# INGLESIDE, ELANORA AND WARRIEWOOD OVERLAND FLOW FLOOD STUDY

DRAFT REPORT


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# INGLESIDE, ELANORA AND WARRIEWOOD OVERLAND FLOW FLOOD STUDY

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| | |
|---|---|
| AEP | Annual Exceedance Probability |
| ARI | Average Recurrence Interval |
| ALS | Airborne Laser Scanning (airborne survey method) |
| ARR | Australian Rainfall and Runoff |
| BoM | Bureau of Meteorology |
| CELLS | Hydraulic modelling software |
| DECC | Department of Environment and Climate Change (now OEH) |
| DEM | Digital Elevation Model |
| DRAINS | Hydrologic modelling software designed for urban catchments |
| FFA | Flood Frequency Analysis |
| FPA | Flood Planning Area |
| GIS | Geographic Information System |
| HEC2 | Hydraulic modelling software |
| IFD | Intensity, Frequency and Duration (Rainfall) |
| LGA | Local Government Area |
| LiDAR | Light Detection and Ranging (airborne survey method) |
| LPI | Land and Property Information |
| m | metres |
| $m^3/s$ | cubic metres per second |
| mAHD | metres above Australian Height Datum |
| MHL | Manly Hydraulics Laboratory |
| MHWS | Mean High Water Spring tide |
| NBC | Northern Beaches Council |
| OEH | Office of Environment and Heritage |
| PMF | Probable Maximum Flood |
| PWD | Public Works Department |
| RORB | Hydrologic modelling software |
| SES | State Emergency Services |
| SOBEK | Hydraulic modelling software |
| STP | Sewage Treatment Plant |
| SWC | Sydney Water Corporation |
| TIN | Triangular Irregular Network |
| TUFLOW | Hydraulic modelling software |
| WBNM | Watershed Bounded Network Model (hydrologic modelling software) |
| XP-Rafts | Hydrologic modelling software |
| 1D/2D | 1 Dimensional and 2 Dimensional hydraulic modelling |

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# FOREWORD

The NSW State Government's Flood Policy provides a framework to ensure the sustainable use of floodplain environments. The Policy is specifically structured to provide solutions to existing flooding problems in rural and urban areas. In addition, the Policy provides a means of ensuring that any new development is compatible with the flood hazard and does not create additional flooding problems in other areas.

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 Councils in the discharge of their floodplain management responsibilities.

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

***1. Flood Study***
- Determine the nature and extent of the flood problem.

***2. Floodplain Risk Management Study***
- Evaluates management options for the floodplain in respect of both existing and proposed development.

***3. Floodplain Risk Management Plan***
- Involves formal adoption by Council of a plan of management for the floodplain.

***4. Implementation of the Plan***
- Construction of flood mitigation works to protect existing development, use of Local Environmental Plans to ensure new development is compatible with the flood hazard.

The Ingleside, Elanora and Warriewood Overland Flow Flood Study constitutes the first stage of the management process for the catchment. This study has been prepared by WMAwater for Northern Beaches Council (NBC) and was undertaken to provide the basis for future management of flood liable lands within the study area.

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# EXECUTIVE SUMMARY

## BACKGROUND

The Ingleside, Elanora and Warriewood Overland Flow Flood Study catchment area (Figure 1) is within the Northern Beaches Council (NBC) local government area (LGA) and includes the suburbs of North Narrabeen, Warriewood, Elanora Heights and part of Ingleside. The catchment is located north of Narrabeen Lagoon and drains to the ocean, with an entrance at Narrabeen Head. The study area covers an area of approximately 1,650 hectares (16.5 $km^2$). The major components of the study are:

- the collection and collation of existing information relevant to the study - this includes the data already held by Council as well as other information, such as rainfall data;
- the collection of additional survey data, particularly cross-sections and major culvert structures, to supplement Council's database;
- the preparation of a hydrologic and hydraulic models capable of defining the flood behaviour for the study area for a wide range of design flood probabilities;
- the interpretation and presentation of model results to describe and categorise flood behaviour and hazard for a range of design storm events for the existing catchment conditions, including road flood affectation information for the SES;
- analysis of hot-spots;
- flood control lot mapping and ground truthing;
- undertaking sensitivity analysis;
- properties at risk analysis;
- risk to life analysis;
- investigating and determining the Flood Planning Area (FPA).

## COMMUNITY CONSULTATION

In collaboration with the NBC a questionnaire was distributed to residents in the study area. The purpose of the questionnaire was to identify which residents had experienced problems with flooding and to collate as much historical flood data as possible. 407 responses were received from the distributed questionnaires.

Of the responses received, 185 respondents had observed an overland flow within the catchment and 99 had experienced flooding of their properties; including 14 with inundation above floor level. 35 respondents indicated that flooding had caused damage to their property.

## MODELLING SUMMARY

The study uses hydrologic and hydraulic modelling techniques in order to define flood behaviour in the study area. The modelling programs used in the study are:

- DRAINS (Hydrologic) – the model converts rainfall to runoff and the flow hydrographs are input into the TUFLOW model.
- TUFLOW (Hydraulic) – The 2D hydraulic model was established to assess the complex overland flow regimes of the urban catchments to analyse flooding behaviour in the study area.

## MODEL CALIBRATION

The models were calibrated against historical flood data to provide robust design flood data. The June 2016 and August 1998 events were chosen for model calibration and the process was undertaken against quantitative gauge data and qualitative community data.

## DESIGN FLOOD MODELLING

Design flood levels in the catchment are a combination of flooding from rainfall over the local catchment, as well as elevated tailwater levels from flooding in Narrabeen Lagoon. Preliminary study results are provided as follows:

- Peak flood depths and extents in Figure B1 to Figure B9;
- Peak flood velocities in Figure B10 to Figure B18;
- Hydraulic hazard in Figure B19 to Figure B22;
- Hydraulic categorisation in Figure B23 to Figure B25.

Design flood results were filtered using the following criteria:

- Depths less than 0.15 m were removed from the result maps;
- Areas of ponding less than 100 $m^2$ were then removed;
- Velocity Depth product greater than 0.3 $m^2/s$ were included in the result maps.

## OVERVIEW OF FLOOD BEHAVIOUR

In the upper portion of the catchment as a result of the steep terrain and low development density, there are few major overland flow paths with significant concentration of flow, outside of the creek channels. These channels contain most of the catchment runoff even in more severe storms like a 1% Annual Exceedance Probability (AEP) flood event. The most notable flood issues are the Ingleside Road and Powderworks Road crossings at Mullet Creek, which are likely to be overtopped relatively frequently.

The southern part of the mid-catchment comprises the residential area of Elanora Heights, draining primarily to Nareen Creek, while the northern part is remnant bushland, draining to Mullet, Fern and Narrabeen Creeks. The catchment is very steep through these areas, resulting in widespread shallow overland flow, with relatively few concentrated flow paths apart from the creek channels. The most notable flood issues in the mid-catchment area are the corner of Powderworks Road and Elanora Road at the outlet of the Elanora Country Club golf course, and the Ponderosa Parade crossing at Narrabeen Creek.

In the lower reaches of the catchment, flooding is significantly more widespread than in the upper areas of the catchment, due to:

- flatter topography;
- relatively small creek channels with regard to the upper catchment area;
- the influence of Warriewood wetlands, and
- backwater influences from Narrabeen Lagoon.

There are large areas of flood storage, subject to significant inundation depths in severe storm events. Flooding of all creeks is out of bank in even relatively small events. The most significant

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overland flooding in the urbanised catchment areas occurs along the stretches where Nareen Creek is piped, with heavy inundation between Tatiara Crescent and Nareen Parade as well as between Narroy Road and Pittwater Road (although this is exacerbated by the flooding of the wetlands below Nareen Parade).

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# 1. INTRODUCTION

This study has been prepared by WMAwater on behalf of Northern Beaches Council (NBC). The study is composed of ten stages:

- Stage 1: Completion of Data Collection and Assessment and Community Consultation Report, Results of Community Survey
- Stage 2: Completion of Hydrology Mapping
- Stage 3: Completion of Hydraulic Modelling – Downstream Boundary, Sensitivity Analysis (including blockages)
- Stage 4: Ground truthing and Site Inspections
- Stage 5: Climate Change and Sea Level Rise
- Stage 6: Properties at Risk Analysis – including Road and Access Impacts, and Risk to Life
- Stage 7: Flood Planning Levels and Flood Planning Area
- Stage 8: Draft Flood Study Report for Public Exhibition
- Stage 9: Final Flood Study Report
- Stage 10: Completion of Contract

## 1.1. Study Objectives

The main objective of this study is to define the flood behaviour under historical and existing floodplain conditions in the study area (Figure 1). This requires collection of historical data, and preparation of computer models capable of simulating the existing drainage network and overland flow paths, so as to determine design flood levels and in this way identify the nature of existing flood risk in the study area. Subsequently the models can be used to aid discussions with the local community regarding drainage problems and potential management. The models can be used to test the catchment's sensitivity to future changes (in particular, changes as a result of potential climate change) and also to evaluate mitigation options at a later stage. The models are also established in a manner that makes them suitable for assessment of impacts from future development proposed in the study area.

The primary specific tasks for the study are as follows:

- the collection and collation of existing information relevant to the study - this includes the data already held by Council as well as other information, such as rainfall data;
- the collection of additional survey data, particularly cross-sections and major culvert structures, to supplement Council's database;
- the preparation of hydrologic and hydraulic models capable of defining the flood behaviour for the study area for a wide range of design flood probabilities;
- the interpretation and presentation of model results to describe and categorise flood behaviour and hazard for a range of design storm events for the existing catchment conditions, including road flood affectation information for the SES;
- analysis of hot-spots;
- flood control lot mapping and ground truthing;
- undertaking sensitivity analysis;

- properties at risk analysis;
- risk to life analysis;
- investigating and ultimately determining the Flood Planning Area (FPA).

The design events investigated include the Probable Maximum Flood (PMF), 0.1%, 0.2%, 0.5%, 1%, 2%, 5%, 10% and 20% AEP flood events. Discussion of the AEP terminology and a glossary of other flood-related terms are provided in Appendix A.

The models and results produced in this study are intended to also form the basis for a subsequent floodplain risk management study where detailed assessment of flood mitigation options and floodplain risk management measures will be undertaken. Therefore, the models established in the flood study need to be suitable for use to assess a range of management options in the floodplain risk management study.

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# 2. BACKGROUND

## 2.1. Study Area

The study area (Figure 1) lies within the Northern Beaches local government area (LGA) and was within the Pittwater Council local government area (LGA) before council amalgamation.

The Ingleside, Elanora and Warriewood Overland Flow Flood Study includes flood affected land in the suburbs of North Narrabeen, Warriewood, Elanora Heights and part of Ingleside. The catchment is located north of Narrabeen Lagoon and drains to the lagoon and then the ocean, through the entrance at Narrabeen Head. The catchment is referred to as the Ingleside, Elanora and Warriewood Overland Flow catchment in this report. The study area covers an area of approximately 1,650 hectares (16.5 $km^2$).

Flooding of the area resulting from rising water in Narrabeen Lagoon has previously been investigated in a separate study (Reference 1). The present study is concerned with potential flooding from rainfall falling directly on the catchment area, and resulting runoff flows as they make their way towards the lagoon. There are several creeks in the study area (Figure 1) including:

- Narrabeen Creek;
- Mullet Creek;
- Fern Creek;
- Nareen Creek; and
- Deep Creek (and minor tributaries).

The present study was commissioned by NBC with funding assistance from the NSW Office of Environment and Heritage (OEH) to define flood behaviour in the catchment. Flood problems have been experienced at a number of locations within the catchment during periods of heavy rainfall.

The catchment has a history of flooding and there is a need to define the extent of flooding and to determine appropriate development controls and floodplain risk management plans. The catchment experienced a number of major flooding which occurred in 1911, 1931, 1942, 1956, 1958, 1961, 1974, 1975, 1977, 1978, 1986, 1987, 1998, 2003, 2011 and 2016. However, many of these events may relate more to rising lagoon floodwaters than to overland flow through the upper catchment. During the June 2016 flood event, the heavy rainfall caused damage to both residential and commercial properties and several roads were inundated within the catchment. Previous studies have identified approximately 1,570 properties to be flood affected (discussed further in Section 2.2).

The land use of the catchment comprises a mix of residential and commercial developments (including some light industrial areas), together with areas of open space such as Elanora Country Club, Boondah Reserve and North Narrabeen Reserve. The Warriewood Wetlands are a significant feature of the lower catchment.

The area is relatively urbanised with a mix of residential, commercial and industrial properties,



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and includes educational institutions such as Elanora Heights Primary School, Narrabeen North Public School, Narrabeen Sports High School and Mater Maria Catholic College. The catchment also contains Warriewood Wetlands which act in a similar fashion to a detention basin, connecting to Mullet Creek and draining to the lagoon.

Elevations in the upper part of the catchment reach approximately 200 mAHD along the western catchment ridge (mapping of the topography from LIDAR aerial survey is shown in Figure 2). The suburbs of Elanora Heights and Ingleside have relatively steep topography and cliffs, where elevation drops sharply, for example by a height of 80 m over a horizontal distance of 200 m. The catchment generally runs from the west to the east.

Drainage elements in the catchment include natural creek channels, kerbs and gutters, pits and pipes, and a network of trunk drainage elements including culverts and concrete-lined or otherwise modified open channels. These drainage assets are primarily owned by NBC.

## 2.2. Previous Studies

Numerous flood studies have been completed which include parts of the study area. Brief summaries of the details relevant to the current study are provided below.

### 2.2.1. Narrabeen Lagoon Flood Study (PWD, 1990)

In 1990 the Public Works Department (PWD) NSW completed the Narrabeen Lagoon Catchment Flood Study (Reference 2), used to determine the design flood levels in Narrabeen Lagoon for the 5% and 1% AEP events and an extreme flood event.

The study used the RORB and WBNM hydrological models to estimate runoff hydrographs and a combination of 1D/2D modelling in HEC2 and CELLS for the hydraulic modelling.

The study found that elevated lagoon levels occurred as a result of either high ocean levels, high catchment rainfall, or a combination of moderate contributions from both flood mechanisms:

The study also found that due to the large amount of flood storage within the catchment, flooding around Narrabeen Lagoon was generally a result of longer duration storms of persistent rainfall, rather than shorter more intense storms.

This study was superseded by the 2013 Narrabeen Lagoon Flood Study by BMT WBM (Section 2.2.5).

### 2.2.2. Nareen Creek Flood Study (Cardno Lawson Treloar, 2005)

In 2005 Cardno Lawson Treloar completed the Nareen Creek Catchment Flood Study (Reference 3), used to determine the flood behaviour for the 20%, 5%, 2% and 1% AEP floods, along with the Probable Maximum Flood. The study also defined provisional hydraulic hazard and categories within the catchment.

The study used the XP-Rafts rainfall-runoff modelling package to estimate runoff hydrographs and SOBEK for the hydraulic modelling in 1D/2D.

The study found that the Nareen Creek catchment was exposed to flooding from:

- Narrabeen Lagoon flooding, with the lower potions of the catchments inundated by floodwaters from the lagoon; and
- Local catchment flooding, with flooding predominantly caused by rainfall within the Nareen Creek catchment.

A range of survey data was supplied or collected as part of the Nareen Creek Study, including:

- Parts of Tatiara Crescent and Nareen Parade – surveyed in 2001, supplied by Council;
- Cross-sections of Nareen Creek downstream of Nareen Parade – undated, supplied by Council;
- Ground survey, including cross-sections of Nareen Creek, various structure details and centrelines of hydraulically important roads – surveyed in 2004, collected by Usher and Company Pty Ltd as part of the study;

The ground survey collected by Usher and Company Pty Ltd has been utilised in the current study to more accurately define the topography and drainage channels in Nareen Creek. This is discussed in more detail later in the report.

The study had a similar focus to the present study, but only for part of the catchment.

### 2.2.3. Warriewood Valley Flood Study (Lawson and Treloar, 2005)

In 2005 Lawson and Treloar completed the Warriewood Valley Flood Study (Reference 4), with the objective of defining the nature and extent of flooding in the study area for the 20%, 5%, 2% and 1% AEP and PMF events. Three major creeks, Narrabeen, Fern and Mullet drain to the catchment.

The study used the RAFTS hydrologic modelling package to determine runoff hydrographs and SOBEK for the hydraulic modelling in 1D/2D. Narrabeen Lagoon water levels, based on the 1990 PWD study, were used for the downstream model boundary conditions

The study found that flooding is widespread in the lower parts of the Warriewood catchment and that in the event of a major flood, cross-catchment flows between Narrabeen and Fern Creeks were likely.

A range of survey data was supplied or collected as part of the Warriewood Valley Flood Study, including:

- Fern Creek, upstream of Garden Street to confluence with wetland – surveyed in 2001 by Degotardi Smith and Partners;
- Narrabeen Creek, including areas upstream and downstream of Ponderosa Parade and Macpherson Street – surveyed between 2000-2003;
- Warriewood Wetlands – surveyed in 2003 by Council;

- Garden Street Bridge and Pittwater Road Bridge over Mullet Creek – surveyed in 2003 by Council;
- Additional aerial and ground survey collected by QASCO for the study.

Council's survey of Warriewood Wetlands has been utilised in the current study to more accurately measure flooding behaviour. Additional survey was also collected in this area to further refine the topography. This is discussed in more detail later in the report.

The study had a similar focus to the present study, but only for part of the catchment.

### 2.2.4. Pittwater Overland Flow Mapping and Flood Study (Cardno, 2013)

In 2013 Cardno completed the Pittwater Overland Flow Mapping and Flood Study (Reference 5). The study aimed to identify properties and areas potentially affected by overland flow rather than "mainstream" flooding. The primary objective was to broadly identify areas of overland flow flood risk, and prioritise areas for more detailed investigation through detailed catchment flood studies such as this one. A range of flood events was considered, including the 20%, 5% and 1% AEP and PMF events.

The entire Pittwater LGA, with the exception of the National Park, was covered as part of the study and a key objective was the definition of significant overland flow paths throughout the study area.

The study utilised the 'Direct Rainfall' (or "rainfall on grid") method. SOBEK was used for hydraulic modelling of the catchment in 2D. Rainfall was applied directly to the 2D terrain, and the hydraulic model automatically routes the flow using a computation process that controls flow routing. The advantage of the method is that catchment outlets do not have to be predefined and flow paths are identified by the model (rather than being assumed), which reduces model setup time. However many elements of the drainage network were not included in detail, and calibration to historical flood events was not undertaken.

The study was a broad preliminary study that identified priority areas for more detailed overland flow studies and highlighted the need to update the 1990 Narrabeen Lagoon Flood Study to ensure that overland flow paths entering the mainstream catchment were appropriately identified and mapped.

### 2.2.5. Narrabeen Lagoon Flood Study (BMT, 2013)

In 2013 BMT WBM completed the Narrabeen Lagoon Flood Study (Reference 1), undertaken with the objectives of defining the existing flood behaviour for a full range of design flood events (50%, 20%, 10%, 5%, 1%, 0.5%, 0.2%, 0.1% AEP and PMF) for rising floodwater from Narrabeen Lagoon, and establishing the basis for floodplain management studies.

As with the previous PWD investigation (Reference 2), the study found that flood behaviour within the Narrabeen Lagoon catchment was influenced by:

- catchment rainfall which is the dominant flooding mechanism;
- ocean flooding which causes some inundation to foreshore areas, but the extent and

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severity is significantly less than overland flow flooding.

Ground levels of the Warriewood and Nareen Creek wetlands were surveyed to create a DEM of the catchment and survey collected in previous Council flood studies (including Nareen Creek Flood Study and Warriewood Valley Flood Study) was used in the development of the hydraulic model.

The study used the XP-RAFTS software to develop the hydrological model for the catchment and the TUFLOW software modelling package for the hydraulic modelling of the catchment using a linked 1D/2D approach.

The study used the April 1998, August 1998 and March 2011 flood events for calibration and validation of the model. The study determined that longer duration events caused the worst flooding conditions in the lower part of the catchment, as the lagoon waterbody has significant flood storage and thus long duration events, which generate high volumes of runoff, are needed to elevate water levels. In the upper reaches of the catchment, short duration events in the order of 2-hours were found to produce peak flood water levels.

Parts of the 2013 Narrabeen Lagoon Flood Study including parts of the constructed digital elevation model (DEM) and the lagoon design flood levels were utilised as inputs for the present study.

## 2.3. Community Consultation

In collaboration with the NBC, a newsletter and questionnaire were distributed to residents within the catchment. The newsletter described the role of the Flood Study and requested information on experiences of flooding in the catchment. 407 responses were received from the distributed questionnaires via both hardcopy and online submissions.

Of the responses received, 185 respondents had observed an overland flow within the catchment and 99 had experienced flooding of their properties; including 14 with inundation above floor level. 35 respondents indicated that flooding had caused damage to their property. These results are summarised in Figure 4A to Figure 4C.

Some of the survey responses relate to mainstream rather than overland flooding issues. Many respondents identified rising waters in local creeks and the closure of Narrabeen Lagoon as their flooding experience. As a result, it is estimated that at least 16 of the survey respondents who reported flooding of their properties probably experienced backwater lagoon flooding rather than overland flooding.

Respondents who submitted their surveys online were unable to provide information on how long they had lived within the catchment area due to an omission in the setup of the online survey. This is reflected in Figure 4A with a high number of “no response”.

The survey responses identified several key areas of concern:

- Flood inundation was more frequently observed in the lower parts of the catchment in

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areas such as Gondola Road, Rickard Road and Windsor Parade.

- Many residents believed that opening Narrabeen Lagoon in flood events would help to solve their flooding problems.
- Many residents have had their daily routines affected and believe that their safety has been put at risk due to localised stormwater flooding.
- Most flood damage was done to backyards, but some properties experienced flooding of garages as well as ground floors of houses.
- Some affected residents have employed their own flood mitigation measures, including installing extra drainage.

In addition to these areas of concern, a significant number of survey respondents identified that their properties were affected during the storm event on the 5th of June 2016. As a result, that storm event has been included in historical rainfall / comparisons with design rainfall intensities and is discussed in Section 3.7.

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# 3. AVAILABLE DATA

## 3.1. Overview

The first stage in the investigation of flooding matters is to establish the nature, size and frequency of the problem. On larger urban river systems such as the Hawkesbury River there are generally stream height and historical records dating back a considerable period, in some cases over one hundred years. However, in smaller urban catchments stream gauges and/or official historical records are generally not available, and there is more uncertainty about the frequency and magnitude of flood problems. Additionally, overland flooding in urban areas is highly dependent on localised changes to development, intensification of development (i.e. increased building sizes and more paved surfaces), and localised drainage features such as kerbs and guttering in roadways. These features are subject to relatively frequent modification and renewal, making it difficult to compare flood behaviour over time.

The Ingleside, Elanora and Warriewood Overland Flow catchment does contain some water level and pluviometer gauges – some of which include data for the 1998, 2011 and 2016 storm events – which have been utilised as part of this study. Despite this, an understanding of historical flooding also needs to be obtained from an examination of Council records, previous flood assessment reports, rainfall records and local knowledge obtained through community consultation (see Section 2.3.)

Ground level and survey information supplied as part of the study was of mixed usability. ALS in urbanised areas and detailed bathymetry of some watercourses (collected as part of previous studies) was generally able to be immediately utilised for modelling, but there were gaps in the Council GIS database (inverts of pits and pipes generally not available), and with ground levels in wetland and creek areas not previously covered by survey. Such gaps are common for such studies, since collecting detailed information about sub-surface drainage networks is expensive and time consuming, and often beyond the resources available to Council. As part of this study, analysis of the available data along with additional survey was undertaken to address the limitations of the data in key areas.

However, it should be recognised that the information about the drainage system for this study is not perfect. For larger floods of interest, such as the 1% AEP event, this is often not a critical issue, since the majority of runoff cannot be contained within the formal drainage network. Such networks are typically only designed to cater for the 20% AEP or 10% AEP flow. Therefore, caution must be exercised when applying the broad catchment modelling results at individual properties, particularly for smaller floods or in areas where the pit/pipe drainage network plays a significant role in the flood behaviour.

## 3.2. Data Sources

Data utilised in the study has been collated from a variety of sources. Table 1 gives a summary of the type of data sourced, the supplier, and its application for the study.

Table 1: Data Sources

| Type of Data | Format Provided (Source) | Application |
|---|---|---|
| Ground levels from ALS data (2011) | DEM (LPI) | Hydrologic and hydraulic models |
| Bathymetry of watercourses | GIS (NBC, Nareen Creek Flood Study, Warriewood Valley Flood Study) | Hydraulic model |
| Bathymetry of wetlands | GIS (NBC, Warriewood Valley Flood Study) | Hydraulic model |
| Bathymetry of Lagoon | GIS (NBC, Narrabeen Lagoon Flood Study) | Hydraulic model |
| Pits, Pipes and Hydraulic Structures | GIS (NBC) | Hydraulic model |
| GIS Information (Cadastre) | GIS (NBC) | Hydraulic model |
| ARR Design Rainfalls | Tabulated (BoM) | Hydrologic model |
| Rainfall Gauge (Daily) | Spreadsheet (BoM) | Hydrologic model |
| Pluviometer (Continuous rainfall) | Spreadsheet (MHL and SWC) | Hydrologic model |
| Water Level Gauge (Continuous) | Spreadsheet (MHL) | Hydrologic model |

## 3.3. Topographic Data

Airborne Laser Scanning (ALS) or Light Detection and Ranging (LiDAR) survey of the catchment and its immediate surroundings was available for the study. It was indicated that the data were collected in 2011 by Land and Property Information (LPI). These data typically have accuracy in the order of:

- +/- 0.15m (for 70% of points) in the vertical direction on clear, hard ground; and
- +/- 0.75m in the horizontal direction.

The accuracy of the ALS data can be influenced by the presence of open water or vegetation (tree or shrub canopy) at the time of the survey.

From this data, a Triangular Irregular Network (TIN) was generated for this study. This TIN was sampled at a regular spacing of 1 m by 1 m to create a Digital Elevation Model (DEM), which formed the basis of the two-dimensional hydraulic modelling for the study (Figure 2).

The bathymetries of Warriewood Wetlands and Nareen Wetlands were available from previous studies and are shown in Table 2.

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Table 2: Surveyed Bathymetry Data from Previous Studies

| Surveyed Locations | Flood Study | Surveyor | Date Surveyed |
|---|---|---|---|
| Nareen Wetlands | Nareen Creek Flood Study (Cardno Lawson Treloar,2005) | Usher and Company Pty Ltd | 2004 |
| Warriewood Wetlands | Warriewood Valley Flood Study (Lawson and Treloar, 2005) | Council | 2003 |

The raw bathymetry data are not available but the processed data were available in the TUFLOW model of the 2013 Narrabeen Lagoon Flood Study (Reference 1). Lagoon bathymetry (pre-dredge and post-dredge) and the interpolated ground level of the new development (ARV Marcus Loane House in Macpherson Street) were also extracted from the 2013 Narrabeen Lagoon Flood Study.

There are some developments which took place after 2011 and they are in the flood prone areas. The ALS did not capture the ground level of these new developments. The site plan of some developments was provided by NBC and the ground levels were interpolated from the site plan. New survey of the remaining topographic sites was collected as part of this study.

## 3.4. Cross-Section Survey

Within the Ingleside, Elanora and Warriewood Overland Flow catchment, the topography of the open watercourse areas is not properly captured by the LiDAR data, as most of the watercourses are covered or surrounded by heavy vegetation. This is because, as mentioned previously, the accuracy of LiDAR data can be influenced by the presence of open water or vegetation.

Previous studies provide some surveyed cross-sections for use in modelling. Some surveyed cross-sections are available from previous studies and they are listed in Table 3. The raw cross-sections were not available but the processed ones were extracted from the TUFLOW model of the 2013 Narrabeen Lagoon Flood Study.

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Table 3: Surveyed Cross-Sections from Previous Study

| Catchment Area | Flood Study | Surveyor | Date Surveyed |
|---|---|---|---|
| Nareen Creek | Nareen Creek Flood Study (Cardno Lawson Treloar,2005) | Usher and Company Pty Ltd | 2004 |
| Nareen Creek | Nareen Creek Flood Study (Cardno Lawson Treloar,2005) | Council | Undated |
| Narrabeen Creek | Warriewood Valley Flood Study (Lawson and Treloar,2005) | J.S. MacDonald and Associates Pty Ltd | 2002 |
| Narrabeen Creek | Warriewood Valley Flood Study (Lawson and Treloar,2005) | Council | 2001 |
| Warriewood Valley | Warriewood Valley Flood Study (Lawson and Treloar, 2005) | QASCO | 2003 |
| Fern Creek | Warriewood Valley Flood Study (Lawson and Treloar, 2005) | Degotardi,Smith and Partners | 2001 |
| Mullet Creek | Warriewood Valley Flood Study (Lawson and Treloar, 2005) | Byrne and Associates Pty Ltd | 1999 |

Supplementary detail survey was therefore obtained to define the bathymetry of key watercourses and structures. Chase Burke and Harvey (CBH Survey) were commissioned to undertake survey of creek cross-sections, hydraulic control structures such as detention basins and their outer embankments as well as culverts and bridges. Indicative survey locations and descriptions are presented on Figure 3. Plans of the cross-section survey are provided in Appendix B.

## 3.5. Pit and Pipe Data

A database of stormwater pits and pipes within the catchment was provided by NBC. The pits and pipes data did not have any invert information although the dimensions and number of pipes were able to be applied directly to the hydraulic model. Where survey information was unavailable, invert levels were typically estimated following site inspections and through analysis of the ALS data. Typically, this approach is considered to provide a reasonable level of detail and modelling accuracy in light of the overall study objectives, although there may be localised inaccuracies for consideration of detailed flood behaviour on the scale of individual properties.

## 3.6. Historical Flood Level Data

The community consultation identified 37 respondents with awareness of flood marks and/or possession of photos which were considered as part of the calibration/validation of the modelling.

## 3.7. Historical Rainfall Data

### 3.7.1. Overview

Rainfall data is recorded either daily (24-hour rainfall totals to 9:00 am) or continuously (pluviometers measuring rainfall in small increments – less than 1 mm). Daily rainfall data has been recorded for over 100 years at many locations within the Sydney basin. However, pluviometers have generally only been installed for widespread use since the 1970s.

Care must be taken when interpreting historical rainfall measurements. Rainfall records may not provide an accurate representation of past flooding due to a combination of factors including local site conditions, human error or limitations inherent to the type of recording instrument used.

Intense rainfall events which cause overland flooding in highly urbanised catchments are usually localised and as such are only accurately represented by a nearby gauge, preferably within the catchment. Gauges sited even only a kilometre away can show very different intensities and total rainfall depths.

### 3.7.2. Rainfall Stations

Table 4 presents a summary of the official rainfall gauges operated by the BoM located close to or within the catchments (mapped on Figure 5).

Table 4: Daily rainfall stations within 5 kms of the centre of the catchment

| Station Number | Station Name | Operating Authority | Distance to catchment centre (km) | Date Opened | Date Closed |
|---|---|---|---|---|---|
| 66141 | Mona Vale Golf Club | BoM | 2.7 | 1997 | Current |
| 66182 | Frenchs Forest (Frenchs Forest Rd) | BoM | 7.7 | 1998 | Current |
| 66044 | Cromer Golf Club | BoM | 3.6 | 1898 | Current |
| 66045 | Newport Bowling Club | BoM | 5.3 | 1931 | Current |
| 66079 | Avalon (Avalon Pde) | BoM | 7.7 | 1958 | Current |
| 66126 | Long Reef Golf Club | BoM | 5.5 | 1965 | 1979 |
| 66183 | Ingleside (Walter Avenue) | BoM | 2.7 | 1984 | Current |
| 66188 | Belrose (Evelyn Place) | BoM | 8.0 | 1991 | Current |
| 66059 | Terrey Hills AWS | BoM | 5.0 | 2004 | Current |

### 3.7.3. Analysis of Rainfall Data

An analysis of the records of the daily rainfall stations Ingleside (Water Avenue) (66183) and Mona Vale Golf Club (66141) was undertaken. Ingleside (Water Avenue) and Mona Vale Golf Club are located to the north and northeast of the catchment as shown on Figure 5. These gauges were chosen for analysis because they are close to the catchment and had relatively continuous periods of record, which covered the longest combined historical period.

From this data (Table 5) it can be seen that April 1998 was by far the largest event recorded at Ingleside. The March 2011, July 2011, February 1997 and August 1998 storm events also were significant but of much lesser total rainfall in a single day. The August 1998 storm event accumulated a significant amount of rainfall in three consecutive days recorded at Mona Vale Golf Club.

Table 5: Large Daily Rainfalls at Ingleside (Water Avenue) and Mona Vale Golf Club

| **Ingleside (Water Avenue) (66183)** | | |
|---|---|---|
| 1984 to Date | | |
| Rank | Date | Rainfall (mm) |
| 1 | 11/04/1998 | 250 |
| 2 | 21/03/2011 | 229 |
| 3 | 22/07/2011 | 141 |
| 4 | 12/02/1997 | 138 |
| 5 | 6/08/1998 | 132 |
| 6 | 31/08/1996 | 127 |
| 7 | 8/08/1998 | 127 |
| 8 | 25/02/1999 | 127 |
| 9 | 7/08/1998 | 126 |
| 10 | 5/02/2002 | 124 |

| **Mona Vale Golf Club (66141)** | | |
|---|---|---|
| 1997 to Date | | |
| Rank | Date | Rainfall (mm) |
| 1 | 29/01/2013 | 136 |
| 2 | 7/08/1998 | 131 |
| 3 | 8/08/1998 | 121 |
| 4 | 11/04/1998 | 120 |
| 5 | 31/08/1996 | 110 |
| 6 | 20/03/2011 | 106 |
| 7 | 5/02/2002 | 104 |
| 8 | 12/02/1997 | 99 |
| 9 | 7/02/2010 | 95 |
| 10 | 6/08/1998 | 94 |

Continuous pluviometer records provide a more detailed description of temporal variations in rainfall.

Table 6: Pluviometers Within and Near the Catchment

| **Station Number** | **Station Name** | **Operating Authority** | **Distance from centre of the catchment (km)** | **Date Opened** | **Date Closed** |
|---|---|---|---|---|---|
| 566146 | Mona Vale | MHL | 3.4 | 1994 | Current |
| 213421 | Middle Creek | MHL | 4.7 | 1995 | Current |
| 566080 | Forestville | MHL | 10.2 | 2013 | Current |
| 213426 | Curl Curl | MHL | 7.9 | 2014 | Current |
| 566150 | Cromer | MHL | 4.3 | 1994 | Current |
| 566149 | Belrose | MHL | 8.5 | 1994 | Current |
| 566145 | Avalon | MHL | 7.5 | 1994 | Current |
| 566152 | Allambie Heights | MHL | 7.6 | 1999 | Current |
| 566051 | Warriewood Valley STP | SWC | 1.5 | 1981 | Current |
| 213411 | Narrabeen Creek | MHL | 1.5 | 1998 | 2010 |

Based on the analysis of daily gauges and the availability of pluviometer data, the five storms in April 1998, August 1998, February 2002, March 2011 and June 2016 were analysed. Comparison of these five rainfall events and design rainfall intensities from ARR 1987 are shown on Figure 6A to Figure 6E.

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### 3.7.4. Analysis of April 1998 Data

The cumulative rainfall depths of pluviometers for April 1998 are shown in Table 7 and Table 8.

Table 7: Continuous Rainfall Data in Different Pluviometers - April 1998

| Station Number | Station Name | Operating Authority | 24 hr Total (to 9am 10/04/98) (mm) | 24 hr Total (to 9am 11/04/98) (mm) |
|---|---|---|---|---|
| 213421 | Middle Creek | MHL | 38 | 202 |
| 566150 | Cromer | MHL | 31 | 160 |
| 566149 | Belrose | MHL | 30 | 222 |
| 566145 | Avalon | MHL | 30 | 103 |
| 566051 | Warriewood Valley STP | SWC | 42 | 145 |

Table 8: Equivalent AEP Rainfall Design Intensities in Different Pluviometers – April 1998

| Station Number | Station Name | Operating Authority | Equivalent Design Rainfall Intensity | | | |
|---|---|---|---|---|---|---|
| | | | 30 mins | 1 hour | 6 hour | 24 hour |
| 213421 | Middle Creek | MHL | 20% AEP | 10% AEP | 5% AEP | 10% AEP |
| 566150 | Cromer | MHL | 50% AEP | 50% AEP | 50% AEP | 50% AEP |
| 566149 | Belrose | MHL | 10% AEP | 5% AEP | 2% AEP | 10% AEP |
| 566145 | Avalon | MHL | 20% AEP | 20% AEP | 1 EY | 1 EY |
| 566051 | Warriewood Valley STP | SWC | 5% AEP | 5% AEP | 50% AEP | 50% AEP |

By checking the locations of pluviometers, it can be observed that the total rainfall depths decreased spatially from south to north. Although Belrose and Middle Creek recorded the largest rainfall, they are far away from the centre of the catchment. The rainfall recorded in Warriewood Valley STP, which is located within the catchment, is more suitable to be used for calibration purposes. The April 1998 event generally tracks above the design 5% AEP rainfall depth for the duration less than 1 hour, and between the 20% AEP and 50% AEP event for the 1 to 6 hour durations.

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### 3.7.5. Analysis of August 1998 Data

The cumulative rainfall depths of pluviometers for August 1998 are shown in Table 9 and Table 10.

