	806.7		
124.6	175.5				325.2	367.3	395.2	553.1	708.4		
125.1	171.6				314.8	354.9	382.3	536.5	639.2		
125.6	167.9				305.0	343.3	369.9	519.9	588.5		

Time (hours)	20yr ARI	50yr ARI	100yr ARI	200yr ARI	500yr ARI	1000yr ARI	2000yr ARI	PMF	1978	1986	1990
126.1	164.4				295.7	332.4	358.1	503.3	550.4		
126.6	161.0				286.8	321.8	346.6	486.0	520.5		
127.1	157.6				278.1	311.7	335.4	469.2	495.6		
127.6	154.4				269.8	302.0	324.8	453.6	474.3		
128.1	151.4				262.1	292.8	314.8	438.6	455.7		
128.6	148.6				254.5	284.1	305.1	423.7	438.6		
129.1	146.0				247.3	275.6	295.7	409.1	422.8		
129.6	143.3				240.0	267.3	286.4	393.9	408.2		
130.1	141.0				233.4	259.4	277.5	379.5	394.6		
130.6	138.8				227.2	252.1	269.0	364.2	381.9		
131.1	136.6				221.3	244.7	260.5	349.7	370.2		
131.6	134.4				215.6	237.9	252.6	335.4	359.1		
132.1	132.2				210.1	231.1	244.9	322.6	348.4		
132.6	130.0				204.7	225.0	237.9	310.6	337.9		
133.1	128.1				199.8	219.4	231.5	299.5	327.7		
133.6	126.2				195.3	213.9	225.3	289.7	317.6		
134.1	124.4				191.7	208.6	219.5	281.1	307.9		
134.6	122.8				187.7	203.6	214.1	273.6	298.5		
135.1	121.1				183.9	199.0	209.2	266.4	289.2		
135.6	119.6				180.0	194.8	204.7	260.3	280.0		
136.1	118.0				176.7	191.3	200.8	253.9	271.2		
136.6	116.7				173.1	187.6	196.7	248.2	262.6		
137.1	115.4				169.9	183.6	192.5	242.8	254.5		
137.6	113.9				166.8	180.2	188.8	237.5	246.8		
138.1	112.7				163.9	176.7	185.4	234.5	239.1		
138.6	111.4				161.0	173.4	182.8	235.3	231.8		
139.1	109.8				157.9	170.4	179.8	232.8	224.9		
139.6	108.4				155.0	167.3	175.8	223.5	218.5		
140.1	107.4				152.5	164.3	172.2	216.9			
140.6	106.7				150.0	161.5	169.8	216.7			
141.1	106.1				147.6	158.6	167.2	215.7			
141.6	105.6				145.2	155.7	164.3	212.6			
142.1	105.1				143.1	153.2	161.6	209.1			
142.6	104.8				140.9	150.7	158.9	204.9			
143.1	104.5				138.5	148.5	156.3	200.4			
143.6	104.3				136.4	146.1	153.7	196.2			