WARRINGAH COUNCIL

ATTACHMENT BOOKLET 3

ORDINARY COUNCIL MEETING

TUESDAY 22 OCTOBER 2013

TABLE OF CONTENTS

Item No **Subject**

A part of BMT in Energy and Environment

Narrabeen Lagoon Flood Study

Final Report
R.N2070.005.04
September 2013

WARRINGAH COUNCIL

PITTWATER COUNCIL

Narrabeen Lagoon Flood Study

Final Report

Prepared For:	Warringah Council
Prepared By:	BMT WBM Pty Ltd (Member of the BMT group of companies)

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Title :	Narrabeen Lagoon Flood Study – Final Report
Author :	Darren Lyons and Joshua Eggleton
Synopsis :	Report for the Narrabeen Lagoon Flood Study covering the development and calibration of computer models, establishment of design flood behaviour and flood mapping.

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EXECUTIVE SUMMARY

Introduction

The Narrabeen Lagoon Flood Study has been prepared for Warringah and Pittwater Councils (The Councils) to define the existing flood behaviour in the Narrabeen Lagoon catchment and establish the basis for subsequent floodplain management activities.

This study updates previous studies on the Lagoon including the Narrabeen Lagoon Flood Study (PWD, 1990) and studies of the individual tributary streams, providing a holistic assessment of flooding within the catchment. The current Flood Study considers land use changes subsequent to previous modelling investigations, the influence of the Narrabeen Lagoon entrance on flood behaviour and the influence of potential climate change.

The primary objective of this Flood Study is to define the flood behaviour under historical, existing and future conditions (incorporating potential impacts of climate change) in the Narrabeen Lagoon catchment for a full range of design flood events. The study provides information on flood levels and depths, velocities, flows, hydraulic categories and provisional hazard categories. The Flood Study has also identified the impact on flood behaviour as a result of future climate change and potential changes in the catchment and lagoon entrance. Specifically, the study incorporates:

- Compilation and review of existing information pertinent to the study and acquisition of additional data including survey as required;
- Undertaking of a community consultation and participation program to identify local flooding concerns, collect information on historical flood behaviour and engage the community in the on-going floodplain management process;
- Development and calibration of appropriate hydrological and hydraulic models;
- Determination of design flood conditions for a range of design events including the Probable Maximum Flood (PMF), 0.1%, 0.2%, 0.5%, 1%, 2%, 5%, 10%, 20% and 50% AEP events for catchment derived flooding and the 0.5%, 1%, 2%, 5%, 10% and 20% AEP events for ocean derived flooding; and
- Assessment of potential impact of climate change using the latest guidelines.

Catchment Description

The Narrabeen Lagoon catchment is located on the northern edge of the Warringah LGA and the south eastern edge of Pittwater LGA on Sydney's northern beaches. The catchment occupies a total area of approximately 55km^2 and drains to the Tasman Sea through a narrow channel to the lagoon entrance at North Narrabeen Beach.

Narrabeen Lagoon (also known as Narrabeen Lakes) is the largest coastal lagoon located in the Sydney metropolitan region with waterway area of 2.2 km^2. The catchment can be separated into a number of major sub-catchments including Nareen Creek, Mullet Creek, Narrabeen Creek (incorporating Fern Creek), Deep Creek, Middle Creek (incorporating Snake Creek, Oxford Creek and Trefoil Creek) and South Creek (incorporating Wheeler Creek).

From an elevation of around 200m AHD in the north west of the catchment around Terrey Hills, and 150m in the south and south west of the catchment around Belrose and Frenchs Forest, the topography of the catchment is undulating and grades relatively steeply from the upper slopes to the floodplain areas around Narrabeen Lagoon and the Warriewood Valley. The areas of minor to moderate slopes are concentrated around the fringes of Narrabeen Lagoon, Warriewood Valley to the north and Oxford Falls in the central area of the catchment within the Middle Creek sub-catchment.

The catchment contains a mixture of land uses, including urban (residential, commercial and industrial), rural, recreational and bushland (including Garigal National Park). The urban suburbs of Elanora Heights, parts of North Narrabeen and Collaroy Plateau are located on the elevated land to the north and south of Narrabeen Lagoon. The suburbs of Narrabeen and parts of North Narrabeen have been developed along the lower floodplain and coastal strip separating the lagoon from the Tasman Sea. Warriewood Valley to the north of the lagoon is also significantly urbanised. The western and southern boundaries of the catchment are also urbanised including the suburbs of Terrey Hills, Frenchs Forest, Beacon Hill and Cromer.

The catchment area to the west of the lagoon is largely natural bushland (incorporating Garigal National Park) covering an area of approximately 20km^2. There are also several recreational reserves located around the lagoon and three major golf courses within the catchment (Mitchell McCotter, 1992).

Historical Flooding

The foreshore of Narrabeen Lagoon has been subjected to flooding numerous times over the last century, of particular note are the following years: 1911, 1931, 1942, 1956, 1958, 1961, 1974, 1975, 1977, 1978, 1986, 1987, 1998 and 2003 (CLT, 2010). The Narrabeen Lagoon Floodplain Risk Management Plan Review (SMEC, 2002b) identified that above floor flooding would occur for 208 residential and 113 commercial properties at the 1% AEP event. Flooding in Narrabeen Lagoon can occur after heavy rain in the catchment or from waves and king tides from the ocean during a severe ocean storm or a combination of both. Flood waters could rise quite quickly and there may be little opportunity for warning or assistance before or during a flood. Depending on entrance conditions and ocean levels, flood waters could remain elevated for many hours.

While previous Flood Studies and Floodplain Management Studies and Plans have been completed for parts of the catchment, this Flood Study update includes all catchments and important processes (such as entrance morphology) in a single state-of-the-art-model. The Flood Study provides an update to the 1990 Narrabeen Lagoon Flood Study and considers the potential impacts of climate change on flood risk within the catchment.

Community Consultation

Community consultation is an important component of the Flood Study. The consultation has aimed to inform the community about the development of the Flood Study and predicted flood behaviour as a precursor to subsequent floodplain management activities. It has provided an opportunity to collect information on their flood experience, their concerns on flooding issues and to collect feedback on the draft flood study.

Model Development

Computer models are the most accurate, cost-effective and efficient tools to assess a catchment's flood behaviour. For the purpose of the Flood Study, a hydrological model and a hydraulic model have been developed.

The **hydrological model** simulates the catchment rainfall-runoff processes, producing the stormwater flows which are used in the hydraulic model.

The **hydraulic model** simulates the flow behaviour of the overland flow paths, creeks and lagoon producing flood inundation extents, levels and velocities.

Information on the topography and characteristics of the catchments and floodplains are built into the hydraulic model. Recorded historical flood data, including rainfall and flood levels, are used to simulate and validate (calibrate and verify) the model. The model produces as outputs, the distribution of flood levels, flow rates (discharges) and flow velocities.

With consideration to the available survey information and local topographical and hydraulic controls, a linked 1D/2D model was developed extending from the Lagoon entrance in North Narrabeen at the downstream limit, to the head of the catchment. The floodplain area modelled within the 2D domain comprises a total area of approximately 55km^2 which includes the Narrabeen Lagoon catchment in its entirety.

Model Calibration and Validation

The selection of suitable historical events for calibration and validation of flood models is largely dependent on the availability of relevant historical flood information. Ideally the calibration and validation process should cover a range of flood magnitudes to demonstrate the suitability of a model for the range of design events to be considered.

Review of the available rainfall and water level data for the Narrabeen Lagoon catchment highlighted three flood events with sufficient data to support a calibration process – the April 1998, August 1998 and March 2011 event. The April 1998 event has been selected as the primary calibration event due to the fact that it resulted in the highest recorded Lagoon water levels since the installation of the water level gauges. Due to data availability, the March 2011 and August 1998 events have been used for model validation.

The models were found to provide a reasonable representation of the observed flood behaviour in the catchment.

Design Event Modelling and Output

The developed models have been applied to derive design flood conditions within the Narrabeen Lagoon catchment. Design rainfall depth is based on the generation of intensity-frequency-duration (IFD) design rainfall curves utilising the procedures outlined in Australian Rainfall and Runoff (2001).

A range of storm durations using standard AR&R (2001) temporal patterns, were modelled in order to identify the critical storm duration for design event flooding in the catchment.

A suite of design event scenarios was defined that is most suitable for future floodplain management planning in Narrabeen Lagoon. Consideration was given to flood events driven by both catchment and ocean processes. The catchment derived events were found to be the critical events in terms of determining maximum flood levels.

The design events simulated include the PMF event, 0.1%, 0.2%, 0.5%, 1%, 5%, 10%, 20% and 50% AEP events for catchment derived flooding and the 0.5%, 1%, 2%, 5%. 10% and 20% AEP events for ocean derived flooding. For the coincident catchment and ocean flooding scenarios, combinations of the 5% AEP and 1% AEP have been simulated.

The model results for the design events considered have been presented in a detailed flood mapping series for the catchment (see Appendix A). The flood data presented includes design flood inundation extents, peak flood water levels and depths and peak flood velocities.

Provisional flood hazard categorisation in accordance with Figure L2 of the NSW Floodplain Development Manual (2005) has been mapped in addition to the hydraulic categories (floodway, flood fringe and flood storage) for flood affected areas.

Sensitivity Testing

A number of sensitivity tests have been undertaken to identify the impacts on the design flood levels. Sensitivity tests included:

- The modelled lagoon entrance berm conditions;
- The coincident catchment and ocean flooding conditions;
- Structure blockages; and
- Changes in the adopted roughness parameters.

Climate Change

The impacts of future climate change are likely to lead to a wide range of environmental responses in coastal lagoons such as Narrabeen Lagoon. These are likely to manifest throughout the physical, chemical and ecological processes that drive local estuarine ecosystems.

Key elements of future climate change (sea level rise, rainfall intensity) have been incorporated into the assessment of future flooding conditions in the Narrabeen Lagoon catchment for consideration in the ongoing floodplain risk management. The key potential influences on flood behaviour incorporated in the assessment include:

- Increases in rainfall intensity for flood producing events;
- Higher ocean water levels (tide and storm surge) under sea level rise;
- Higher entrance berm heights under sea level rise; and
- Higher initial Lagoon water levels under sea level rise.

Conclusions

Provided below is a summary of the key findings of the Flood Study, in particular some of the important considerations for future floodplain risk management in the catchment:

- The design flood conditions documented in the report typically provide for a small increase in previously adopted design flood conditions for Narrabeen Lagoon. The main contributing factor to this change is the way the entrance condition has been modelled. In addition to advances in the software to simulate entrance breakout response, the initial conditions in respect to berm elevations and initial water levels in the Lagoon have been represented more conservatively in the current study.
- Longer duration events (9-36 hours) typically provide for the worst case flooding conditions in Narrabeen Lagoon. With the Lagoon waterbody being a significant flood storage, events of longer duration are required to generate sufficient flood runoff volumes from the catchment to elevate Lagoon water levels. In the lower reaches of all the tributary catchments, flood levels are dominated by the Lagoon flooding conditions. The peak flood water level in the Lagoon extends a significant distance up the tributary channels. In the upper reaches of the tributary catchments, shorter duration events of the order of 2-hours provide the critical flood condition in terms of peak flood water level.
- The rise in flood water levels can be relatively fast from the catchment's response to rainfall. Even for the longer duration events providing for the highest peak flood water levels in the Lagoon, the main period of rise in Lagoon water level can occur over a few hours. The April 1998 flood event (used for model calibration in the current study) is an example of such a response in the catchment. Flood levels in the tributary catchments may also rise significantly faster owing to the shorter critical durations in these catchments. This potentially rapid inundation has implications for flood warning and emergency response, particularly in flood situations where property and access roads may be quickly inundated.
- Catchment derived flooding events represent the dominant flooding mechanism in Narrabeen Lagoon. Whilst some ocean flooding scenarios will provide for inundation of some foreshore areas, the extent and severity of flooding is significantly less than the corresponding catchment derived event magnitude. The entrance condition has some influence on catchment flood behaviour with higher entrance berm levels providing for higher peak flood levels. The existing entrance management policy provides for manual breakout of the Lagoon entrance at defined trigger levels in preparation for imminent flooding. Irrespective of the successful implementation of a manual entrance breakout, significant flood inundation may be expected during major catchment flood events.
- There are a number of areas within the Narrabeen Lagoon catchment which represent the most significant flood risk exposure to existing property. The worst affected areas are typically in the lower parts of the catchment and most severely impacted on by major flooding in Narrabeen Lagoon. These areas include the foreshore areas of the Lagoon (e.g. Lakeside Park, Wimbledon Avenue, west of Lagoon Street) and the low-lying floodplain areas adjacent to Nareen Creek (e.g. Gondola Road, Nareen Parade) and Mullet Creek (e.g. Garden Street, Warraba Road).
- Peak design flood water levels are expected to progressively increase as the impacts of climate change manifest. For the Narrabeen Lagoon catchment, potential sea level rise will provide for a worsening of existing flood conditions through higher ocean water levels (tide and storm surge),

higher entrance berm and higher initial water levels in the Lagoon. Robust land use planning and development policies will be required to ensure future flood risks are not unduly exacerbated in light of predicted flood behaviour under potential climate change scenarios.