Table 9: Continuous Rainfall Data in Different Pluviometers - August 1998

| Station Number | Station Name | Operating Authority | 72 hr Total (to 9am 08/08/98) (mm) |
|---|---|---|---|
| 566146 | Mona Vale | MHL | 304 |
| 213421 | Middle Creek | MHL | 361 |
| 566150 | Cromer | MHL | 343 |
| 566149 | Belrose | MHL | 293 |
| 566145 | Avalon | MHL | 264 |
| 566051 | Warriewood Valley STP | SWC | 378 |
| 213411 | Narrabeen Creek | MHL | 412 |

Table 10: Equivalent AEP Rainfall Design Intensities in Different Pluviometers – August 1998

| Station Number | Station Name | Operating Authority | Equivalent AEP Design Rainfall Intensity | | | |
|---|---|---|---|---|---|---|
| | | | 30 mins | 1 hour | 6 hour | 24 hour |
| 566146 | Mona Vale | MHL | <1 EY | 1 EY | 1 EY | 50% AEP |
| 213421 | Middle Creek | MHL | <1 EY | <1 EY | 1 EY | 50% AEP |
| 566150 | Cromer | MHL | <1 EY | <1 EY | 50% AEP | 50% AEP |
| 566149 | Belrose | MHL | <1 EY | <1 EY | 1 EY | 50% AEP |
| 566145 | Avalon | MHL | <1 EY | 1 EY | 1 EY | 50% AEP |
| 566051 | Warriewood Valley STP | SWC | <1 EY | <1 EY | 50% AEP | 10% AEP |
| 213411 | Narrabeen Creek | MHL | <1 EY | 1 EY | 50% AEP | 10% AEP |

The pluviometer in Narrabeen Creek recorded the largest three-day rainfall. This pluviometer is located in the downstream part of Narrabeen Creek. Comparing the event at this gauge to design rainfall intensities, the rainfall is less than or equivalent to 1 EY event for durations less than 1 hours. However, equivalent design rainfall intensities increased sharply at the gauge with the 24 hour and 48 hour durations being equivalent to 10% AEP and 1% AEP storms respectively.

The equivalent design rainfall intensities increased sharply from the duration of 9 hours to 36 hours, with 20% and 1% AEP respectively.

### 3.7.6. Analysis of March 2011 Data

The cumulative rainfall depths of pluviometers for March 2011 are shown in Table 11 and Table 12.

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Table 11: Continuous Rainfall Data in Different Pluviometers - March 2011

| Station Number | Station Name | Operating Authority | 24 hr total to 9am 19/03/11 (mm) | 24 hr total to 9am 20/03/11 (mm) | 24 hr total to 9am 21/03/11 (mm) | 72 hr total to 9am 21/03/11 (mm) |
|---|---|---|---|---|---|---|
| 566146 | Mona Vale | MHL | 82 | 106 | 42 | 229 |
| 213421 | Middle Creek | MHL | 46 | 135 | 45 | 226 |
| 566150 | Cromer | MHL | 62 | 121 | 40 | 223 |
| 566149 | Belrose | MHL | 60 | 121 | 35 | 216 |
| 566145 | Avalon | MHL | 68 | 110 | 36 | 214 |
| 566051 | Warriewood Valley STP | SWC | 71 | 115 | 45 | 230 |

Table 12: Equivalent AEP Rainfall Design Intensities in Different Pluviometers – March 2011

| Station Number | Station Name | Operating Authority | Equivalent AEP Design Rainfall Intensity | | | |
|---|---|---|---|---|---|---|
| | | | 30 mins | 1 hour | 6 hour | 24 hour |
| 566146 | Mona Vale | MHL | 1 EY | 1 EY | 1 EY | 50% AEP |
| 213421 | Middle Creek | MHL | <1 EY | <1 EY | <1 EY | 50% AEP |
| 566150 | Cromer | MHL | <1 EY | 1 EY | 1 EY | 1 EY |
| 566149 | Belrose | MHL | <1 EY | <1 EY | <1 EY | 1 EY |
| 566145 | Avalon | MHL | 1 EY | 1 EY | 50% AEP | 50% AEP |
| 566051 | Warriewood Valley STP | SWC | <1 EY | <1 EY | 1 EY | 50% AEP |

Warriewood Valley STP recorded the largest rainfall depths in the two-day storm event. This storm is relatively small, as the design intensities are below 20% AEP for all durations.

### 3.7.7. Analysis of June 2016 Data

The cumulative rainfall depths of pluviometers for June 2016 are shown in Table 13 and Table 14.

Table 13: Continuous Rainfall Data in Different Pluviometers – June 2016

| Station Number | Station Name | Operating Authority | 24 hr total to 9am 05/06/16 (mm) | 24 hr total to 9am 06/06/16 (mm) |
|---|---|---|---|---|
| 566146 | Mona Vale | MHL | 114.5 | 120.5 |
| 213421 | Middle Creek | MHL | 122.5 | 111 |
| 566150 | Cromer | MHL | 99.5 | 99.5 |
| 566149 | Belrose | MHL | 130 | 128.5 |
| 566145 | Avalon | MHL | 85.5 | 88.5 |

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Table 14: Equivalent AEP Rainfall Design Intensities in Different Pluviometers – June 2016

| Station Number | Station Name | Operating Authority | Equivalent AEP Design Rainfall Intensity | | | |
|---|---|---|---|---|---|---|
| | | | 30 mins | 1 hour | 6 hour | 24 hour |
| 566146 | Mona Vale | MHL | <1EY | 1 EY | 50% AEP | 10% AEP |
| 213421 | Middle Creek | MHL | <1 EY | <1 EY | 50% AEP | 10% AEP |
| 566150 | Cromer | MHL | <1 EY | <1 EY | 1 EY | 20% AEP |
| 566149 | Belrose | MHL | <1 EY | <1 EY | <1 EY | 1 EY |
| 566145 | Avalon | MHL | <1EY | <1 EY | 1 EY | 50% AEP |

Belrose recorded the largest rainfall depths in the two-day storm event but had relatively low rainfall intensities, equivalent to a 50% AEP design storm or less across the shorter durations that produce overland flow in the catchment. Rainfall for the gauges at Mona Vale and Middle Creek was equivalent to a 1 EY design rainfall or less for durations less than one hour but increased sharply. For longer durations of 24 and 48 hours, the rainfall was equivalent to a 10% AEP storm at those two gauges, but this would be more relevant to flooding in the lagoon than overland flow.

It is important to note when reviewing the equivalent rainfall intensities for all four events that shorter rainfall durations are likely to be more relevant to overland flow flooding conditions (and thus more relevant to this study) than longer rainfall durations which are more relevant for Narrabeen Lagoon flooding.

### 3.7.8. Design Rainfall Data

New design rainfall depths were released by the BoM in July 2013. Whilst it is expected that the new design rainfall depths will undergo minor revisions as they are independently verified, it is unlikely they will change substantially within the Sydney metropolitan area. The 2013 design rainfall estimates require other information from the revision of ARR including temporal patterns, aerial reduction factors, losses and base flows before they can be used in design flood estimation. Given that this project was substantially underway before the revised version of ARR was published in late 2016, WMAwater were instructed by Council that design rainfall intensities and techniques from ARR1987 should continue to be used (Reference 6). OEH indicated support for Council in its direction to complete the study using ARR1987, and suggested that whenever a future review of the study area was carried out it would include checking against ARR2016.

The design rainfall intensity-frequency-duration (IFD) data were obtained from the BoM online design rainfall tool or extracted from those results and are provided on Table 15.

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Table 15: Rainfall IFD Data at the catchment centre (ARR 1987)

| DURATION | 1 EY | 50% AEP | 20% AEP | 10% AEP | 5% AEP | 2% AEP | 1% AEP | 0.5% AEP | 0.2% AEP | 0.1% AEP |
|---|---|---|---|---|---|---|---|---|---|---|
| 5Mins | 98.1 | 126 | 159 | 178 | 204 | 237 | 262 | 285 | 318 | 344 |
| 6Mins | 91.8 | 118 | 149 | 167 | 191 | 222 | 246 | 270 | 301 | 326 |
| 10Mins | 75.3 | 96.7 | 123 | 139 | 159 | 185 | 205 | 225 | 252 | 273 |
| 20Mins | 55 | 71 | 91.7 | 104 | 120 | 140 | 156 | 169 | 190 | 204 |
| 30Mins | 44.7 | 57.9 | 75.3 | 85.5 | 98.8 | 116 | 130 | 141 | 159 | 173 |
| 1Hr | 30.5 | 39.5 | 51.8 | 59 | 68.5 | 80.9 | 90.4 | 100 | 113 | 123 |
| 2Hrs | 20.3 | 26.3 | 34.4 | 39.2 | 45.5 | 53.7 | 60.1 | 66 | 74 | 81 |
| 3Hrs | 15.9 | 20.6 | 26.9 | 30.6 | 35.4 | 41.7 | 46.6 | 51 | 58 | 63 |
| 6Hrs | 10.5 | 13.5 | 17.5 | 19.9 | 22.9 | 26.9 | 30 | 33.1 | 37.3 | 41 |
| 12Hrs | 6.85 | 8.84 | 11.4 | 12.9 | 14.9 | 17.5 | 19.4 | 21.5 | 24.2 | 26.3 |
| 24Hrs | 4.37 | 5.66 | 7.38 | 8.39 | 9.7 | 11.4 | 12.8 | 14.2 | 16 | 17.4 |
| 48Hrs | 2.68 | 3.49 | 4.63 | 5.31 | 6.2 | 7.37 | 8.27 | 9.16 | 10.4 | 11.25 |
| 72Hrs | 1.96 | 2.56 | 3.42 | 3.94 | 4.62 | 5.51 | 6.19 | 6.91 | 7.87 | 8.53 |

The Probable Maximum Precipitation (PMP) estimates were derived according to BoM guidelines, namely the Generalised Short Duration Method (Reference 8) and are summarised in Table 16. The ellipses for the PMP are shown on Figure 7.

Table 16: PMP Design Rainfalls

| Duration | Design Rainfall Depth (mm) |
|---|---|
| 15 minutes | 140 |
| 30 minutes | 220 |
| 45 minutes | 277 |
| 1 hour | 326 |
| 1.5 hours | 372 |
| 2 hours | 417 |
| 3 hours | 466 |
| 6 hours | 585 |

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# 4. MODELLING METHODOLOGY

## 4.1. Overview

The Ingleside, Elanora and Warriewood overland flow catchment has a mix of pervious and impervious surfaces and piped and overland flow drainage systems. This creates a complex hydrologic and hydraulic flow regime which requires a dual hydrologic and hydraulic analysis to address.

Estimation of flood behaviour in the catchment was undertaken as a two-stage process consisting of:

1. Hydrologic modelling to convert rainfall estimates to overland flow runoff;
2. Hydraulic modelling to estimate overland flow distributions, flood levels and velocities.

Hydrologic modelling was undertaken using DRAINS (Reference 10), a widely utilised hydrologic modelling software for urban catchments. Design rainfall depths and patterns specified in ARR (Reference 6) were input into the DRAINS modelling software and the runoff hydrographs produced were then input into the hydraulic model.

Hydraulic modelling was undertaken using TUFLOW (Reference 11), a widely utilised 1D and 2D flood simulation software. Runoff hydrographs from the DRAINS hydrologic model were input into the TUFLOW model which was then used to estimate flood depths, velocities and hazards in the study area. Hydraulic modelling was carried out on a fixed 2 m grid.

There are several stream-flow gauges in the catchment with the potential to be used for flood frequency analysis; but due to the range and quality of the data, estimation of design floods and/or calibration of the hydrologic model (independent of the hydraulic model) was not possible.

## 4.2. Hydrologic Model

DRAINS (Reference 10) is a hydrologic/hydraulic modelling software that can simulate a full storm hydrograph and is capable of describing the flood behaviour of a catchment and pipe system for both real storm and design storm events. It is designed for analysing urban or partly urban catchments with artificial drainage elements.

The DRAINS model is broadly characterised by the following features:

- A hydrological component based on the theory applied in the ILSAX model;
- An application of the hydraulic grade line method for hydraulic analysis throughout the drainage system; and
- A graphical display of network connections and results.

The use of DRAINS within this study was limited to some minor upstream catchment routing and development of hydrological inputs into the TUFLOW hydraulic model. DRAINS generates a full hydrograph of surface flows arriving at each pit. Runoff hydrographs for each sub-catchment area are calculated using the time area method.

## 4.3. Hydraulic Model

The TUFLOW (Reference 11) modelling package was utilised for this study. The TUFLOW modelling package includes a finite difference numerical model for the solution of the depth averaged shallow water flow equations in two dimensions. The TUFLOW software is produced by BMT WBM and has been widely used for a range of similar projects. The model is capable of dynamically simulating complex overland flow regimes. It is especially applicable to the hydraulic analysis of flooding in urban areas which is typically characterised by short duration events and a combination of supercritical and subcritical flow behaviour, and interactions between overland flow and a sub-surface drainage network.

In addition to 2D modelling of overland flows, TUFLOW can model drainage elements (pipes) as 1D elements as well as modelling creeks or open channels in 1D if required. The 1D and 2D components of the model can be dynamically linked during the simulation. In TUFLOW the ground topography is represented as a uniformly-spaced grid with a ground elevation and a Manning's "n" roughness value assigned to each grid cell. The grid cell size is determined as a balance between the model result definition required and the computer run time (which is largely determined by the total number of grid cells, and the number of "wet" cells). A cell size of 2 m by 2 m was found to provide an appropriate balance for this study.

## 4.4. Flood Frequency Analysis

Flood Frequency Analysis (FFA) uses the record of past flooding at a site to determine design event discharge. Through a statistical analysis of flood events, the AEP of a given discharge can be determined. This analysis can be used to confirm output design flows from the hydrologic model independent of the hydraulic model. FFA can also be useful for design flow estimation where the length and quality of the observed record and the accuracy of the rating curve are considered adequate.

There are several water level gauges present along the Northern beaches including the following within the Ingleside, Elanora and Warriewood overland flow catchment:

- Mullet Creek at Garden Street,
- Narrabeen Lagoon at Narrabeen Caravan Park, and
- Narrabeen Lagoon at Narrabeen Bridge.

Of these three gauges only Mullet Creek at Garden Street has the potential to be used for FFA in determining flows. The other two gauges measure levels within Narrabeen Lagoon rather than the northern tributary creeks which are the main focus of this study. The storm characteristics which produce flooding in the lagoon are likely to be quite different to those that produce flash flooding in the tributary creeks.

Data collected from the Mullet Creek gauge (Diagram 1) may be useful for hydrologic model calibration in the future but it is not useable for FFA at present as there is no rating curve for the gauge to derive flows from the water level measurements. This is common for gauges on relatively small urban catchments, since the catchment response occurs very quickly and it is

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difficult to mobilise hydrographers to obtain velocity readings.

As can be seen in Diagram 1, the data received for the Mullet Creek gauge:

- Does not have a particularly long record of length (<25 years);
- Has some instances of missing information (including one of the major known flood events in 2011); and
- Includes data that can be used as part of calibration/validation process for the larger events in April 1998, August 1998 and February 2002.

Therefore, although FFA was not undertaken as part of this study, the gauge provides some useful information about the relative flood magnitude of various historical events at a single location, as well as data points suitable for use as part of the joint hydrologic/hydraulic model calibration.

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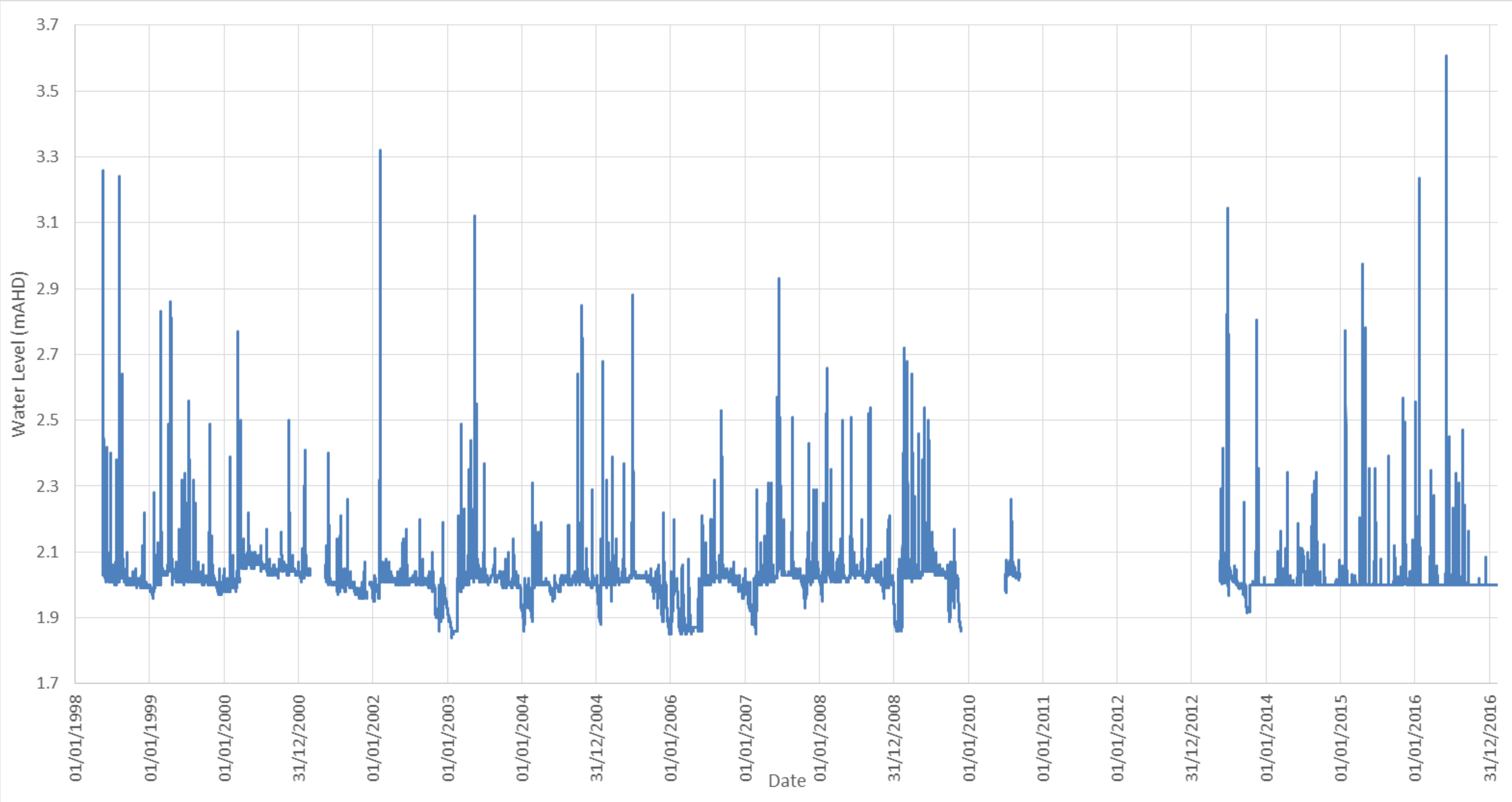
Diagram 1: Water Level Data from the Mullet Creek Stream Gauge (MHL)



## 4.5. Historical Event Calibration and Validation

In order to reconcile observed historical flooding, and the "design" flood events considered in this study, the flood model must be calibrated to and validated against historically observed data. Calibration involves comparisons of model results against observed historical floods, and modifying the model parameters if required to more accurately reflect the key flood mechanisms. If records are available from multiple storms, validation can be undertaken to ensure that the calibration model parameter values are acceptable in other storm events with no additional alteration of values.

Recorded rainfall and stream-flow data are required for calibration of the hydrologic model, while historic records of flood levels, velocities and inundation extents can be used for the calibration of hydraulic model parameters. In the absence of such data, model verification using limited historical data is the only option and a detailed sensitivity analysis of the different model input parameters constitutes current best practice.

The choice of calibration or verification events for flood modelling depends on a combination of the severity of the flood event and the quality of the available data. Quantitative information was obtained from the MHL water level gauge at Mullet Creek. Qualitative information has been provided by residents through the community consultation process with regard to their properties being flood affected. In some cases, this information was used to estimate flood depths and extents. The majority of observations were from the June 2016 storm, a recent event that was identified in the community consultation as having caused significant flooding problems in the Ingleside, Elanora and Warriewood overland flow catchment. Residents also identified April 1998, August 1998 and March 2011 as being significant events. Of these four events, Mullet Creek gauge data was available for the August 1998 and June 2016 events.

## 4.6. Design Flood Modelling

Design flood modelling was undertaken using the methodology outlined in Australian Rainfall and Runoff (Reference 6):

- design outflows for localised sub-catchments were obtained from the DRAINS hydrologic model, using standard design storms, and applied as inflows to the TUFLOW model;
- the TUFLOW model was used to estimate and map the flood behaviour for a range of flood events;
- sensitivity analyses were undertaken to assess the relative effect of changing various TUFLOW and DRAINS modelling parameters and catchment assumptions.

# 5. HYDROLOGIC MODEL SETUP

## 5.1. Sub-catchment delineation

The total catchment area inputted into the DRAINS model is 16.5 km$^2$ consisting of 882 sub-catchments with an average sub-catchment size of 1.9 hectares (this is influenced by the larger upstream catchments – the typical sub-catchment size in the lower catchment areas is significantly smaller). This relatively fine-resolution sub-catchment delineation ensures that where significant overland flow paths exist in the catchment, they are accounted for and incorporated into hydraulic routing in the model. The sub-catchment delineation is shown on Figure 9.

## 5.2. Impervious Surface Area

Runoff from connected impervious surfaces (such as roads, gutters, roofs or concrete surfaces) occurs significantly faster than from pervious surfaces. This disparity results in a faster concentration of flow within the downstream area of the catchment as well as increased peak flow in some situations. This is accounted for in the model through an estimate of the proportion of both impervious and pervious surfaces.

Determining the pervious and impervious areas of each sub-catchment was estimated by determining the proportion of the sub-catchment area covered by different surface types (from aerial photography supplied by NBC) and then estimating the impervious percentage of each surface type as summarised in Table 17 below.

Table 17: Impervious Percentage per Land-use

| Material | Impervious Percentage |
|---|---|
| Roads/Pavements | 100% |
| Light Vegetation/Grass/Field | 50% |
| Medium Vegetation/Crop/Plantation | 30% |
| Heavy Vegetation | 10% |
| Residential low density | 50% |
| Residential high density | 70% |
| Industrial/Commercial | 100% |
| Lake or estuary/ocean | 0% |
| Concrete-lined channel | 0% |
| Waterway/channels minimal vegetation | 0% |
| Waterway/channels vegetated | 0% |

## 5.3. Sub-catchment Slope

The slope of each sub-catchment was determined using an automated algorithm based on:

- Minimum and maximum elevation in each sub-catchment (from LiDAR);
- An indicative subcatchment length estimated from the ratio of the catchment area to its perimeter.



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Typical slopes used for each sub-catchment were in the range of 12% to 17% with an average of 13%. The minimum sub-catchment slope was less than 1% and the maximum was over 30%. This high slope and range of values is unusual for a typical Sydney catchment, but is representative of the steep topography of the catchment, particularly the escarpment areas separating the upper and lower catchment.

## 5.4. Rainfall Losses

Methods for modelling the proportion of rainfall that is "lost" to infiltration are outlined in ARR (Reference 6). The methods are of varying degrees of complexity, with the more complex options only suitable if sufficient data are available. The method most typically used for design flood estimation is to apply an initial and continuing loss to the rainfall. The initial loss represents the wetting of the catchment prior to runoff starting to occur and the continuing loss represents the ongoing infiltration of water into the saturated soils while rainfall continues.

Rainfall losses from a paved or impervious area are considered to consist of only an initial loss (an amount sufficient to wet the pavement and fill minor surface depressions). Losses from grassed areas are comprised of an initial loss and a continuing loss. The continuing loss is calculated from an infiltration equation curve incorporated into the model and is based on the selected representative soil type and antecedent moisture condition.

The adopted loss parameters are summarised in Table 18. These are generally consistent with the parameters adopted in flood studies in similar catchments within the Sydney metropolitan area.

Table 18: Adopted Rainfall Loss Parameters

| **RAINFALL LOSSES** | |
|---|---|
| Paved Area Depression Storage (Initial Loss) | 1.0 mm |
| Grassed Area Depression Storage (Initial Loss) | 5.0 mm |
| **SOIL TYPE** | 3 |
| Slow infiltration rates (may have layers that impede downward movement of water). This parameter, in conjunction with the AMC, determines the continuing loss | |
| **ANTECEDENT MOISTURE CONDITONS (AMC)** | 3 |
| Description | Rather wet |
| Total rainfall in 5 Days preceding the design storm burst | 12.5 to 25 mm |

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# 6. HYDRAULIC MODEL SETUP

## 6.1. TUFLOW

The study implemented a TUFLOW model with a cell size of 2 m by 2 m. This resolution provides an appropriate balance between providing sufficient detail for roads and overland flow paths and workable computational run-times. The model grid was established by sampling from a triangulation of filtered ground points from the 2011 LiDAR dataset.

The TUFLOW hydraulic model extends from Mona Vale Road to the west and north and is bounded by Narrabeen Lagoon to the south and the Tasman Sea to the east. The total area included in the 2D model is 16.5 km$^2$ and the extents of the TUFLOW model are included as Figure 10.

## 6.2. Boundary Locations

### 6.2.1. Inflows

For local sub-catchments within the TUFLOW model domain, local runoff hydrographs were extracted from the DRAINS model (see Section 4.2). These were applied to the receiving area of the sub-catchments within the 2D domain of the hydraulic model. These inflow locations (shown on Figure 10) typically correspond with gutters, stormwater inlet pits, drainage reserves or open watercourses features which have typically been constructed to receive intra-lot drainage and sheet runoff flows from upstream catchment areas.

### 6.2.2. Downstream Boundary

A downstream boundary was input along the south-east boundary of the model. This corresponded to the area where the model boundary intersects Narrabeen Lagoon and the Tasman Sea as shown on Figure 10. The tailwater levels at the downstream boundary are dependent on water levels in Narrabeen Lagoon, and thus different tailwater assumptions were adopted for different events.

For the calibration events, the tailwater levels were set to the variable historical gaugings for Narrabeen Lagoon at the Narrabeen Bridge gauge recorded during the calibration events.

For the design events, the tailwater levels were initially based on the 5% AEP and 1% AEP design flood levels determined in the Narrabeen Lagoon Flood Study (Reference 1). However, it was later found that such high tailwater levels had undue influence on flood behaviour at the downstream end of the catchment particularly in more frequent events, and especially given that flood behaviour from Narrabeen Lagoon is well represented in the 2013 Narrabeen Lagoon Flood Study. For this reason, flood events up to and including the 1% AEP event had a coincident tailwater assumption equal to the average tide level in Narrabeen Lagoon at the Narrabeen Bridge gauge. Events rarer than the 1% AEP utilised the 5% AEP and 1% AEP design flood levels determined in the Narrabeen Lagoon Flood Study. These are summarised in Table 19.

Table 19: Design Event Coincident Narrabeen Lagoon Tailwater Assumptions

| Narrabeen North Overland Design Rainfall | Narrabeen Lagoon Coincident Tailwater Assumption | Adopted Narrabeen Lagoon Peak Level (mAHD) |
|---|---|---|
| 20% AEP | Average Narrabeen Bridge Water Level | 0.43 |
| 10% AEP | Average Narrabeen Bridge Water Level | 0.43 |
| 5% AEP | Average Narrabeen Bridge Water Level | 0.43 |
| 2% AEP | Average Narrabeen Bridge Water Level | 0.43 |
| 1% AEP | Average Narrabeen Bridge Water Level | 0.43 |
| 0.5% AEP | 5% AEP Narrabeen Lagoon | 2.7 |
| 0.2% AEP | 5% AEP Narrabeen Lagoon | 2.7 |
| 0.1% AEP | 5% AEP Narrabeen Lagoon | 2.7 |
| PMF | 1% AEP Narrabeen Lagoon | 3.0 |

A sensitivity assessment was undertaken for the 1% AEP event, where the 5% AEP Narrabeen Lagoon level was used. Results are provided in Section 9.

## 6.3. Surface Roughness

The hydraulic efficiency of the flow paths within the TUFLOW model is represented in part by the hydraulic roughness or friction factor formulated as Manning's "n" values. This factor describes the net influence of bed roughness and incorporates the effects of vegetation and other features which may affect the hydraulic performance of the particular flow path.

The Manning's 'n' values adopted for the study area, including flow paths (overland, pipe and in-channel), are shown in Table 20. These values have been adopted based on site inspection and past experience in similar floodplain environments. The values are consistent with typical values given in Chow, 1959 (Reference 12) and Henderson, 1966 (Reference 13). The spatial variation in Manning's "n" is shown in Figure 11.

Table 20: Manning's "n" values adopted in TUFLOW

| Surface | Manning's "n" adopted |
|---|---|
| Concrete Pipes | 0.015 |
| Concrete-lined Channel | 0.02 |
| Roads/Pavements | 0.025 |
| Light Vegetation | 0.04 |
| Medium Vegetation | 0.07 |
| Dense Vegetation | 0.10 |
| Urban Residential | 0.05 |
| Residential high density | 0.05 |
| Industrial/Commercial | 0.03 |
| Lake or estuary/ocean | 0.03 |
| Waterway (Light Vegetation) | 0.03 |
| Waterway (Medium Vegetation | 0.07 |



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## 6.4. Hydraulic Structures

### 6.4.1. Buildings

Buildings and other significant objects likely to obstruct flow were incorporated into the model based on building footprints defined from aerial photography. These types of features were modelled as impermeable obstructions to flow and thus had no assumed flood storage capacity. Building delineation was validated in key overland flow areas by site inspection and using Google "Streetview" photographs.

### 6.4.2. Fencing and Obstructions

Smaller localised obstructions (such as fences) can be represented in TUFLOW in several ways including as impermeable obstructions, a percentage blockage or as an energy loss. The obstructions may also be approximated generally by increasing Manning's roughness for certain land use areas (such as residential) to represent the typical type of fencing used in such areas.

The majority of fences in the catchment were not modelled, as they can be difficult to identify and generally do not affect flow behaviour significantly in areas of shallow flow.

### 6.4.3. Bridges and Culverts

Detailed schematisation of key hydraulic structures was included in the hydraulic model, at the locations indicated on Figure 10. Bridges were generally modelled as 2D layer constrictions. The modelling parameter values for the bridges were based on the geometrical properties of the structures obtained from detailed survey, site visits and through the use of Google "Streetview" photographs. The parameters assumed for modelled bridges were confirmed during the ground truthing stage.

### 6.4.4. Sub-surface Drainage Network

The stormwater drainage network was modelled in TUFLOW as a 1D network dynamically linked to the 2D overland flow domain. This stormwater network includes conduits such as pipes and box culverts, and stormwater pits, including inlet pits and junction manholes. The schematisation of the stormwater network was undertaken using the pit and pipe GIS layers supplied by NBC.

The pit and pipe data supplied by Council did not have invert information supplied and in many cases pit sizes were also absent from the data set. While some inverts were estimated from LiDAR data following a field trip, or obtained as part of the survey undertaken in Section 3.4 the majority of pit inlets and pipe sizes were determined from the following principles:

- All sag and on-grade pits were modelled as having an invert 1.5 m below the recorded ground level;
- All junction pits were modelled as having an invert 1.5 m below the recorded ground level;
- All pipe openings were modelled as having an invert 0.1m above recorded ground level;
- Pits without a size supplied were estimated based on the sizing of similar pit types in the same area;

- Pipes without a size supplied were estimated based on the sizing of connected upstream and downstream pipes.

Following this initial estimation, further corrections to pit inverts were undertaken to correct pipes with negative slope or pipes that were located above ground in the model. Some of the assumptions utilised in pit inlet estimation were confirmed during the ground truthing stage.

Details of the 1D solution scheme for the pit and pipe network are provided in the TUFLOW user manual (Reference 11). For the modelling of inlet pits the "R" pit channel type was utilised, which requires a width and height dimension for the inlet in the vertical plane. The width dimension represents the effective length inlet exposed to the flow, and the vertical dimension reflects the depth of flow where the inlet becomes submerged, and the flow regime transitions from the weir equation to the orifice equation. For lintel inlets, the width was based on the length of the opening. For inlet grates, the width was based on the perimeter of the grate. For combined lintel and grate inlets, the inlet width was the combination of the lintel and grate edge lengths, minus the portion of the grate adjacent to the lintel (to avoid double counting). This method applies to both sag and on-grade pits.

Figure 12 shows the location and dimensions of drainage lines within the study catchment included in the TUFLOW model.

#### 6.4.5. Road Kerbs and Gutters

LIDAR typically does not have sufficient resolution to adequately define the kerb/gutter system within roadways. The density of the aerial survey points is in the order of one per square metre, and the kerb/gutter feature is generally of a smaller scale than this, so the LIDAR does not pick up a continuous line of low points defining the drainage line along the edge of the kerb.

To deal with this issue, Reference 14 provides the following guidance:

> *"Stamping a preferred flow path into a model grid/mesh (at the location of the physical kerb/gutter system) may produce more realistic model results, particularly with respect to smaller flood events that are of similar magnitude to the design capacity of the kerb and gutter. Stamping of the kerb/gutter alignment begins by digitising the kerb and gutter interval in a GIS environment. This interval is then used to select the model grid/mesh elements that it overlays in such a way that a connected flow path is selected (i.e. element linkage is orthogonal). These selected elements may then be lowered relative to the remaining grid/mesh."*

The road gutter network plays a key role for overland flow in the Ingleside, Elanora and Warriewood overland flow catchment. In order to model the system effectively, the gutters were stamped into the mesh using the method described above. The method used was to digitise breaklines along the gutter lines, and reduce the ground levels along those model cells by 0.1 m, creating a continuous flow path in the model.

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## 6.5. Blockage Assumptions

### 6.5.1. Background

In order to determine design flood behaviour the likelihood and consequences of blockage needs to be considered. Guidance on the application of blockage can be found in ARR Revision Project 11: Blockage of Hydraulic Structures, 2014 (Reference 15).

Blockage of hydraulic structures can occur with the transportation of materials by flood water. The potential quantity and size of debris reaching a structure from a contributing source area depends on several factors. ARR guidelines suggest adopted design blockage factors are based upon consideration of:

- the availability of debris;
- the ability for it to mobilise; and
- the ability for it to be transported to the structure.

The availability of debris is dependent on factors such as the potential for soil erosion, local geology, the source area, vegetative cover, the degree of urbanisation, land clearing and preceding wind and rainfall. The type of materials that can be mobilised can vary greatly between catchment and individual flood events.

The likelihood of blockage at a particular structure depends on whether or not debris is able to bridge across the structure inlet or become trapped within the structure. Research into culvert blockage in Wollongong showed a correlation with blockage and opening width. The most likely blockage to occur at a structure is determined by considering the potential quantity and type of debris along with the structure opening size.

### 6.5.2. Adopted Design Blockage

For all bridges and culverts with inlet headwalls (i.e. not pipes which do not have stormwater pits at the upstream end), a methodology in accordance with the ARR Blockage Guidelines (Reference 15) was incorporated into design event modelling. The ARR methodology considers blockage due to various sources and takes into account the:

- debris type and dimensions;
- debris availability;
- debris mobility;
- debris transportability;
- structure interaction.

Debris characteristics were considered to be uniform across the catchment. A summary of the adopted design blockage design blockage levels is provided below in Table 21. Note that only pipes with open channel sections immediately upstream were assumed to block (i.e. at headwalls). Pipes with connections from stormwater inlets were not assumed to be blocked, as the inlets themselves are subject to a blockage assumption.

Table 21: Adopted Pipe Blockage Factors

| Equivalent Pipe Diameter Size (m) | Adopted Blockage |
|---|---|
| < 1.2 | 50% |
| >=1.2 | 25% |

Additionally, a uniform deck underside blockage factor of 5% was applied to all bridges within the catchment.

Sensitivity analysis was undertaken on these assumptions, and it was determined that blockage was not a critical issue for design flood levels in the catchment (see Section 9).

## 6.6. Model Mass Balance Checks

The cumulative mass error from the model is an indication of whether the numerical implementation of the shallow water equations is resulting in artificial creation or destruction of water. A high mass balance error can indicate unreliable modelling results, since the model would not be accurately representing the amount of stormwater runoff in the catchment.

The cumulative error was less than 0.7% for all design events modelled (Table 22). This is a relatively low error reflective of reasonable model “health” and schematisation.

Table 22: Model Cumulative Error – Design Events

| Design Event | Cumulative Mass Error |
|---|---|
| PMF | -0.65% |
| 0.1% AEP | -0.32% |
| 0.2% AEP | -0.27% |
| 0.5% AEP | -0.24% |
| 1% AEP | -0.66% |
| 2% AEP | -0.64% |
| 5% AEP | -0.69% |
| 10% AEP | -0.66% |
| 20% AEP | -0.66% |

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# 7. MODEL CALIBRATION

## 7.1. Overview

The accuracy of a flood model system must be confirmed prior to defining design flood behaviour through model calibration and validation. Calibration involves modifying initial model parameter values to produce modelled results that concur with observed data. Validation is undertaken to ensure that the calibration model parameter values are acceptable in other storm events with no additional alteration of values. Ideally the modelling system should be calibrated and validated to multiple events, but this requires adequate historical flood observations and sufficient pluviometer rainfall data.

Typically, in urban areas calibration/validation information is lacking. Issues which may prevent a thorough calibration of hydrologic and hydraulic models are:

- There is only a limited amount of historical flood information available for the study area. For example, in the Sydney metropolitan area there are only a few water level recorders in urban catchments similar to that of the study area; and
- Rainfall records for past floods are limited and there is a lack of temporal information describing historical rainfall patterns (pluviometers) within the catchment.

Neither of these issues is as prevalent in the Narrabeen North study due to the presence of good quality pluviometer and water level data from both MHL and Sydney Water; but they are still relevant due to the large catchment area, the sparse placing of the gauges throughout the catchment and the proximity of the catchment to the ocean.

## 7.2. Summary of Calibration Event Data

The choice of calibration/validation events for flood modelling depends on a combination of the severity of the flood event and the quality of the data available. The severity of flood events in the Narrabeen North catchment were determined from an analysis of BoM daily read gauges and MHL pluviometers for the period from 1996 – 2016. From this analysis, the following dates were initially identified:

- April 1998;
- August 1998;
- March 2011.

These dates were included in community consultation documents in an attempt to obtain community identified flood affectation during those storm events. The community consultation process provided some calibration/validation data for all three events and also identified June 2016 as a fourth potential calibration/validation date.

### 7.2.1. Recorded Gauge Information

Pluviometer data from the Warriewood STP (Figure 5) was available for the April 1998, August 1998, March 2011 and June 2016 storm events. However, water level gauge data for the Mullet Creek at Narrabeen gauge (Station Number 707659) was only available for the August 1998 and

June 2016 storm events. For this reason, detailed hydraulic calibration/validation of the model was only undertaken against the August 1998 and June 2016 events.

Water level gauge data was also obtained from MHL for the Narrabeen Lagoon at the Narrabeen Bridge gauge (Station Number 213422). This data was used in setting tailwater levels at the downstream model boundary.