- Warringah Council's existing Entrance Management OMS is to open the entrance at a defined trigger water level (currently 1.3m AHD). With potential sea level rise, normal tide levels in the Lagoon will approach and eventually exceed the current trigger levels. Future openings would need to be at significantly higher trigger levels to be effective. Low-lying land currently impacted by flooding may also be subject to regular (or permanent) tidal inundation at some time in the future.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

afflux	The change in water level from existing conditions resulting from a change in the watercourse or floodplain – e.g. construction of a new bridge.
annual exceedance probability (AEP)	The chance of a flood of a given size (or larger) 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 (i.e. a 1 in 20 chance) of a peak discharge of 500 m^3/s (or larger) occurring in any one year. (see also average recurrence interval)
Australian Height Datum (AHD)	National survey datum corresponding approximately to mean sea level.
astronomical tide	Astronomical tide is the cyclic rising and falling of the Earth's oceans water levels resulting from gravitational forces of the Moon and the Sun acting on the Earth.
attenuation	Weakening in force or intensity
average recurrence interval (ARI)	The long-term average number of years between the occurrence of a flood as big as (or larger than) the selected event. For example, floods with a discharge as great as (or greater than) the 20yr ARI design flood will occur on average once every 20 years. ARI is another way of expressing the likelihood of occurrence of a flood event. (see also annual exceedance probability)
Australian Rainfall and Runoff (AR&R)	Engineers Australia publication pertaining to rainfall and flooding investigations in Australia
calibration	The adjustment of model confuguration and key parameters to best fit an observed data set
catchment	The catchment at a particular point is the area of land that drains to that point.
critical duration	The critical duration is the design storm duration which provides the highest peak water levels for a given design flood (e.g. 1% AEP) at a given location. For example, if the following design durations were modelled - 2-hour, 6-hour, 9-hour and 12-hour – and the 9-hour duration resulted in the highest peak water level at a given location then the critical duration for that location would be 9-hours.
design flood event	A hypothetical flood representing a specific likelihood of occurrence (for example the 100yr ARI or 1% AEP flood).
development	Existing or proposed works that may or may not impact upon flooding. Typical works are filling of land, and the construction of roads, floodways and buildings.
discharge	The rate of flow of water measured in tems 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).

flood	Relatively high river or creek flows, which overtop the natural or artificial banks in any part of a stream, river, estuary, lake or dam, and inundate floodplains and/or local overland flooding associated with major drainge before entering a watercourse and/or coastal inundation resulting from super elevated sea levels and/or waves overtopping coastline defences.
flood behaviour	The pattern / characteristics / nature of a flood.
flood fringe	Land that may be affected by flooding but is not designated as floodway or flood storage. These areas are low-velocity backwaters within the floodplain. Filling of these areas generally has little consequence to overall flood behaviour.
flood hazard	The potential risk to life and limb and potential damage to property resulting from flooding. The degree of flood hazard varies with circumstances across the full range of floods.
flood level	The height or elevation of floodwaters relative to a datum (typically the Australian Height Datum). Also referred to as "stage".
flood liable land	see flood prone land
floodplain	Land adjacent to a river or creek that is periodically inundated due to floods. The floodplain includes all land that is susceptible to inundation by the probable maximum flood (PMF) event.
floodplain management	The co-ordinated management of activities that occur on the floodplain.
floodplain risk management plan	A document outlining a range of actions aimed at improving floodplain management. The plan is the principal means of managing the risks associated with the use of the floodplain. A floodplain risk management plan needs to be developed in accordance with the principles and guidelines contained in the NSW Floodplain Management Manual. The plan usually contains both written and diagrammatic information describing how particular areas of the floodplain are to be used and managed to achieve defined objectives.
flood planning levels (FPLs)	Flood Planning Levels selected for planning purposes are derived from a combination of the adopted flood level plus freeboard, as determined in floodplain management studies and incorporated in floodplain risk management plans. Selection should be based on an understanding of the full range of flood behaviour and the associated flood risk. It should also take into account the social, economic and ecological consequences associated with floods of different severities. Different FPLs may be appropriate for different categories of landuse and for different flood plans. The concept of FPLs supersedes the "standard flood event". As FPLs do not necessarily extend to the limits of flood prone land, floodplain risk management plans may apply to flood prone land beyond that defined by the FPLs.
flood prone land	Land susceptible to inundation by the probable maximum flood (PMF) event. Under the merit policy, the flood prone definition should not be seen as necessarily precluding development. Floodplain Risk Management Plans should encompass all flood prone land (i.e. the entire floodplain).

flood storage	Floodplain areas where floodwaters accumulate before being conveyed downstream. These areas are important for detention and attenuation of flood peaks.
floodway	Areas and flowpaths where a significant proportion of floodwaters are conveyed during a flood (including all bank-to-bank creek sections).
freeboard	A factor of safety usually expressed as a height above the adopted flood level thus determing the flood planning level. Freeboard tends to compensate for factors such as wave action, localised hydraulic effects and uncertainties in the design flood levels.
geomorphology	The study of the origin, characteristics and development of land forms.
gauging (tidal and flood)	Measurement of flows and water levels during tides or flood events.
historical flood	A flood that has actually occurred.
hydraulic	The term given to the study of water flow in rivers, estuaries and coastal systems.
hydrodynamic	Pertaining to the movement of water
hydrograph	A graph showing how a river or creek's discharge changes with time.
hydrographic survey	Survey of the bed levels of a waterway.
hydrologic	Pertaining to rainfall-runoff processes in catchments
hydrology	The term given to the study of the rainfall-runoff process in catchments.
hyetograph	A graph showing the depth of rainfall over time.
intensity frequency duration (IFD) curve	A statistical representation of rainfall showing the relationship between rainfall intensity, storm duration and frequency (probability) of occurrence.
intermittently closed and open lake/lagoon (ICOLL)	A Lake/Lagoon that is separated from the ocean by a sand beach barrier or berm and is subject to forces that act to close the entrance (waves, tides and wind) and those that act to maintain an open entrance (flood flows and dredging), which results in the Lake/Lagoon being intermittently closed and open to the ocean.
isohyet	Equal rainfall contour
LiDAR	Light Detection and Ranging –a remote sensing method used to generate ground surface elevation. Typically acquired through airborne surveys from which an aeroplane can cover large areas.
morphological	Pertaining to geomorphology

overland flow	Overland flow is surface run off before it enters a waterway. It is caused by rainfall which flows downhill along low points concentrating in gullies, channels, surface depressions and stormwater systems.
peak flood level, flow or velocity	The maximum flood level, flow or velocity that occurs during a flood event.
pluviometer	A rainfall gauge capable of continously measuring rainfall intensity
probable maximum flood (PMF)	An extreme flood deemed to be the maximum flood likely to occur.
probability	A statistical measure of the likely frequency or occurrence of flooding.
riparian	The interface between land and waterway. Literally means "along the river margins"
runoff	The amount of rainfall from a catchment that actually ends up as flowing water in the river or creek.
shoaled entrance	Closed or partially closed entrance condition due to the build up sand which restricts the waterway opening.
stage	See flood level.
stage hydrograph	A graph of water level over time.
sub-critical	Refers to flow in a channel that is relatively slow and deep
topography	The shape of the surface features of land
velocity	The speed at which the floodwaters are moving. A flood velocity predicted by a 2D computer flood model is quoted as the depth averaged velocity, i.e. the average velocity throughout the depth of the water column. A flood velocity predicted by a 1D or quasi-2D computer flood model is quoted as the depth and width averaged velocity, i.e. the average velocity across the whole river or creek section.
validation	A test of the appropriateness of the adopted model configuration and parameters (through the calibration process) for other observed events.
water level	See flood level.

1 INTRODUCTION

The Narrabeen Lagoon Flood Study is being prepared for Warringah and Pittwater Councils (The Councils) to define the existing flood behaviour in the Narrabeen Lagoon catchment and establish the basis for subsequent floodplain management activities.

This study will update previous studies on the Lagoon including the Narrabeen Lagoon Flood Study (PWD, 1990) and studies of the individual tributary streams, providing a holistic assessment of flooding within the catchment. The current Flood Study considers land use changes subsequent to previous modelling investigations, the influence of the Narrabeen Lagoon entrance on flood behaviour and the influence of potential climate change.

This document has been prepared for Warringah and Pittwater Councils to meet the objectives of the NSW State Government's Flood Prone Land Policy, with financial assistance from the NSW and Commonwealth Governments through the Natural Disaster Resilience Program. This document does not necessarily represent the opinions of the NSW or Commonwealth Governments.

The study was undertaken in a staged approach as outlined below:

- Stage 1 - Collection, Compilation and Review of Available Information;
- Stage 2 - Hydrological Analysis;
- Stage 3 - Hydraulic Modelling;
- Stage 4 - Climate Change Analysis; and
- Stage 5 - Final Reporting.

An interim report outlining the methodologies, analysis and key outcomes has been provided at the completion of each stage. This report is the Stage 5 Final Report documenting the Study's overall objectives, results and recommendations.

1.1 Study Location

The Narrabeen Lagoon catchment encompasses an area of approximately 55km^2 and is located on the northern edge of the Warringah Council Local Government Area (LGA) and the south eastern edge of Pittwater Council LGA on Sydney's northern beaches as shown in Figure 1-1. Narrabeen Lagoon (also known as Narrabeen Lakes) is the largest coastal lagoon located in the Sydney metropolitan region with waterway area of 2.2 km^2. The catchment includes a number of major sub-catchments including Nareen Creek, Mullet Creek, Narrabeen Creek (incorporating Fern Creek), Deep Creek, Middle Creek (incorporating Snake Creek, Oxford Creek and TreFoil Creek) and South Creek (incorporating Wheeler Creek).

The LGA boundary lies on the northern bank of the Narrabeen Lagoon waterbody and as such Warringah Council manages the waterbody itself, while Pittwater Council is responsible for the management of foreshores that lie within the Pittwater LGA.

Title: **Study Locality**

Figure: 1-1 Rev: A

BMT WBM endeavours to ensure that the information provided in this map is correct at the time of publication. BMT WBM does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.

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Approx. Scale

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The lagoon drains to the Tasman Sea through a narrow channel to the lagoon entrance at North Narrabeen beach. The entrance opening is subject to forces that act to close the entrance (waves, tides and wind) and those that act to maintain an open entrance (flood flows and dredging), which results in the Lagoon being defined as an intermittently closed and open Lake/Lagoon (ICOLL).

The catchment contains a mixture of land uses, including urban (residential, commercial and industrial), rural, recreational and bushland.

A more detailed description of the Study Area is presented in Section 2.1.

1.2 Study Background

A Flood Study (PWD, 1990), a Floodplain Management Study (Mitchell McCotter, 1992) and a Floodplain Management Plan (SMEC, 2002), have previously been completed to define and manage the flood behaviour in Narrabeen Lagoon. These previous studies focussed on the lagoon and its surrounding foreshore with no consideration given to catchment wide flood behaviour.