### 7.2.2. Community Flood Observations

The community consultation process identified 36 locations with potential overland flood affectation. While some identified specific dates (the June 2016 event in particular), many simply identified flooding occurring in heavy rainfall. For this reason, where specific dates were not provided community identified flooding was compared against both the August 1998 and June 2016 events. Similarly, where flooding was identified as occurring simply in 1998, flood marks/descriptions were compared against the August 1998 event. Most responses received as part of the community consultation did not contain specific flood marks against which the flood models could be measured. For this reason, the models were qualitatively measured against the descriptions provided.

A description of each recorded flood level obtained through the community consultation process is given in Table 23.

Table 23: Historic Flood Observations

| ID | Description of Flooding | Flood Event |
|---|---|---|
| 5525015 | Road in front of property flooded | 2016 |
| 5515183 | Nareen Creek floods Narroy Park which in turn floods the road and property | All |
| 5502003 | Flooding on the street in front of the property | 2016 |
| 5503233 | Front yard and street flooded | All |
| 5504182 | Backyard flooding | 2011 |
| 5505640 | Water flooded down driveway and through garage | Aug-98 |
| 5507439 | East end of Macpherson Street and South end of Garden Street | All |
| 5004126208 | Garden Street | 2016 |
| 4985889114 | Back of the property near Warriewood Reserve | 2016 |
| 4980095469 | Property | 1998 |
| 4980014650 | Tatiara Crescent, Nareen Parade, Gondola Road | 2016 |
| 4973867442 | Water encroached from wetlands | 2016 |
| 4968248495 | Water run down gully in neighbouring property and flooded house | 2016 |
| 4965681414 | Overflowing of Narrabeen creek onto road near the end of Macpherson Street | 2016 |
| 4954264506 | Water on road west of sewage treatment plant. North east corner of 1 Vuko Place Warriewood subject to minor flooding. | All |
| 4953332754 | Mullet creek floods back fence | All |
| 5525002 | Flooding behind house and in garage | All |

| ID | Description of Flooding | Flood Event |
|---|---|---|
| 5525011 | Property | 2016 |
| 5515818 | Large storm events cause flooding in garage | All |
| 5511104 | Property flooded by runoff from Woorarra Road | All |
| 5027000831 | Runoff from Dewrang Reserve through property | All |
| 5004590268 | House flooded due to runoff from properties above | All |
| 4979120475 | House flooded due to runoff from properties above | All |
| 4958256649 | Area around house and carport flooded in heavy rain | All |
| 5504270 | Flooding of factory floor | 2016 |
| 5516582 | Property flooded over ground floor level | 2011 |
| 5525012 | Flooding in front and back yards | 2011, 2016 |
| 5503159 | Macpherson Street off Warriewood Road flooded in heavy rain | 2016 |
| 5503176 | Flooding of Progress park and Garden, corner of Powderworks Road and Garden Street. Water at back door. | 2016 |
| 5505107 | Macpherson Street, Boondah Road | 2016 |
| 5511108 | Water flows through carport at rear of property, runoff from neighbours | 2016 |
| 5509908 | Council reserve near property flooded | All |
| 4965452694 | Water runs in a depression along the left side of the road runs from the road into our property | All |
| 4955795773 | Flooding from stormwater drain in a property to the south | All |
| 4953794058 | Water came onto the property from the open drain behind 62 Collins Street | 2016 |
| 4953923784 | A few centimetres of water on the front lawn after heavy rain | 2011 |

## 7.3. Hydrologic Model Validation

A basic hydrologic model validation was undertaken by checking the specific yield for all sub-catchments in comparison with results from similar areas in other studies. The specific yield is calculated by dividing the area in hectares by the maximum flow generated from the sub-catchment. The average specific yield for the 1% AEP event for all sub-catchments was 0.59 ($m^3$/s/ha), which is reasonably consistent with results from other urban Sydney catchments close to the coast.

## 7.4. Hydraulic Model Calibration/Validation

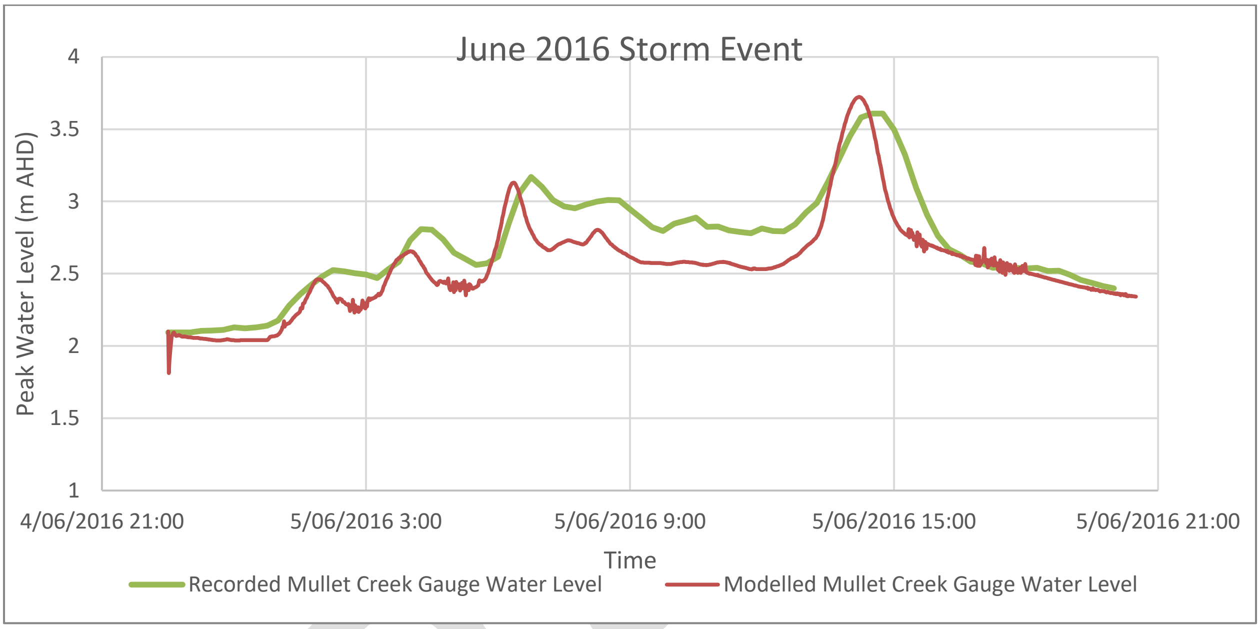
The peak rainfall period from each event was extracted from the pluviometer data supplied by Sydney Water and input into the DRAINS model developed as part of the study. Runoff hydrographs for each sub-catchment were input into the TUFLOW hydraulic model. The results from the TUFLOW model were compared quantitatively against the water level gauge data at Mullet Creek and qualitatively against community observed flooding.

### 7.4.1. June 2016 Calibration

Calibration of the hydraulic model was undertaken by comparing the peak gauge level recorded at the Mullet Creek Gauge to model results for the June 2016 event (see Diagram 2). A comparison of data collected from the community consultation (Section 2.3) to modelled historical events was also undertaken.

Diagram 2 shows a reasonable match between the recorded and modelled levels at the gauge in terms of both the shape (both showing a multi-peak event) and magnitude as the recorded peak was 3.6 mAHD compared with a modelled peak of 3.7 mAHD. The model shows a reasonable match, given the uncertainty associated with the rainfall data across the catchment.

Diagram 2: June 2016 Mullet Creek Gauge Comparison




The results shown in Table 24 are a comparison of community observations and modelled flooding behaviour for the June 2016 flood event. As can be seen in the table, there is a correlation between most flood observations and modelled flood behaviour, although 7 of the 31 flooding observations are not reflected in the modelling. While this seems high, 6 of the 7 locations are located on ridges at the head of steep drops and 1 is located on high ground in the upper part of the catchment. Flood descriptions for nearly all locations generally refer to intra-lot drainage from neighbours or poor drainage at the property itself being the primary cause of flooding, and not necessarily significant overland flow paths. Therefore the model was not modified to artificially introduce inflows that would match this local intra-lot drainage, and the flood marks were ignored for model calibration purposes.

Table 24: Historical Observation vs Flood Model June 2016 Event

| ID | Description of Flooding from Response | Calibration Match |
|---|---|---|
| 5525015 | Road in front of property flooded | Good |
| 5515183 | Nareen Creek floods Narroy Park which in turn floods the road and property | Good |
| 5502003 | Flooding on the street in front of the property | Good |
| 5503233 | Front yard and street flooded | Good |
| 5507439 | East end of Macpherson Street and South end of Garden Street | Good |
| 5004126208 | Garden Street | Good |
| 4985889114 | Back of the property near Warriewood Reserve | Reasonable |
| 4980014650 | Tatiara Crescent, Nareen Parade, Gondola Road | Good |
| 4973867442 | Water encroached from wetlands | Good |
| 4968248495 | Water run down gully in neighbouring property and flooded house | Good |
| 4965681414 | Overflowing of Narrabeen creek onto road near the end of Macpherson Street | Good |
| 4954264506 | Water on road west of sewage treatment plant. North east corner of 1 Vuko Place Warriewood subject to minor flooding. | Good |
| 4953332754 | Mullet creek floods back fence | Good |
| 5525002 | Flooding behind house and in garage | Poor |
| 5525011 | Property | Reasonable |
| 5515818 | Large storm events cause flooding in garage | Poor |
| 5511104 | Property flooded by runoff from Woorarra Road | Reasonable |
| 5027000831 | Runoff from Dewrang Reserve through property | Poor |
| 5004590268 | House flooded due to runoff from properties above | Poor |
| 4979120475 | House flooded due to runoff from properties above | Poor |
| 4958256649 | Area around house and carport flooded in heavy rain | Poor |
| 5504270 | Flooding of factory floor | Poor |
| 5525012 | Flooding in front and back yards | Reasonable |
| 5503159 | Macpherson Street off Warriewood Road flooded in heavy rain | Reasonable |
| 5503176 | Flooding of Progress park and Garden, corner of Powderworks Road and Garden Street. Water at back door. | Reasonable |
| 5505107 | Macpherson Street, Boondah Road | Reasonable |
| 5511108 | Water flows through carport at rear of property, runoff from neighbours | Reasonable |
| 5509908 | Council reserve near property flooded | Reasonable |
| 4965452694 | Water runs in a depression along the left side of the road runs from the road into our property | Reasonable |
| 4955795773 | Flooding from stormwater drain in a property to the south | Reasonable |
| 4953794058 | Water came onto the property from the open drain behind 62 Collins Street | Reasonable |

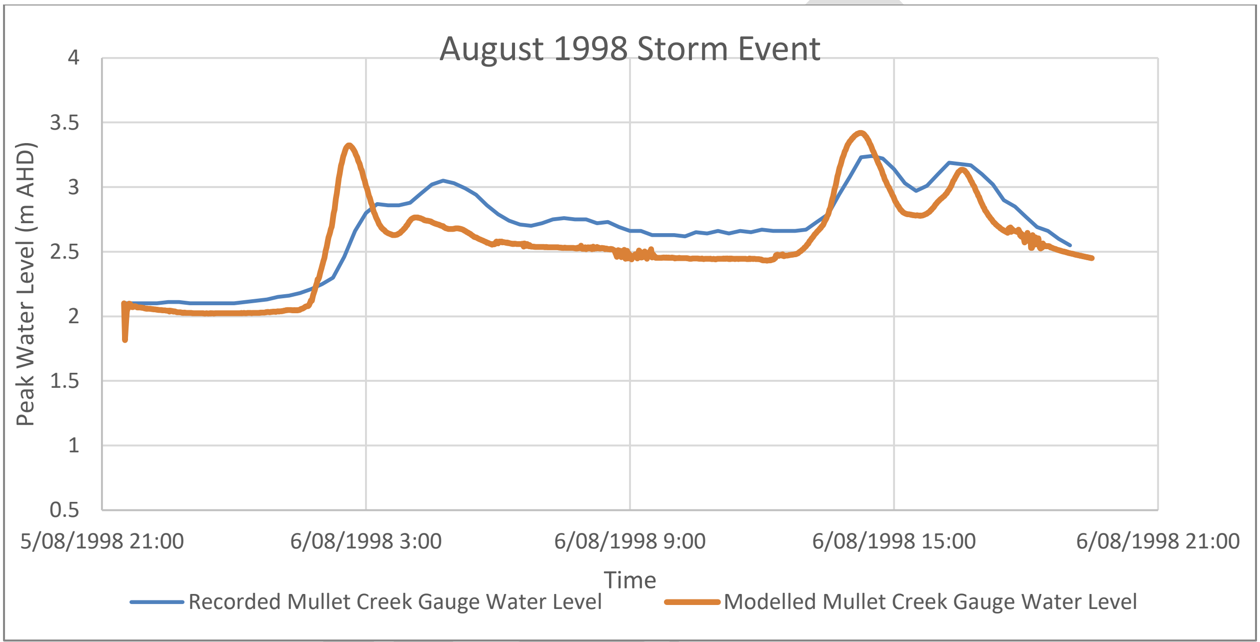
### 7.4.2. August 1998 Validation

Validation was undertaken for the August 1998 event. A comparison with data collected from the community consultation was also undertaken for this event.

The results in Diagram 3 show a reasonable match between the recorded and modelled levels at the gauge in terms of both the shape (both showing a multi-peak event) and magnitude as the recorded peak was 3.2 mAHD compared with a modelled peak of 3.4 mAHD. The model shows a reasonable match, given the uncertainty associated with the rainfall data across the catchment.

Similar to the June 2016 event, there are discrepancies between the recorded and modelled gauge profiles but generally the model shows a good level of calibration with the recorded event when the proximity of the pluviometer to the water level gauge and the rest of the catchment is considered.

Diagram 3: August 1998 Mullet Creek Gauge Comparison




The results shown in Table 25 show a reasonable match between most flood observations and modelled flood behaviour, with 6 of the 17 flooding observations not reflected in the modelling (see Section 7.4.1 above for an explanation of this behaviour).

Table 25: Historical Observation vs Flood Model August 1998 Event

| ID | Description of Flooding from Response | Calibration Accuracy |
|---|---|---|
| 5515183 | Nareen Creek floods Narroy Park which in turn floods the road and property | Good |
| 5503233 | Front yard and street flooded | Good |
| 5505640 | Water flooded down driveway and through garage | Good |
| 5507439 | East end of Macpherson Street and South end of Garden Street | Good |
| 4980095469 | Property | Good |
| 4954264506 | Water on road west of sewage treatment plant. North east corner of 1 Vuko Place Warriewood subject to minor flooding. | Good |
| 4953332754 | Mullet creek floods back fence | Good |
| 5525002 | Flooding behind house and in garage | Poor |
| 5515818 | Large storm events cause flooding in garage | Poor |
| 5511104 | Property flooded by runoff from Woorarra Road | Reasonable |
| 5027000831 | Runoff from Dewrang Reserve through property | Poor |
| 5004590268 | House flooded due to runoff from properties above | Poor |
| 4979120475 | House flooded due to runoff from properties above | Poor |
| 4958256649 | Area around house and carport flooded in heavy rain | Poor |
| 5509908 | Council reserve near property flooded | Reasonable |
| 4965452694 | Water runs in a depression along the left side of the road runs from the road into our property | Reasonable |
| 4955795773 | Flooding from stormwater drain in a property to the south | Reasonable |

### 7.4.3. Calibration Summary

Generally, the model accurately represents flooding behaviour as described by residents and as recorded at the Mullet Creek gauge. Although there were some discrepancies between the recorded and modelled gauge levels, the similar shape and peak flood levels recorded at the gauge for the August 1998 and June 2016 is considered reflective of an accurate match of both events.

Most resident flood observations were also reflected in the model, with the exceptions (as discussed above) being local drainage issues generally occurring on high ground rather than significant overland flow paths. Given both of these factors, it is considered that the model has been accurately calibrated to and validated against historical flooding in the catchment.

Maps of the modelled depths for the two validation events are shown on Figure 13 and Figure 14. The peak depth maps for the events show a good match between areas of significant flooding and locations where flood issues were reported by the community.

# 8. DESIGN EVENT MODELLING

## 8.1. Overview

Design flood levels in the catchment are a combination of flooding from rainfall over the local catchment, as well as elevated tailwater levels from flooding in Narrabeen Lagoon.

## 8.2. Downstream Boundary Levels – Narrabeen Creek

In addition to runoff from the catchment, downstream areas can also be influenced by high water levels near Narrabeen Lagoon. Consideration must therefore also be given to accounting for the joint probability of coincident flooding from Narrabeen Lagoon.

A full joint probability analysis to consider the interaction of these two mechanisms is beyond the scope of the present study. It is accepted practice to estimate design flood levels in these situations using a 'peak envelope' approach that adopts the highest of the predicted levels from the two mechanisms.

Design flood levels for Narrabeen Lagoon flooding are provided in Reference 1 and the adopted boundary conditions are summarised in Table 19 (refer Section 6.2.2).

## 8.3. Critical Duration – Overland Flooding

To determine the critical storm duration for various parts of the catchment (i.e. the duration that produces the highest flood level), modelling of the 1% AEP and PMF events was undertaken for a range of design storm durations from 30 minutes to 12 hours, using temporal patterns from ARR (Reference 6). An envelope of the model results was created, and the storm duration producing the maximum flood depth was determined for each grid point within the study area. It was found that the critical duration for the 1% AEP storm was generally 2 hours although there were large storage areas for which the 9 hour storm was critical. For this reason an embedded storm approach was utilised which encompassed the peak of the 2 hour storm within the full volume of the 9 hour storm (this was adopted for all other design storms except for the PMF). The critical duration for the PMF was 30 minutes.

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## 8.4. Design Flood Results

Preliminary design flood results are included as follows:

- Peak flood depths and extents in Figure B1 to Figure B9;
- Peak flood velocities in Figure B10 to Figure B18;
- Hydraulic hazard in Figure B19 to Figure B22;
- Hydraulic categorisation in Figure B23 to Figure B25.

Design flood results were filtered using the following criteria:

- Depths less than 0.15 m were removed from the result maps;
- Areas of ponding less than 100 $m^2$ were then removed; and
- Velocity Depth product greater than 0.3 $m^2/s$ were included in the result maps.

### 8.4.1. Overview of Flood Behaviour

The nature of flooding in the catchment varies significantly between the relatively low-density development on the upper catchment plateau, and the more urbanised flatter lower catchment.

In the upper portion of the catchment (atop the plateau between Mona Vale Road and Deep Creek) development is relatively low density. The land use comprises low density residential and commercial (light agricultural) development, some remnant bush land and two golf courses. The creeks remain in a relatively natural state. As a result of the steep terrain and low development density, there are few major overland flow paths with significant concentration of flow, outside of the creek channels. These channels contain most of the catchment runoff even in more severe storms like a 1% AEP event. The most notable flood issues are the Ingleside Road and Powderworks Road crossings at Mullet Creek, which are likely to be overtopped relatively frequently.

The catchment falls away steeply from the upper plateau. The southern part of the mid-catchment comprises the residential area of Elanora Heights, draining primarily to Nareen Creek, while the northern part is remnant bushland, draining to Mullet, Fern and Narrabeen Creeks. The catchment is very steep through these areas, resulting in widespread shallow overland flow, with relatively few concentrated flow paths apart from the creek channels. The most notable flood issues in the mid-catchment area are the corner of Powderworks Road and Elanora Road at the outlet of the Elanora Country Club golf course, and the Ponderosa Parade crossing at Narrabeen Creek.

In the lower reaches of the catchment (below Ponderosa Parade in the northern part of the catchment, and through the suburbs of Warriewood and North Narrabeen) flooding is significantly more widespread than in the upper areas of the catchment, due to:

- flatter topography;
- relatively small creek channels with regard to the upper catchment area;
- the influence of Warriewood Wetlands, and
- backwater influences from Narrabeen Lagoon.

There are large areas of flood storage, subject to significant inundation depths in severe storm



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events. Flooding of all creeks is out of bank in events as small as the 20% AEP with inundation occurring at:

- Narrabeen Creek along the Brands Lane development and other areas of Macpherson Street, the sewage treatment plant near Boondah Road and between Boondah Reserve and Warriewood Square;
- Mullet Creek along Warriewood Wetlands and Garden Street (particularly at Warraba Road);
- Fern Creek along Honeyeater Grove and Warriewood Wetlands; and
- Nareen Creek, which overtops and causes significant flooding between Tatiara Crescent where it is first piped and Narrabeen Lagoon where it eventually discharges.

The most significant overland flooding in the urbanised catchment areas occurs along the stretches where Nareen Creek is piped, with heavy inundation between Tatiara Crescent and Nareen Parade as well as between Narroy Road and Pittwater Road (although this is exacerbated by the flooding of the wetlands below Nareen Parade).

### 8.4.2. Results Summary

Peak flood levels, depths and flows at key locations within the catchment are summarised below. A summary of peak flood depth and level results at key locations as shown in Figure 15 and details are shown in Table 26, Table 27 and Table 28 . The locations coincide with those used for sensitivity analysis discussed in Section 9.

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Table 26: Peak Flood Levels (mAHD) at Key Locations

| Location ID | AEP | | | | | | | | PMF |
|---|---|---|---|---|---|---|---|---|---|
| | 20% | 10% | 5% | 2% | 1% | 0.5% | 0.2% | 0.1% | |
| H01 | 66.85 | 66.89 | 66.93 | 66.95 | 66.96 | 66.99 | 67.02 | 67.04 | 67.35 |
| H02 | 4.99 | 5.06 | 5.14 | 5.2 | 5.27 | 5.33 | 5.39 | 5.44 | 5.81 |
| H03 | 4.99 | 5.06 | 5.14 | 5.2 | 5.27 | 5.33 | 5.4 | 5.46 | 5.94 |
| H04 | 18.79 | 18.87 | 18.99 | 19.07 | 19.16 | 19.22 | 19.33 | 19.43 | 19.93 |
| H05 | 0.43 | 0.43 | 0.43 | 0.43 | 0.43 | 2.7 | 2.7 | 2.7 | 3 |
| H06 | N/A | N/A | N/A | N/A | N/A | 2.7 | 2.7 | 2.7 | 3 |
| H07 | 2.01 | 2.11 | 2.2 | 2.28 | 2.35 | 2.9 | 2.93 | 2.96 | 3.38 |
| H08 | 0.59 | 0.68 | 0.81 | 0.93 | 1.05 | 2.7 | 2.7 | 2.7 | 3.04 |
| H09 | 2.01 | 2.09 | 2.18 | 2.26 | 2.33 | 2.9 | 2.92 | 2.95 | 3.35 |
| H10 | N/A | N/A | N/A | 2.37 | 2.47 | 3.11 | 3.2 | 3.28 | 3.83 |
| H11 | N/A | N/A | 2.6 | 2.69 | 2.74 | 3.11 | 3.2 | 3.27 | 3.82 |
| H12 | 3.94 | 4 | 4.07 | 4.11 | 4.15 | 4.2 | 4.25 | 4.31 | 4.89 |
| H13 | 16.51 | 16.57 | 16.64 | 16.7 | 16.77 | 16.82 | 16.88 | 16.92 | 17.29 |
| H14 | 2.09 | 2.11 | 2.18 | 2.26 | 2.33 | 2.88 | 2.9 | 2.92 | 3.26 |
| H15 | 2.72 | 2.76 | 2.81 | 2.86 | 2.89 | 3.03 | 3.07 | 3.11 | 3.65 |
| H16 | 2.07 | 2.1 | 2.18 | 2.27 | 2.33 | 2.89 | 2.91 | 2.94 | 3.32 |
| H17 | 5.31 | 5.37 | 5.45 | 5.51 | 5.58 | 5.64 | 5.71 | 5.77 | 6.45 |
| H18 | 11.8 | 11.82 | 11.84 | 11.86 | 11.87 | 11.89 | 11.92 | 11.93 | 12.04 |
| H19 | 3.1 | 3.17 | 3.26 | 3.34 | 3.42 | 3.58 | 3.67 | 3.73 | 4.16 |
| H20 | 2.44 | 2.57 | 2.73 | 2.9 | 3.01 | 3.33 | 3.39 | 3.44 | 3.89 |
| H21 | 52.58 | 52.6 | 52.61 | 52.61 | 52.62 | 52.62 | 52.64 | 52.65 | 52.68 |
| H22 | 101.51 | 101.55 | 101.58 | 101.58 | 101.6 | 101.62 | 101.65 | 101.67 | 101.87 |
| H23 | 90.13 | 90.14 | 90.16 | 90.17 | 90.19 | 90.2 | 90.22 | 90.23 | 90.33 |
| H24 | 2.03 | 2.08 | 2.16 | 2.25 | 2.32 | 2.88 | 2.9 | 2.92 | 3.29 |
| H25 | 2.03 | 2.08 | 2.16 | 2.25 | 2.32 | 2.85 | 2.87 | 2.89 | 3.16 |
| H26 | 2.04 | 2.08 | 2.15 | 2.24 | 2.31 | 2.85 | 2.87 | 2.89 | 3.17 |
| H27 | 2.08 | 2.13 | 2.17 | 2.21 | 2.3 | 2.81 | 2.82 | 2.83 | 3.07 |
| H28 | 2.56 | 2.57 | 2.59 | 2.6 | 2.6 | 2.71 | 2.71 | 2.71 | 3.02 |
| H29 | 75.72 | 75.75 | 75.79 | 75.81 | 75.84 | 75.86 | 75.89 | 75.92 | 76.19 |
| H30 | 101.54 | 101.58 | 101.62 | 101.65 | 101.68 | 101.71 | 101.78 | 101.82 | 102.29 |
| H31 | 99.84 | 99.89 | 99.94 | 99.98 | 100.02 | 100.05 | 100.09 | 100.13 | 100.36 |
| H32 | 2.69 | 2.73 | 2.84 | 2.96 | 3.06 | 3.35 | 3.41 | 3.46 | 3.9 |
| H33 | 4.96 | 4.97 | 4.99 | 5 | 5.02 | 5.03 | 5.04 | 5.06 | 5.14 |

Table 27: Peak Flood Depths (m) at Key Locations

| Location ID | AEP | | | | | | | | PMF |
|---|---|---|---|---|---|---|---|---|---|
| | 20% | 10% | 5% | 2% | 1% | 0.5% | 0.2% | 0.1% | |
| **H01** | 0.24 | 0.27 | 0.31 | 0.34 | 0.36 | 0.38 | 0.41 | 0.43 | 0.73 |
| **H02** | 0.9 | 0.97 | 1.05 | 1.11 | 1.18 | 1.24 | 1.3 | 1.35 | 1.72 |
| **H03** | 0.42 | 0.49 | 0.57 | 0.63 | 0.7 | 0.76 | 0.83 | 0.89 | 1.37 |
| **H04** | 1.31 | 1.39 | 1.52 | 1.59 | 1.68 | 1.75 | 1.86 | 1.95 | 2.46 |
| **H05** | 0.93 | 0.93 | 0.93 | 0.93 | 0.93 | 3.2 | 3.2 | 3.2 | 3.5 |
| **H06** | N/A | N/A | N/A | N/A | N/A | 1.75 | 1.75 | 1.75 | 2.05 |
| **H07** | 1.2 | 1.3 | 1.4 | 1.48 | 1.54 | 2.1 | 2.13 | 2.15 | 2.57 |
| **H08** | 1.06 | 1.15 | 1.28 | 1.4 | 1.52 | 3.17 | 3.17 | 3.17 | 3.51 |
| **H09** | 0.92 | 1 | 1.09 | 1.17 | 1.24 | 1.81 | 1.83 | 1.86 | 2.26 |
| **H10** | N/A | N/A | N/A | 0.09 | 0.19 | 0.83 | 0.92 | 1 | 1.54 |
| **H11** | N/A | N/A | 0.12 | 0.21 | 0.26 | 0.63 | 0.72 | 0.8 | 1.34 |
| **H12** | 0.31 | 0.37 | 0.43 | 0.48 | 0.52 | 0.56 | 0.62 | 0.68 | 1.26 |
| **H13** | 0.11 | 0.17 | 0.25 | 0.3 | 0.37 | 0.42 | 0.48 | 0.53 | 0.89 |
| **H14** | 0.17 | 0.19 | 0.26 | 0.34 | 0.41 | 0.96 | 0.98 | 1 | 1.35 |
| **H15** | 0.04 | 0.07 | 0.12 | 0.16 | 0.19 | 0.34 | 0.38 | 0.41 | 0.95 |
| **H16** | 0.78 | 0.81 | 0.89 | 0.97 | 1.04 | 1.6 | 1.63 | 1.65 | 2.03 |
| **H17** | 0.25 | 0.31 | 0.39 | 0.45 | 0.51 | 0.58 | 0.65 | 0.7 | 1.39 |
| **H18** | 0.19 | 0.21 | 0.23 | 0.25 | 0.26 | 0.28 | 0.3 | 0.31 | 0.42 |
| **H19** | 0.74 | 0.81 | 0.9 | 0.98 | 1.06 | 1.23 | 1.31 | 1.37 | 1.8 |
| **H20** | 0.44 | 0.58 | 0.73 | 0.9 | 1.02 | 1.33 | 1.39 | 1.44 | 1.89 |
| **H21** | 0.14 | 0.16 | 0.17 | 0.18 | 0.19 | 0.19 | 0.2 | 0.21 | 0.24 |
| **H22** | 0.28 | 0.31 | 0.34 | 0.36 | 0.38 | 0.4 | 0.42 | 0.44 | 0.64 |
| **H23** | 0.18 | 0.19 | 0.2 | 0.22 | 0.24 | 0.25 | 0.26 | 0.28 | 0.38 |
| **H24** | 0.17 | 0.23 | 0.31 | 0.4 | 0.47 | 1.03 | 1.05 | 1.07 | 1.44 |
| **H25** | 0.12 | 0.17 | 0.25 | 0.33 | 0.4 | 0.94 | 0.96 | 0.98 | 1.25 |
| **H26** | 0.09 | 0.13 | 0.2 | 0.29 | 0.36 | 0.9 | 0.91 | 0.93 | 1.21 |
| **H27** | 0.15 | 0.2 | 0.23 | 0.28 | 0.37 | 0.87 | 0.89 | 0.9 | 1.14 |
| **H28** | 0.28 | 0.29 | 0.3 | 0.31 | 0.32 | 0.42 | 0.42 | 0.42 | 0.73 |
| **H29** | 0.44 | 0.48 | 0.52 | 0.54 | 0.56 | 0.58 | 0.62 | 0.64 | 0.92 |
| **H30** | 0.36 | 0.4 | 0.44 | 0.48 | 0.52 | 0.55 | 0.6 | 0.63 | 1.11 |
| **H31** | 0.32 | 0.37 | 0.43 | 0.47 | 0.51 | 0.54 | 0.58 | 0.62 | 0.84 |
| **H32** | 0.02 | 0.06 | 0.17 | 0.29 | 0.39 | 0.68 | 0.74 | 0.79 | 1.23 |
| **H33** | 0.29 | 0.3 | 0.32 | 0.33 | 0.35 | 0.36 | 0.37 | 0.39 | 0.47 |

Table 28: Peak Flows ($m^3/s$) at Key Locations

| ID | Location | Type | AEP | | | | | | | | PMF |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 20% | 10% | 5% | 2% | 1% | 0.5% | 0.2% | 0.1% | |
| Q01 | Mullet Creek Under Jacksons Road | Pipe | 24.76 | 27.78 | 31.29 | 34.27 | 36.07 | 25.26 | 25.29 | 31.37 | 18.01 |
| | | Overland | 0.29 | 0.33 | 2.11 | 9.58 | 19.42 | 88.49 | 107.51 | 123.3 | 260.46 |
| Q02 | Nareen Creek Under Pittwater Road | Pipe | 12.45 | 14.31 | 16.21 | 18 | 19.46 | 14.76 | 15.79 | 16.58 | 18.86 |
| | | Overland | 0 | 0 | 0 | 0 | 0.01 | 11.23 | 14.11 | 16.81 | 117.6 |
| Q03A | Open Channel Section of Nareen Creek | Pipe | 12.1 | 13.81 | 15.46 | 16.95 | 18.39 | 14.71 | 16.3 | 17.53 | 47.71 |
| | | Overland | 1.3 | 1.72 | 2.89 | 4.93 | 6.69 | 22.08 | 25.14 | 28.17 | 107.7 |
| Q04 | Narrabeen Creek Under Boondah Road | Pipe | 19.43 | 20.89 | 22.1 | 23.32 | 24.59 | 22.2 | 24.8 | 26.91 | 36.24 |
| | | Overland | 3.48 | 3.54 | 3.58 | 3.57 | 3.53 | 0.01 | 0 | 0 | 0.02 |
| Q05 | Narrabeen Creek Under Macpherson Street | Pipe | 15.9 | 15.82 | 15.9 | 15.93 | 15.96 | 16 | 16.01 | 16.01 | 16.53 |
| | | Overland | 20.31 | 23.76 | 28.43 | 32.52 | 37.08 | 41.22 | 47.67 | 52.9 | 115.06 |
| Q06 | Narrabeen Creek Under Macpherson Street | Pipe | 7.68 | 7.86 | 8.04 | 8.16 | 8.28 | 8.39 | 8.51 | 8.6 | 8.95 |
| | | Overland | 13.64 | 15.9 | 18.77 | 21.06 | 23.76 | 26.5 | 30.2 | 33.24 | 74.42 |
| Q07 | Narrabeen Creek Under Macpherson Street | Pipe | 32.4 | 32.73 | 32.97 | 33.34 | 33.62 | 31.88 | 32.07 | 31.89 | 33.51 |
| | | Overland | 32.65 | 44.5 | 59.47 | 73.69 | 88.09 | 103.35 | 122.79 | 140.39 | 394.96 |
| Q08 | Piped Nareen Creek Inflow | Pipe | 7.33 | 7.36 | 7.41 | 7.39 | 7.41 | 7.22 | 7.23 | 7.29 | 7.58 |
| Q09 | Piped Nareen Creek Outflow | Pipe | 9.78 | 9.91 | 10 | 9.99 | 9.97 | 9.66 | 9.73 | 9.78 | 10.2 |
| Q10 | Outflow from Golf Course | Pipe | 0.77 | 0.8 | 0.84 | 0.87 | 0.9 | 0.92 | 0.96 | 0.99 | 1.34 |
| Q11 | Outflow from Maralinga Avenue Park | Pipe | 2.49 | 2.58 | 2.71 | 2.8 | 2.9 | 3.02 | 3.15 | 3.21 | 4.92 |
| Q12 | Upstream Mullet Creek Flow | Overland | 14.47 | 17.04 | 20.36 | 23.13 | 26.02 | 28.99 | 32.52 | 36.67 | 79.2 |
| Q13 | Overland Flow Over Warraba Road | Overland | 1.29 | 1.86 | 2.63 | 3.32 | 3.61 | 3.24 | 3.5 | 3.76 | 11.02 |
| Q14 | Mullet Creek Flow Under Pittwater Road Bridge | Overland | 45.22 | 51.15 | 59.45 | 70.69 | 80.58 | 83.98 | 94.66 | 102.74 | 120.96 |
| Q15 | Overland Flow U/S of Open Channel Nareen Creek | Overland | 16.93 | 20.04 | 24.56 | 28.47 | 32.48 | 42.34 | 47.87 | 52.75 | 146.17 |

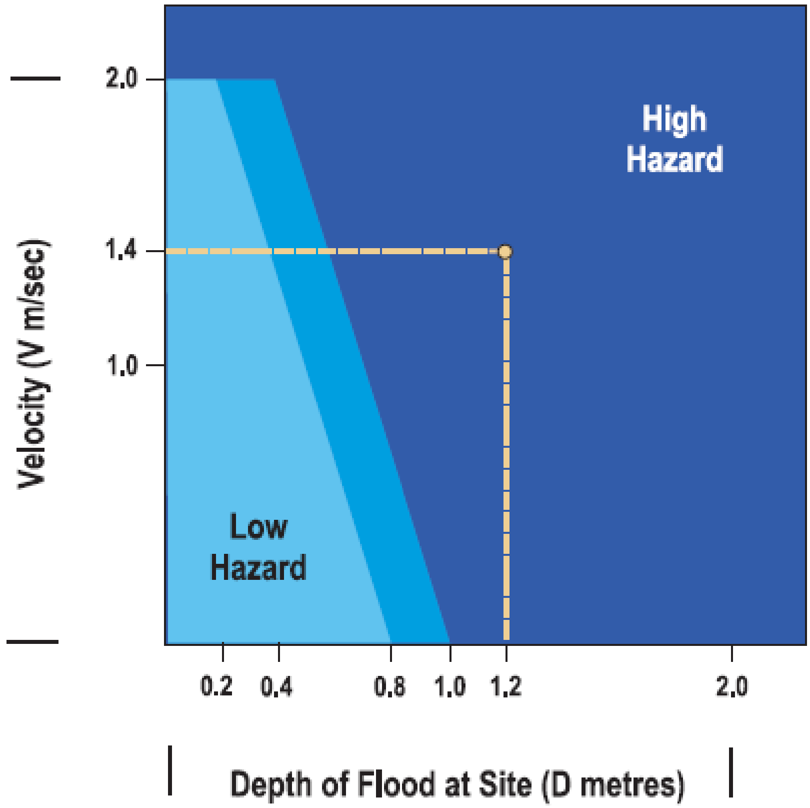
## 8.5. Flood Hazard Categorisation

Hazard classification plays an important role in informing floodplain risk management in an area. Hydraulic hazard categories were by two methods – one in accordance with the NSW Floodplain Development Manual (Reference 16), and the other in accordance with the Australian Disaster Resilience Handbook Collection (Reference 17). Each is discussed below.

### 8.5.1. Floodplain Development Manual

Hydraulic hazard categories were determined in accordance with Appendix L of the NSW Floodplain Development Manual (Reference 16), the relevant section of which is shown in Diagram 4. For the purposes of this report, the transition zone is considered to be high hazard.

Diagram 4: Hydraulic Hazard Categories

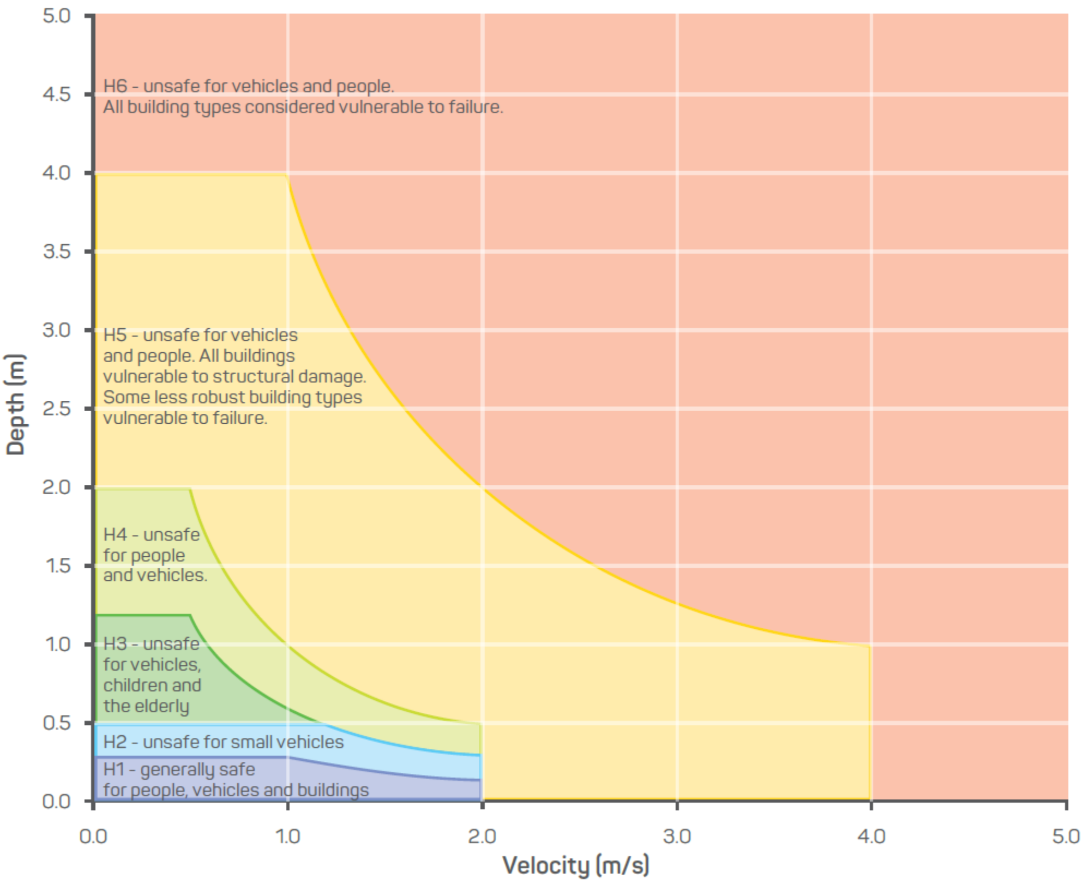



Hydraulic hazard categories for the range of design flood events modelled are displayed on Figure B19 to Figure B22.

### 8.5.2. Risk to Life (Australian Emergency Management Institute Hazard)

In recent years, there have been a number of developments in the classification of hazards. Research has been undertaken to assess the hazard to people, vehicles and buildings based on flood depth, velocity and velocity depth product. The Australian Disaster Resilience Handbook Collection deals with floods in Handbook 7 (Managing the Floodplain: A Guide to Best Practice in Flood Risk Management in Australia). The supporting guideline 7-3 (Reference 17) contains information relating to the categorisation of flood hazard. A summary of this categorisation is provided in Diagram 5.

Diagram 5: General flood hazard vulnerability curves (Source: Reference 17)




This classification provides a more detailed distinction and practical application of hazard categories, identifying the following 6 classes of hazard:

- H1 – No constraints, generally safe for vehicles, people and buildings;
- H2 – Unsafe for small vehicles;
- H3 – Unsafe for all vehicles, children and the elderly;
- H4 – Unsafe for all people and all vehicles;
- H5 – Unsafe for all people and all vehicles. All building types vulnerable to structural damage. Some less robust building types vulnerable to failure. Buildings require special engineering design and construction; and
- H6 – Unsafe for all people and all vehicles. All building types considered vulnerable to failure.

The hazard maps using the Australian Emergency Management Institute (AEMI) classification are presented in Figure B26 and Figure B27 for the 1% AEP and PMF events respectively.

## 8.6. Hydraulic Categorisation

Principles for determining hydraulic categories, namely floodway, flood storage and flood fringe, are described in the Floodplain Development Manual (Reference 16). However, there is no widely accepted technical definition of hydraulic categorisation that would be suitable for all catchments, and different approaches are used by different consultants and authorities, based on the specific features of the study catchment in question.

For this study, hydraulic categories were defined by the following criteria, which correspond in part with the criteria proposed by Howells et al, 2003 (Reference 18):

- Floodway is defined as areas where:
  - the peak value of velocity multiplied by depth (V x D) > 0.25 $m^2/s$ **AND** peak velocity > 0.25 m/s, OR
  - peak velocity > 1.0 m/s

The remainder of the floodplain is either Flood Storage or Flood Fringe,

- Flood Storage comprises areas outside the floodway where peak depth > 0.2 m; and
- Flood Fringe comprises areas outside the Floodway where peak depth < 0.2 m.

Hydraulic categories for the 5% AEP, 1% AEP and PMF events are displayed on Figure B23 to Figure B25.

## 8.7. Preliminary Flood Emergency Response Classification

The design flood modelling was assessed in accordance with guidelines for Emergency Response Planning (ERP) outlined in Reference 19. These guidelines are generally more applicable to riverine flooding where:

- Significant flood warning time is available;
- Emergency response action can be taken prior to the flood; and
- Long term isolation may occur requiring possible resupply or evacuation.

For urban areas affected by overland flow, which generally have little or no flood warning times and short isolation times, it is less clear how to apply these classifications. Flash flooding from local catchment and overland flow generally occurs as a direct response to intense rainfall without significant warning, and for most flood affected properties in the catchment, sheltering in place (inside the home or building) is likely to present less risk to life than attempting to drive or wade through floodwaters. The issue of flood isolation is less critical for urban flash flooding than for rural flooding as it is unlikely that access will be cut for more than a few hours.

The design modelling indicates that in the PMF event some properties will be subject to high hazard flooding (depths greater than 1.0 m) and numerous roads will be cut (depths across the road greater than 0.3 m). Without floor level survey, it is unclear what the depth above floor would be for many of these buildings, but for the purpose of this preliminary classification it has been assumed this depth would present potential risk-to-life. The modelling indicates in some cases that access routes for properties will be cut prior to potential flooding of buildings. Where estimated depths are greater than 1.0 m, these properties have been classified as “Low Flood Island/Low Trapped Perimeter” areas according to Reference 19. Properties tagged as “Low Flood Island/Low Trapped Perimeter” have a real risk of injury or death if residents become trapped in their homes during a flood.

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Due to the nature of flooding in this catchment – where flood depths in urban areas are highest at the downstream end and deep flood waters are otherwise localised within channel and wetland areas – with the exception of locations tagged "Low Flood Island/Low Trapped Perimeter", sheltering in place is generally appropriate for all other flood affected properties. However, classifications have been provided for nearly all properties for the PMF flood event should evacuation of properties need to occur. This classification is shown on Figure C1.

## 8.8. Preliminary "True" Flood Hazard Categorisation

The hydraulic hazards were reviewed in this study to consider other factors such as:

- Rate of rise of floodwater;
- Flood duration;
- Risk to life; and
- Evacuation.

These factors and related comments are provided in Table 29.

Table 29: Weightings for Assessment of True Hazard

| Criteria | Weight | Comment |
|---|---|---|
| **Rate of Rise of Floodwaters** | High | The rate of rise in the creek channels and onset of overland flow along roads would be very rapid, which would not allow time for residents to prepare for the onset of flooding. |
| **Duration of Flooding** | Low | The duration for local catchment flooding will generally be less than around 6 hours, resulting in inconvenience to affected residents but not generally a significant increase in hazard. |
| **Effective Flood Access** | High | Roads within the catchment will generally be inundated prior to property inundation, which may restrict vehicular access during a flood. |
| **Size of the Flood** | Medium | The hazard can change significantly at some locations with the magnitude of the flood. The particularly hazardous areas are the lower catchment reaches, especially in Nareen Creek. However, these higher hazard areas are generally already captured by the hydraulic hazard criteria. |
| **Effective Warning and Evacuation Times** | High | There is very little, if any, warning time. During the day residents will be aware of the heavy rain but at night (if asleep) residential and non-residential building floors may be inundated with no prior warning. |
| **Additional Concerns such as Bank Erosion, Debris, Wind Wave Action** | Low | The main concern would be debris blocking culverts or bridges. This is considered to have a high probability of occurrence and will significantly increase the hazard. There is also the possibility of vehicles being swept into the main channels (as occurred in Newcastle in June 2007) causing blockage. However design modelling for this study includes blockage and the hydraulic hazard classification therefore includes this factor. Wind wave action is unlikely to be an issue but waves from traffic may be, due to the proximity of flood prone properties to main traffic routes. |

| Criteria | Weight | Comment |
|---|---|---|
| **Evacuation Difficulties** | Low | Given the quick response of the catchment pre-flood evacuation is unlikely to occur. There may be significant difficulties evacuating people who become trapped in their houses, but only if the depth is sufficient to present a risk to life. This factor is already captured by the hydraulic hazard classification, and therefore was not given significant weight for assessing true hazard. |
| **Flood Awareness of the Community** | Medium | Urban communities in general have relatively low flood awareness and a short "community memory" for historical flood events. |
| **Depth and Velocity of Floodwaters** | High | In areas of overland flow roads are subject to fast flowing water. In the main creek channels velocities and depth would be high. There is always a risk of a car or pedestrian being swept into the open channel while attempting to cross swiftly flowing waters at major creek crossings. However this factor is largely included in the hydraulic hazard calculation metrics. |

Factors with high weighting in relation to the assessment of true hazard are generally related to the lack of flood warning, the dangers of driving on flooded roads and the potential for flooding to cut access to properties prior to above-floor flooding of buildings. In most cases, sheltering in place inside properties will present less risk to life than attempting evacuation via flooded routes. There are some properties where remaining inside would present a high risk to life due to high flood depths, but these properties are generally already classified as high hazard under the hydraulic hazard criteria.

When considering the Flood Emergency Response classifications (section 8.7), the higher risk classification such as "Low Flood Island" and "High Flood Island" generally overlapped with areas already classified as "high hazard" using the hydraulic hazard criteria; and in areas where this was not the case, the duration and intensity of flooding did not justify a change.

In general, it was found that any area where a high flood hazard classification was justified based on consideration of the criteria and weighting outlined in Table 29 was already designated high hazard as a result of the depth/velocity criteria used to develop the hydraulic hazard. Therefore the "true" hazard categories were assessed to be the same as the hydraulic hazard (see Figure B19 to Figure B22).

## 8.9. Road Inundation

Flood level hydrographs showing flooding of key roads are provided in Figure C3 to Figure C11 (locations shown on Figure C2). These figures are included to provide the SES with an understanding of the period of time that the road may be subject to hazard and inundation for the design events considered.

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# 9. SENSITIVITY ANALYSIS

## 9.1. Overview

Sensitivity analyses were undertaken for the hydrologic and hydraulic models to assess the influence of model parameter values on design flood levels and flow. These sensitivity analyses for the 1% AEP event are summarised in Table 30.

Table 30: Overview of Sensitivity Analyses

| Scenario | Description |
|---|---|
| **Rainfall Increase** | Sensitivity to rainfall and runoff estimates were assessed by increasing rainfall intensities by 10%, 20% and 30%. |
| **Antecedent Moisture Conditions** | Sensitivity to loss rates were assessed by varying the antecedent rainfall (the rainfall occurring prior to the start of the storm event) in the drains model. |
| **Soil Type** | Sensitivity to loss rates were assessed by varying soil types in the DRAINS model. |
| **Manning's "n"** | The hydraulic roughness values were increased and decreased by 20% |
| **Pipe Blockage** | Sensitivity to blockage of all pipes with inlet headwalls was assessed for 0 and 75% blockage |
| **Coincident Flooding of Narrabeen Lagoon** | The effects of changes in downstream tailwater levels at Narrabeen Lagoon were assessed for a MHWS, 2050 and 2100 sea level rise scenarios. |

## 9.2. Sensitivity Analysis Results

Results comparing the peak flood level sensitivity for each of the sensitivity tests are included in Table 31 to Table 36 and the results are discussed in more detail in below. The locations referred to in the tables are the same locations from the results tables in Section 8.4.2 (shown on Figure 15).

### 9.2.1. Rainfall Increase

The effect of increasing the design rainfalls by 10%, 20% and 30% was evaluated for the 1% AEP design event. Increases in rainfall would increase peak levels observed throughout the study area, except at Narrabeen Lagoon itself. Generally, each incremental 10% increase in rainfall results in an increase in peak flood levels between 0.02 m and 0.03 m at most of the locations analysed (see Table 31 below).

### 9.2.2. Antecedent Moisture Conditions Variations

The antecedent moisture condition for design modelling was Type 3, indicating a rather wet catchment. For the purpose of sensitivity analysis:

- Type 2 – Rather dry; and
- Type 4 – Saturated, were assessed.

Changing the moisture conditions was generally found to not cause a significant change to peak flood levels, except for a couple of localised locations (such as the Jubilee Avenue Bridge at Narrabeen Creek. See Table 32 below for the change in peak 1% AEP flood levels at various locations.

### 9.2.3. Soil Type Variations

The adopted soil type for design modelling was Type 3, indicating moderate infiltration rates. For the purpose of sensitivity analysis:

- Soil Type 2 – higher infiltration rates, moderately well drained with reduction to runoff and peak flood levels and flows; and
- Soil Type 4 – high runoff potential, very slow infiltration with increases to runoff and peak flood levels and flows, were assessed.

Changing the soil type to increase drainage (Type 2) was found to have a significant impact on peak flood levels with 0.5 m decreases shown in locations throughout the catchment as well as reductions in the flood extent. Changing the soil type to decrease drainage (Type 4) was generally found to not cause a significant change to peak flood levels. See Table 33 below for the change in peak 1% AEP flood levels at various locations.

### 9.2.4. Roughness Variations

Overall peak flood level results were shown to change with variations in the roughness parameter. In general, a decrease in friction led to a decrease in peak flood levels and an increased in friction led to an increase. The roughness parameters were increased and decreased by 20% in the sensitivity tests. See Table 34 below for the change in peak 1% AEP flood levels at various locations.

### 9.2.5. Blockage Variation

Sensitivity to the design blockage assumptions (see Section 6.5) was tested by modelling a higher and lower blockage scenario. In the higher blockage scenario, debris blockage at bridges was assumed to be 10%, and blockage at culverts was assumed to be 50% / 75% depending on size (compared to 25% / 50% in the design modelling). In the lower blockage scenario, debris blockage at bridges was assumed to be 0%, and blockage at culverts was assumed to be 0% / 25% depending on size.

Peak flood levels were found not to be sensitive to the blockage assumptions for culverts and bridges with inlet headwalls. The number of blocked pipes is small, and the capacity of these structures during large events like the 5% AEP and 1% AEP is typically small compared with the total flow. The impacts of blockage are therefore relatively small and localised, and blockage is not considered a critical parameter for the design flood modelling. See Table 35 below for the change in peak 1% AEP flood levels at various locations.



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### 9.2.6. Downstream Tailwater Levels

The following sensitivity scenarios were tested for the static downstream tailwater level assumption at Narrabeen Lagoon:

- The tailwater level for the 1% AEP event was increased from the average tide level at Narrabeen Bridge (0.43 mAHD – obtained by taking the average value at the Narrabeen Lagoon gauge at Narrabeen Bridge) to the 5% AEP Narrabeen Lagoon flood level (2.7 mAHD – obtained from the 2013 Narrabeen Lagoon Flood Study) in order to replicate worst case coincident flooding of Narrabeen Lagoon.

Additionally, various sea level rise scenarios were tested:

- The tailwater level for the 1% AEP event (the average tide level at Narrabeen Bridge) was increased by 0.4 m and 0.9 m in order to match the expected sea level rise by 2050 and 2100 respectively.

In the downstream of the catchment, variations in tailwater levels proved to be significant with increases of greater than 2 m and an increase in flood extent for the 5% AEP lagoon tailwater and increases of up to 0.4 m and 0.9 m for the 2050 and 2100 tailwater scenarios respectively. In the upstream sections of the catchment variations in peak flood levels are negligible due to the distance from the downstream boundary and the steep catchment slopes. See Table 36 below for the change in peak 1% AEP flood levels at various locations.

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Table 31: Results of Rainfall Intensity Analysis

| Location ID | Location (see Figure 15) | 1% AEP Sensitivity Change in Peak Water Level (m) | | |
|---|---|---|---|---|
| | | +10% | +20% | +30% |
| H1 | Maralinga Ave | 0.02 | 0.04 | 0.07 |
| H2 | Macpherson Street | 0.07 | 0.11 | 0.15 |
| H3 | Brands Lane | 0.07 | 0.12 | 0.17 |
| H4 | Jubilee Avenue Bridge | 0.07 | 0.16 | 0.24 |
| H5 | Narrabeen Bridge South Creek | 0.00 | 0.00 | 0.00 |
| H6 | Ocean St Road Bridge | 0.00 | 0.00 | 0.00 |
| H7 | Narroy Road | 0.06 | 0.11 | 0.16 |
| H8 | Pittwater Road Bridge | 0.17 | 0.33 | 0.56 |
| H9 | Lido Avenue | 0.06 | 0.12 | 0.17 |
| H10 | Jacksons Road on Mullet Creek West | 0.11 | 0.23 | 0.36 |
| H11 | Jacksons Road | 0.05 | 0.08 | 0.13 |
| H12 | Garden Street Bridge over Mullet Creek | 0.05 | 0.09 | 0.14 |
| H13 | Macpherson Street Bridge | 0.05 | 0.10 | 0.14 |
| H14 | Rickard Road | 0.06 | 0.12 | 0.17 |
| H15 | Nareen Parade Flow | 0.03 | 0.06 | 0.09 |
| H16 | Gondola Road | 0.06 | 0.12 | 0.17 |
| H17 | Tatiara Crescent | 0.06 | 0.11 | 0.16 |
| H18 | Garden Street Bridge over Fern Creek | 0.02 | 0.05 | 0.07 |
| H19 | Macpherson Street Bridge | 0.07 | 0.15 | 0.21 |
| H20 | Boondah Road Bridge | 0.10 | 0.17 | 0.24 |
| H21 | Cooleena Road | 0.01 | 0.01 | 0.02 |
| H22 | Powderworks Road | 0.02 | 0.03 | 0.05 |
| H23 | Foxall Street | 0.02 | 0.03 | 0.04 |
| H24 | Verona Street | 0.06 | 0.12 | 0.17 |
| H25 | Minarto Lane | 0.06 | 0.12 | 0.17 |
| H26 | Windsor Parade | 0.06 | 0.12 | 0.17 |
| H27 | Grenfell Ave | 0.06 | 0.12 | 0.16 |
| H28 | Wakehurst Parkway | 0.01 | 0.02 | 0.02 |
| H29 | Koorangi Avenue | 0.02 | 0.06 | 0.08 |
| H30 | Ingleside Road Over Mullet Creek | 0.03 | 0.07 | 0.10 |
| H31 | Powderworks Road over Mullet Creek | 0.03 | 0.06 | 0.09 |
| H32 | Pittwater Road | 0.09 | 0.16 | 0.22 |
| H33 | Warriewood Road | 0.01 | 0.03 | 0.04 |

*Levels at bridges and road crossings are at the road centreline.*

Table 32: Results of Antecedent Moisture Variation Sensitivity Analysis

| Location ID | Location (see Figure 15) | 1% AEP Sensitivity Change in Peak Water Level (m) | |
|---|---|---|---|
| | | Drier Catchment | Wetter Catchment |
| H1 | Maralinga Ave | 0.00 | 0.00 |
| H2 | Macpherson Street | 0.00 | 0.00 |
| H3 | Brands Lane | 0.00 | 0.00 |
| H4 | Jubilee Avenue Bridge | 0.00 | 0.00 |
| H5 | Narrabeen Bridge South Creek | 0.00 | 0.00 |
| H6 | Ocean St Road Bridge | 0.00 | 0.00 |
| H7 | Narroy Road | -0.01 | 0.00 |
| H8 | Pittwater Road Bridge | -0.03 | 0.02 |
| H9 | Lido Avenue | -0.01 | 0.00 |
| H10 | Jacksons Road on Mullet Creek West | -0.02 | 0.01 |
| H11 | Jacksons Road | -0.01 | 0.00 |
| H12 | Garden Street Bridge over Mullet Creek | 0.00 | 0.00 |
| H13 | Macpherson Street Bridge | 0.00 | 0.00 |
| H14 | Rickard Road | 0.00 | 0.00 |
| H15 | Nareen Parade Flow | 0.00 | 0.00 |
| H16 | Gondola Road | -0.01 | 0.00 |
| H17 | Tatiara Crescent | 0.00 | 0.00 |
| H18 | Garden Street Bridge over Fern Creek | 0.00 | 0.00 |
| H19 | Macpherson Street Bridge | -0.01 | 0.00 |
| H20 | Boondah Road Bridge | -0.03 | 0.01 |
| H21 | Cooleena Road | 0.00 | 0.00 |
| H22 | Powderworks Road | 0.00 | 0.00 |
| H23 | Foxall Street | 0.00 | 0.00 |
| H24 | Verona Street | -0.01 | 0.00 |
| H25 | Minarto Lane | -0.01 | 0.00 |
| H26 | Windsor Parade | 0.00 | 0.00 |
| H27 | Grenfell Ave | -0.01 | 0.00 |
| H28 | Wakehurst Parkway | 0.00 | 0.00 |
| H29 | Koorangi Avenue | 0.00 | 0.00 |
| H30 | Ingleside Road Over Mullet Creek | 0.00 | 0.00 |
| H31 | Powderworks Road over Mullet Creek | 0.00 | 0.00 |
| H32 | Pittwater Road | -0.02 | 0.01 |
| H33 | Warriewood Road | 0.00 | 0.00 |

*Levels at bridges and road crossings are at the road centreline.*

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Table 33: Results of Soil Type Variation Sensitivity Analysis

| Location ID | Location (see Figure 15) | 1% AEP Sensitivity Change in Peak Water Level (m) | |
|---|---|---|---|
| | | Increased Infiltration | Decreased Infiltration |
| H1 | Maralinga Ave | 0 | 0 |
| H2 | Macpherson Street | -0.02 | 0.01 |
| H3 | Brands Lane | -0.02 | 0.01 |
| H4 | Jubilee Avenue Bridge | -0.03 | 0.01 |
| H5 | Narrabeen Bridge South Creek | 0 | 0 |
| H6 | Ocean St Road Bridge | 0 | 0 |
| H7 | Narroy Road | -0.02 | 0.01 |
| H8 | Pittwater Road Bridge | -0.1 | 0.06 |
| H9 | Lido Avenue | -0.02 | 0.01 |
| H10 | Jacksons Road on Mullet Creek West | -0.07 | 0.04 |
| H11 | Jacksons Road | -0.04 | 0.02 |
| H12 | Garden Street Bridge over Mullet Creek | -0.01 | 0.01 |
| H13 | Macpherson Street Bridge | -0.02 | 0.01 |
| H14 | Rickard Road | -0.02 | 0.01 |
| H15 | Nareen Parade Flow | 0 | 0 |
| H16 | Gondola Road | -0.02 | 0.01 |
| H17 | Tatiara Crescent | -0.01 | 0 |
| H18 | Garden Street Bridge over Fern Creek | -0.01 | 0 |
| H19 | Macpherson Street Bridge | -0.03 | 0.02 |
| H20 | Boondah Road Bridge | -0.08 | 0.04 |
| H21 | Cooleena Road | 0 | 0 |
| H22 | Powderworks Road | 0 | 0 |
| H23 | Foxall Street | 0 | 0 |
| H24 | Verona Street | -0.02 | 0.01 |
| H25 | Minarto Lane | -0.02 | 0.01 |
| H26 | Windsor Parade | -0.02 | 0.01 |
| H27 | Grenfell Ave | -0.03 | 0.01 |
| H28 | Wakehurst Parkway | 0 | 0 |
| H29 | Koorangi Avenue | 0 | 0 |
| H30 | Ingleside Road Over Mullet Creek | -0.01 | 0 |
| H31 | Powderworks Road over Mullet Creek | 0 | 0 |
| H32 | Pittwater Road | -0.07 | 0.03 |
| H33 | Warriewood Road | 0 | 0 |

*Levels at bridges and road crossings are at the road centreline.*

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Table 34: Results of Roughness Sensitivity Analysis

| Location ID | Location (see Figure 15) | 1% AEP Sensitivity Change in Peak Water Level (m) | |
|---|---|---|---|
| | | Decreased Friction (-20%) | Increased Friction (+20%) |
| H1 | Maralinga Ave | -0.02 | 0.07 |
| H2 | Macpherson Street | -0.07 | 0.05 |
| H3 | Brands Lane | -0.07 | 0.05 |
| H4 | Jubilee Avenue Bridge | -0.18 | 0.17 |
| H5 | Narrabeen Bridge South Creek | 0.00 | 0.00 |
| H6 | Ocean St Road Bridge | 0.00 | 0.00 |
| H7 | Narroy Road | 0.00 | 0.00 |
| H8 | Pittwater Road Bridge | 0.04 | -0.04 |
| H9 | Lido Avenue | 0.00 | 0.00 |
| H10 | Jacksons Road on Mullet Creek West | -0.06 | 0.06 |
| H11 | Jacksons Road | -0.02 | 0.02 |
| H12 | Garden Street Bridge over Mullet Creek | -0.03 | 0.04 |
| H13 | Macpherson Street Bridge | -0.02 | 0.00 |
| H14 | Rickard Road | 0.00 | 0.00 |
| H15 | Nareen Parade Flow | -0.03 | 0.03 |
| H16 | Gondola Road | 0.00 | 0.00 |
| H17 | Tatiara Crescent | -0.03 | 0.02 |
| H18 | Garden Street Bridge over Fern Creek | 0.00 | 0.02 |
| H19 | Macpherson Street Bridge | -0.05 | 0.05 |
| H20 | Boondah Road Bridge | -0.03 | 0.02 |
| H21 | Cooleena Road | -0.03 | 0.02 |
| H22 | Powderworks Road | 0.00 | -0.02 |
| H23 | Foxall Street | 0.00 | 0.00 |
| H24 | Verona Street | 0.00 | -0.01 |
| H25 | Minarto Lane | 0.00 | -0.01 |
| H26 | Windsor Parade | 0.01 | -0.01 |
| H27 | Grenfell Ave | 0.01 | -0.01 |
| H28 | Wakehurst Parkway | 0.00 | 0.00 |
| H29 | Koorangi Avenue | 0.00 | 0.01 |
| H30 | Ingleside Road Over Mullet Creek | 0.00 | 0.00 |
| H31 | Powderworks Road over Mullet Creek | -0.01 | 0.01 |
| H32 | Pittwater Road | -0.03 | 0.02 |
| H33 | Warriewood Road | 0.00 | 0.00 |

*Levels at bridges and road crossings are at the road centreline.*

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Table 35: Results of Blockage Sensitivity Analysis

| Location ID | Location (see Figure 15) | 1% AEP Sensitivity Change in Peak Water Level (m) | |
|---|---|---|---|
| | | Reduced Blockage | Increased Blockage |
| H1 | Maralinga Ave | 0.00 | 0.00 |
| H2 | Macpherson Street | 0.00 | 0.00 |
| H3 | Brands Lane | 0.00 | 0.01 |
| H4 | Jubilee Avenue Bridge | -0.08 | -0.04 |
| H5 | Narrabeen Bridge South Creek | 0.00 | 0.00 |
| H6 | Ocean St Road Bridge | 0.00 | 0.00 |
| H7 | Narroy Road | 0.00 | 0.00 |
| H8 | Pittwater Road Bridge | 0.00 | 0.09 |
| H9 | Lido Avenue | 0.00 | 0.00 |
| H10 | Jacksons Road on Mullet Creek West | 0.00 | 0.01 |
| H11 | Jacksons Road | 0.00 | 0.00 |
| H12 | Garden Street Bridge over Mullet Creek | 0.00 | 0.00 |
| H13 | Macpherson Street Bridge | 0.00 | 0.01 |
| H14 | Rickard Road | 0.00 | 0.00 |
| H15 | Nareen Parade Flow | 0.00 | 0.00 |
| H16 | Gondola Road | 0.00 | 0.00 |
| H17 | Tatiara Crescent | 0.00 | 0.00 |
| H18 | Garden Street Bridge over Fern Creek | 0.00 | 0.00 |
| H19 | Macpherson Street Bridge | 0.00 | 0.00 |
| H20 | Boondah Road Bridge | 0.00 | 0.00 |
| H21 | Cooleena Road | 0.00 | 0.00 |
| H22 | Powderworks Road | 0.00 | 0.00 |
| H23 | Foxall Street | 0.00 | 0.00 |
| H24 | Verona Street | 0.00 | 0.00 |
| H25 | Minarto Lane | 0.00 | 0.00 |
| H26 | Windsor Parade | 0.00 | 0.00 |
| H27 | Grenfell Ave | 0.00 | 0.00 |
| H28 | Wakehurst Parkway | 0.00 | 0.00 |
| H29 | Koorangi Avenue | 0.00 | 0.00 |
| H30 | Ingleside Road Over Mullet Creek | 0.00 | 0.00 |
| H31 | Powderworks Road over Mullet Creek | 0.00 | 0.00 |
| H32 | Pittwater Road | 0.00 | 0.00 |
| H33 | Warriewood Road | 0.00 | 0.00 |

*Levels at bridges and road crossings are at the road centreline.*

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Table 36: Results of Tailwater Variation Analysis

| Location ID | Location (see Figure 15) | 1% AEP Sensitivity Change in Peak Water Level (m) | | |
|---|---|---|---|---|
| | | 5% AEP Lagoon | 2050 SLR | 2100 SLR |
| H1 | Maralinga Ave | 0.00 | 0.00 | 0.00 |
| H2 | Macpherson Street | 0.00 | 0.00 | 0.00 |
| H3 | Brands Lane | 0.00 | 0.00 | 0.00 |
| H4 | Jubilee Avenue Bridge | 0.00 | 0.00 | 0.00 |
| H5 | Narrabeen Bridge South Creek | 2.27 | 0.40 | 0.90 |
| H6 | Ocean St Road Bridge | 2.27 | 0.40 | 0.90 |
| H7 | Narroy Road | 0.54 | 0.00 | 0.01 |
| H8 | Pittwater Road Bridge | 1.38 | 0.01 | 0.07 |
| H9 | Lido Avenue | 0.55 | 0.00 | 0.01 |
| H10 | Jacksons Road on Mullet Creek West | 0.58 | 0.00 | 0.01 |
| H11 | Jacksons Road | 0.31 | 0.00 | 0.01 |
| H12 | Garden Street Bridge over Mullet Creek | 0.00 | 0.00 | 0.00 |
| H13 | Macpherson Street Bridge | 0.00 | 0.00 | 0.00 |
| H14 | Rickard Road | 0.54 | 0.00 | 0.01 |
| H15 | Nareen Parade Flow | 0.11 | 0.00 | 0.00 |
| H16 | Gondola Road | 0.54 | 0.00 | 0.01 |
| H17 | Tatiara Crescent | 0.00 | 0.00 | 0.00 |
| H18 | Garden Street Bridge over Fern Creek | 0.00 | 0.00 | 0.00 |
| H19 | Macpherson Street Bridge | 0.11 | 0.00 | 0.01 |
| H20 | Boondah Road Bridge | 0.26 | 0.00 | 0.01 |
| H21 | Cooleena Road | 0.00 | 0.00 | 0.00 |
| H22 | Powderworks Road | 0.00 | 0.00 | 0.00 |
| H23 | Foxall Street | 0.00 | 0.00 | 0.00 |
| H24 | Verona Street | 0.54 | 0.00 | 0.01 |
| H25 | Minarto Lane | 0.53 | 0.00 | 0.02 |
| H26 | Windsor Parade | 0.52 | 0.01 | 0.02 |
| H27 | Grenfell Ave | 0.49 | 0.01 | 0.02 |
| H28 | Wakehurst Parkway | 0.10 | 0.00 | 0.00 |
| H29 | Koorangi Avenue | 0.00 | 0.00 | 0.00 |
| H30 | Ingleside Road Over Mullet Creek | 0.00 | 0.00 | 0.00 |
| H31 | Powderworks Road over Mullet Creek | 0.00 | 0.00 | 0.00 |
| H32 | Pittwater Road | 0.24 | 0.00 | 0.01 |
| H33 | Warriewood Road | 0.00 | 0.00 | 0.00 |

*Levels at bridges and road crossings are at the road centreline.*

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# 10. PRELIMINARY FLOOD PLANNING AREA

## 10.1. Background

Land use planning is an effective means of minimising flood risk and damages from flooding. Land use planning for flooding can be achieved through the use of:

- A Flood Planning Area (FPA), which identifies land that is subject to flood related development controls; and
- A Flood Planning Level (FPL), which identifies the minimum floor level applied to development proposals within the FPA.

Defining FPAs and FPLs in urban areas can be complicated by the variability of flow conditions between mainstream and local overland flow. Traditional approaches developed for riverine or "mainstream" flow areas often cannot be applied in steeper urban overland flow areas. Additionally, defining the area of flood affectation due to overland flow (which by its nature includes shallow flow) involves determining at which point flow is significant enough to be classified as "flooding" rather than just a drainage or local runoff issue. In some areas of overland flow, the difference in peak flood level between events of varying magnitude can be so minor that applying the typical freeboard can result in an FPL greater than the PMF level.

The FPA should include properties where development would result in impacts on flood behaviour in the surrounding area and in areas of high hazard where there is a risk to safety or life. The FPL is determined in addition to this with the purpose of decreasing the likelihood of over-floor flooding of buildings.

The Floodplain Development Manual (Reference 16) suggests that the FPL generally be based on the 1% AEP event plus an appropriate freeboard (typically 0.5 m). However, it also recognises that different freeboards may be deemed appropriate due to local conditions provided adequate justification is provided.

Further consideration of flood planning areas and levels is typically undertaken as part of the Floodplain Risk Management Study to determine what should be included in the Floodplain Risk Management Plan.

## 10.2. Methodology

The methodology used for defining the flood planning area is consistent with that adopted in a number of similar studies throughout the Sydney metropolitan area. It divides the flood area between "mainstream" and "overland" flooding areas using the following criteria:

- <u>Mainstream flooding</u>: Areas along the main creeks or trunk drainage alignment, where flow is sufficiently deep and there is sufficient relief that freeboard can be added to the flood surface and the extent then "stretched" to include adjacent land. The mainstream part of the study was defined as:
    - All creeks draining to Narrabeen Lagoon (Fern Creek, Nareen Creek, Narrabeen Creek, Mullet Creek etc.); and
    - Wetland areas which form part of the above creeks.

The FPA along this reach was defined as the peak flood level plus freeboard, with the level extended perpendicular to the flow direction either side of the flow path.

- Overland flooding: For overland flow areas, addition of 0.5m freeboard and stretching generally produces an over-estimate of the land subject to flood risk, because the stretching extends across land in a way that would not actually occur, even with significant additional flow from a much larger storm. Flows are typically relatively shallow and fast moving in these areas, and adding 0.5 freeboard is not appropriate, since even the PMF may only be 0.1m to 0.2m deeper. It is therefore appropriate to use a larger modelled design flood event than the 1% AEP to account for uncertainty in the results, instead of adding 0.5m freeboard and stretching. The advantage of this approach is that it includes consideration of flow momentum from actual model results. In overland flow areas, it was considered appropriate to use the filtered 0.2% AEP extent as a representation of the 1% AEP flood risk including an allowance for uncertainty. The filtered 0.2% AEP extent was used as the FPA in these overland flow areas, subject to consideration of additional criteria as described in Section 10.3 below.

Figure B28 identifies the extent of the preliminary FPA developed using the methodology above.

## 10.3. Identification of Preliminary Flood Control Lots

Flood tagging is the process by which lots are identified as flood liable. “Tagged” lots are subject to Section 10.7 notification (under the EP&A Act) indicating that the properties are subject to flood related development controls. This simply means that should development of the lots occur, flooding will need to be considered and Council’s LEP, DCP and other relevant flood related policies will apply.

The flood tagging of properties for the Ingleside, Elanora and Warriewood Overland Flow Flood Study involved two steps which are displayed in Diagram 1.

1. **Geographic Information System (GIS) Analysis** – This involved the application of automated computer algorithms based on Northern Beaches Council’s mapping criteria for preliminary identification.
2. **Desktop/Field Ground Truthing** – Properties were inspected with regard to a range of considerations including survey information, flood model results mapping, Council infrastructure information and visually (in regard to local topography and features) to identify properties that should be included or omitted from the preliminary GIS identification.

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Diagram 6: Two Step Flood Tagging Process

| Step 1. GIS Analysis | Step 2. Desktop/Visual Ground Truthing |
|---|---|
| • 0.2% AEP flood extent identified using hydraulic modelling. This represents the 1% AEP risk level with an allowance for uncertainty, rather than adding freeboard and stretching.<br>• Filtering applied to results<br>• Inundated cadastral lots identified<br>• Lots with only tribial or minor affectation (e.g. less than 1m inside the boundary) removed from tagging database. | • Initial tagged lots identified in Stage 1 are reviewed alongside flood depth information, building footprint information and the DTM (ground elevation data)<br>• Visual review undertaken to identify lots which may have been omitted or may have mistakenly been identified as tagged<br>• Lots with local topographic or other features are assessed via site visit |

**Step One – GIS Analysis**

GIS Software was used to filter the raw hydraulic modelling results and apply additional preliminary tagging criteria.

The initial result filtering was undertaken according to Northern Beaches Council specifications for the 0.2% AEP event:

- **Depth Filter** – Exclude results below 150 mm depth;
- **Velocity-Depth Filter** – Include results if the Velocity x Depth product > 0.3 $m^2/s$ (even if previously excluded by the Depth Filter); and
- **Small Pond Filter** – Remove isolated ‘puddles’ or ‘orphans’ smaller than 100 $m^2$.

GIS software was then used to identify initial properties that were inundated by the filtered results, with consideration of additional criteria. For example, if the extent was less than 1 m inside property boundaries, these properties were not tagged.