Due to changes within the catchment over the past 20 years, as well as the need to take into consideration the impacts of climate change on the flooding of coastal environments, up-to date information is required to accurately predict the flood behaviour and impacts of climate change and sea level rise on the catchment. This current Flood Study aims to use this information to update flood modelling to provide details on existing and future flood risk including the potential impacts of climate change in the Narrabeen Lagoon catchment.

The Flood Study update will also utilise significant advances in the methodologies used to predict flood behaviour, including updates in modelling techniques and the capture of high quality ground level data (LiDAR).

In addition to the previously mentioned studies, more recent flood studies and flood modelling has been undertaken for some of the main tributary catchments of Narrabeen Lagoon, including:

- South Creek Flood Study (WMA, 2006);
- South Creek Floodplain Risk Management Study and Plan (Cardno Lawson Treloar, 2008)
- Middle Creek Flood Modelling (DHI, 2009)
- Nareen Creek Flood Study (Cardno Lawson Treloar, 2005)
- Nareen Creek Floodplain Risk Management Study and Plan DRAFT (Cardno Lawson Treloar, 2009)
- Warriewood Valley Flood Study (Cardno Lawson Treloar, 2005)
- Warriewood Valley Flood Study Addendum 1 (Cardno Lawson Treloar, 2005).

This Flood Study will aim to incorporate and enhance the outputs from these previous studies where possible.

1.3 The Need for Floodplain Management at Narrabeen Lagoon

The foreshore of Narrabeen Lagoon has been subjected to flooding numerous times over the last century, of particular note are the following years: 1911, 1931, 1942, 1956, 1958, 1961, 1974, 1975, 1977, 1978, 1986, 1987, 1998 and 2003 (CLT, 2010). The Narrabeen Lagoon FRMP Review (SMEC, 2002b) identified that above floor flooding would occur for 208 residential and 113 commercial properties at the 1% AEP event. Flooding in Narrabeen Lagoon can occur after heavy rain in the catchment or from waves and king tides from the ocean during a severe ocean storm or a combination of both. Flood waters could rise quite quickly and there may be little opportunity for warning or assistance before or during a flood. Depending on entrance conditions and ocean levels, flood waters could remain elevated for many hours.

SMEC (2002a and 2002b) states that the primary flood affected areas in Narrabeen Lagoon catchment are:

- Lakeside Caravan Park and the surrounding residential area north of the lagoon entrance;
- The Mullet Creek area, from Pittwater Road to Jacksons Road;
- Narrabeen Creek floodplain including Centro Warriewood Square Shopping Centre;
- The Wimbledon Avenue peninsula;
- The eastern side of the entrance channel;
- Sydney Academy of Sport and Recreation (formerly NSW Academy of Sport); and
- The southern foreshore of the Central Basin including The Esplanade and Jamieson Park.

In order to reduce the risk to existing flood prone properties and manage the future land use of flood prone land, effective floodplain management strategies are required.

While previous Flood Studies and Floodplain Management Studies and Plans have occurred in the catchment, this Flood Study update includes all catchments and important processes (such as entrance morphology) in a single state-of-the-art-model. The Flood Study provides an update to the 1990 Narrabeen Lagoon Flood Study and also considers the potential impacts of climate change on flood risk within the catchment.

1.4 The Floodplain Management Process

The NSW Government's Flood Prone Land Policy is directed towards providing solutions to existing flooding problems in developed areas and potential future increases in flood risk and ensuring that new development is compatible with the flood hazard and does not create additional flooding problems in other areas. Consideration is also given to the change in flood risk to existing and future development through potential climate change. Policy and practice are defined in the NSW Government's Floodplain Development Manual (2005).

Under the Policy the management of flood liable land remains the responsibility of Local Government. The NSW Government subsidises floodplain management studies and flood mitigation works to manage existing problems and provides specialist technical advice to assist The Councils in the discharge of their floodplain management responsibilities.

The Policy provides for technical and financial support by the NSW Government through the four sequential stages shown in Table 1-1.

Table 1-1 Stages of Floodplain Management

	Stage	Description
1	Formation of a Committee	Established by Council and includes community group representatives and State agency specialists.
2	Data Collection	Past data such as flood levels, rainfall records, land use, soil types etc.
3	**Flood Study**	**Determines the nature and extent of the flood problem.**
4	Floodplain Risk Management Study	Evaluates management options for the floodplain in respect of both existing and proposed developments.
5	Floodplain Risk Management Plan	Involves formal adoption by Council of a plan of management for the floodplain.
6	Implementation of the Floodplain Risk Management 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.

This study represents Stage 3 of the above process and aims to provide an understanding of existing and future flood behaviour within the Narrabeen Lagoon catchment.

1.4.1 Climate Change Policy

Climate change is expected to have adverse impacts upon sea levels and rainfall intensities, both of which may have significant influence on flood behaviour at specific locations. The primary impacts of climate change in coastal areas are likely to result from sea level rise, which, coupled with a potential increase in the frequency and severity of storm events, may lead to increased coastal erosion, tidal inundation and flooding.

In 2009 the NSW State Government announced the NSW Sea Level Rise Policy Statement (DECCW, 2009) that adopted sea level rise planning benchmarks to ensure consistent consideration of sea level rise in coastal areas of NSW. These planning benchmarks adopted increases (above 1990 mean sea level) of 40 cm by 2050 and 90 cm by 2100. However, on 8 September 2012 the NSW Government announced its Stage One Coastal Management Reforms which no longer recommend state-wide sea level rise benchmarks for use by local councils. Instead councils have the flexibility to consider local conditions when determining future hazards of potential sea level rise.

Accordingly, it is recommended by the NSW Government that councils should consider information on historical and projected future sea level rise that is widely accepted by scientific opinion. This may include information in the NSW Chief Scientist and Engineer's Report entitled 'Assessment of the Science behind the NSW Government's Sea Level Rise Planning Benchmarks' (2012).

The NSW Chief Scientist and Engineer's Report (2012) acknowledges the evolving nature of climate science, which is expected to provide a clearer picture of the changing sea levels into the future. The report identified that:

- The science behind sea level rise benchmarks from the 2009 NSW Sea level Rise Policy Statement was adequate;
- Historically, sea levels have been rising since the early 1880's;
- There is considerable variability in the projections for future sea level rise; and
- The science behind the future sea level rise projections is continually evolving and improving.

As the majority of analysis and modelling tasks associated with this current Flood Study were completed prior to the announcement of the NSW Government's Coastal Management Reforms in September 2012, the potential impacts of sea level rise have been based on sea level rise projections from the 2009 NSW Sea Level Rise Policy Statement. Given that the Chief Scientist and Engineer's Report identifies the science behind these sea level rise projections as adequate, it was agreed between The Councils and BMT WBM that the potential impacts of sea level rise for the Narrabeen Lagoon catchment were based on the best available information during preparation of this report.

For Narrabeen Lagoon, rising sea level is expected to increase the frequency, severity and duration of flooding. This is particularly the case when the entrance is open, with potentially more ocean water flowing through the entrance and into the main body of the Lagoon.

Projected sea level rise will also result in higher sand levels at the Lagoon entrance when it is closed. This means that the lagoon water levels will need to be even higher in the future in order to initiate effective break-out channels, resulting in increased flood risk to foreshore properties.

In 2007 the NSW Government released a guideline for practical consideration of climate change in the floodplain management process that advocates consideration of increased design rainfall intensities of up to 30%. Accordingly, this increase in design rainfall intensity will translate into increased flood inundation in the Narrabeen Lagoon catchment. Future planning and floodplain management in the catchment will need to take due consideration of this increased flood risk.

In consultation with The Councils and the Office of Environment and Heritage (OEH), a range of climate change sensitivity tests incorporating combinations of sea level rise and increased design rainfall intensity were formulated. The results of these sensitivity tests (refer Section 8) were then compared to the base case (i.e. models with existing sea level and climate) model results in order to assess the potential increase in flood risk due to climate change.

1.5 Study Objectives

The primary objective of this Flood Study is to define the flood behaviour under historical, existing and future conditions (incorporating potential impacts of climate change) in the Narrabeen Lagoon catchment for a full range of design flood events. The study will provide information on flood levels and depths, velocities, flows, hydraulic categories and provisional hazard categories. The Flood Study is to be used to identify the impact on flood behaviour as a result of future climate change and potential changes in the catchment and lagoon entrance. Specifically, the study incorporates:

- Compilation and review of existing information pertinent to the study and acquisition of additional data including survey as required;

- Community consultation and participation program to identify local flooding concerns, collect information on historical flood behaviour, advise on the outcomes of the flood study and flood behaviour predictions, and engage the community in the on-going floodplain management process;
- Development and calibration of appropriate hydrological and hydraulic models;
- Determination of design flood conditions for a range of design events including the Probable Maximum Flood (PMF), 0.1%, 0.2%, 0.5%, 1%, 2%, 5%, 10%, 20% and 50% AEP events for catchment derived flooding and the 0.5%, 1%, 2%, 5%, 10% and 20% AEP events for ocean derived flooding, and coincident catchment and ocean flooding scenarios combining the 5% AEP and 1% AEP events; and
- Examination of potential impact of climate change using the latest guidelines.

The models and results produced in this study are intended to:

- Outline the flood behaviour within the catchment to aid in Council's management of flood risk; and
- 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.

1.6 About This Report

This report documents the Study's objectives, results and recommendations.

Section 1 introduces the study.

Section 2 provides an overview of the study and summary of background information.

Section 3 outlines the community consultation program undertaken.

Section 4 details the development of the computer models.

Section 5 details the hydraulic model calibration and validation process.

Section 6 details the design flood conditions.

Section 7 details the design flood results and associated flood mapping including sensitivity tests.

Section 8 details the climate change analysis.

2 STUDY APPROACH

2.1 The Study Area

2.1.1 Catchment Description

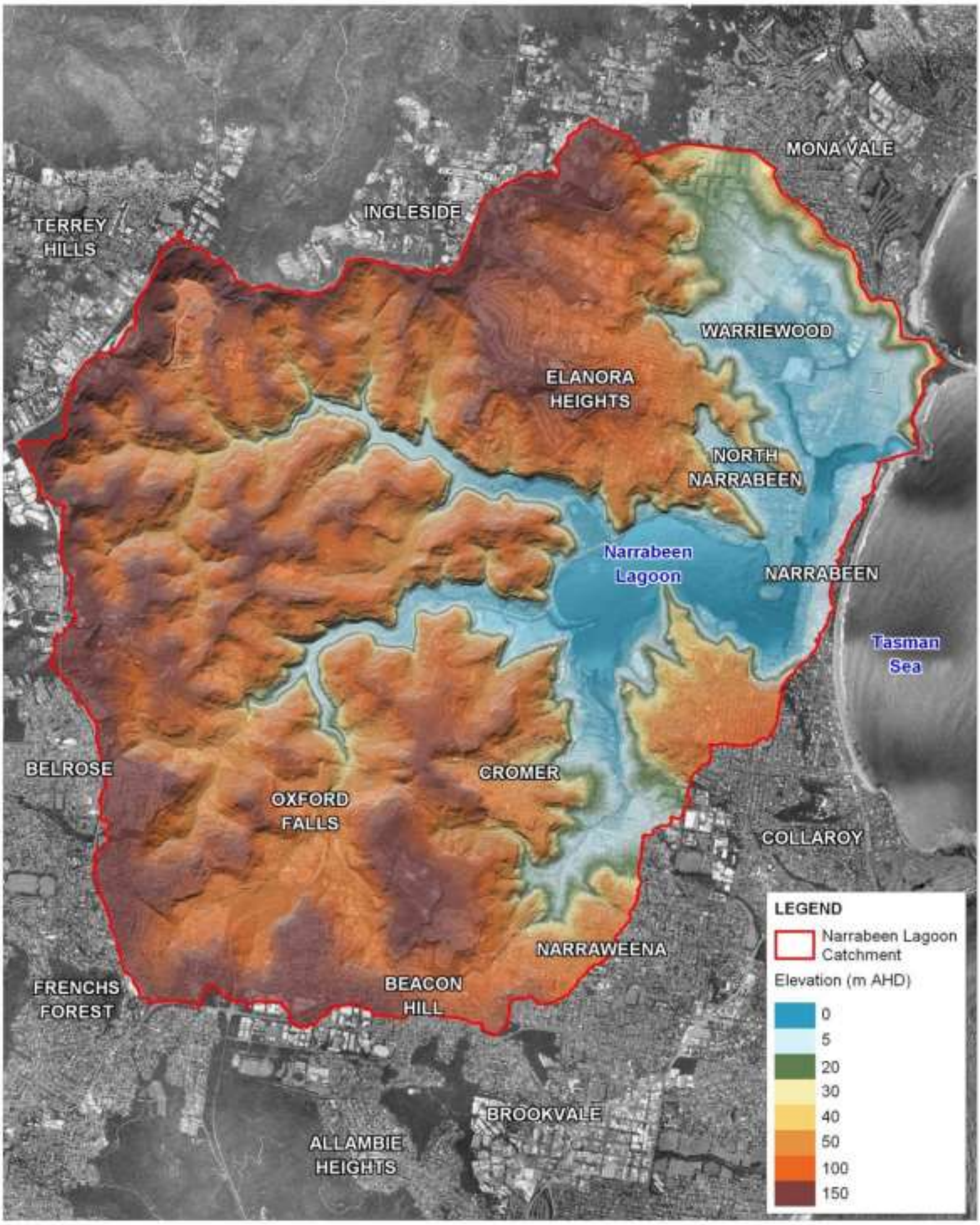
The Narrabeen Lagoon catchment is located on the northern edge of the Warringah LGA and the south eastern edge of Pittwater LGA on Sydney's northern beaches as shown in Figure 1-1. The catchment occupies a total area of approximately 55km^2 and drains to the Tasman Sea through a narrow channel to the lagoon entrance at North Narrabeen Beach.