The results were then mapped for the ground truthing stage. The GIS Analysis process is summarised in Diagram 7 below:

Diagram 7: GIS Analysis

**Filter results based on Northern Beaches Council Mapping Criteria** → **Calculate the spatial and percentage inundation of property** → **Identify those lots subject to tagging criteria** → **Map GIS processing results**

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**Step Two – Ground Truthing**

Ground truthing refers to analysis by an experienced floodplain management engineer, to confirm that a property is sufficiently affected by overland flow issues to require tagging. The process can involve both desktop analysis using available computer datasets such as aerial photographs and GIS information, as well as visual field inspection. The overall aim of the exercise is to identify lots that are affected by flooding (whether identified or missed in the initial automated tagging process) and to avoid tagging lots that are likely only affected by local stormwater or drainage issues (i.e. from within the property or a single neighbouring property, rather than a genuine overland flow path emanating from an upstream catchment area). Desktop analysis involves the inspection of cadastre in conjunction with the filtered flood results, LiDAR data, building footprints and drainage infrastructure. Visual inspection of local topography and features not easily identifiable during the desktop analysis is also undertaken where required (not necessarily for every property).

The ground truthing process identifies:

- Properties that should be tagged for flood related development control, which were *omitted* in the initial automated GIS tagging process; and
- Properties that should not be tagged for flood related development control, which were *included* in the initial automated GIS tagging process.
- For other properties, confirmation that the status from the initial automated process was correct.

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# 11. DESIGN FLOOD BEHAVIOUR ANALYSIS

## 11.1. Pipe Capacity Assessment

The design flood results were used to determine how frequently the stormwater pipe system capacity is likely to be exceeded throughout the catchment. Defining the capacity of a pipe is not straightforward, as it depends on multiple factors including shape, the flow regime (e.g. upstream or downstream controlled), inlet and outlet connection, pipe grade, and other factors.

TUFLOW provides output indicating the proportion of the cross-section area of a pipe that has flow in it. For this assessment, pipes were assumed to be "full" when the flow area was equal to or in excess of 85% of the pipe's cross-sectional area. This is the point at which circular pipes tend to be close to their most efficient, since at 100% of cross-sectional area the additional friction from the top of the pipe reduces pipe conveyance. Similarly, box culverts designed for a supercritical flow regime will typically be designed for free surface flow approximately 80% of the depth of the culvert, as when flow touches the pipe soffit it will typically "trip" the flow regime to become sub-critical, resulting in lower capacity, depending on the pipe grade. Additionally, due to energy losses associated with adjoining pits, inlets, bends etc., some culverts may never reach "100% full" capacity although they may be 90% full for a range of design events (e.g. from the 5% AEP through to the PMF). In such circumstances, it is informative to know the design storm for which the pipe is almost at its maximum capacity.

Figure 16 shows the pipe capacity assessment. The majority of the pipes have less than 20% AEP capacity (that is, they are effectively "full" in the 20% AEP event), although there is significant variation in capacity across the catchment particularly in more urbanised areas. Piped sections of creek have various capacities across the catchment:

- Less than 5% AEP capacity for Mullet Creek pipe under Jacksons Road;
- Less than 10% AEP Capacity for Narrabeen Creek pipe under Jacksons Road;
- Less than 20% AEP capacity for Mullet Creek pipe under Garden Street;
- Less than 20% AEP capacity for Narrabeen Creek pipe under Macpherson Street;
- Less than 20% AEP capacity for Fern Creek pipe under Garden Street.

These results are typical for urban trunk drainage networks.

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## 11.2. Hot-Spot Analysis

Some of the key flood-prone areas or “Hot-Spots” within the catchment are discussed in detail below. Figure 17 provides an overview of the locations discussed.

### 11.2.1. HS1 – Elanora Country Club Outflow

The Elanora Country Club outflow is located at its north-east corner and impacts the area between Powderworks Road and Mullet Creek. It is affected by both piped flow and overland run-off from the golf course and surrounding areas which runs downhill into Mullet Creek.

Elanora Country Club and Powderworks Road are located at an elevation above 105 mAHD and drain to areas of Mullet Creek at elevations as low as 40 mAHD. There is a steady slope from the outlet pipe to Wesley Street (80 mAHD) before a steeper drop into the creek.

Runoff from Elanora Country Club is channelled into a 900 mm pipe at Powderworks Road, which initially feeds into a short 1200 mm pipe across Powderworks Road but ultimately flows into a 750 mm pipe, which drains into Mullet Creek. Multiple kerb inlets along Powderworks Road feed into a 600 mm pipe (which runs through 195 Powderworks Road) and drains the eastern side of the area to Mullet Creek further downstream. Overland flow which exceeds the capacity of the piped system ponds along Powderworks Road, Foxall Street and Wesley Street.

Design flood levels and depths along Powderworks Road and flows in and out of the region are summarised in Table 37. The locations of these results, as well as localised depth mapping and hydrographs for the 1% AEP event are shown on Figure B31.

Table 37: Design Flow Behaviour in the Pipe System near the Elanora Country Club Outflow

| Design Event | Peak Flood Level (mAHD) | Peak Flood Depth (m) | Peak Inflow ($m^3/s$) | Peak Outflow ($m^3/s$) |
|---|---|---|---|---|
| 20% AEP | 101.5 | 0.3 | 7.0 | 7.6 |
| 10% AEP | 101.5 | 0.4 | 8.2 | 9.2 |
| 5% AEP | 101.6 | 0.4 | 9.7 | 11.1 |
| 2% AEP | 101.6 | 0.4 | 10.9 | 12.7 |
| 1% AEP | 101.6 | 0.4 | 12.4 | 14.6 |
| 0.5% AEP | 101.6 | 0.5 | 13.8 | 16.6 |
| 0.2% AEP | 101.6 | 0.5 | 15.8 | 19.3 |
| 0.1% AEP | 101.6 | 0.5 | 17.4 | 21.4 |
| PMF | 101.8 | 0.7 | 42.1 | 56.8 |

The low point on Powderworks Road has a peak flood depth of 0.3 m in the 20% AEP event, increasing only slightly to 0.4 m in the 1% event and to 0.7 m in the PMF event. Flood conditions also scale with rarity, with minor flooding of properties and ponding on roads in the 20% AEP event increasing in depth and extent all the way up to the 0.1% AEP event before a significant increase in both in the PMF event.

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With the exception of the outflow pipe from the golf course, the pipe network in the region has a less than 20% AEP capacity. This results in flow running overland from the large golf course catchment and following the steady grade directly into Mullet Creek in relatively frequent (20% AEP) events. As can be seen in Table 37, and the 1% AEP hydrographs on Figure B31 the inflows and outflows for each event have similar peaks (the increase to peak outflow is caused by additional local catchment stormwater flow from Foxall Street and Wesley Street) and follow similar flow behaviours; both results of the steady grade and low pipe capacity.

### 11.2.2. HS2 – Iluka Avenue

Koorangi Avenue Park is located to the south of Iluka Avenue in Elanora Heights, and acts as a catchment for flow originating from the plateau to the north of, and along Iluka Avenue. The area is affected by overland run-off from the golf course and Iluka Avenue.

The top of Iluka Avenue is located at an elevation above 105 mAHD and drains to Koorangi Avenue at an elevation below 75 mAHD, following a steady slope. Multiple kerb inlets along Iluka Avenue, Canungra Place and Koorangi Avenue funnel some of the stormwater runoff in the region through a 375 mm pipe that runs from the top of Iluka Avenue and discharges (via an 825 mm pipe) into Koorangi Avenue Park. However flow in the area is primarily overland and driven by slope and the catchment terrain, which funnels flow through the front of properties on Iluka Avenue and the rear of properties in Canungra Place.

Design flood levels and depths along Koorangi Avenue and flows in and out of the region are summarised in Table 38. The location of these results, as well as localised depth mapping and hydrographs for the 1% AEP event are shown on Figure B32.

Table 38: Design Flow Behaviour in the Pipe System near Koorangi Avenue Park

| Design Event | Peak Flood Level (mAHD) | Peak Flood Depth (m) | Peak Inflow ($m^3/s$) | Peak Outflow ($m^3/s$) |
|---|---|---|---|---|
| 20% AEP | 75.7 | 0.4 | 0.8 | 3.9 |
| 10% AEP | 75.7 | 0.4 | 0.9 | 4.8 |
| 5% AEP | 75.8 | 0.5 | 1.1 | 6.1 |
| 2% AEP | 75.8 | 0.5 | 1.2 | 7.0 |
| 1% AEP | 75.8 | 0.5 | 1.4 | 8.1 |
| 0.5% AEP | 75.8 | 0.5 | 1.5 | 9.2 |
| 0.2% AEP | 75.9 | 0.6 | 1.7 | 10.7 |
| 0.1% AEP | 75.9 | 0.6 | 1.9 | 11.9 |
| PMF | 76.2 | 0.9 | 4.9 | 30.2 |

The low point on Koorangi Avenue has a peak flood depth of 0.4 m in the 20% AEP event, increasing only slightly to 0.5 m in the 1% event but with a larger increase to 0.9 m in the PMF event. Flood conditions scale only slightly with rarity, with only minor increases to flooding of properties and flooding on roads from the 20% AEP event up to the 0.1% AEP event.

Inflows at the top of Iluka Avenue increase only slightly for events up to the PMF (0.8 $m^3/s$ in the

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20% AEP, 1.4 $m^3/s$ in the 1% AEP), but outflows into the park increase steadily from the 20% to 1% AEP events (3.9 – 8.1 $m^3/s$) with a bigger increase in the PMF (30.2 $m^3/s$). The steady slope to the park, concentration of flow along Iluka Avenue (see below) and additional catchment area to the north-east all contribute to this inflow-outflow difference.

There is a significant localised overland flow path that runs through the front of properties on Iluka Avenue. Properties along this stretch (from 71 to 57 Iluka Avenue) generally have front yards at a level lower than the road and the buildings themselves, causing a localised low point which creates the flowpath. Localised ponding on the road at Koorangi Avenue is similarly a result of the sag point being located opposite Koorangi Avenue Park.

### 11.2.3. HS3 – Piped (Upstream) Nareen Creek

The upstream piped section of Nareen Creek is located to the north-west of Cooleena Road in Elanora Heights. The area acts as an inflow into an upstream section of Nareen Creek, with catchment topography and the location of pipes suggesting the area may have formed part of Nareen Creek pre-development.

A major drainage line consisting of a pipe of varying 750 to 1050 mm diameter runs from Kywong Road to the outlet into Nareen Creek, with several pipes and multiple kerb inlets in the area contributing flow. There is a steady grade running from the plateau of the Elanora Country Club down to Cooleena Road before a steep cliff into Nareen Creek which contributes a significant amount of overland flow run-off.

Design flood levels and depths along Cooleena Road and flows in and out of the region are summarised in Table 39. The locations of these results, as well as localised depth mapping and hydrographs for the 1% AEP event are shown on Figure B33.

Table 39: Design Flow Behaviour in the Pipe System upstream of Nareen Creek

| Design Event | Peak Flood Level (mAHD) | Peak Flood Depth (m) | Peak Inflow ($m^3/s$) | Peak Outflow ($m^3/s$) |
|---|---|---|---|---|
| 20% AEP | 53.8 | 0.3 | 3.5 | 8.0 |
| 10% AEP | 53.8 | 0.3 | 4.1 | 9.4 |
| 5% AEP | 53.9 | 0.3 | 5.1 | 11.3 |
| 2% AEP | 53.9 | 0.4 | 5.9 | 12.5 |
| 1% AEP | 53.9 | 0.4 | 7.3 | 14.3 |
| 0.5% AEP | 54.0 | 0.4 | 8.3 | 16.5 |
| 0.2% AEP | 54.0 | 0.5 | 9.9 | 18.5 |
| 0.1% AEP | 54.0 | 0.5 | 11.2 | 20.8 |
| PMF | 54.3 | 0.8 | 30.0 | 49.4 |

The lower point on Cooleena Road has a peak flood depth of 0.3 m in the 20% AEP event, increasing to 0.4 m in the 1% AEP event before a much larger increase to 0.8 m in the PMF event. Flood conditions scale only slightly with rarity, with only minor increases to flooding of properties and flooding on roads from the 20% AEP event up the 0.1% AEP event but with a more significant

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increase in both along with flood extent in the PMF event.

Inflows and outflows from the area increase marginally with events up to the PMF, with peak inflows of 3.5 $m^3/s$ in the 20% AEP event and 7.3 $m^3/s$ in the 1% AEP event, and peak outflows of 8.0 $m^3/s$ in the 20% AEP event and 14.3 $m^3/s$ in the 1% AEP event. This similarity in flows is a result of the low capacity of pipes in the region (less than a 20% AEP), with increases in flow driven by higher water pressure upstream in rarer events.

Overland flow through the area is dominated by the slope towards Nareen Creek. Flow is fairly constant between Powderworks Road and Cooleena Road across all events, with ponding at low points in properties increasing with event rarity. Heavy ponding in particular occurs on Lesley Close where the road level generally sits significantly lower than the surrounding properties. It also occurs at 28A Cooleena Road which sits downstream of the Lesley Close low point and runs down to pond on the sag point on Cooleena Road upstream of Nareen Creek.

#### 11.2.4. HS4 – Piped (Downstream) Nareen Creek

The downstream piped section of Nareen Creek begins at the corner of Bellara Avenue and Tatiara Crescent in North Narrabeen and continues to the south-east. The area lies between two open-channel sections of Nareen Creek, a steep narrow channel to the north-west and a flatter channel with significant wetlands surrounds to the south-east. A varying 3m to 4m wide box culvert connects the two channels underneath Nareen Parade and Bellara Avenue and a varying 1200 to 1350 mm diameter pipe drains flows from bushland areas to the north of Anana Road into the upper channel.

The terrain between the two channels is relatively flat, but there is a constant slope from the outlet of the northern Nareen Creek and the wetlands area. Multiple kerb inlets along Rickard Road, Nareen Parade, Tatiara Crescent and Bellara Avenue funnel local stormwater into the major drainage line via smaller pipes. A steeper slope runs between Anana Road and the flatter area at the Narrabeen RSL club.

Design flood levels and depths along Tatiara Crescent and flows in and out of the region are summarised in Table 40. The locations of these results, as well as localised depth mapping and hydrographs for the 1% AEP event are shown on Figure B34.

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Table 40: Design Flow Behaviour in the Pipe System downstream of Nareen Creek

| Design Event | Peak Flood Level (mAHD) | Peak Flood Depth (m) | Peak Inflow ($m^3/s$) | Peak Outflow ($m^3/s$) |
|---|---|---|---|---|
| 20% AEP | 5.2 | 0.6 | 10.7 | 19.1 |
| 10% AEP | 5.3 | 0.7 | 12.6 | 22.5 |
| 5% AEP | 5.4 | 0.8 | 14.8 | 26.9 |
| 2% AEP | 5.4 | 0.8 | 16.7 | 30.8 |
| 1% AEP | 5.5 | 0.9 | 18.8 | 35.0 |
| 0.5% AEP | 5.6 | 1.0 | 21.2 | 41.2 |
| 0.2% AEP | 5.7 | 1.1 | 24.1 | 46.6 |
| 0.1% AEP | 5.7 | 1.1 | 26.8 | 51.6 |
| PMF | 6.4 | 1.8 | 65.6 | 140.8 |

The low point on Tatiara Crescent has a peak flood depth of 0.6 m in the 20% AEP event, increasing to 0.9 m in the 1% AEP event with a large increase to 1.8 m in the PMF event. Generally increases to property / road flooding, ponding and flood extents are observed with an increase in event rarity in the region.

Flows in the region scale with event rarity, with outflows approximately double the inflows. Pipe capacity in the region is low, with the piped sections of Nareen Creek (both upstream and downstream) having less than a 20% AEP capacity. This low capacity contributes significantly to flood behaviour in the region. In the 1% AEP event the peak flow in Nareen Creek upstream of the piped section is 18.8 $m^3/s$, almost triple the flow capacity of pipe. As the pipe does not have the capacity to carry the full channel flow, excess flow breaks out of bank and runs across the urban areas flooding properties before entering into the Nareen wetlands downstream. This excess flow creates a significant overland flow path through the rear of properties in Nareen Parade as early as the 20% AEP event.

### 11.2.5. HS5 – Nareen Creek Open Channel

The open channel section of Nareen Creek begins immediately upstream of Narroy Road in North Narrabeen and drains to Narrabeen Lagoon via a pipe underneath Pittwater Road. The area lies to the south-east of the Nareen Creek wetlands and has a significant contributing catchment consisting of much of Elanora Heights and North Narrabeen.

The channel itself is approximately 6 m wide and runs for around 350 m from the Nareen Creek wetlands to the pipe underneath Pittwater Road. A second small channel (around 3 m wide) contributes flow from Rickard Road, Gondola Road and Lido Avenue before joining the major channel downstream of the Narroy Road Bridge. Pittwater Road sits at a crest level of 3 mAHD, up to 1 m higher than the ground levels in the region. In addition to the second open channel, several pit inlets and smaller pipes contribute stormwater flow from the surrounding streets.

The terrain surrounding the Nareen Creek open channel contributes significantly to its flooding issues. The urban area surrounding the open channel sits at an elevation of around 2 mAHD, but the plateaus of Elanora Heights and North Narrabeen (to the south-west and north respectively)



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are at elevations above 60 mAHD. Additionally, Pittwater Road is located at an elevation approximately 0.5 m higher than the surrounding urban area which restricts overland flows from the area.

Design flood levels and depths along Lido Avenue and flows within the region are summarised in Table 41. The locations of these results, as well as localised depth mapping and hydrographs for the 1% AEP event are shown on Figure B35.

Table 41: Design Flow Behaviour in Nareen Creek (Open Channel)

| Design Event | Peak Flood Level (mAHD) | Peak Flood Depth (m) | Peak Inflow ($m^3/s$) | Peak Outflow ($m^3/s$) |
|---|---|---|---|---|
| 20% AEP | 2.1 | 0.3 | 11.6 | 13.2 |
| 10% AEP | 2.2 | 0.4 | 14.0 | 15.2 |
| 5% AEP | 2.3 | 0.5 | 17.7 | 17.3 |
| 2% AEP | 2.3 | 0.5 | 21.7 | 19.8 |
| 1% AEP | 2.4 | 0.6 | 25.6 | 22.1 |
| 0.5% AEP | 2.9 | 1.1 | 42.1 | 39.5 |
| 0.2% AEP | 2.9 | 1.1 | 47.3 | 43.3 |
| 0.1% AEP | 3.0 | 1.2 | 52.2 | 47.3 |
| PMF | 3.4 | 1.6 | 155.4 | 114.9 |

The low point on Lido Avenue has a peak flood depth of 0.3 m in the 20% AEP event, increasing to 0.6 m in the 1% AEP event with a larger increase to 1.6 m in the PMF event; although it should be noted, the open channel section of Nareen Creek is close to the downstream boundary and all events rarer than the 1% AEP event incorporate elevated tailwater levels. These elevated tailwaters influence both piped and overland outflow from the region.

Overland flow into the area is significant, and although the open channel section of Nareen Creek carries a significant amount of flow, it does overflow. In the 1% AEP event, the peak overland flow in the area upstream of the open channel section of Nareen Creek is over 25 $m^3/s$, which is double the peak open channel inflow. This is less of an issue in smaller events where excess flow runs along the roadways without entering into property, but for events rarer than the 2% AEP, excess floodwaters breach the gutter system and inundate properties with flooding increasing with event rarity.

In frequent events (20% and 10% AEP), outflows from the region are higher than inflows as the open channel has enough capacity to take in much of the flow. For mid-range events (5% AEP to 1% AEP), the open channel outflow begins to reach its capacity but flood waters are not yet high enough to spill over the elevated ground levels at the interface of both Gondola Road/Pittwater Road and Rickard Road/Pittwater Road; and as a result inflows exceed outflows and more widespread flooding occurs. For rare events (0.5% AEP to PMF), elevated tailwaters restrict open channel outflows but cause higher flood levels, which in turn spill over the elevated ground levels at the Pittwater Road interface. Increases to flood inflows and elevated tailwaters coupled with the open channel restriction further exacerbate flooding conditions in the region.



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### 11.2.6. HS6 – Lakeside Holiday (Caravan) Park

Lakeside Holiday (Caravan) Park is located on the eastern side of Pittwater Road to the north of Narrabeen Lagoon. The area is affected by overland run-off from elevated areas of North Narrabeen particularly to the east, which runs downhill towards Pittwater Road and Narrabeen Lagoon. While sections of Lakeside Holiday (Caravan) Park are at elevations as low as 2 mAHD (particularly areas to the south near the Lagoon), flooding conditions are more severe in the north-eastern corner of the site at the corner of Walsh Street and Narrabeen Park Parade where catchment topography causes heavy ponding. Runoff from elevated areas to the north enters the Caravan Park through a low point on Walsh Street.

Runoff along Narrabeen Park Parade is channelled into a 1500 mm pipe that discharges south at Narrabeen Lagoon. Multiple kerb inlets in the Caravan Park channel local flows into the pipe.

Design flood levels and depths along Walsh Street and flows in and out of the region are summarised in Table 42. The locations of these results, as well as localised depth mapping and hydrographs for the 1% AEP event are shown on Figure B36.

Table 42: Design Flow Behaviour in the Pipe System in Lakeside Holiday (Caravan) Park

| Design Event | Peak Flood Level (mAHD) | Peak Flood Depth (m) | Peak Inflow ($m^3/s$) | Peak Outflow ($m^3/s$) |
|---|---|---|---|---|
| 20% AEP | 3.3 | 0.9 | 1.5 | 0.0 |
| 10% AEP | 3.3 | 1.0 | 2.4 | 0.0 |
| 5% AEP | 3.4 | 1.0 | 3.7 | 1.0 |
| 2% AEP | 3.5 | 1.1 | 4.9 | 2.2 |
| 1% AEP | 3.5 | 1.2 | 6.0 | 3.2 |
| 0.5% AEP | 3.6 | 1.2 | 6.8 | 6.2 |
| 0.2% AEP | 3.6 | 1.3 | 8.2 | 7.8 |
| 0.1% AEP | 3.6 | 1.3 | 9.2 | 9.2 |
| PMF | 3.7 | 1.4 | 13.7 | 14.9 |

The low point on Walsh Street has a peak flood depth of 0.9 m in the 20% AEP event, increasing to 1.2 m in the 1% AEP event and to 1.4 m in the PMF event. Flooding increases with flood rarity with flood extents roughly doubling between the 5% AEP and 1% AEP events and doubling again between the 1% AEP and PMF events.

Terrain and tailwater elevations in Narrabeen Lagoon have a significant impact on outflows out of the area. In more frequent events (20% to 5% AEP), elevated road levels to the north and south of the Caravan Park act as levees to outflow causing water to pool without escaping. In mid-range events (2% to 1% AEP), additional flow elevates floodwaters allowing a steadier outflow. In rare events (0.5% AEP to PMF), elevated tailwaters increase flood levels in the region which coupled with the increase in inflows, increase peak outflows from the region.

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### 11.2.7. HS7 – Macpherson Street near Brands Lane Warriewood

Macpherson Street near Brands Lane in Warriewood is located between Narrabeen Creek (to the north) and Fern Creek (to the south). The area is affected by overland run-off from elevated areas to the west which drains to Narrabeen Creek, Fern Creek and the Warriewood wetlands.

Properties along the Macpherson Street area (which includes streets accessible off Macpherson Street such as Forest Road, Regent Way and Brands Lane for example) are generally at a higher elevation than water levels in both Narrabeen and Fern Creeks. However in rarer events, or potentially due to the effects of sea level rise caused by climate change, water levels in the creeks have the potential to overtop the banks and flood into properties in the area.

Local overland runoff in the area is channelled to the two creeks through multiple kerb inlets which drain to both Narrabeen and Fern Creeks. Major drainage lines are located under 26-28 Macpherson Street (a 1050 mm pipe) and under Warriewood Brook (a 900 mm pipe). Overland flow exceeding the stormwater pipe capacity ponds along Macpherson Street, Brands Lane and Fantail Avenue.

Design flood levels and depths along Macpherson Street and flows within the creeks upstream and downstream of the region are summarised in Table 43. The locations of these results, as well as localised depth mapping and hydrographs for the 1% AEP event are shown on Figure B37.

Table 43: Design Flow Behaviour along Macpherson Street Warriewood

| Design Event | Peak Flood Level (mAHD) | Peak Flood Depth (m) | Peak Inflow ($m^3/s$) | Peak Outflow ($m^3/s$) | Peak Inflow ($m^3/s$) | Peak Outflow ($m^3/s$) |
|---|---|---|---|---|---|---|
| | | | Fern Creek | | Narrabeen Creek | |
| 20% AEP | 101.5 | 0.3 | 9.3 | 12.8 | 29.0 | 32.7 |
| 10% AEP | 101.5 | 0.4 | 10.9 | 15.0 | 32.2 | 35.9 |
| 5% AEP | 101.6 | 0.4 | 12.7 | 17.7 | 36.8 | 40.0 |
| 2% AEP | 101.6 | 0.4 | 14.2 | 20.2 | 40.9 | 43.7 |
| 1% AEP | 101.6 | 0.4 | 15.8 | 23.1 | 45.8 | 47.5 |
| 0.5% AEP | 101.6 | 0.5 | 17.4 | 26.1 | 50.8 | 52.5 |
| 0.2% AEP | 101.6 | 0.5 | 19.6 | 30.4 | 56.8 | 61.6 |
| 0.1% AEP | 101.6 | 0.5 | 21.2 | 34.0 | 61.4 | 71.2 |
| PMF | 101.8 | 0.7 | 47.9 | 78.3 | 108.6 | 152.2 |

The low point on Macpherson Street has a peak flood depth of 0.3 m in the 20% AEP event, increasing only slightly to 0.4 m in the 1% event and to 0.7 m in the PMF event. Flooding on roads is present for the full range of design events, with the extent and depths increasing marginally with flood rarity up to the 0.1% AEP event before a bigger increase in the PMF.

Comparisons of peak inflows and outflows for the two creeks show that overland flow in the area along Macpherson Street contributes to a significant increase in flow in both creeks; although it should be noted that overland flow in areas to the north of Narrabeen Creek and the south of Fern

Creek (i.e. those areas on the other side of the creeks to Macpherson Street) will also cause increases.

Flooding of properties along Fern Creek and Narrabeen Creek may occur in rare events or as the result of sea level rise caused by climate change. In the 1% AEP event, some individual properties close to the banks may be affected by flooding from the creeks, but in the PMF (which most closely matches the FPL of 1% AEP level + 0.5 m in the creek), flooding is much more significant with high flood depths through a number of properties. While the PMF cannot be used interchangeably with the FPL, a consideration of the 1% AEP and the PMF events indicates that the FPL would likely cut the eastern end of Macpherson Street, the Garden Street Bridge over Fern Creek and the Macpherson Street Bridge over Narrabeen Creek, cutting all road evacuation for properties along Macpherson Street.

## 11.3. Peak Height Profiles

The peak flood level profile along Nareen Creek is provided on Figure B38B to Figure B38D. In the region upstream of Tatiara Crescent the range from the 20% to the 0.1% AEP flood level is less than 1 m. At all locations the range from the 20% AEP to the 0.1% AEP flood level is less than 1m with the PMF being significantly higher. There is a slight divergence in the flood levels further downstream, as rarer events (larger than the 1% AEP) use elevated tailwater conditions that are reflected in the flood levels, particularly at the outlet into Narrabeen Lagoon (at the downstream end of the Nareen Creek Open Channel).

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# 12. CLIMATE CHANGE

## 12.1. Background

Scientific investigation to estimate the effect of increasing amounts of greenhouse gases on the earth surface temperature is ongoing. Changes to surface and atmospheric temperatures are likely to affect climate and sea levels, although the extent of any permanent change can only be established with certainty through scientific observation over several decades. Nevertheless, it is prudent to consider the possible range of impacts climate change may have on flooding.

The latest research by the United National Intergovernmental Panel on Climate Change provides evidence of the occurrence of climate change and sea level rise as a result of increasing greenhouse gases. In this regard, the following points can be made:

- Greenhouse gas concentrations are increasing;
- Global sea levels have risen 0.1 – 0.25 m in the past century;
- Uncertainties limit the accuracy to which future climate change and sea level rise can be projected and predicted.

## 12.2. Climate Change Sensitivity

The effect of climate change on the study area was investigated for the 1% AEP design and PMF events. The following scenarios were modelled:

- 1% AEP design storm event plus 0.9 m sea level rise;
- 1% AEP design storm event with a 10% increase in rainfall plus 0.9 m sea level rise;
- 1% AEP design storm event with a 30% increase in rainfall plus 0.9 m sea level rise;
- PMF storm event plus 0.9 m sea level rise;
- PMF storm event with a 10% increase in rainfall plus 0.9 m sea level rise;
- PMF storm event with a 30% increase in rainfall plus 0.9 m sea level rise.

Depth and velocity mapping for both the 1% AEP and PMF events with a 30% increase in rainfall plus 0.9 m sea level rise are included as Figure D1 to Figure D4.

Comparisons of the various climate change scenarios with the no-climate change scenarios are included as Figure D5 to Figure D10. In the 1% AEP event, sea level rise causes only minor increases to flood levels in the area surrounding the open-channel section of Nareen Creek and the wetlands to the north of Mullet Creek. Increases in rainfall have an effect on flood levels further upstream in the catchment, but the combined effect of both a rainfall increase and sea level rise has the largest impact on the Mullet Creek outflow to Narrabeen Lagoon.

In the PMF event, sea level rise causes increases to flood levels of greater than 0.5 m along Nareen Creek, Mullet Creek and the shoreline of Narrabeen Lagoon, and increased rainfall causes some increases to flood levels in the catchment upstream and major increases to levels in all areas south of the Warriewood Wetlands. This is to be expected given the high volume of rainfall in the PMF storm event and the 1% AEP Narrabeen Lagoon tailwater adopted at the downstream boundary.

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- Residents of the catchment;
- Northern Beaches Council;
- NSW Office of Environment and Heritage;
- Bureau of Meteorology;
- State Emergency Services

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# 14. GLOSSARY

## TERMINOLOGY OF FLOOD RISK

Australian Rainfall and Runoff (Reference 7) recommends terminology that is not misleading to the public and stakeholders. Therefore the use of terms such as “recurrence interval” and “return period” are no longer recommended as they imply that a given event magnitude is only exceeded at regular intervals such as every 100 years. However, rare events may occur in clusters. For example there are several instances of an event with a 1% chance of occurring within a short period, for example the 1949 and 1950 events at Kempsey. Historically the term Average Recurrence Interval (ARI) has been used.

| Frequency Descriptor | EY | AEP (%) | AEP (1 in x) | ARI |
|---|---|---|---|---|
| Very Frequent | 12 | | | |
| | 6 | 99.75 | 1.002 | 0.17 |
| | 4 | 98.17 | 1.02 | 0.25 |
| | 3 | 95.02 | 1.05 | 0.33 |
| | 2 | 86.47 | 1.16 | 0.5 |
| | 1 | 63.21 | 1.58 | 1 |
| Frequent | 0.69 | 50 | 2 | 1.44 |
| | 0.5 | 39.35 | 2.54 | 2 |
| | 0.22 | 20 | 5 | 4.48 |
| | 0.2 | 18.13 | 5.52 | 5 |
| | 0.11 | 10 | 10 | 9.49 |
| Rare | 0.05 | 5 | 20 | 20 |
| | 0.02 | 2 | 50 | 50 |
| | 0.01 | 1 | 100 | 100 |
| Very Rare | 0.005 | 0.5 | 200 | 200 |
| | 0.002 | 0.2 | 500 | 500 |
| | 0.001 | 0.1 | 1000 | 1000 |
| | 0.0005 | 0.05 | 2000 | 2000 |
| Extreme | 0.0002 | 0.02 | 5000 | 5000 |
| | | | ↓ | |
| | | | PMP/ PMPDF | |

ARR 2016 recommends the use of Annual Exceedance Probability (AEP). Annual Exceedance Probability (AEP) is the probability of an event being equalled or exceeded within a year. AEP may be expressed as either a percentage (%) or 1 in X. Floodplain management typically uses the percentage form of terminology. Therefore a 1% AEP event or 1 in 100 AEP has a 1% chance of being equalled or exceeded in any year. ARI and AEP are often mistaken as being interchangeable for events equal to or more frequent than 10% AEP. The table below describes how they are subtly different.

For events more frequent than 50% AEP, expressing frequency in terms of Annual Exceedance Probability is not meaningful and misleading particularly in areas with strong seasonality. Statistically a 0.5 EY event is not the same as a 50% AEP event, and likewise an event with a 20% AEP is not the same as a 0.2 EY event. For example an event of 0.5 EY is an event which would, on average, occur every two years. A 2 EY event is equivalent to a design event with a 6 month Average Recurrence Interval where there is no seasonality, or an event that is likely to occur twice in one year.

The Probable Maximum Flood is the largest flood that could possibly occur on a catchment. It is related to the Probable Maximum Precipitation (PMP). The PMP has an approximate probability. Due to the conservativeness applied to other factors influencing flooding a PMP does not translate to a PMF of the same AEP. Therefore an AEP is not assigned to the PMF.

This report has adopted the approach recommended by ARR and uses % AEP for all events of 50% AEP or rarer and EY for all events more frequent than this.

# GLOSSARY OF TERMS

(Taken from the Floodplain Development Manual - April 2005)

| | |
|---|---|
| **Annual Exceedance Probability (AEP)** | The chance of a flood of a given or larger size occurring in any one year, usually expressed as a percentage. For example, if a peak flood discharge of 500 $m^3/s$ has an AEP of 5%, it means that there is a 5% chance (that is one-in-20 chance) of a 500 $m^3/s$ or larger event occurring in any one year (see ARI). |
| **Australian Height Datum (AHD)** | A common national surface level datum approximately corresponding to mean sea level. |
| **Average Annual Damage (AAD)** | Depending on its size (or severity), each flood will cause a different amount of flood damage to a flood prone area. AAD is the average damage per year that would occur in a nominated development situation from flooding over a very long period. |
| **catchment** | The land area draining through the main stream, as well as tributary streams, to a particular site. It always relates to an area above a specific location. |
| **consent authority** | The Council, government agency or person having the function to determine a development application for land use under the EP&A Act. The consent authority is most often the Council, however legislation or an EPI may specify a Minister or public authority (other than a Council), or the Director General of DIPNR, as having the function to determine an application. |
| **development** | Is defined in Part 4 of the Environmental Planning and Assessment Act (EP&A Act).<br><br>**infill development:** refers to the development of vacant blocks of land that are generally surrounded by developed properties and is permissible under the current zoning of the land. Conditions such as minimum floor levels may be imposed on infill development. |

| | |
|---|---|
| | **new development:** refers to development of a completely different nature to that associated with the former land use. For example, the urban subdivision of an area previously used for rural purposes. New developments involve rezoning and typically require major extensions of existing urban services, such as roads, water supply, sewerage and electric power.<br>**redevelopment:** refers to rebuilding in an area. For example, as urban areas age, it may become necessary to demolish and reconstruct buildings on a relatively large scale. Redevelopment generally does not require either rezoning or major extensions to urban services. |
| **discharge** | The rate of flow of water measured in terms of volume per unit time, for example, cubic metres per second ($m^3/s$). Discharge is different from the speed or velocity of flow, which is a measure of how fast the water is moving for example, metres per second (m/s). |
| **DRAINS** | Stormwater Drainage System design and analysis program. |
| **effective warning time** | The time available after receiving advice of an impending flood and before the floodwaters prevent appropriate flood response actions being undertaken. The effective warning time is typically used to move farm equipment, move stock, raise furniture, evacuate people and transport their possessions. |
| **emergency management** | A range of measures to manage risks to communities and the environment. In the flood context it may include measures to prevent, prepare for, respond to and recover from flooding. |
| **flash flooding** | Flooding which is sudden and unexpected. It is often caused by sudden local or nearby heavy rainfall. Often defined as flooding which peaks within six hours of the causative rain. |
| **flood** | Relatively high stream flow which overtops the natural or artificial banks in any part of a stream, river, estuary, lake or dam, and/or local overland flooding associated with major drainage before entering a watercourse, and/or coastal inundation resulting from super-elevated sea levels and/or waves overtopping coastline defences excluding tsunami. |
| **flood awareness** | Flood awareness is an appreciation of the likely effects of flooding and a knowledge of the relevant flood warning, response and evacuation procedures. |
| **flood education** | Flood education seeks to provide information to raise awareness of the flood problem so as to enable individuals to understand how to manage themselves an their property in response to flood warnings and in a flood event. It invokes a state of flood readiness. |
| **flood fringe areas** | The remaining area of flood prone land after floodway and flood storage areas have been defined. |
| **flood liable land** | Is synonymous with flood prone land (i.e. land susceptible to flooding by the probable maximum flood (PMF) event). Note that the term flood liable land covers the whole of the floodplain, not just that part below the flood planning level (see flood planning area). |
| **floodplain** | Area of land which is subject to inundation by floods up to and including the probable maximum flood event, that is, flood prone land. |
| **floodplain risk management options** | The measures that might be feasible for the management of a particular area of the floodplain. Preparation of a floodplain risk management plan requires a detailed evaluation of floodplain risk management options. |

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**floodplain risk management plan** A management plan developed in accordance with the principles and guidelines in this manual. Usually includes both written and diagrammetic information describing how particular areas of flood prone land are to be used and managed to achieve defined objectives.

**flood plan (local)** A sub-plan of a disaster plan that deals specifically with flooding. They can exist at State, Division and local levels. Local flood plans are prepared under the leadership of the State Emergency Service.

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

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

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

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

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

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

**existing flood risk:** the risk a community is exposed to as a result of its location on the floodplain.
**future flood risk:** the risk a community may be exposed to as a result of new development on the floodplain.
**continuing flood risk:** the risk a community is exposed to after floodplain risk management measures have been implemented. For a town protected by levees, the continuing flood risk is the consequences of the levees being overtopped. For an area without any floodplain risk management measures, the continuing flood risk is simply the existence of its flood exposure.

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

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

**freeboard** Freeboard provides reasonable certainty that the risk exposure selected in deciding on a particular flood chosen as the basis for the FPL is actually provided. It is a



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| | factor of safety typically used in relation to the setting of floor levels, levee crest levels, etc. Freeboard is included in the flood planning level. |
| **habitable room** | **in a residential situation:** a living or working area, such as a lounge room, dining room, rumpus room, kitchen, bedroom or workroom.<br>**in an industrial or commercial situation:** an area used for offices or to store valuable possessions susceptible to flood damage in the event of a flood. |
| **hazard** | A source of potential harm or a situation with a potential to cause loss. In relation to this manual the hazard is flooding which has the potential to cause damage to the community. Definitions of high and low hazard categories are provided in the Manual. |
| **hydraulics** | Term given to the study of water flow in waterways; in particular, the evaluation of flow parameters such as water level and velocity. |
| **hydrograph** | A graph which shows how the discharge or stage/flood level at any particular location varies with time during a flood. |
| **hydrology** | Term given to the study of the rainfall and runoff process; in particular, the evaluation of peak flows, flow volumes and the derivation of hydrographs for a range of floods. |
| **LiDAR** | Surveying method that measures distances via laser. |
| **local overland flooding** | Inundation by local runoff rather than overbank discharge from a stream, river, estuary, lake or dam. |
| **local drainage** | Are smaller scale problems in urban areas. They are outside the definition of major drainage in this glossary. |
| **mainstream flooding** | Inundation of normally dry land occurring when water overflows the natural or artificial banks of a stream, river, estuary, lake or dam. |
| **major drainage** | Councils have discretion in determining whether urban drainage problems are associated with major or local drainage. For the purpose of this manual major drainage involves:<br>• the floodplains of original watercourses (which may now be piped, channelised or diverted), or sloping areas where overland flows develop along alternative paths once system capacity is exceeded; and/or<br>• water depths generally in excess of 0.3 m (in the major system design storm as defined in the current version of Australian Rainfall and Runoff). These conditions may result in danger to personal safety and property damage to both premises and vehicles; and/or<br>• major overland flow paths through developed areas outside of defined drainage reserves; and/or<br>• the potential to affect a number of buildings along the major flow path. |
| **mathematical/computer models** | The mathematical representation of the physical processes involved in runoff generation and stream flow. These models are often run on computers due to the complexity of the mathematical relationships between runoff, stream flow and the distribution of flows across the floodplain. |
| **minor, moderate and major flooding** | Both the State Emergency Service and the Bureau of Meteorology use the following definitions in flood warnings to give a general indication of the types of problems expected with a flood: |

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|---|---|
| | **minor flooding:** causes inconvenience such as closing of minor roads and the submergence of low level bridges. The lower limit of this class of flooding on the reference gauge is the initial flood level at which landholders and townspeople begin to be flooded.<br>**moderate flooding:** low-lying areas are inundated requiring removal of stock and/or evacuation of some houses. Main traffic routes may be covered.<br>**major flooding:** appreciable urban areas are flooded and/or extensive rural areas are flooded. Properties, villages and towns can be isolated. |
| **modification measures** | Measures that modify either the flood, the property or the response to flooding. |
| **peak discharge** | The maximum discharge occurring during a flood event. |
| **Probable Maximum Flood (PMF)** | The PMF is the largest flood that could conceivably occur at a particular location, usually estimated from probable maximum precipitation, and where applicable, snow melt, coupled with the worst flood producing catchment conditions. Generally, it is not physically or economically possible to provide complete protection against this event. The PMF defines the extent of flood prone land, that is, the floodplain. The extent, nature and potential consequences of flooding associated with a range of events rarer than the flood used for designing mitigation works and controlling development, up to and including the PMF event should be addressed in a floodplain risk management study. |
| **Probable Maximum Precipitation (PMP)** | The PMP is the greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends (World Meteorological Organisation, 1986). It is the primary input to PMF estimation. |
| **probability** | A statistical measure of the expected chance of flooding (see AEP). |
| **RAFTS** | Runoff routing model for hydrologic and hydraulic analysis of storm water drainage and conveyance systems. |
| **risk** | Chance of something happening that will have an impact. It is measured in terms of consequences and likelihood. In the context of the manual it is the likelihood of consequences arising from the interaction of floods, communities and the environment. |
| **RORB** | General runoff and streamflow routing program used to calculate flood hydrographs from rainfall and other channel inputs. |
| **runoff** | The amount of rainfall which actually ends up as streamflow, also known as rainfall excess. |
| **SOBEK** | Integrated 1D/2D modelling suite for flood modelling, flood forecasting and optimisation of drainage systems. |
| **stage** | Equivalent to water level. Both are measured with reference to a specified datum. |
| **stage hydrograph** | A graph that shows how the water level at a particular location changes with time during a flood. It must be referenced to a particular datum. |
| **TUFLOW** | One-dimensional (1D) and two-dimensional (2D) flood and tide simulation software (hydraulic model). |
| **survey plan** | A plan prepared by a registered surveyor. |
| **water surface profile** | A graph showing the flood stage at any given location along a watercourse at a particular time. |

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# Figures

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FIGURE 1
**STUDY AREA**


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FIGURE 2
**LIDAR SURVEY DATA**

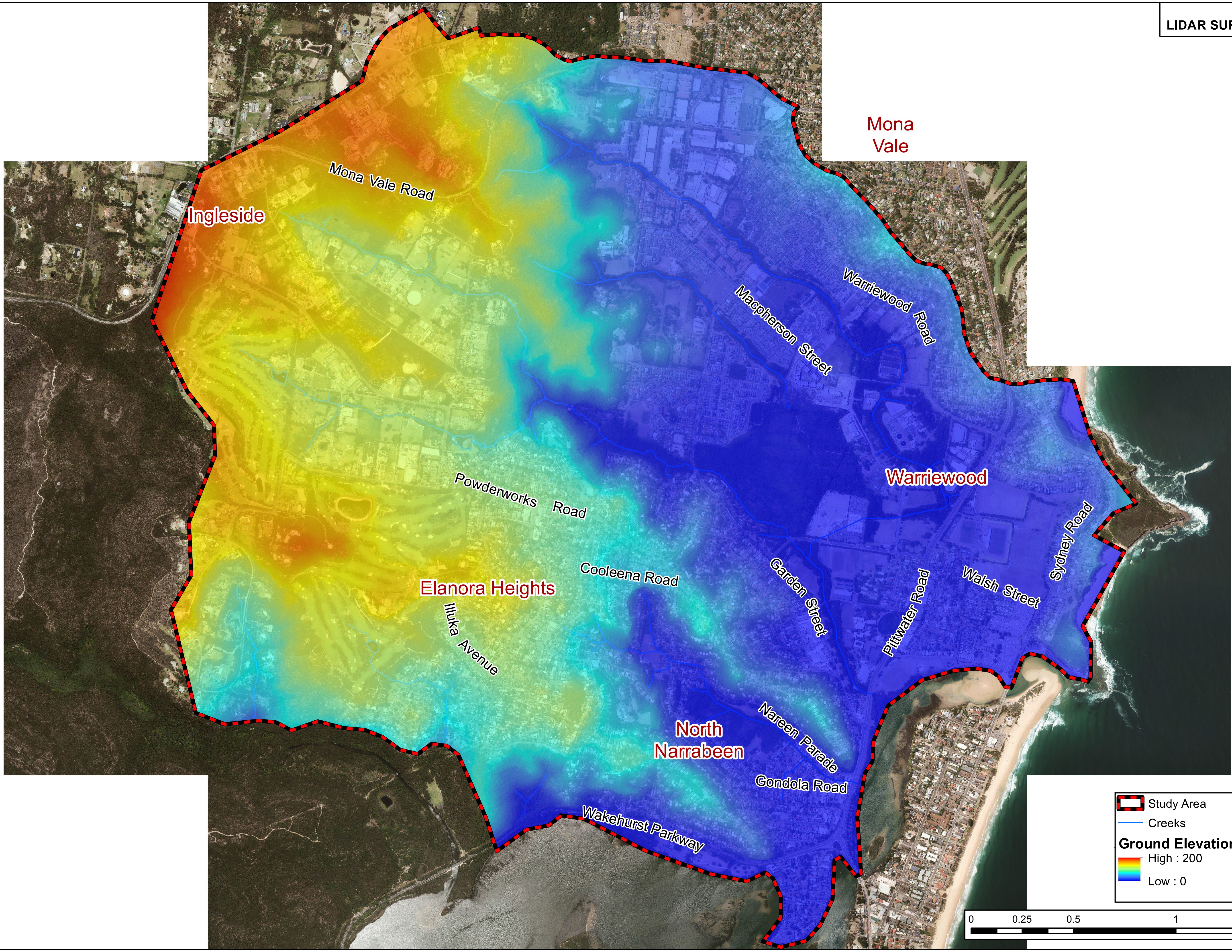


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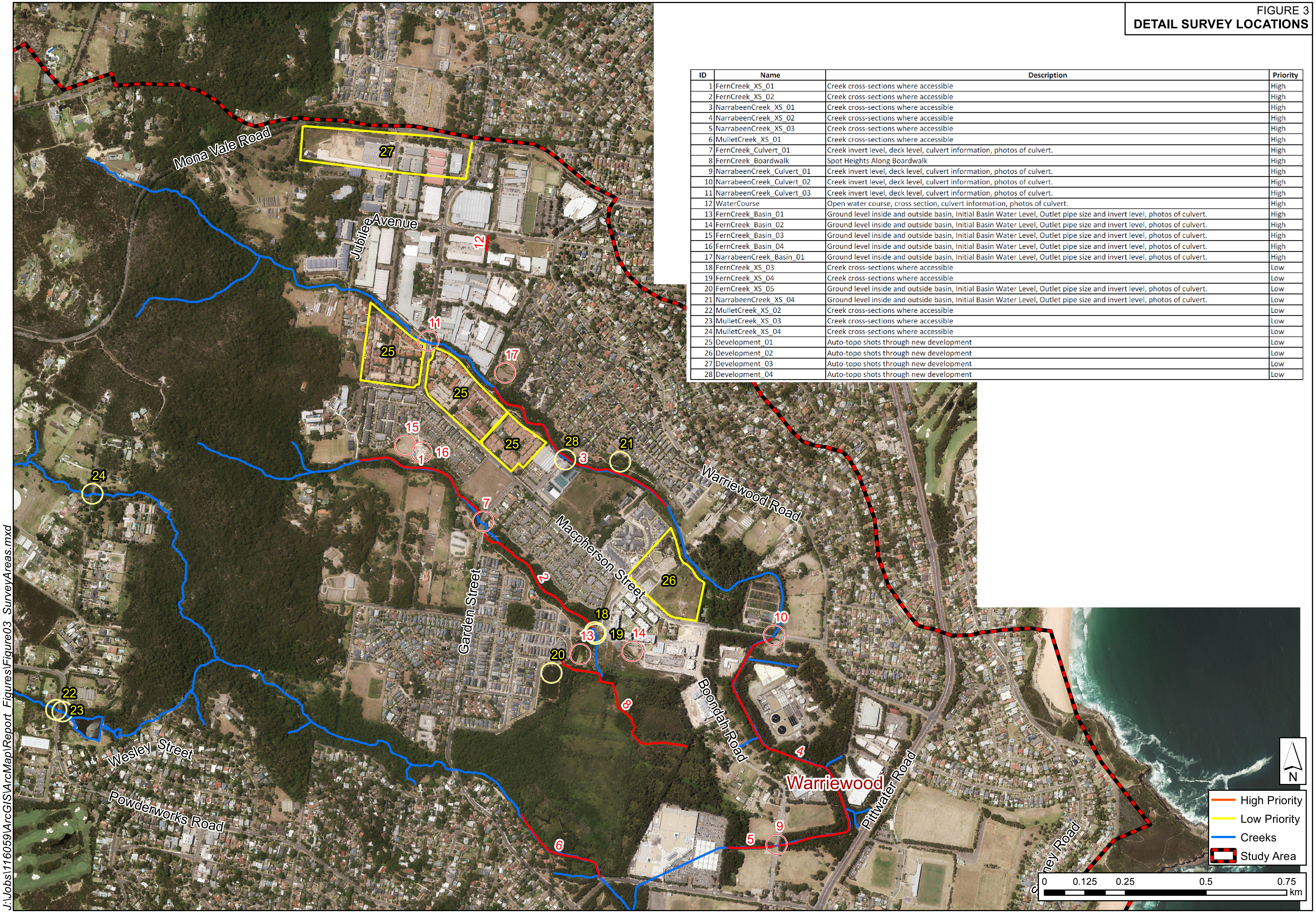
FIGURE 3
# DETAIL SURVEY LOCATIONS

| ID | Name | Description | Priority |
|---|---|---|---|
| 1 | FernCreek_XS_01 | Creek cross-sections where accessible | High |
| 2 | FernCreek_XS_02 | Creek cross-sections where accessible | High |
| 3 | NarrabeenCreek_XS_01 | Creek cross-sections where accessible | High |
| 4 | NarrabeenCreek_XS_02 | Creek cross-sections where accessible | High |
| 5 | NarrabeenCreek_XS_03 | Creek cross-sections where accessible | High |
| 6 | MulletCreek_XS_01 | Creek cross-sections where accessible | High |
| 7 | FernCreek_Culvert_01 | Creek invert level, deck level, culvert information, photos of culvert. | High |
| 8 | FernCreek_Boardwalk | Spot Heights Along Boardwalk | High |
| 9 | NarrabeenCreek_Culvert_01 | Creek invert level, deck level, culvert information, photos of culvert. | High |
| 10 | NarrabeenCreek_Culvert_02 | Creek invert level, deck level, culvert information, photos of culvert. | High |
| 11 | NarrabeenCreek_Culvert_03 | Creek invert level, deck level, culvert information, photos of culvert. | High |
| 12 | WaterCourse | Open water course, cross section, culvert information, photos of culvert. | High |
| 13 | FernCreek_Basin_01 | Ground level inside and outside basin, Initial Basin Water Level, Outlet pipe size and invert level, photos of culvert. | High |
| 14 | FernCreek_Basin_02 | Ground level inside and outside basin, Initial Basin Water Level, Outlet pipe size and invert level, photos of culvert. | High |
| 15 | FernCreek_Basin_03 | Ground level inside and outside basin, Initial Basin Water Level, Outlet pipe size and invert level, photos of culvert. | High |
| 16 | FernCreek_Basin_04 | Ground level inside and outside basin, Initial Basin Water Level, Outlet pipe size and invert level, photos of culvert. | High |
| 17 | NarrabeenCreek_Basin_01 | Ground level inside and outside basin, Initial Basin Water Level, Outlet pipe size and invert level, photos of culvert. | High |
| 18 | FernCreek_XS_03 | Creek cross-sections where accessible | Low |
| 19 | FernCreek_XS_04 | Creek cross-sections where accessible | Low |
| 20 | FernCreek_XS_05 | Ground level inside and outside basin, Initial Basin Water Level, Outlet pipe size and invert level, photos of culvert. | Low |
| 21 | NarrabeenCreek_XS_04 | Ground level inside and outside basin, Initial Basin Water Level, Outlet pipe size and invert level, photos of culvert. | Low |
| 22 | MulletCreek_XS_02 | Creek cross-sections where accessible | Low |
| 23 | MulletCreek_XS_03 | Creek cross-sections where accessible | Low |
| 24 | MulletCreek_XS_04 | Creek cross-sections where accessible | Low |
| 25 | Development_01 | Auto-topo shots through new development | Low |
| 26 | Development_02 | Auto-topo shots through new development | Low |
| 27 | Development_03 | Auto-topo shots through new development | Low |
| 28 | Development_04 | Auto-topo shots through new development | Low |

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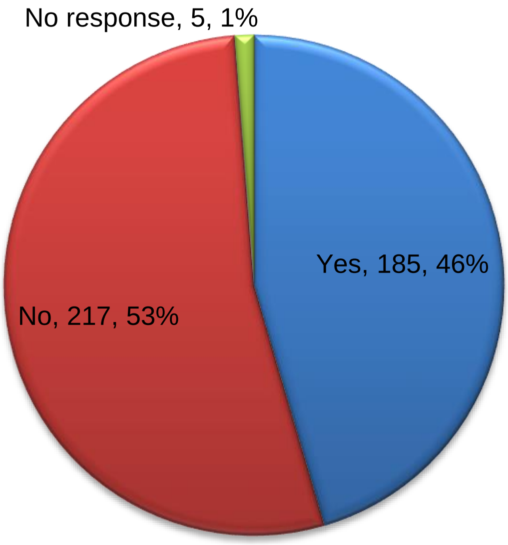
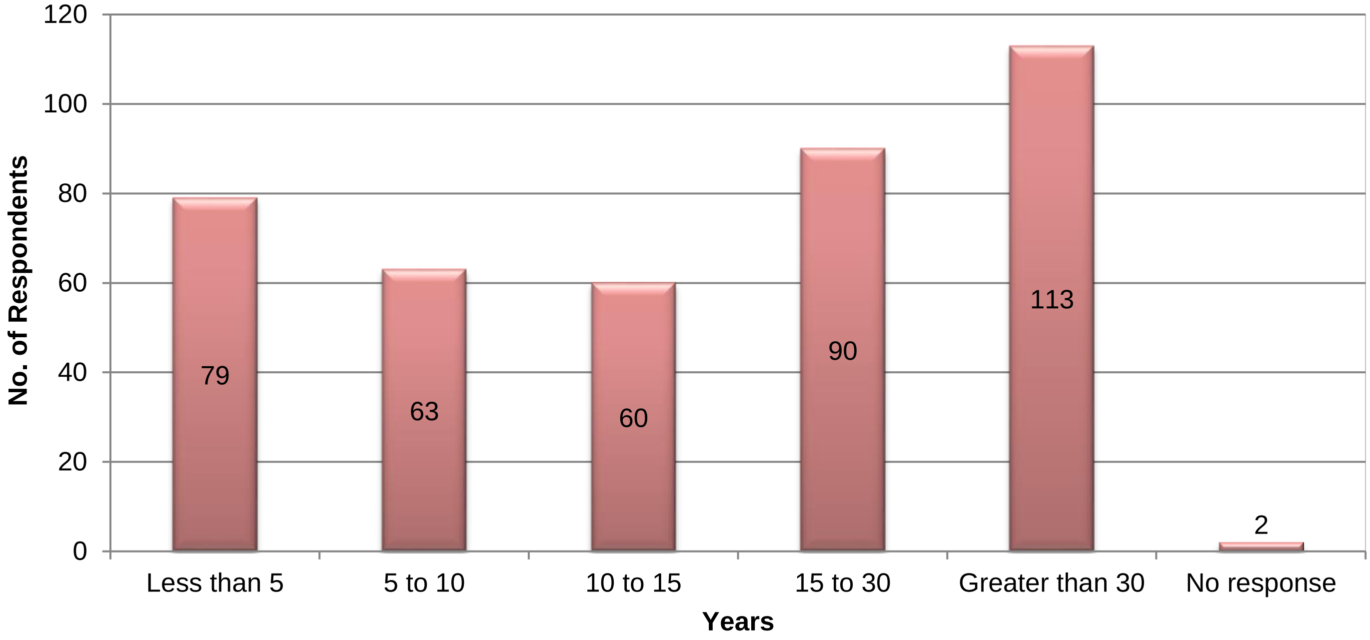
## Knowledge of Overland Flow Paths




## Period of Living/Owning/Working on Property




## Length of Residence in Area

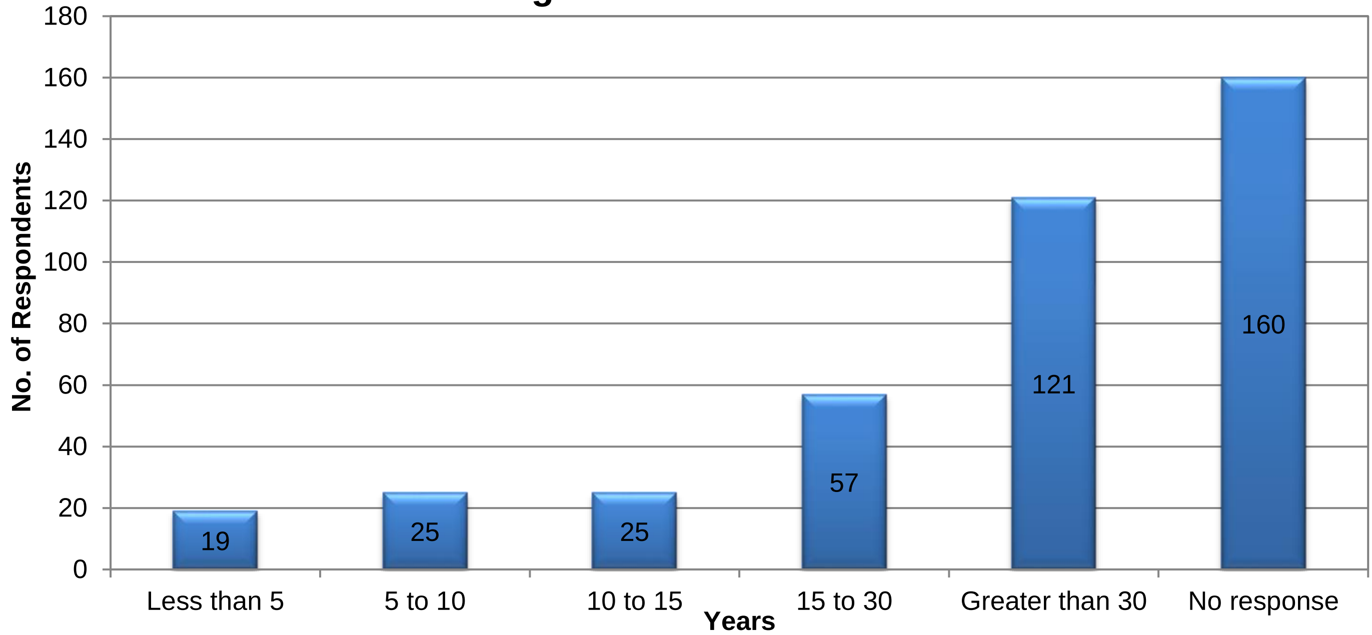
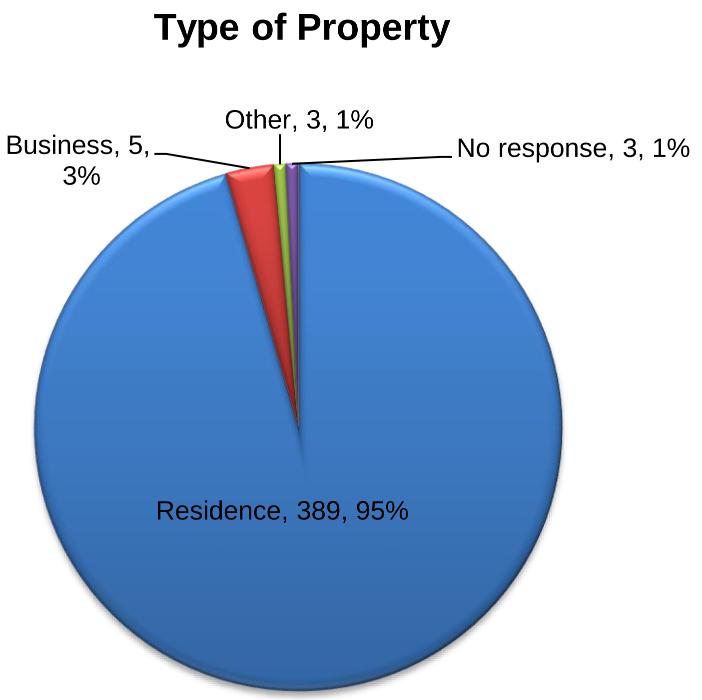
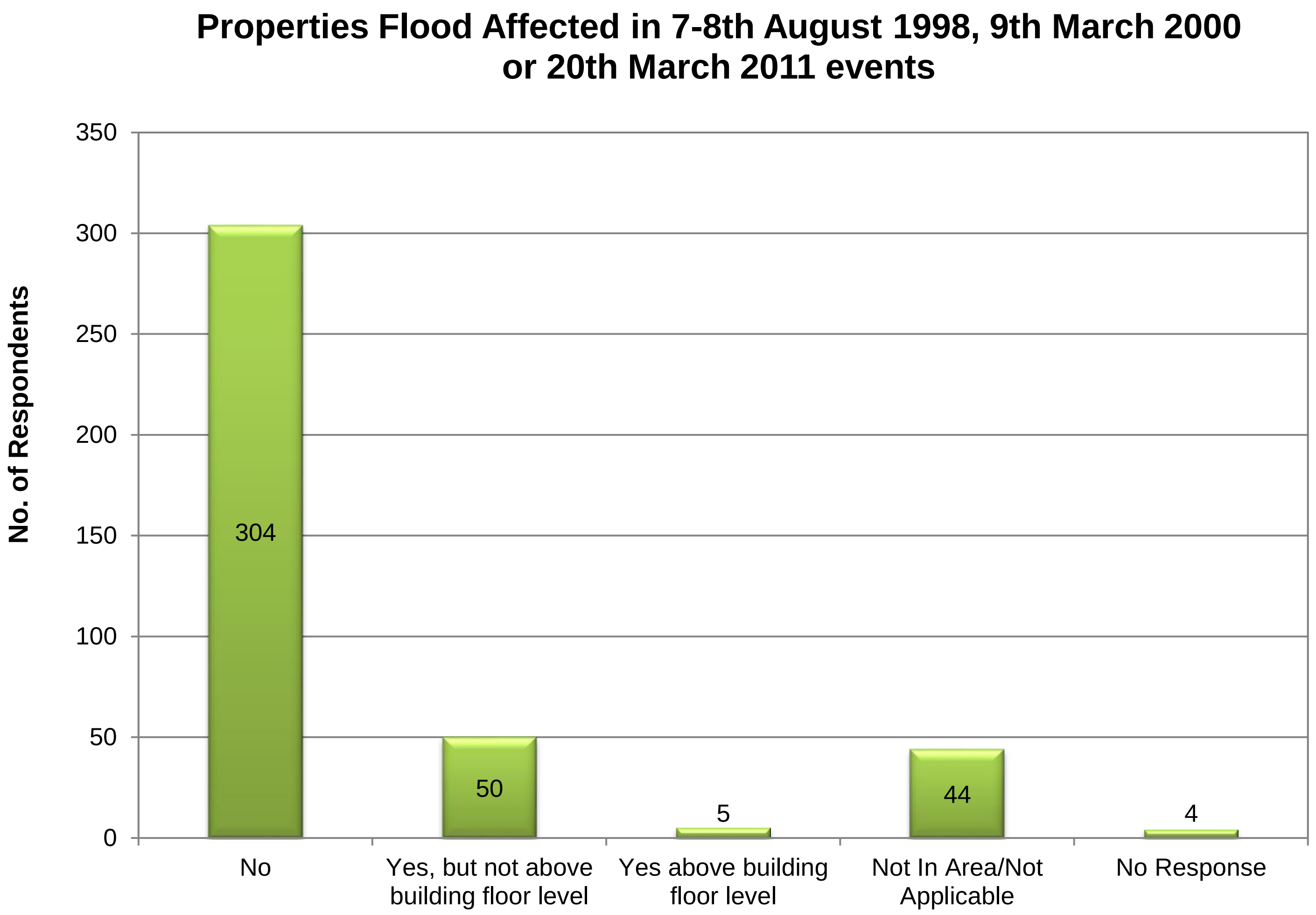


FIGURE 4B
**COMMUNITY RESPONSES**



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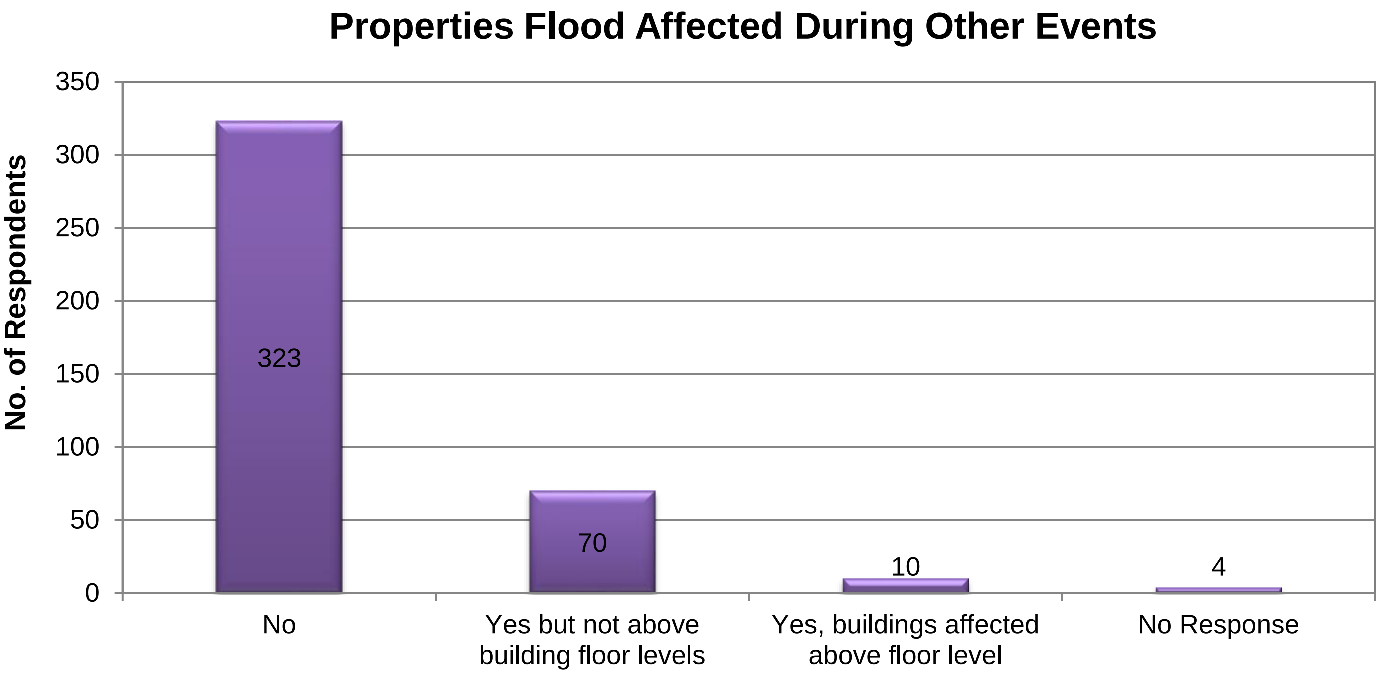
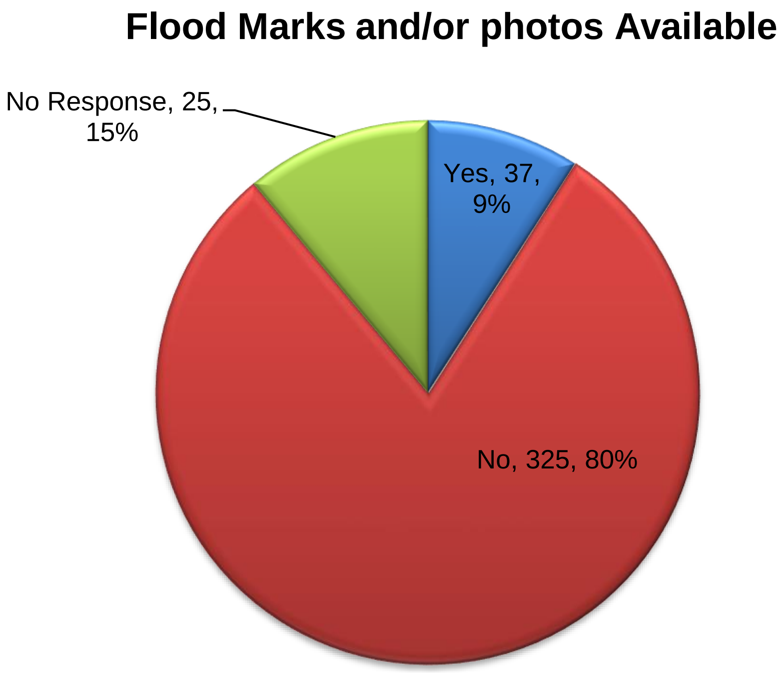


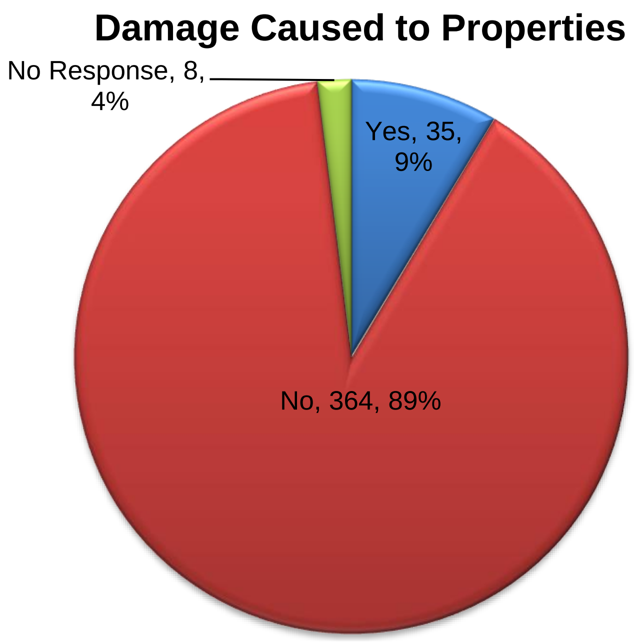
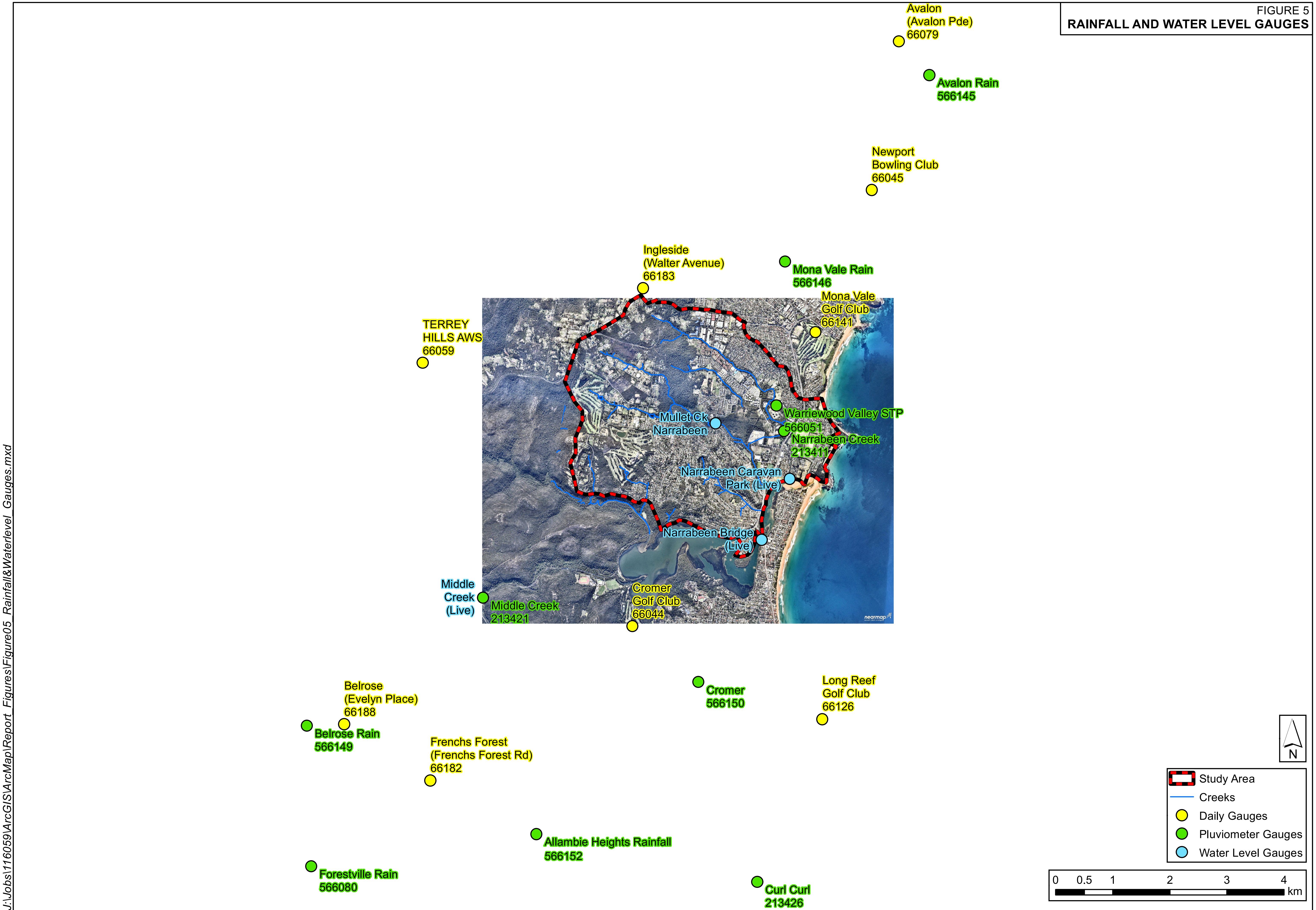