Narrabeen Lagoon (also known as Narrabeen Lakes) is the largest coastal lagoon located in the Sydney metropolitan region with waterway area of 2.2 km^2. The catchment can be separated into a number of major sub-catchments including Nareen Creek, Mullet Creek, Narrabeen Creek (incorporating Fern Creek), Deep Creek, Middle Creek (incorporating Snake Creek, Oxford Creek and Trefoil Creek) and South Creek (incorporating Wheeler Creek). Details of the major sub-catchments within the wider Narrabeen Lagoon catchment are presented in Table 2-1.

Table 2-1 Catchment Details (PWD, 1990)

Catchment	Main Stream Length (km)	Area (km^2)	% Total Area
Warriewood Valley (Mullet, Fern & Narrabeen Creeks)	5.76	9.7	18
Deep Creek	7.34	15.6	29
Middle Creek	8.12	14.2	26
South Creek	4.96	7.9	14
Nareen Creek	2.52	1.6	3
Narrabeen Lagoon	n/a	2.2	4
Other Areas (Local Catchments / Lagoon Foreshore)	n/a	3.6	6
Total		54.7	100

The topography of the catchment is shown in Figure 2-1. From elevation of around 200m AHD in the north west of the catchment around Terrey Hills, and 150m in the south and south west of the catchment around Belrose and Frenchs Forest, the topography of the catchment is undulating and grades relatively steeply from the upper slopes to the floodplain areas around Narrabeen Lagoon and the Warriewood Valley. The areas of minor to moderate slopes are concentrated around the fringes of Narrabeen Lagoon, Warriewood Valley to the north and Oxford Falls in the central area of the catchment within the Middle Creek sub-catchment.



Title: **Topography of the Narrabeen Lagoon Catchment**

Figure: **2-1**

Rev: **A**

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The catchment contains a mixture of land uses, including urban (residential, commercial and industrial), recreational and bushland (including Garigal National Park). The urban suburbs of Elanora Heights, parts of North Narrabeen and Collaroy Plateau are located on the elevated land to the north and south of Narrabeen Lagoon. The suburbs of Narrabeen and parts of North Narrabeen have been developed along the lower floodplain and coastal strip separating the lagoon from the Tasman Sea. Warriewood Valley to the north of the lagoon is also significantly urbanised. The western and southern boundaries of the catchment are also urbanised including the suburbs of Terrey Hills, Frenchs Forest, Beacon Hill and Cromer.

The catchment area to the west of the lagoon is largely natural bushland (incorporating Garigal National Park) covering an area of approximately 20km^2. There are also several recreational reserves located around the lagoon and three major golf courses within the catchment (Mitchell McCotter, 1992).

2.1.2 Narrabeen Lagoon Entrance

As stated in Section 2.1.1 Narrabeen Lagoon drains to the Tasman Sea through a narrow channel (approximately 30 metres wide) at North Narrabeen Beach. The entrance opening is subject to forces that act to close the entrance (waves, tides and wind) and those that act to maintain an open entrance (flood flows and dredging), which results in the Lagoon being defined as an intermittently closed and open Lake/Lagoon (ICOLL).

The Narrabeen Lagoon entrance naturally closes due to the littoral movement of sand into the lagoon entrance as a result of wave, current and wind process along Narrabeen Beach with the volume of sand moved into the entrance exceeding the volume of sand removed from the entrance by the outgoing tide (Warringah Council, 1996). Studies over the past 30 years have confirmed that ocean waves and currents, wind borne sand and ocean storms act to close the entrance while flood events open it (Gordon, 2006).

Historical records show that prior to 1970 the Lagoon was predominantly closed. However, by the early 1970's The Councils found that it was necessary to mechanically open the lagoon on a regular basis in order to allay growing community concerns including potential flooding within the catchment and water quality within the lagoon (Gordon, 2006). The lagoon is now predominantly open due to large scale routine dredging within the entrance channel, which has been occurring every four years since 1975. The water levels in Narrabeen Lagoon are maintained at approximately 0.2-0.4m AHD by a natural rock weir at the lagoon entrance.

The procedures and responsibilities for management of Narrabeen Lagoon entrance are outlined in the Lagoon Entrance Management Operational Management Standard (Warringah Council, 2012). One of the main responsibilities concerning the lagoon entrance management is the timing of mechanical lagoon breakouts in order to mitigate the effects of flooding in the catchment.

The water level within the lagoon and at the entrance is monitored by two water level gauges. These gauges are supplied through the Northern Beaches Flood Warning and Information Network, which is a regional partnership approach with Manly, Warringah and Pittwater Councils, Office of Environment and Heritage and Bureau of Meteorology. The system provides a network of strategically placed rainfall, water level and flow gauges across the Northern Beaches. This information is then made available in real time through a webpage. A series of alarms are placed on water level and rainfall gauges to alert The Councils and SES of the likelihood of flooding in the area.

The Lagoon Entrance Management Operational Management Standard (Warringah Council, 2012) outlines the following conditions when a mechanical opening of the lagoon is to be undertaken:

- Scenario 1 - The lagoon has been closed for an extended period of time (months) at a level approximately between 1.0 – 1.3m AHD, there is potential damage to threatened and protected species and moderate to heavy rainfall is forecast.
- Scenario 2 - The lagoon water level is at or exceeding 1.3m AHD. Water level recorders indicate increasing lagoon water levels and moderate to heavy rainfall is forecast.

2.2 Compilation and Review of Available Data

2.2.1 Previous Flood Studies

A detailed review of previous investigations within the Narrabeen Lagoon catchment and available data for the current Flood Study was undertaken by Cardno Lawson Treloar in 2010.

In 1990 a Flood Study on the Lagoon and surrounds was completed, largely focused on the lower areas of the catchment around the Lagoon and tributary confluences. The hydraulic modelling undertaken for the study utilised one-dimensional (1D) modelling techniques.

Since 2005 a number of detailed two-dimensional (2D) flood studies have been undertaken in the Narrabeen Lagoon tributary catchments often extending to the upstream extents of the catchment.

Details of previous flood studies undertaken within the Narrabeen Lagoon catchment are presented below.

2.2.1.1 Narrabeen Lagoon Flood Study (PWD, 1990)

In 1990 the Public Works Department (PWD) NSW completed a Flood Study of the Narrabeen Lagoon catchment. The objective of the study was to determine the design flood levels in Narrabeen Lagoon for the 5%, 1% AEP floods together with an extreme flood event.

The study stated that elevated lagoon levels may result from the following combinations:

- High ocean levels and low rainfall;
- Low ocean levels and high rainfall; and
- Moderate to high ocean levels and moderate to high rainfall.

Runoff hydrographs for the study area were estimated using the RORB and WBNM hydrological models. The flooding behaviour of the catchment was modelled using a combination of the 1D backwater HEC2 model for the catchment and creeks and the quasi 2D hydraulic model Cells for the Lagoon. The Cells model was upgraded to include a sediment transport calculation (based on the Ackers and White formulation) to enable any changes in channel cross sections at the Lagoon entrance to be modelled.

The model was calibrated using the August 1986 and March 1977 flood events and then validated using the November 1961, May 1974 and March 1975 flood events. Three other events were noted but were not modelled, including:

- March 1942 – Highest lagoon level (2.7 m AHD) though lagoon remained closed through the event so is not considered typical;
- February 1977 – insufficient calibration data (peak Lagoon level of 1.44m AHD at Ocean Street); and
- March 1978 – insignificant event (Lagoon level < 1.5m AHD).

For the 1% flood event the peak flood level in the main body of the Lagoon (west of Pittwater Rd) was estimated at 2.92 m AHD. For the 5% flood event the peak lagoon water levels was estimated at 2.54 m AHD. Extreme flood levels are predicted to reach 4.61 m AHD. During these model runs the entrance was set at 1.3 m AHD and the inshore ocean conditions were between 1.8 – 2 m AHD. For the extreme flood the ocean level was set to 2.7 m AHD (taken from the May 1974 storm conditions).

The study found that due to the large capacity for storage, flooding around Narrabeen Lagoon is more sensitive to the duration of the rainfall, rather than the intensity. Rainfall events of 24hrs or longer tended to generate higher lagoon water levels, than shorter duration events.

2.2.1.2 *Nareen Creek Flood Study (Cardno Lawson Treloar, 2005)*

In 2005 Cardno Lawson Treloar were engaged by Pittwater Council to undertake a Flood Study of the Nareen Creek catchment. The objective of the study was to determine the flood behaviour under existing conditions for the 1%, 2%, 5% and 20% AEP floods together with Probable Maximum Flood (PMF).

The Nareen Creek catchment has an area of 1.6km^2. The study area, for which the detailed flood behaviour has been assessed, includes Nareen Creek, extending downstream of the waterfall near Eungai Crescent to the wetland area and downstream to Pittwater Road and the Wakehurst Parkway.

The Nareen Creek catchment is exposed to two different mechanisms of flooding:

- Narrabeen Lagoon Flooding - whereby the lower portions of the catchment are inundated by the floodwaters of the Lagoon; and
- Local Catchment Flooding - whereby the flooding is predominantly caused by rainfall falling within the Nareen Creek catchment. Given the relatively small size of the catchment, this is likley to be a flash flooding condition.

Council supplied a range of survey data including parts of Tatiara Crescent and Nareen Parade (surveyed in 2001) and cross-sections of Nareen Creek downstream of Nareen Parade (un-dated – though likely to be prior to creek rehabilitation works in the area). Additional survey collected for the Flood Study included aerial survey (undertaken by Fugro in June 2004) and ground survey (collected by Usher in August 2004). The aerial survey was converted into a 5m digital elevation map (DEM) grid through the use of photogrammetric analysis. Three-dimensional strings defining major terrain features such as creek banks, creek inverts, building outlines, road centrelines and curbing was also defined in the survey.

Runoff hydrographs for the Flood Study were estimated using the XP-RAFTS rainfall-runoff modelling package. Due to a lack of continuous water level records in the catchment (lagoon or tributary) for historical flood events, available local rainfall was used to calibrate the model against observed peak flood levels for 3 events (August 1986, October 1987 and April 1998).

SOBEK 1D/2D was used for hydraulic modelling. The defined creeks within the catchment were modelled as 1D channels underlying the 2D grid. The downstream boundary of the model was defined based on the results of the Narrabeen Lagoon Flood Study (PWD, 1990). The hydraulic model was calibrated to the August 1986, October 1987 and April 1998 storm events.

The study has also defined provisional flood hazard and hydraulic categories for the flood affected areas.