FIGURE 5
RAINFALL AND WATER LEVEL GAUGES

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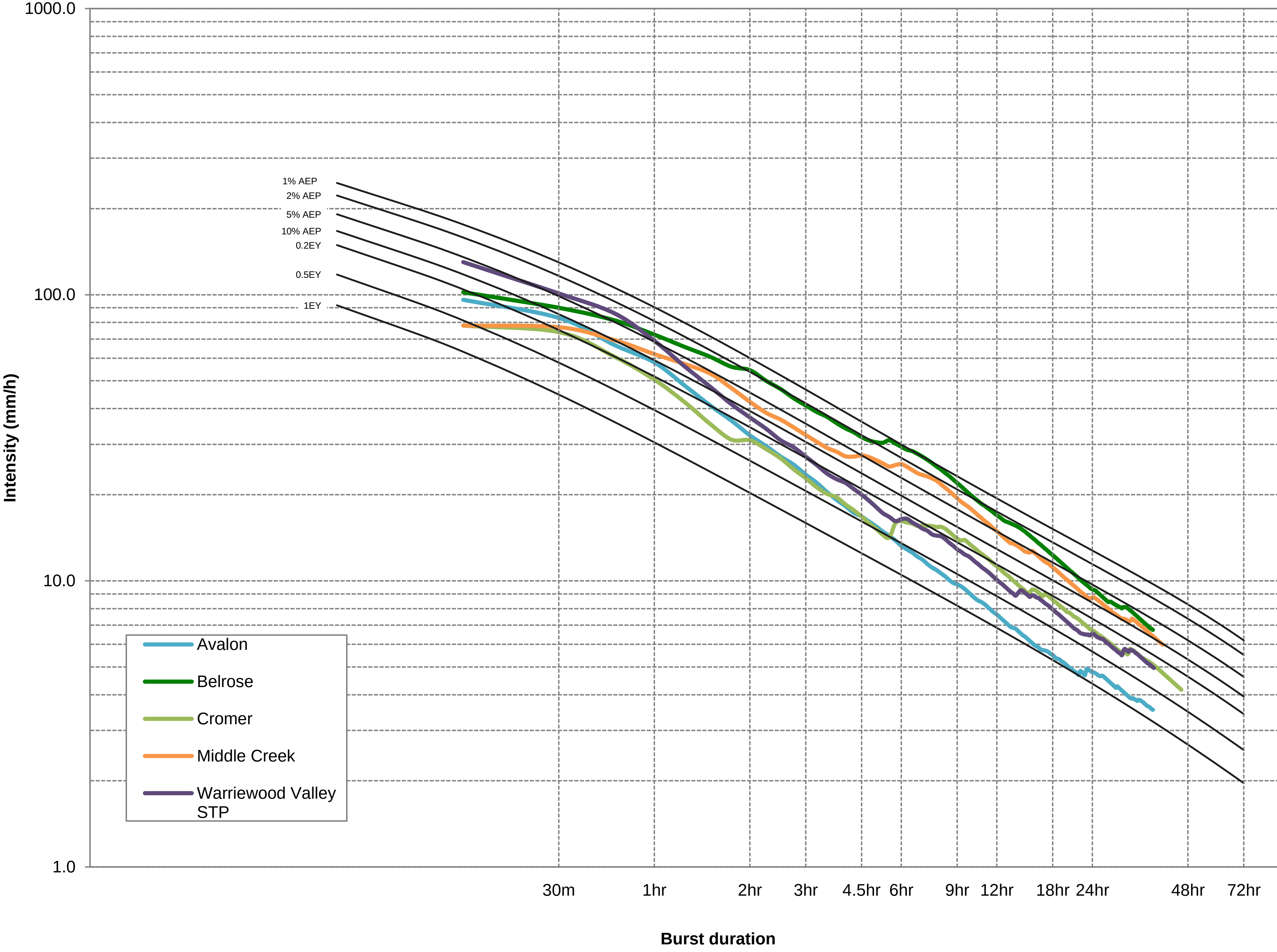


FIGURE 6A
**HISTORICAL RAINFALL VERSUS AR&R 1987 IFD APRIL 1998 RAINFALL EVENT**

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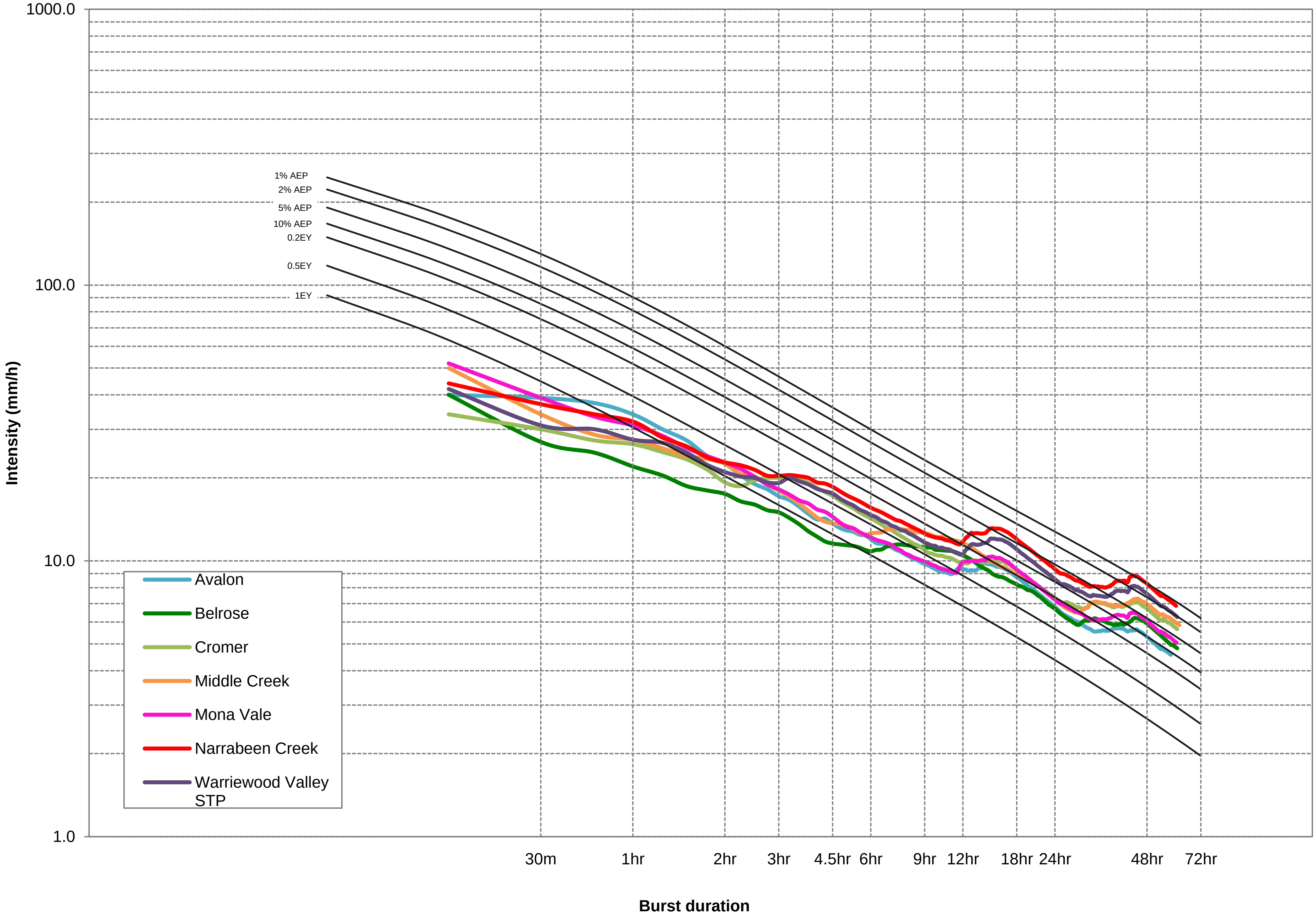


FIGURE 6B
**HISTORICAL RAINFALL VERSUS AR&R 1987 IFD AUGUST 1998 RAINFALL EVENT**

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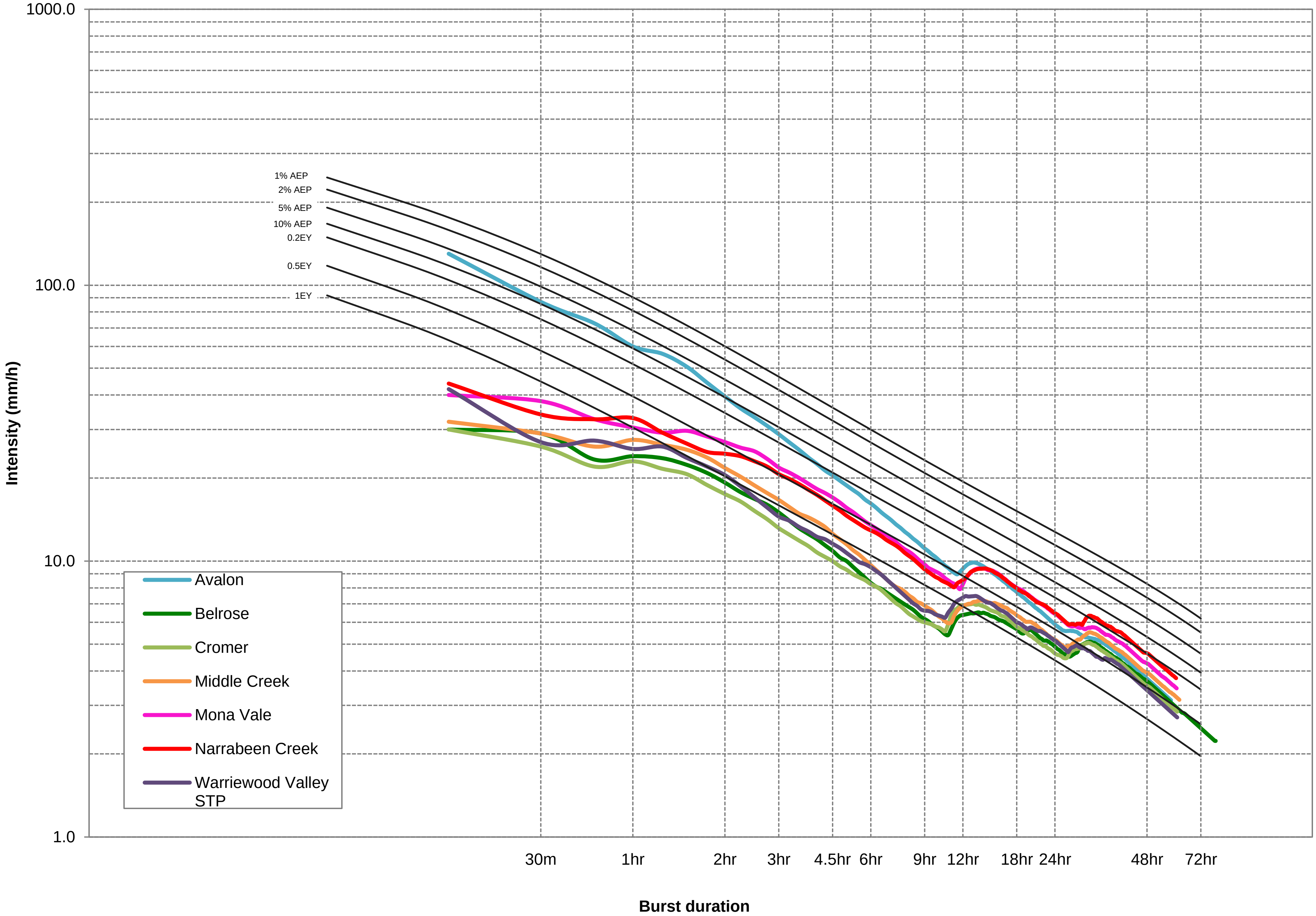


FIGURE 6C
**HISTORICAL RAINFALL VERSUS AR&R 1987 IFD FEBRUARY 2002 RAINFALL EVENT**

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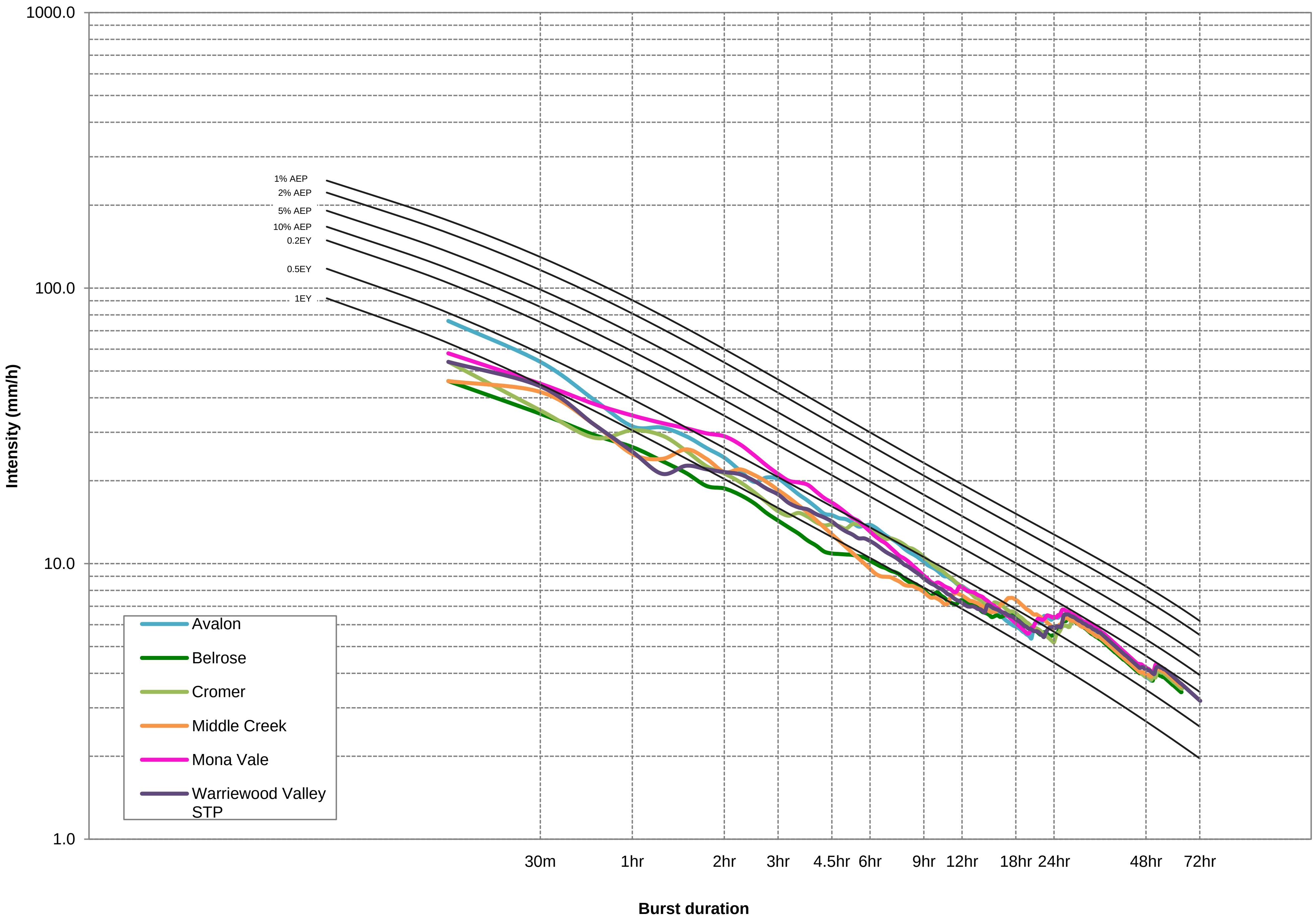


FIGURE 6D

**HISTORICAL RAINFALL VERSUS AR&R 1987 IFD**

**MARCH 2011 RAINFALL EVENT**

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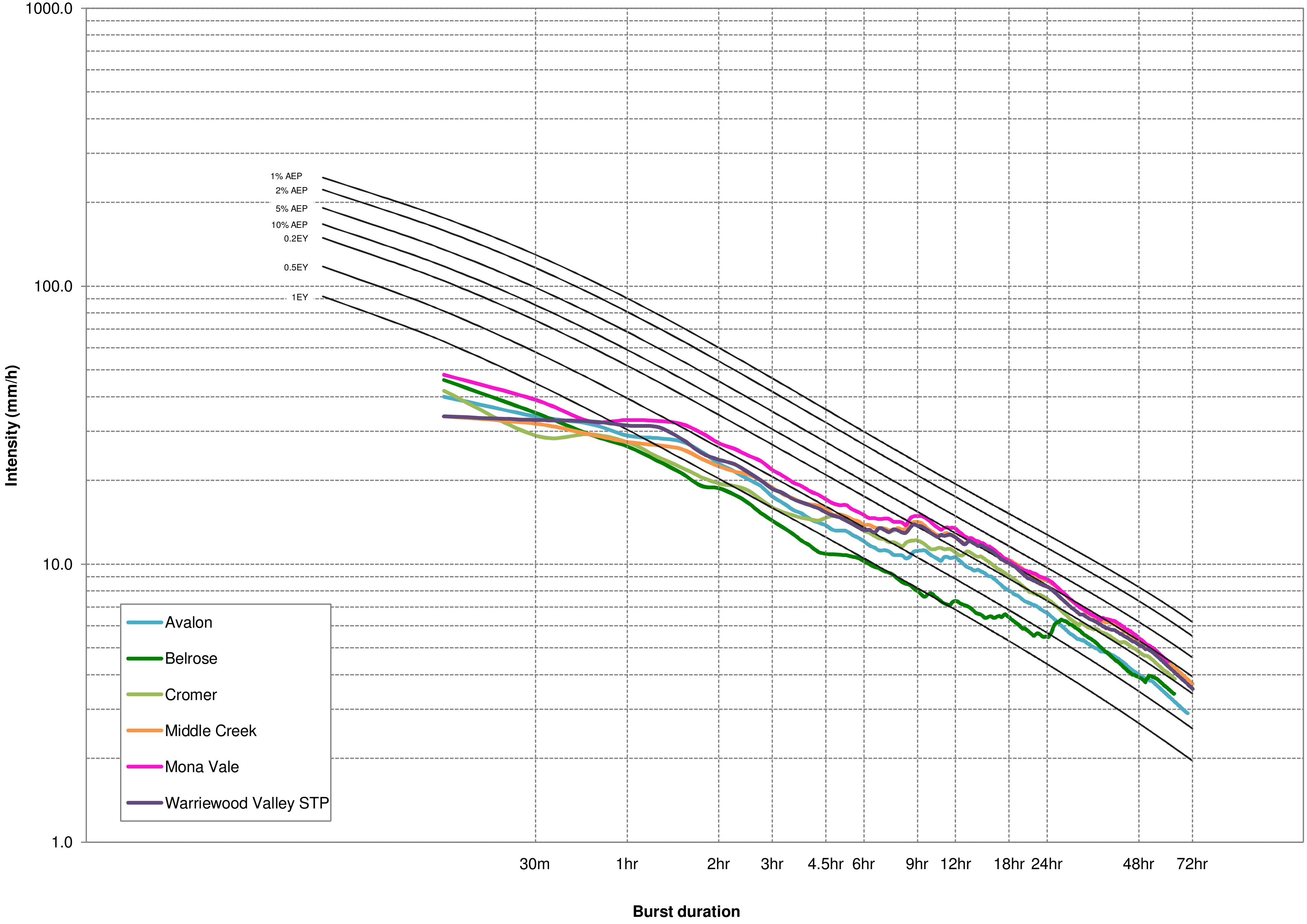


FIGURE 6E
**HISTORICAL RAINFALL VERSUS AR&R 1987 IFD**
**JUNE 2016 RAINFALL EVENT**

# FIGURE 7
**PMF ELLIPSES**

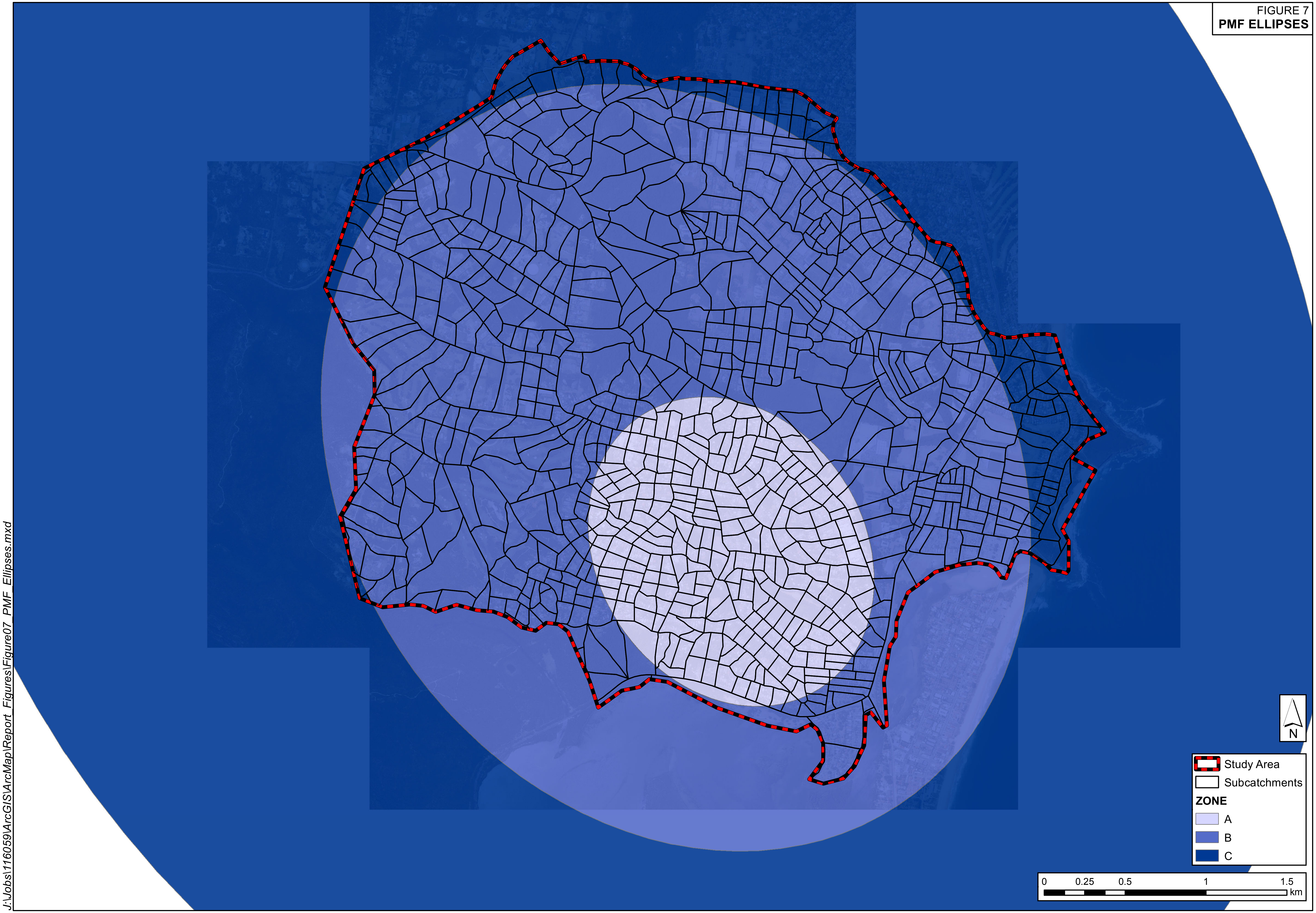


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FIGURE 8A

**RECORDED CUMULATIVE RAINFALL DEPTHS**

**APRIL 1998 RAINFALL EVENT**

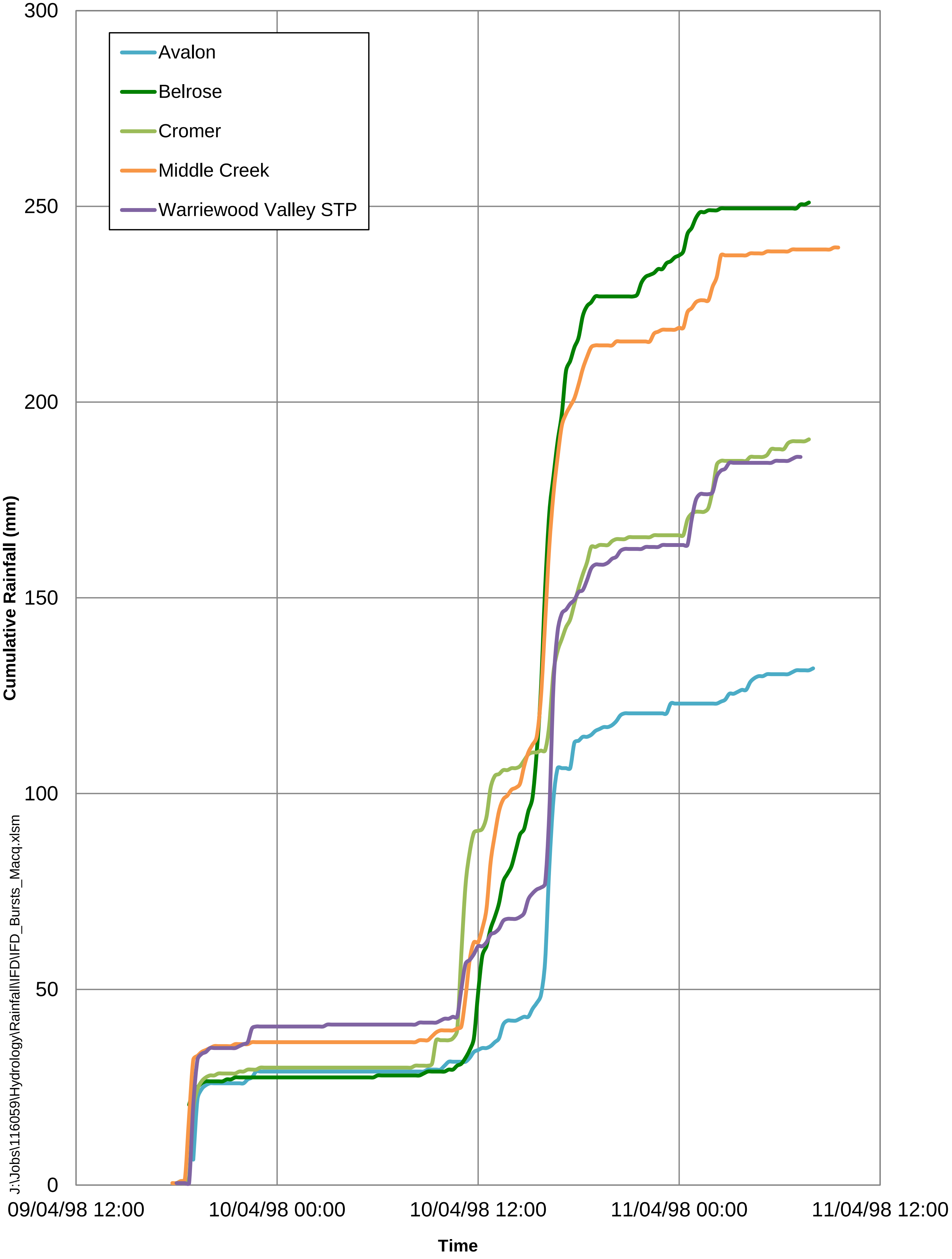


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FIGURE 8B

**RECORDED CUMULATIVE RAINFALL DEPTHS**
**AUGUST 1998 RAINFALL EVENT**

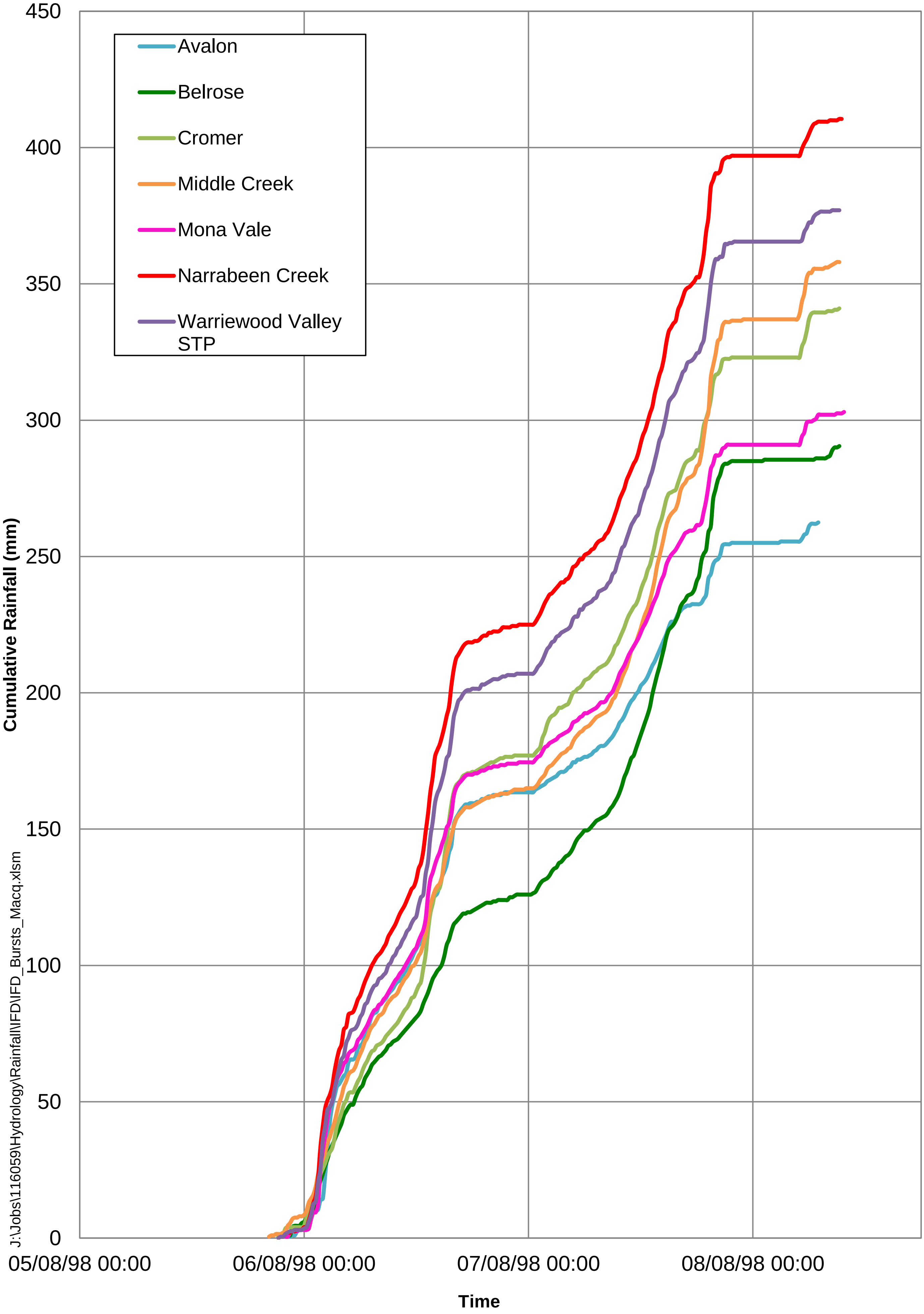


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FIGURE 8C
**RECORDED CUMULATIVE RAINFALL DEPTHS**
**FEBRUARY 2002 RAINFALL EVENT**

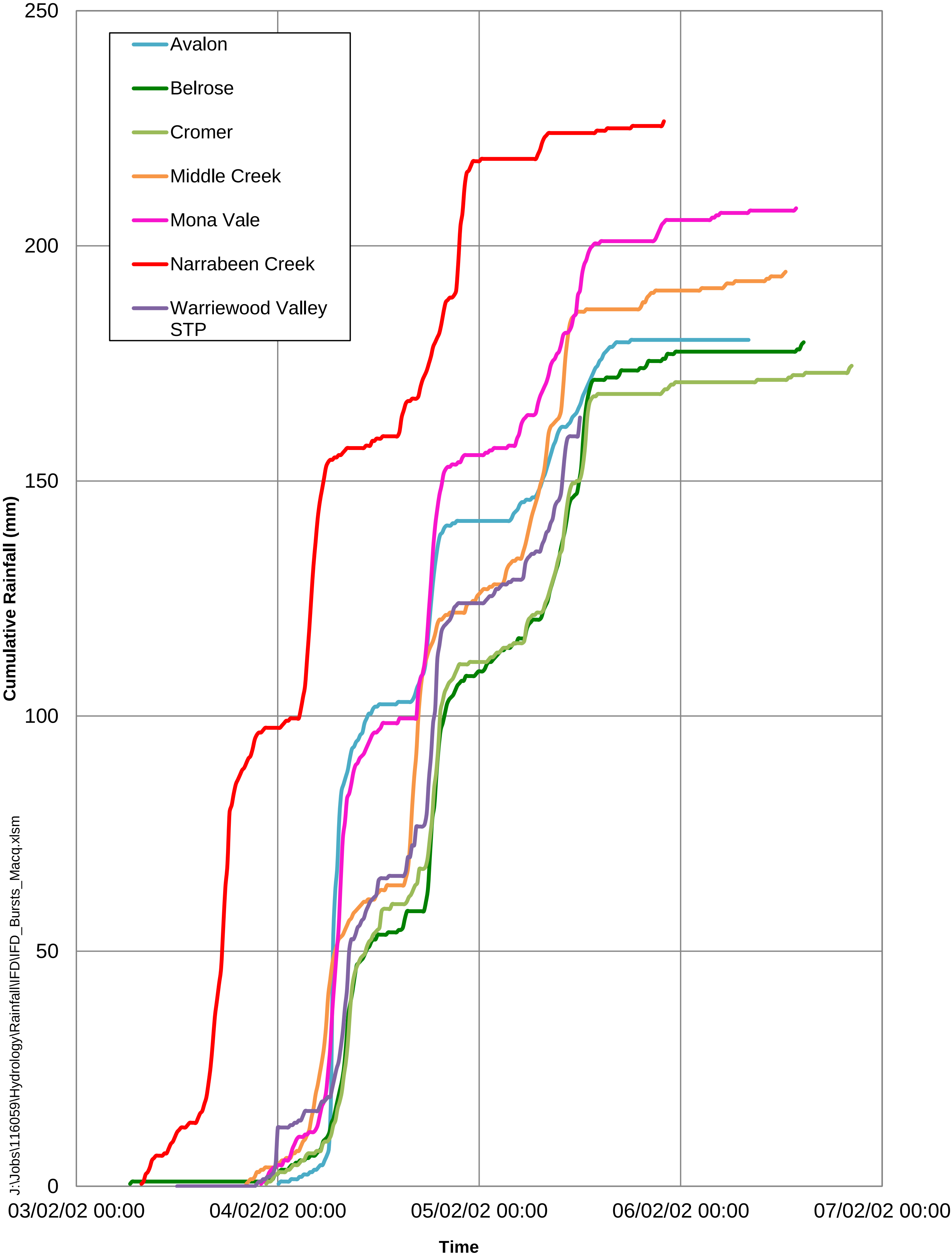


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FIGURE 8D

**RECORDED CUMULATIVE RAINFALL DEPTHS**
**MARCH 2011 RAINFALL EVENT**

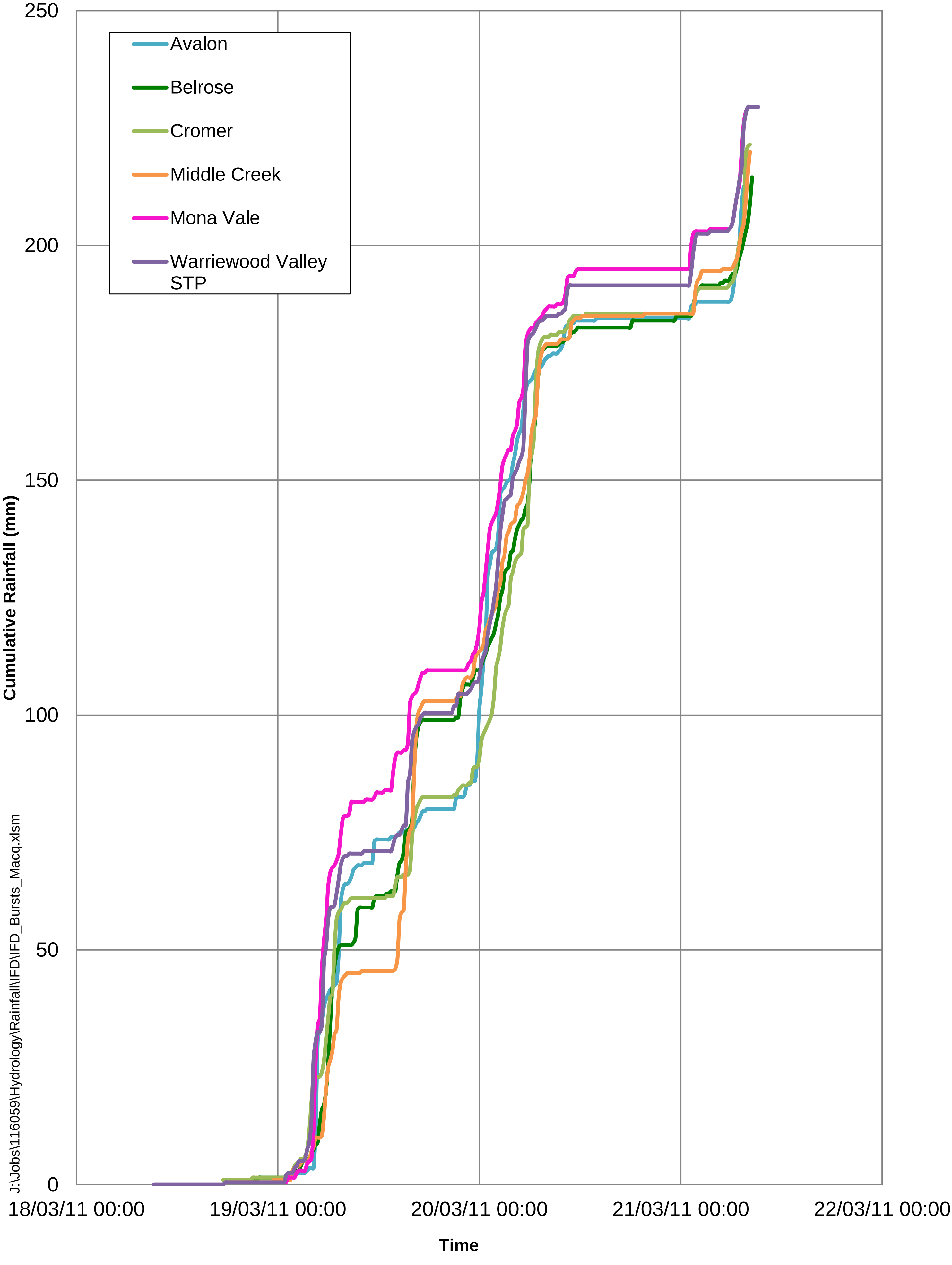

FIGURE 8E

**RECORDED CUMULATIVE RAINFALL DEPTHS**

**JUNE 2016 RAINFALL EVENT**

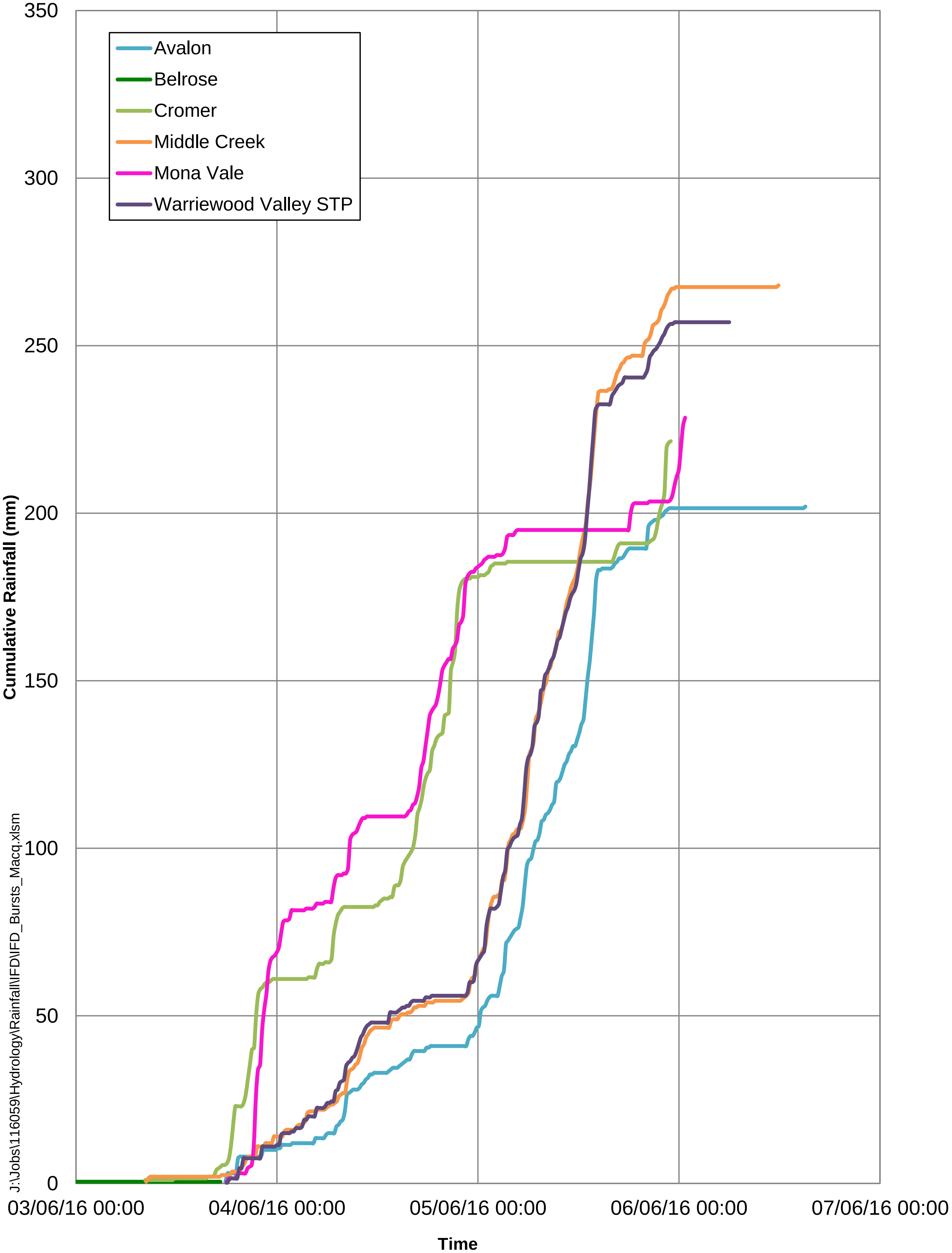


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FIGURE 9
**DRAINS SUBCATCHMENTS**