2.2.1.3 Warriewood Valley Flood Study (Lawson and Treloar, 2005)

In 2005 Lawson and Treloar were engaged by Pittwater Council to undertake a Flood Study for the Warriewood Valley. The objective of the study was to define the nature and extent of flooding in the study area for a range of design events.

The Warriewood Valley catchment has a total area of 9.04km^2. Three major creeks, Narrabeen, Fern and Mullet drain the catchment. At the time of the study the Warriewood Valley catchment was undergoing rapid residential development as part of the Warriewood Valley Urban Land Release and the creeks have been subject to modification to enhance environmental values and provide flood protection.

Council supplied a range of cross-section and structure data collected between 2000 and 2003. Additional aerial and ground survey was collected by QASCO for the study. This included aerial photography captured on 1 July 2003. The 2003 QASCO aerial survey was converted into a 5m digital elevation map (DEM) grid through the use of photogrammetric analysis, however a 10m grid resolution was used for the hydraulic modelling of Warriewood Valley. Three-dimensional strings defining major terrain features such as: creek banks, creek inverts, building outlines, road centrelines and curbing was also defined in the survey.

Estimation of flooding behaviour was undertaken by developing two mathematical models to simulate the hydrological and hydraulic aspects of flooding. The hydrological modelling package RAFTS was utilised to determine catchment runoff and for routing flows through the catchment. Predicted hydrographs from RAFTS were then input to the dynamically linked one-dimensional/two-dimensional hydraulic model, SOBEK for the determination of peak flood level, velocity and discharge for various design rainfall events. The design events investigated for this study were the 20% AEP, 5% AEP, 2% AEP and 1% AEP events together with the Probable Maximum Flood (PMF).

Flood levels within the catchment for the storm events of April 1998 and February 2002 were available for calibration of the hydrological and hydraulic models. These events were chosen on the basis of availability of rainfall and recorded gauge data. The models were satisfactorily calibrated to the two flood events.

Narrabeen Lagoon water levels were used for the model downstream boundary condition. Lagoon water levels were based on the PWD (1990) study.

In 2005 an addendum to the Flood Study (Addendum 1) was undertaken to update the study to incorporate the land changes that had occurred within the catchment as a result of the significant development within the Valley between March 2003 and November 2004.

2.2.1.4 Middle Creek Flood Modelling (DHI, 2009)

In 2009 DHI were engaged by Warringah Council to undertake a flood modelling study of Middle Creek. The objective of the study was to assess the potential measures to mitigate flooding from Middle Creek onto the Wakehurst Parkway. The potential mitigation measures investigated have included removal of culverts on the creek, removing sediment build-up from sections of the creek and construction of a detention basin.

Warringah Council provided LiDAR data covering the Middle Creek catchment and its surrounding area. The LiDAR data were collected on the 15th and 16th March 2007. In addition to the LiDAR data, ground survey data was collected for 39 cross-sections (including some culverts and bridges) and a levee section.

Runoff hydrographs for the Flood Study were estimated using the XP-RAFTS rainfall-runoff modelling package. Calibration data is available for three storm events (6 September 2008, 1 April 2009 and 2 April 2009) with the highest event being the 6 September 2008 selected for calibration.

MIKE FLOOD (a linked 1D/2D model), was used for hydraulic modelling. The model allows addition of a 2D domain (MIKE 21) to a 1D network (MIKE 11) with the two components dynamically coupled and solved simultaneously. The 1D (MIKE 11) component of the model comprised eight structures (culverts and bridges), two branches and 55 cross-sections (of which 52 were derived from ground survey and three from the LiDAR DEM). The 2D (MIKE 21) area grid resolution was set to 5m, which gave a total of 476,000 cells covering an area of about 11.9 km^2.

The downstream boundary condition has been applied as a fixed water level based on the PWD (1990) study. Inflows generated from XP_RAFTS were applied to either the 1D or 2D model domain.

Model design events included the 6 and 9 hour, 20%, 5%, 1% AEP and PMF flood events. The water level in Narrabeen Lagoon (model downstream boundary) was set to 0.8 mAHD.

2.2.1.5 South Creek Flood Study (Webb McKeown and Associates, 2006)

In 2006 Webb McKeown and Associates completed a Flood Study for the South Creek catchment (incorporating the Wheeler Creek subcatchment). The objectives of the study were to define the flood behaviour of the South Creek catchment and prepare flood hazard and flood extent maps for a range of design events. The South Creek flood model was subsequently refined by Cardno in 2008 as part of the South Creek Floodplain Risk Management Study and Plan.

Flooding within the South Creek catchment may occur as a result of a combination of factors including:

- Elevated Lagoon levels – affecting the lower reaches of South Creek due to persistent rain across the entire Lagoon catchment;
- Elevated water levels within South Creek and its tributaries as a result of intense rain over the South Creek catchment;

- Local overland flows (not considered in study);
- Local winds causing waves that could affect Cromer Golf Course (not considered in study).

Flooding in the South Creek catchment is typically due to intense short storms of 2 hours duration or less (as occurred in April 1998 event) in contrast to flooding in Narrabeen Lagoon which is usually due to longer, high volume events of 48 hours or more (as occurred in August 1986 event).

Warringah Council provided cross-section survey data collected in 2002 for approximately 6 km of the South Creek study reach. Some cross-sections were extended in 2004 to enable mapping of the PMF. Details of eight structures (road-crossings) were also surveyed. The South Creek Flood Study (WMA, 2006) shows that approximately 250 MIKE 11 cross-sections were extracted from a DEM of the survey data. The actual number of surveyed cross-sections is not mentioned in the Flood Study.

Runoff hydrographs for the Flood Study were estimated using the WBNM rainfall-runoff modelling package. Based on the topographic features (from 2m contour data), the catchment was divided into 24 sub-catchments.

No water level time-series data is available in the catchment, therefore the process of model calibration was limited to matching individual peak flood levels in the hydraulic model only. Hydrological parameters were based on recommended values within AR&R, WMA experience and PWD (1990). The study adopted an initial loss of 0 mm, a continuing loss of 2.5 mm/h and a lag parameter value of 1.68. Using the above parameters the WBNM model was used to define flow hydrographs throughout the catchment for the April 1998 and March 2003 flood events by applying pluviometer data from the Middle Creek, Cromer, Belrose or Allambie gauges.

MIKE 11 (1D model), was used for hydraulic modelling. The model extends from just downstream of Booker Avenue to the confluence with Narrabeen Lagoon. A 1.65 km section of the lower reaches of Wheeler Creek was also included. For all runs a nominal lagoon level of 1 m AHD was defined as the tailwater condition.

Six (6) flood marks were available for the April 1998 event which was selected for model calibration. Only a single flood mark was available for the March 2003 validation event. The model calibration approach adopted included:

- Deriving inflows from WBNM configured using recommended (though uncalibrated) parameter values;
- Adopting the rainfall pattern obtained from the Middle Creek pluviometer;
- Adjusting Manning's 'n' values until the model best matched observed flood levels.

Model design events included the 2 hour (except 1 hour for PMF), 20%, 10%, 2%, 1% AEP and PMF flood events.

A comparison between the WMA (2006) and PWD (1990) 1% AEP event peak water levels was made. Differences between peak flows and water levels were attributed to the current study using a more rigorous, fully dynamic modelling approach that utilised detailed survey data in conjunction with available historical information.

2.2.1.6 Summary Table of Narrabeen Lagoon Flood Studies

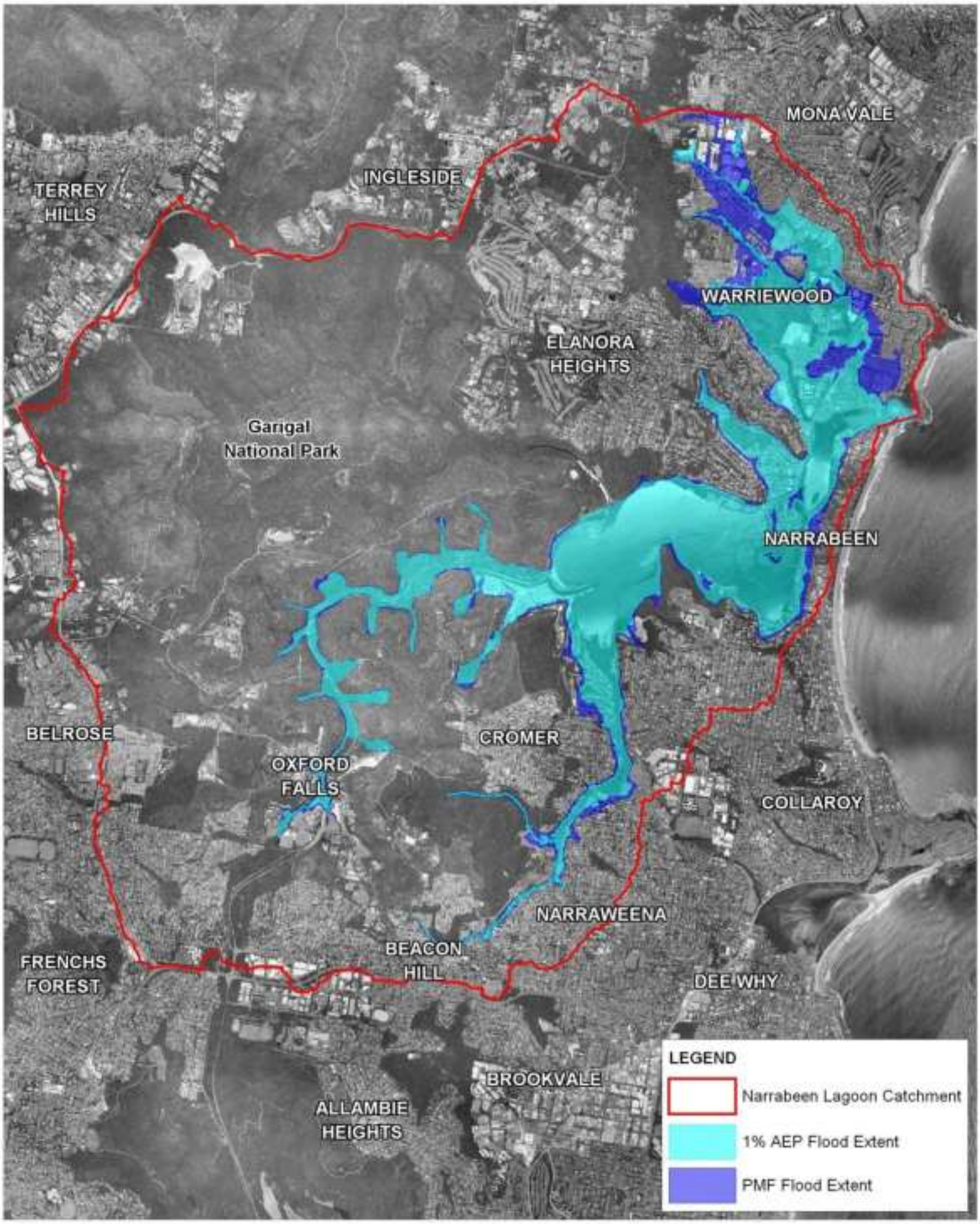
Table 2-2 summarises the hydrological and hydraulic models and calibration/ validation events used in relevant Narrabeen Lagoon (and associated catchments) flood studies.

Table 2-2 Summary of Previous Flood Studies

Catchment	Report	Model (Hydrological / Hydraulic)	Calibration & (Validation) Events
Narrabeen Lagoon	PWD (1990)	RORB & WBNM HEC2 & CELLS	Aug 1986, March 1977 (Nov 1961, May 1974, Mar 1975)
Nareen Creek	CLT (2005)	XP_RAFTS SOBEK 1D/2D	Aug 1986, Oct 1987, April 1998
Warriewood Valley	L & T (2005)	XP_RAFTS SOBEK 1D/2D	Aug 1998, Feb 2002
Middle Creek	DHI (2009)	XP_RAFTS MIKE FLOOD 1D/2D	Sept 2008
South Creek	WMA (2008)	WBNM MIKE 11 (1D only)	April 1998 (March 2003)

Figure 2-2 presents the previously mapped 1% AEP and PMF flood extents for each of the flood studies previously completed within the Narrabeen Lagoon catchment.