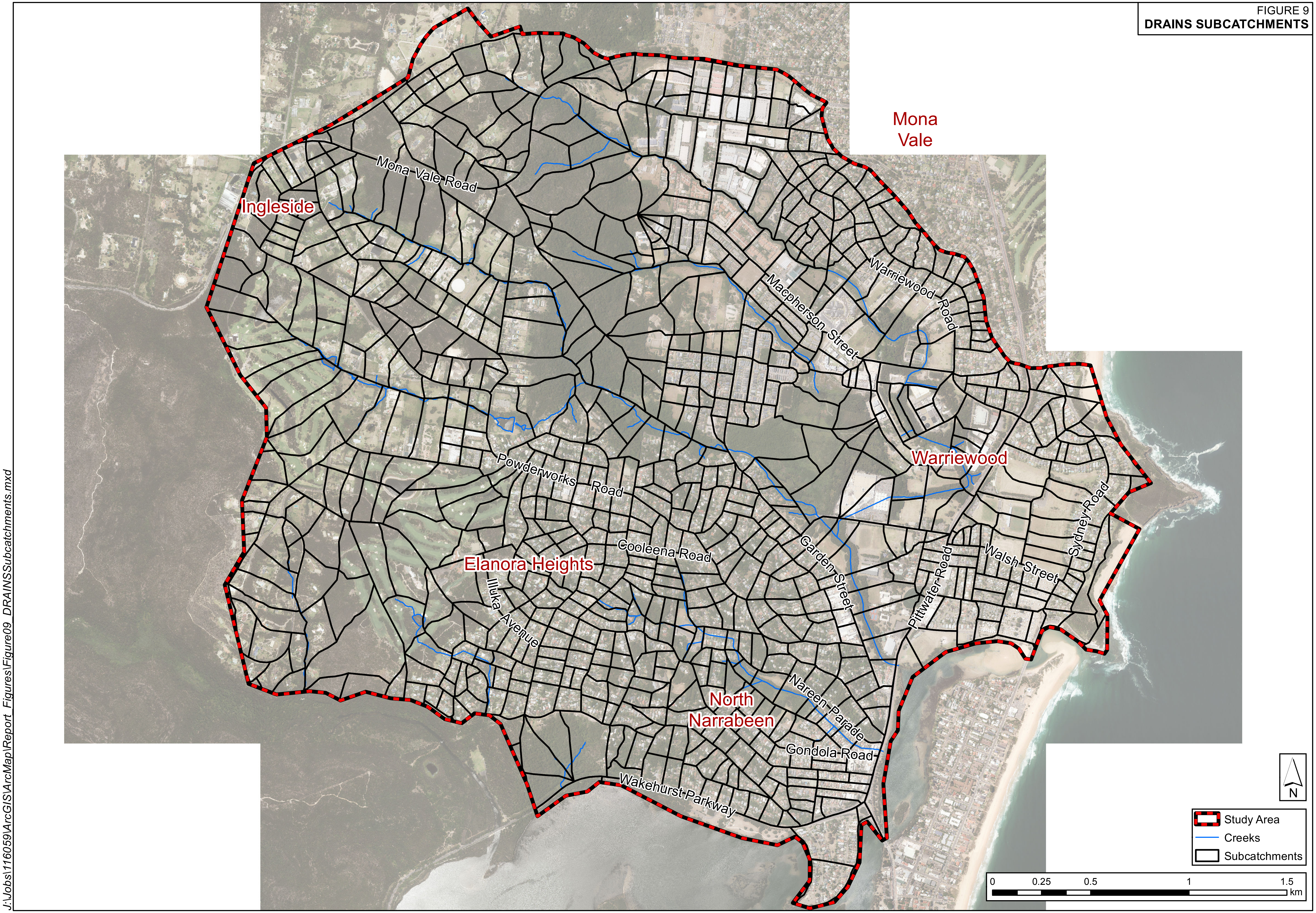


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FIGURE 10
**TUFLOW MODEL SCHEMATISATION**

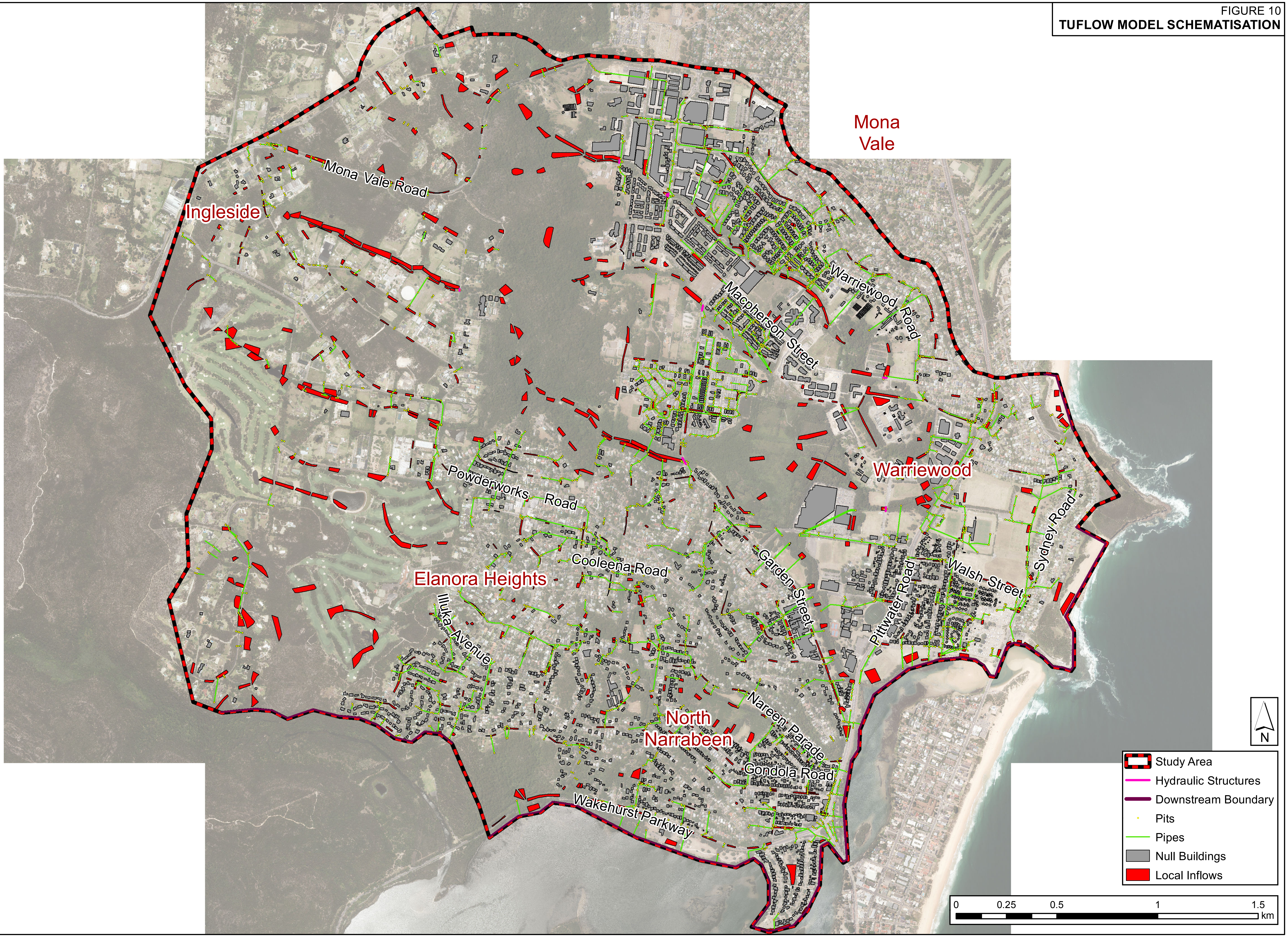


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FIGURE 11
**MANNINGS 'n' ROUGHNESS (2D)**

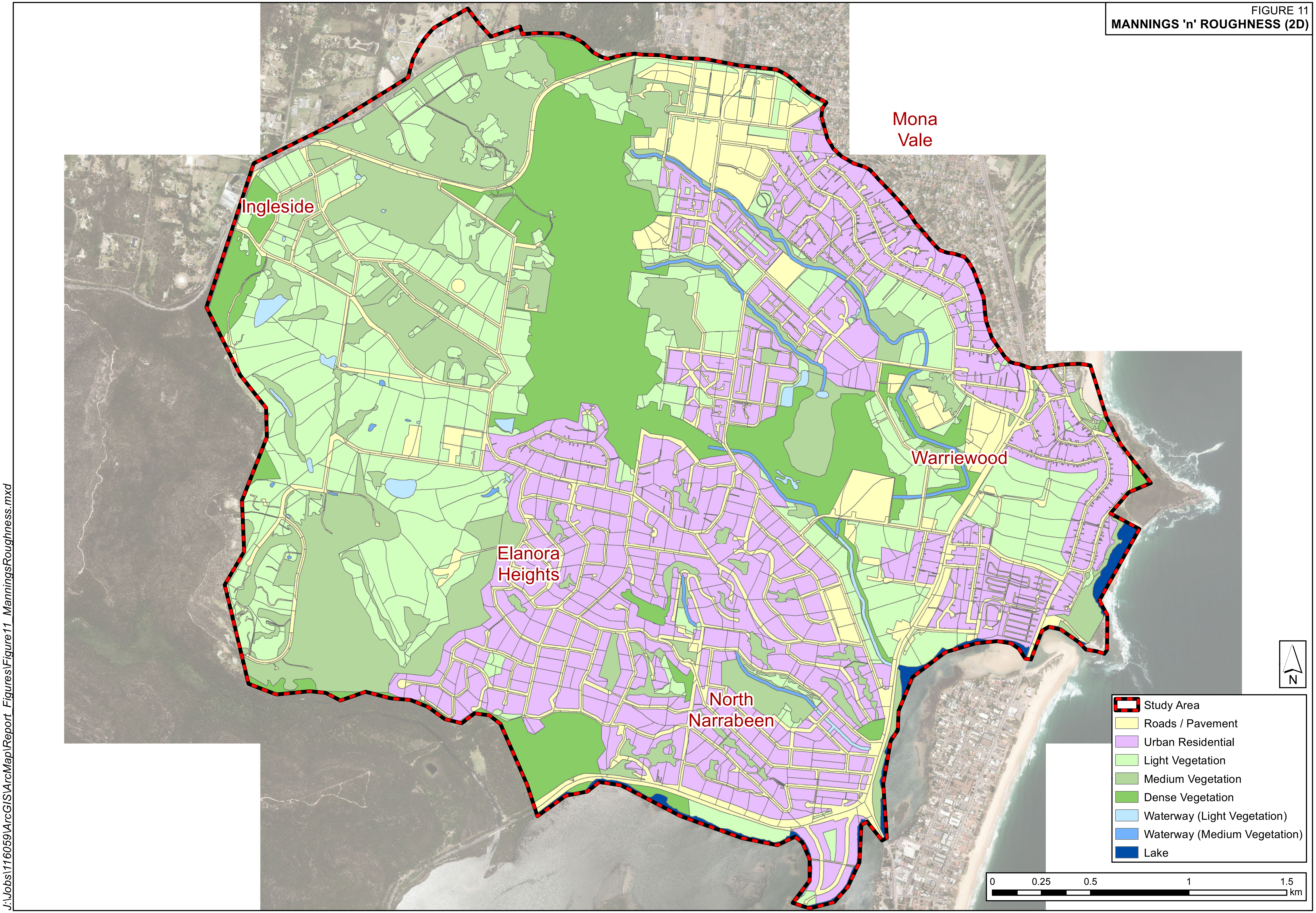


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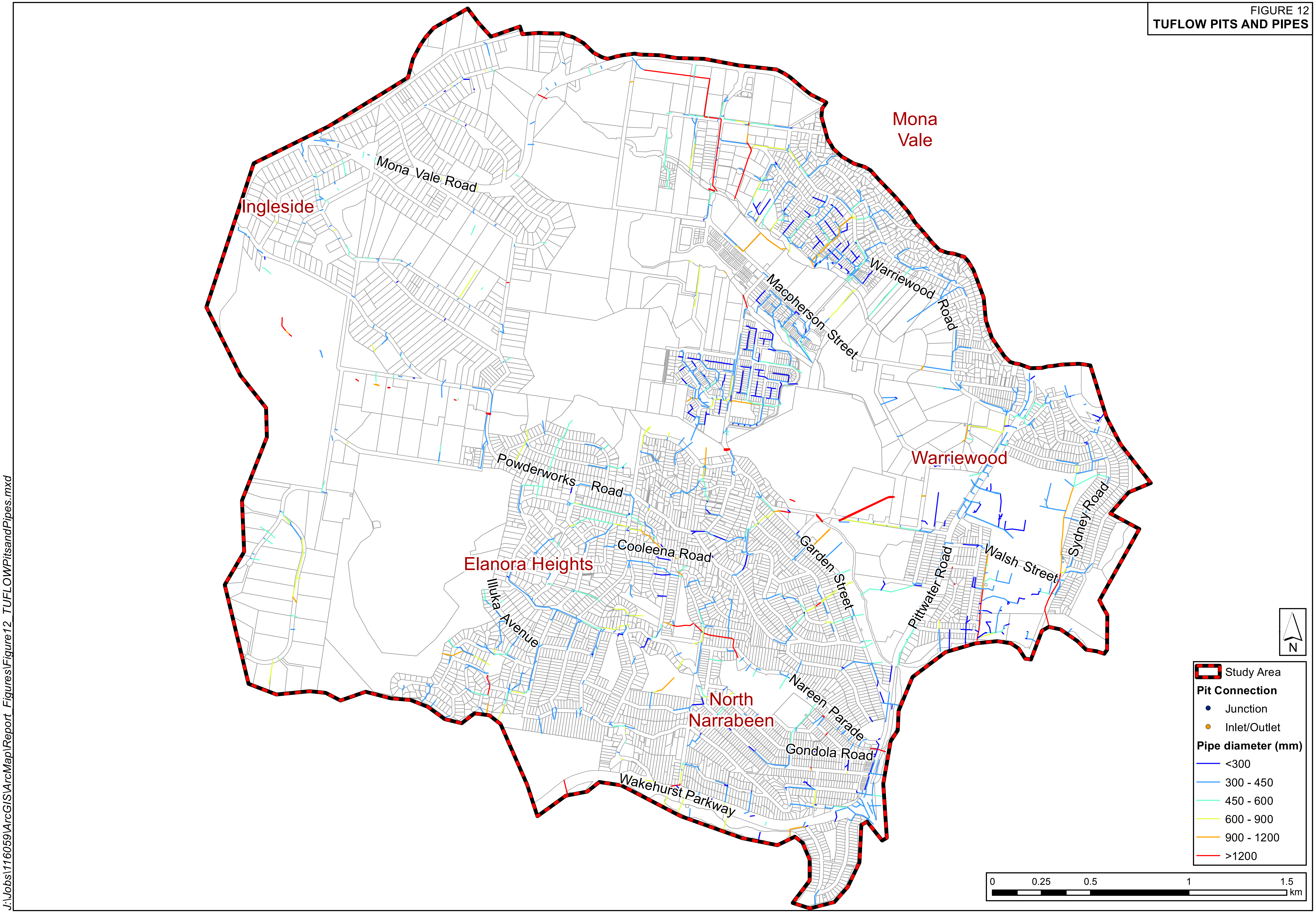
FIGURE 12
**TUFLOW PITS AND PIPES**

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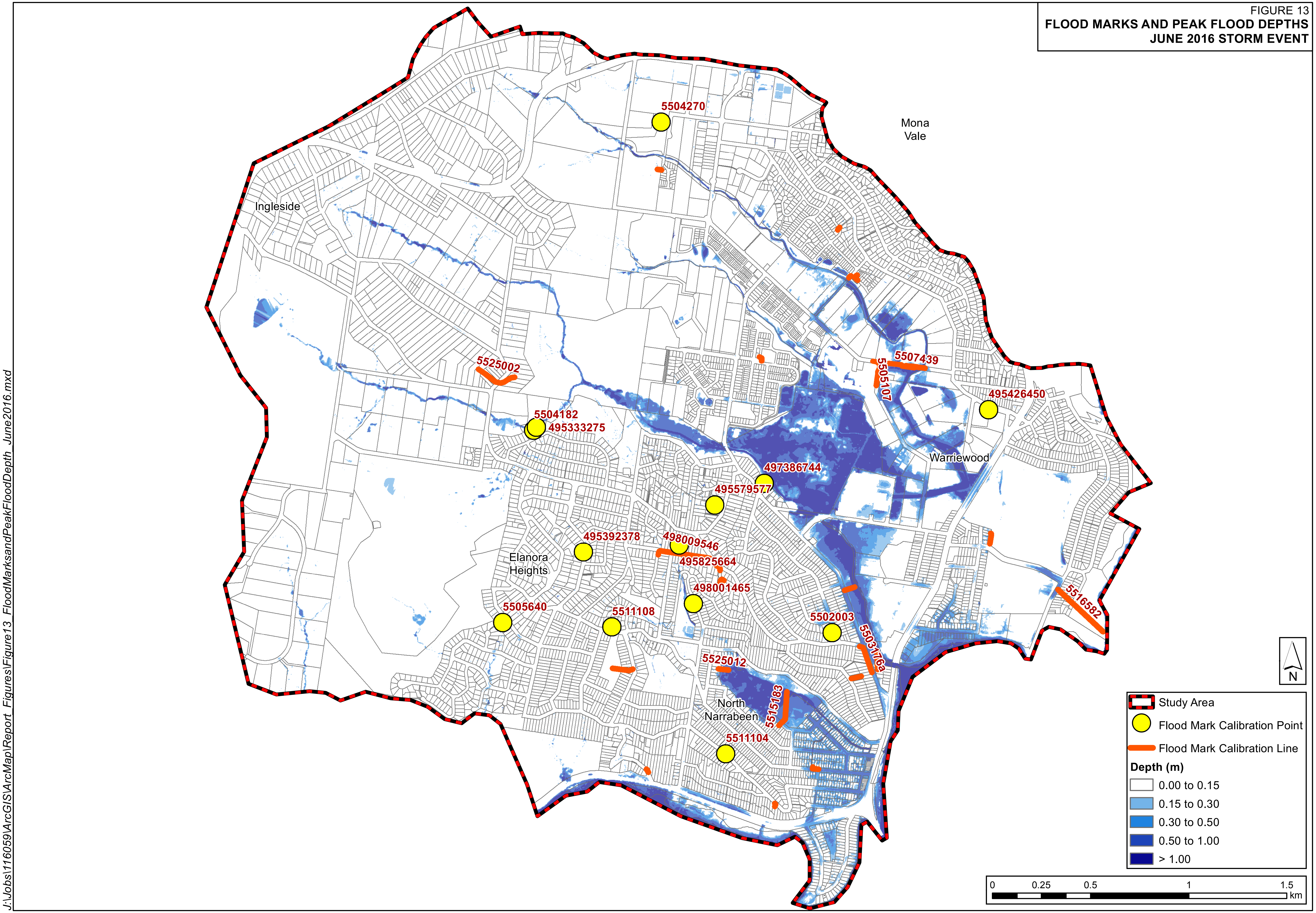



FIGURE 13
**FLOOD MARKS AND PEAK FLOOD DEPTHS JUNE 2016 STORM EVENT**

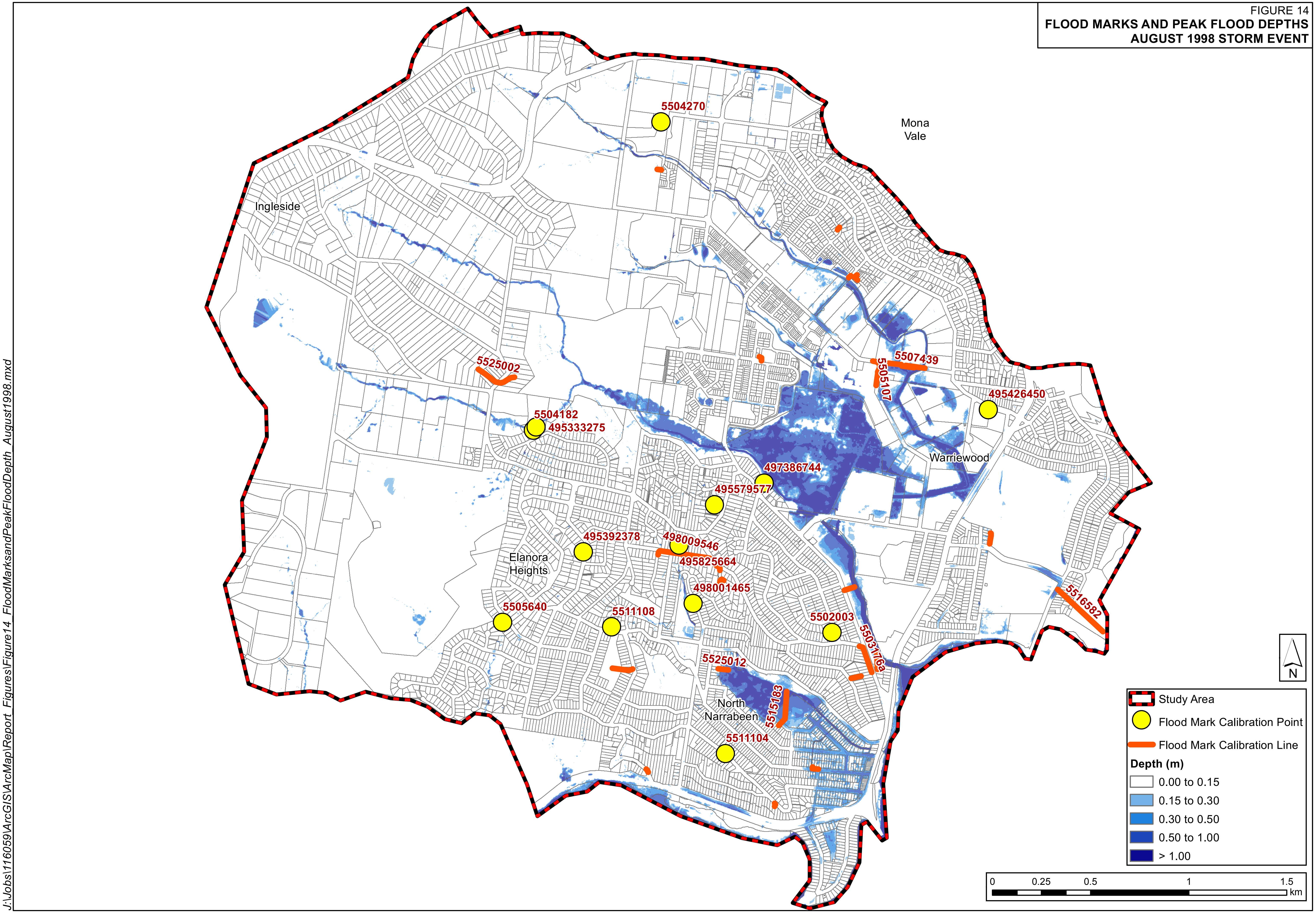
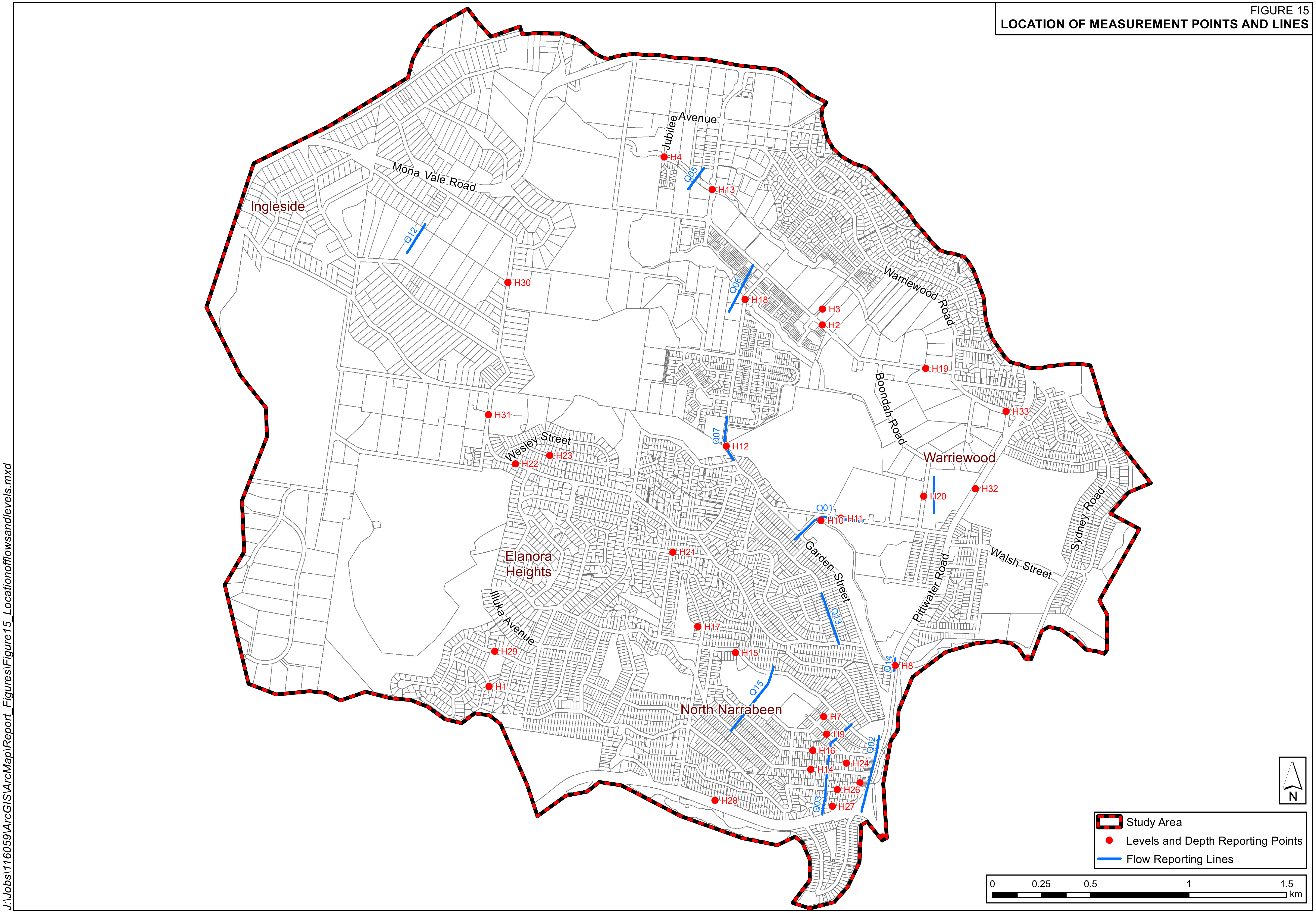



FIGURE 14
**FLOOD MARKS AND PEAK FLOOD DEPTHS**
**AUGUST 1998 STORM EVENT**

J:\Jobs\116059\ArcGIS\ArcMap\Report_Figures\Figure14_FloodMarksandPeakFloodDepth_August1998.mxd

FIGURE 15
## LOCATION OF MEASUREMENT POINTS AND LINES



NOTE: ALL PIPES BELOW 450mm REMOVED FROM MAPPING

FIGURE 16
**PIPE CAPACITY ASSESSMENT**

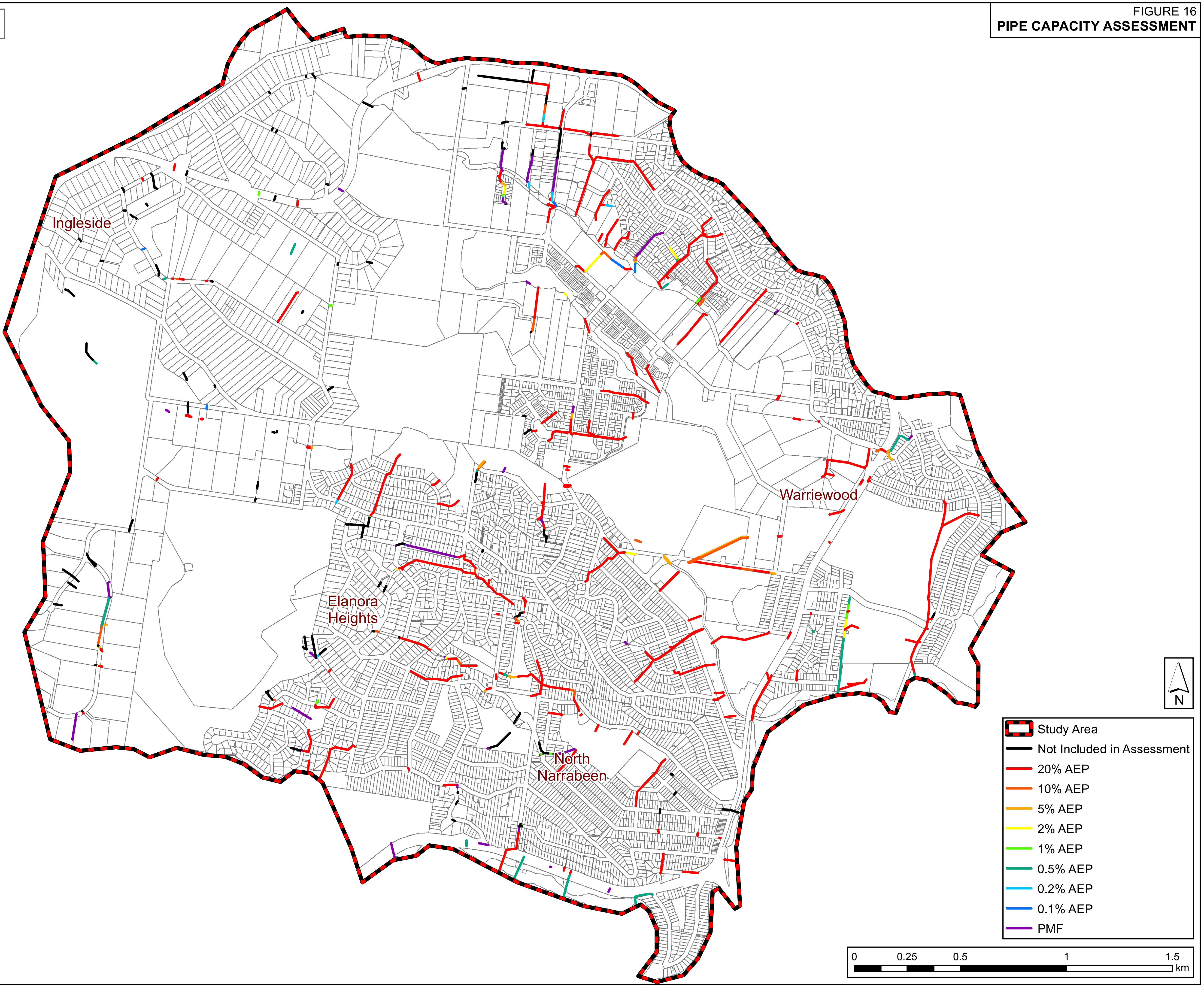



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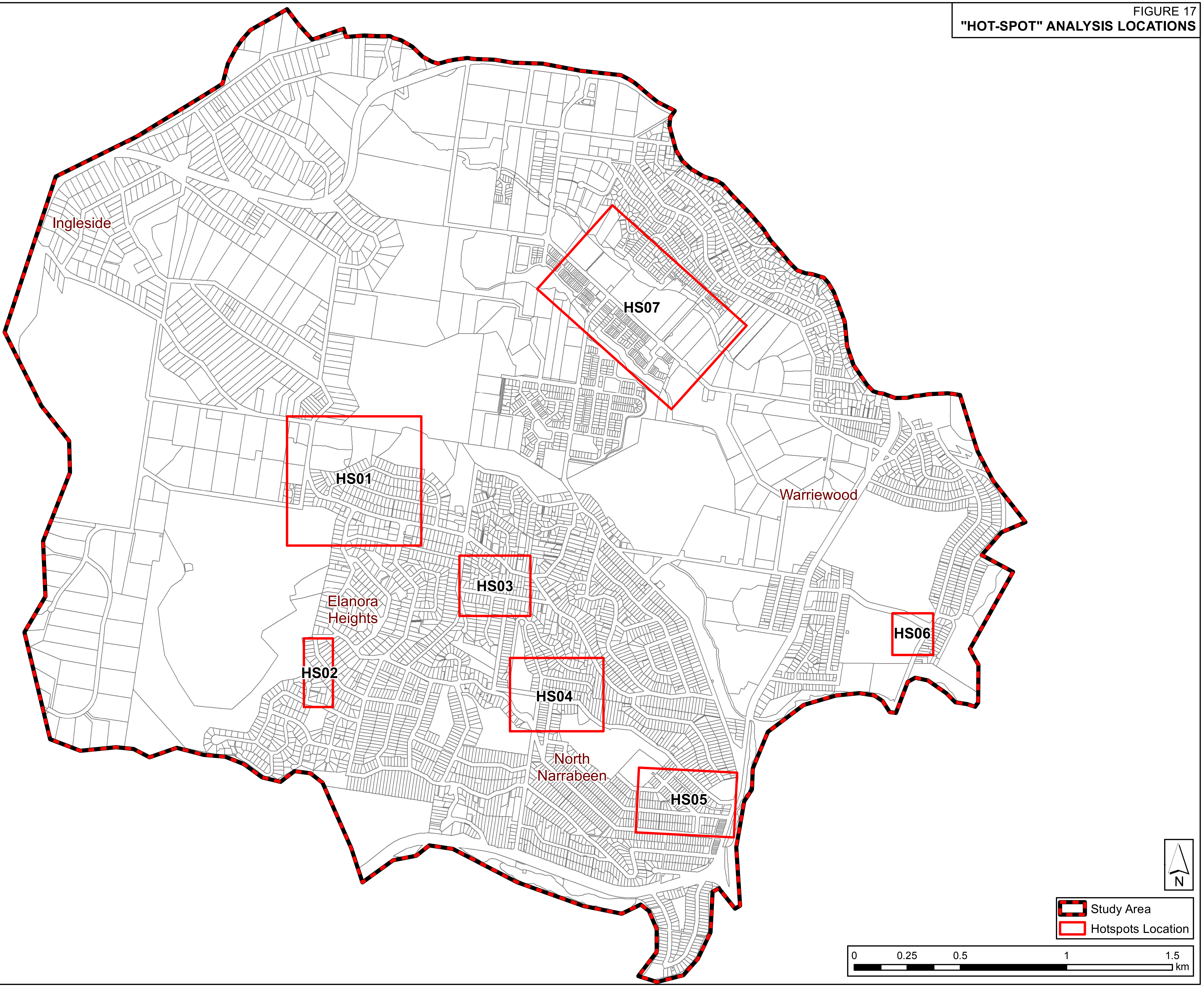
FIGURE 17
**"HOT-SPOT" ANALYSIS LOCATIONS**




J:\Jobs\116059\ArcGIS\ArcMap\Report_Figures\Figure17_LocationofFloodHotspots.mxd