Figure 2-3 presents the mainstream creeks covered by each of the previously completed flood studies. This Flood Study will provide an up to date catchment wide flood model that will effectively update and fill in the gaps of the previous investigations to ensure a holistic catchment approach.



Title:
Previously Modelled Flood Extents

Figure: **2-2** Rev: **A**

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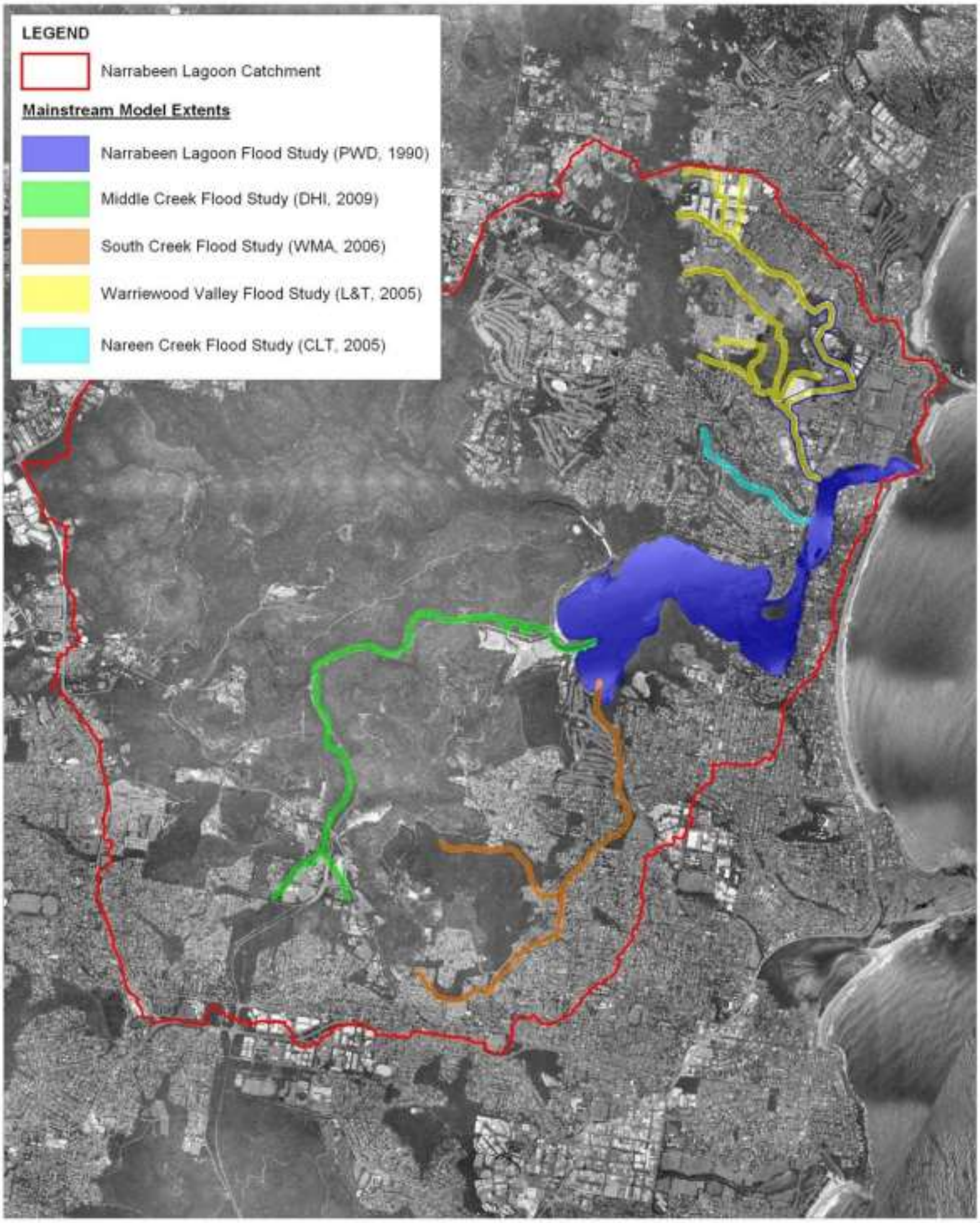

Title:
Narrabeen Lagoon Flood Studies
Previous Hydraulic Model Mainstream Extents

Figure: **2-3**

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2.2.2 Water Level Data

The MHL operates three continuous water level gauges within the Narrabeen Lagoon catchment. Two gauges are located within the Lagoon (at Pittwater Rd bridge and Ocean St bridge) while a third is located on Middle Creek. Three other water level gauges which were located on Narrabeen, Mullet and Fern Creeks, have been decommissioned. Gauge names and start and end dates are provided in Table 2-3. The locations of the three operational MHL water level gauges are shown in Figure 2-4.

Table 2-3 Narrabeen Lagoon Water Level Data Gauges (MHL)

Name	Start Year	End Year
Pittwater Road Bridge (Narrabeen Br.)	Aug 1994	Ongoing
Narrabeen Lake (Ocean St. Carpark)	Aug 1986	Ongoing
Middle Creek Bridge	Apr 1995	Ongoing
Middle Creek	May 1992	Jan 1994
Narrabeen Creek	May 1998	Sept 2010
Mullet Creek	Aug 1986[1]	Oct 2010
Fern Creek	May 1998	May 2008

[1]Data only provided for the Mullet Creek Gauge from May 1998

2.2.3 Historical Flood Levels

Historical flood data has been used in model calibration to determine appropriate model parameters (such as initial and continuing losses and also roughness values) and in model validation to improve confidence in model predictions. A review of available data indicates that there is sufficient data available for the proposed calibration and validation process. A summary of peak Narrabeen Lagoon flood levels is presented in Table 2-4.

Table 2-4 Historical Peak Narrabeen Lagoon Flood Levels (m AHD)

Date	Flood Level (mAHD)	Flood Mechanism	Source
March 1942	2.7	Runoff (lagoon closed)	PWD (1990)
June 1956	2.15	Storm Surge	PWD (1990)
May 1974	2.42	Storm Surge	PWD (1990)
Aug 1986	2 – 2.2	Runoff & Storm Surge	PWD (1987b)
April 1998	1.9	Runoff	MHL
March 2011	1.8	Runoff	MHL

Additional historical flood level data were targeted as part of the community consultation process (refer Section 3 for further details). In addition to water level records, other historical data sets such as photographs of flood events can provide important information on historical flood events. The Councils have provided photographs of several historical flood events that have occurred in the Narrabeen Lagoon catchment.

Further discussion on recorded flood levels for historical events used in model calibration is presented in Section 5.

Title:
Water Level Gauges in the Narrabeen Lagoon Catchment

Figure: **2-4**

Rev: **A**

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2.2.4 Rainfall Data

The MHL operates six pluviometers within or in close vicinity to the Narrabeen Lagoon catchment with an additional pluviometer in the catchment operated by Sydney Water. The location and period of record for each pluviometer are presented in Table 2-5.

Table 2-5 Summary of Pluviometers in the Narrabeen Lagoon Catchment

Location	Start / End Date	Type
Sydney Water Warriewood Valley STP	21/4/95 – Current	Continuous 15 min interval data
MHL - Belrose	31/5/94 – Current	Continuous 15 min interval data
MHL - Cromer	6/3/94 – Current	Continuous 15 min interval data
MHL – Middle Creek	21/4/94 – Current	Continuous 15 min interval data
MHL – Narrabeen Creek	15/5/98 – Current	Continuous 15 min interval data
MHL – Mona Vale	27/6/94 – Current	Continuous 15 min interval data
MHL – Allambie	22/6/99 – Current	Continuous 15 min interval data

In addition to the pluviometers, there are ten daily read rainfall gauges (including closed gauges) operated by the Bureau of Meteorology (BoM) located within or in close vicinity to the Narrabeen Lagoon catchment. The daily read rainfall gauges are shown in Table 2-6 with their respective period of record. The distribution of these rainfall gauges (including the pluviometers) is shown in Figure 2-5.

Table 2-6 Summary of BoM Daily Read Gauges in the Narrabeen Lagoon Catchment

Gauge No.	Location	Start Year	End Year
66044	Cromer Golf Club	1898	current
66123	Ingleside	1964	1977
66126	Collaroy Golf Club	1965	current
66183	Ingleside (Walter Av.)	1984	current
66141	Mona Vale Golf Club	1969	current
66077	Terrey Hills	1963	1966
66059	Terrey Hills AWS	2004	current
66188	Belrose (Evelyn Place)	1991	current
66182	Frenchs Forest (Frenchs Forest Rd)	1957	current
66127	Beacon Hill RAAF	1968	1973

Further discussion on recorded rainfall data for historical events is presented with the model calibration and validation data in Section 5.

Title:
Rainfall Gauges in the Vicinity of the Narrabeen Lagoon Catchment

Figure: **2-5**

Rev: **A**

BMT WBM endeavours to ensure that the information provided in this map is correct at the time of publication. BMT WBM does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.

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0 1 2km
Approx. Scale

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2.2.5 Ocean Tide Data

Ocean tide (water level) data will be used for the downstream water level boundary to drive the hydraulic model of the Lagoon. MHL has collected ocean tide data for Sydney at Middle Head with 15 minute interval data available since 1987.

2.2.6 Topographic Data

Raw LiDAR data (in the form of ground surface points) was provided for the entire Narrabeen Lagoon catchment by The Councils. The LiDAR data were collected on the 15th and 16th March 2007 by AAM Hatch. The LiDAR data was supplied with a stated vertical accuracy +/- 0.15m @ 68% confidence and horizontal accuracy +/- 0.55m @ 68% confidence. It should be noted that the stated vertical and horizontal accuracy of the LiDAR data is only applicable to land surface areas. The LiDAR data points were used to derive a high resolution (2m grid) digital elevation model (DEM) of the entire Narrabeen Lagoon catchment.

The most recent Lagoon bathymetry (covering the Lagoon in its entirety) was collected by the Department of Infrastructure, Planning and Natural Resources (DIPNR – now OEH) as part of the Estuary Management Program between November 2004 and February 2005. The bathymetric survey points were converted into a DEM of Narrabeen Lagoon.

Additional Lagoon bathymetry (covering part of the eastern basin and lagoon entrance) was collected by Cardno as part of dredging works undertaken in 2006 and 2011. Bathymetric surveys were taken before and after the dredging works. The bathymetric survey points were converted into a DEM of the Narrabeen Lagoon entrance channel. The following Lagoon entrance bathymetric survey data was provided for this Study:

- 2nd July 2006 – Pre-dredge survey;
- 8th December 2006 – Post-dredge survey;
- 3rd August 2011 – Pre-dredge survey;
- 31st October 2011 - Post-dredge survey; and
- 14th November 2011 - Post-dredge survey.

The LiDAR data and Lagoon bathymetry data combined to provide the required elevation data used in the development of the hydraulic model (refer to Section 4.2.2).

2.2.7 Survey Data

In addition to the topographic data discussed in Section 2.2.6, a range of channel and ground survey data was available from previous flood studies within the Narrabeen Lagoon.

The channel and ground survey data was used to ground truth the LiDAR data. It was found that in some areas, such as Warriewood and Nareen Creek wetlands, dense vegetation cover can result in incorrect ground levels being recorded. The LiDAR survey also detects water surface levels, not bed levels, in the Lagoon and its tributaries. In order to rectify these possible errors in the LiDAR data the channel and ground survey data was used to create a DEM for both the Warriewood and Nareen Creek wetlands, and assign bed levels to tributary alignments (the bed levels in the Lagoon were assigned using the bathymetric survey data outlined in Section 2.2.6).

The channel and ground survey data used in the development of the hydraulic model is presented in Table 2-7.

Table 2-7 Survey Data Sources

Catchment Area	Flood Study	Surveyor	Date Surveyed
South Creek	South Creek Flood Study (WMA, 2006)	Council	2002
South Creek	South Creek Flood Study (WMA, 2006)	Mepstead and Associates Pty Ltd	2004
Middle Creek	Middle Creek Flood Modelling (DHI, 2009)	Byrne and Associates Pty Ltd	2008
Nareen Creek	Nareen Creek Flood Study (Cardno Lawson Treloar, 2005)	Fugro Spatial Solutions Pty Ltd	2004
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 Wetlands	Warriewood Valley Flood Study (Lawson and Treloar, 2005)	Council	2003
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

A number of recent developments in the Warriewood Valley have incorporated channel modification works. Pittwater Council provided data where available for major earthworks/land form changes associated with individual developments. This data was largely from design reports and work-as-executed drawings as available. The models have incorporated development completed to March 2012. During the course of the study, Pittwater Council also obtained additional cross section survey for the recently completed channel works on Narrabeen Creek upstream of Ponderosa Parade.

2.2.8 Council Data

Digitally available information such as aerial photography, cadastral boundaries, topography, watercourses, drainage networks, land zoning, vegetation communities and soil landscapes were provided by The Councils in the form of GIS datasets.

The following aerial photography was utilised for this Study:

- Pittwater LGA – 2007 Aerial Photography.
- Warringah LGA – 2009 Aerial Photography (1998 and 2008 Aerial Photography also supplied).

The following property boundaries (cadastre) were utilised for this study:

- Pittwater LGA – Cadastre dated 21st April 2010.
- Warringah LGA – Property Boundaries dated 10th February 2011.

2.3 Community Consultation

The success of a floodplain management plan hinges on its acceptance by the community, residents within the study area, and other stake-holders. This can be achieved by involving the local community at all stages of the decision-making process. This includes the collection of their ideas and knowledge of flood behaviour in the study area, together with discussing the issues and outcomes of the study with them.

The key elements of the consultation program undertaken for the study are discussed in Section 3.

2.4 Development of Computer Models

2.4.1 Hydrological Model

For the purpose of the Flood Study, a hydrological model (discussed in Section ⊓) was developed to simulate the rate of storm runoff from the catchment. The model predicts the amount of runoff from rainfall and the attenuation of the flood wave as it travels down the catchment. This process is dependent on:

- Catchment area, slope and surface coverage;
- Variation in distribution, intensity and amount of rainfall; and
- Antecedent conditions of the catchment.

The output from the hydrological model is a series of flow hydrographs at selected locations such as at the boundaries of the hydraulic model. These hydrographs are used by a hydraulic model to simulate the passage of a flood through the Narrabeen Lagoon catchment to the downstream study limits at the Lagoon entrance into the Tasman Sea.

2.4.2 Hydraulic Model

The hydraulic model (discussed in Section 4.2) developed for this study provides for a two-dimensional (2D) representation of the Narrabeen Lagoon catchment.

The hydraulic model is applied to determine flood levels, velocities and depths across the study area for historical and design events. The developed models can be used as a tool to assess various flood mitigation options in subsequent floodplain risk management studies.

2.5 Calibration and Sensitivity Testing of Models

The hydrological and hydraulic models were calibrated and verified to available historical flood event data to establish the values of key model parameters and confirm that the models were capable of adequately simulating real flood events.

The following criteria are generally used to determine the suitability of historical events to use for calibration or validation:

- The availability, completeness and quality of rainfall and flood level event data;

- The amount of reliable data collected during the historical flood information survey; and
- The variability of events – preferably events would cover a range of flood sizes.

The available historical information highlighted three flood events with sufficient data to support a calibration process – the April 1998, August 1998 and March 2011 events. The April 1998 event has been selected as the primary calibration event due to the fact that it resulted in the highest recorded Lagoon water levels since the installation of the MHL water level gauges. Due to data availability, the March 2011 and August 1998 events have been used for model validation.

The calibration and validation of the model are presented in Section 5.

3 COMMUNITY CONSULTATION

3.1 The Community Consultation Process

Community consultation has been an important component of the current study. The consultation has aimed to inform the community about the development of the flood study and its likely outcome as a precursor to subsequent floodplain management activities. It has provided an opportunity to collect information on their flood experience, their concern on flooding issues and to collect feedback and ideas on potential floodplain management measures and other related issues.

The key elements of the consultation process have been as follows:

- Media release and notices in the Manly Daily to inform the wider community of the study;
- Development and maintenance of a project web-page providing general information on the study background and objectives, reporting progress of the flood study against key milestones, and providing preliminary study output;
- Distribution of a questionnaire, letter and newsletter to all landowners, residents and businesses located within the existing extreme flood extents for Narrabeen Lagoon; and
- Public exhibition of the draft Flood Study including four days of community information sessions.

These elements are discussed in detail below. Copies of relevant consultation material are included in Appendix B.

3.2 Media Release

A media release, including four Manly Daily advertisements followed by a Manly Daily article, informed the wider community of the study, canvassed any existing flooding issues and informed the community of the community consultation process to be carried out as part of the study. Similar releases were also made advertising the Public Exhibition of the Draft Flood Study Report discussed in Section 3.6.

3.3 Information Website

A website has been established to keep the community informed on the study progress. The website has further information on flooding in Narrabeen Lagoon and was updated throughout the study as new information became available. Community members were also able to complete the community questionnaire (refer Section 3.4) and send photographs through the website.

Website address: http://gis.wbmpl.com.au/narrabeenlagoon/About.html (note: the project website will be discontinued following completion of the study).

3.4 Community Questionnaire

A questionnaire, letter and newsletter were distributed to all landowners, residents and businesses located within the existing extreme flood extents from previous studies completed in the Narrabeen

Lagoon catchment (see Figure 2-2). The purpose of the questionnaire was to collect information on previous flood experience and flooding issues. The focus of the questionnaire was to find any historical flooding information that may be useful for correlating with predicted flooding behaviour from the modelling.

Council received back 147 responses to the community questionnaire. The responses have been compiled into a GIS layer by BMT WBM.

The focus of the questionnaire was to gather relevant flood information from the community, including photographs, observed flood depths and descriptions of flood behaviour within the catchment. Council received approximately 86 photos of flooding within the Narrabeen Lagoon catchment. The majority of these photos depicted flooding in the lower catchment surrounding the main body of Narrabeen Lagoon. Limited information was received for the tributary channels.

Photographs and comments relating to flood behaviour contained within the responses were extracted where useful for model calibration purposes.

3.5 Community Information Sessions

During the public exhibition of the Draft Narrabeen Lagoon Flood Study Report (refer Section 3.6) a series of community information sessions were held to:

- Provide the community with an overview of the study and objectives;
- Provide the community with property specific study outcomes including Flood Planning Levels (FPLs) and inundation maps;
- Provide the community with an opportunity to communicate any concerns or questions relating to the study; and
- Provide The Councils with a means to obtain some feedback from the local community on the future direction of the floodplain management process (i.e. Floodplain Management Study and Plan).

Prior to the Public Exhibition, The Councils sent a notification letter to all property owners and residents located within the preliminary PMF extent, advising that their property had been identified as being affected by future flood events. The letter also advised the dates of the public exhibition of the Draft Narrabeen Lagoon Flood Study Report (refer Section 3.6), how to obtain further information, and how to make a submission to Council. The letter was accompanied by a community guide brochure (included in Appendix B) to provide further background information on the study.

Community information sessions comprised 15 minute discussion sessions between individual community members and representatives from both the relevant Council and BMT WBM. Community information sessions were held on the following dates:

- 9.30am – 5.00pm on 20 July 2013, at the Coastal Environment Centre, North Narrabeen;
- 9.30am – 5.00pm on 22 July 2013, at the Tramshed Arts and Community Centre, Narrabeen;
- 9.30am – 5.00pm on 26 July 2013, at the Coastal Environment Centre, North Narrabeen; and
- 9.30am – 5.00pm on 30 July 2013, at the Coastal Environment Centre, North Narrabeen;

A total of 60 individual discussion sessions were held across the four dates. The majority of community members were concerned with the impact of being included within the FPA and PMF extents, and the subsequent potential impact on planning certificates, property value and insurance premiums. Many of the attendees also provided formal submissions to the Public Exhibition of the Draft Report, as discussed in Section 3.6.

3.6 Public Exhibition of Draft Report

The Draft Narrabeen Lagoon Flood Study Report was placed on public exhibition for a period of four weeks from 15 July to 12 August 2013. The draft report was placed on display at Warringah and Pittwater Council, Council Libraries and other public centres. It was also made available for viewing/download on the study website (http://gis.wbmpl.com.au/narrabeenlagoon/About.html), and via the Warringah and Pittwater Council websites.

Public comment on the draft report was invited from the community with 17 formal submissions received by The Councils. The distribution of the submissions within the catchment area is shown in Figure 3-1 (note that one submission was received from a property located outside the study catchment and is therefore not shown in Figure 3-1). Shown for reference are the Flood Planning Area (FPA) and Probable Maximum Flood (PMF) extents. Further reference to the FPA and PMF extents is provided in the Narrabeen Lagoon Flood Study - Flood Planning Levels Report – Warringah Council (BMT WBM, 2013a) and Narrabeen Lagoon Flood Study - Flood Planning Levels and Categories Report – Pittwater Council (BMT WBM, 2013b).

As shown in Table 3-1, the majority of the submissions related to inclusion of the property in the FPA. Most of these residents were concerned with the potential impact on planning certificates, property value and insurance premiums.

Table 3-1 Classification of Exhibition Submissions

Extent	Number of Submissions
Flood Planning Area	11
Probable Maximum Flood	3
Not Flood Affected	3

The majority of submissions requested a review of the FPA or PMF extent or were related to future floodplain management issues to be addressed in the Floodplain Risk Management Study. The principal concern of many landowners was the inclusion of their properties within the defined FPA or PMF extent. Through the discussions with landowners, much of the conjecture can be attributed to the following issues:

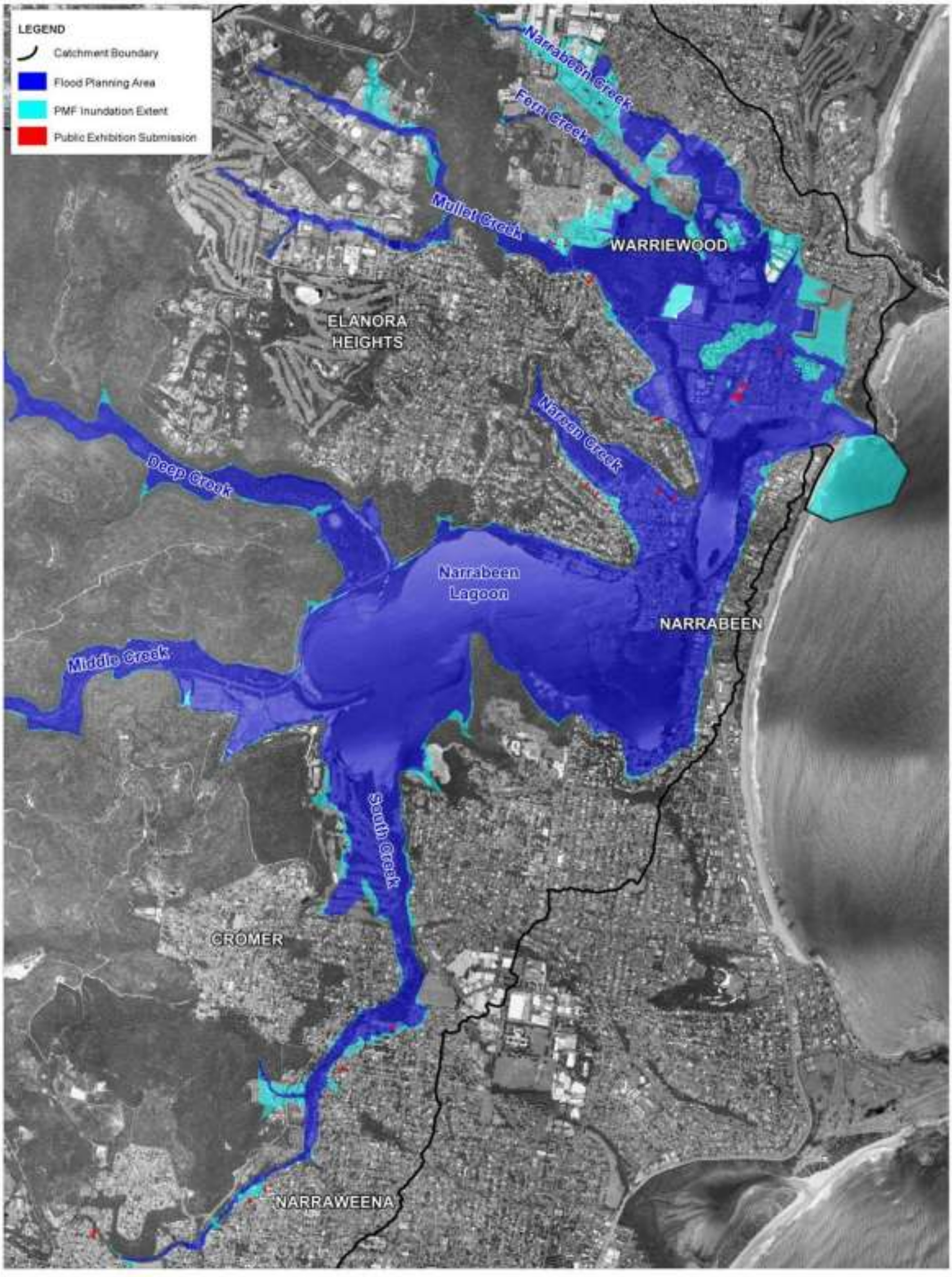
- There was some misunderstanding in the community between lot and building footprint in terms of flood affectation. Many owners of lots identified as flood prone noted that their building was actually located outside the FPA extent, and was therefore not at risk of flooding. It was explained that development controls were applied to cadastral lots (not building footprints) and that development applications were assessed on an individual basis.

- The magnitude of the 1% AEP event was questioned particularly in relation to historical events in the catchment. Many residents noted that flood conditions they had experienced in previous events were significantly less severe than the design flood conditions established in the study. In comparing rainfall conditions associated with previous flood events with the design flood rainfall conditions, it is evident that the historical events referred to by the community members were significantly lower magnitude events in comparison to the design flood conditions used for flood planning purposes.
- The concept of Probable Maximum Flood proved somewhat difficult for some to appreciate. This is not uncommon given the severity and magnitude of the event, particularly compared to normal conditions in the catchment and even previously experienced flood events. Whilst it was explained that residential planning controls do not apply at the PMF level, many residents were concerned about being included within the PMF extent and the associated connotation that their property was "flood affected".

A number of other common issues/comments were raised during the information sessions and formal submissions as summarised below:

- Heightened concern that the completion of the Flood Study and publicly available information would detrimentally affect property values and insurance premiums;
- The influence of Narrabeen Lagoon entrance management as a means of reducing flood risk (e.g. opening procedures and trigger levels for mechanical opening);
- The opportunity for Lagoon dredging in order to reduce flood risk;
- Review of main drainage structures and bridge crossings with specific mention of "choke" points which are considered to exacerbate flooding;
- The application of Council development control plans in relation to flooding and specific requirements for future development of individual properties in terms of flood related development controls;
- Potential for further development in the Warriewood Valley and Ingleside to increase the flood risk to existing properties; and
- Localised problems such as bank erosion, stormwater drainage maintenance and improvements.

Many of these issues will be considered further in the subsequent Floodplain Risk Management Study.



Title:
Narrabeen Lagoon Flood Study - Distribution of Public Exhibition Submissions

Figure: 3-1

Rev: A

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4 MODEL DEVELOPMENT

Computer models are the most accurate, cost-effective and efficient tools to assess a catchment's flood behaviour. Traditionally, for the purpose of the Flood Study, a hydrological model and a hydraulic model are developed.

The **hydrological model** simulates the catchment rainfall-runoff processes, producing the stormwater flows which are used in the hydraulic model.

The **hydraulic model** simulates the flow behaviour of the overland flow paths, creeks and lagoon producing flood inundation extents, levels and velocities.

Information on the topography and characteristics of the catchments and floodplains are built into the hydraulic model. Recorded historical flood data, including rainfall and flood levels, are used to simulate and validate (calibrate and verify) the model. The model produces as outputs, the distribution of flood levels, flow rates (discharges) and flow velocities.

Development of hydrological and hydraulic models follows a relatively standard procedure:

1. Discretisation of the catchment, floodplain, etc.
2. Incorporation of physical characteristics (floodplain levels, structures etc).
3. Establishment of hydrographic databases (rainfall, flood flows, flood levels) for historic events.
4. Calibration to one or more historic floods (calibration is the adjustment of parameters within acceptable limits to reach agreement between modelled and measured values). The hydrological and hydraulic models were calibrated interactively.
5. Validation to one or more other historic floods (validation is a check on the performance of the model without further adjustment of parameters).
6. Sensitivity analysis of parameters to measure dependence of the results upon model assumptions.

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

- establishing design flood conditions (as part of the current flood study);
- determining levels for planning control; and
- modelling development or management options to assess the hydraulic impacts (as part of the floodplain risk management study).

4.1 Hydrological Model

The hydrological model simulates the rate at which rainfall runs off the catchment. The amount of rainfall runoff from the catchment is dependent on:

- the catchment slope, area, vegetation, urbanisation and other characteristics;
- variations in the distribution, intensity and amount of rainfall; and
- the antecedent moisture conditions (dryness/wetness) of the catchment.

These factors are represented in the model by:

- Sub-dividing (discretising) the catchment into a network of sub-catchments inter-connected by channel reaches representing the creeks and rivers. The sub-catchments are delineated, where practical, so that they each have a general uniformity in their slope, landuse, vegetation density, etc;
- The amount and intensity of rainfall is varied across the catchment based on available information. For historical events, this can be very subjective if little or no rainfall recordings exist.
- The antedecent moisture conditions are modelled by varying the amount of rainfall which is "lost" into the ground and "absorbed" by storages. For very dry antedecent moisture conditions, there is typically a higher initial rainfall loss.

The output from the hydrological model is a series of flow hydrographs at selected locations such as at the boundaries of the hydraulic model. These hydrographs are used by the hydraulic model to simulate the passage of the flood through the Narrabeen Lagoon catchment.

The RAFTS-XP software was used to develop the hydrological model using the physical characteristics of the catchment including catchment areas, ground slopes and vegetation cover as detailed in the following sections.

4.1.1 Catchment Delineation

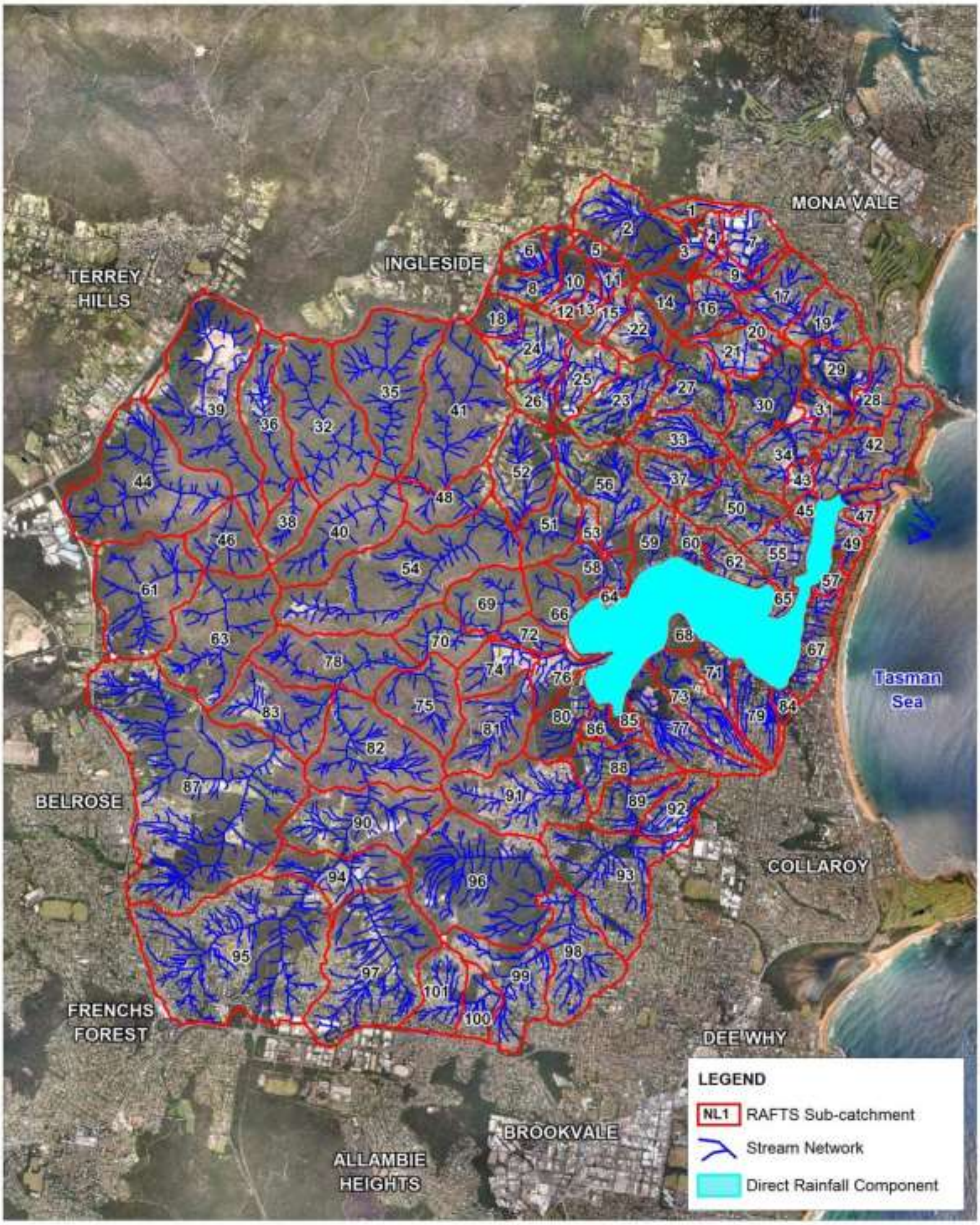
The Narrabeen Lagoon catchment drains an area of $55km^2$ to the lagoon entrance into the Tasman Sea. For the hydrological model this area has been delineated into 101 sub-catchments as shown in Figure 4-1. The sub-catchment delineation provides for generation of flow hydrographs at key confluences or inflow points to the hydraulic model.

Table 4-1 summarises the key catchment parameters adopted in the RAFTS-XP model, including catchment area, vectored slope and PERN (roughness) value estimated from the available topographic information and aerial photography. The adopted PERN values considered the proportion of forested catchment to developed area.

Impervious areas and land use/surface roughness areas were classified using a combination of aerial photography and cadastral information (refer Section 2.2.8). It is noted that in some areas, such as the Warriewood Valley, significant land development has occurred since the late 1990's. Accordingly, some changes in the land use patterns need to be reflected in the models over the appropriate time periods considering the dates of the key calibration events, the dates of collection of key data (e.g. aerial photography) and the present day condition to be used for design purposes in the remainder of the study.

Table 4-1 RAFTS-XP Sub-catchment Properties

Catchment Label	Area (ha)	Slope (%)	Impervious Area (%)	PERN	Catchment Label	Area (ha)	Slope (%)	Impervious Area (%)	PERN
NL1	12.33	2.6	31.9%	0.03	**NL52**	59.06	13.7	15.3%	0.03
NL2	68.09	13.9	15.3%	0.04	**NL53**	9.3	18.8	17.0%	0.03
NL3	14.14	6.2	23.6%	0.03	**NL54**	175.27	4.0	1.1%	0.10
NL4	11.2	3.1	55.2%	0.02	**NL55**	34.53	0.0	47.5%	0.03
NL5	9.99	10.4	22.1%	0.06	**NL56**	72.68	12.3	23.2%	0.03
NL6	16.64	8.4	26.3%	0.03	**NL57**	9.15	4.0	52.9%	0.02
NL7	31.22	2.0	68.6%	0.02	**NL58**	31.31	1.4	3.9%	0.10
NL8	29.73	10.2	18.3%	0.03	**NL59**	25.73	11.0	24.1%	0.04
NL9	18.93	2.1	48.2%	0.03	**NL60**	13.17	12.9	48.6%	0.03
NL10	18.54	5.4	13.2%	0.05	**NL61**	106.4	6.6	2.7%	0.10
NL11	10.82	7.2	15.4%	0.03	**NL62**	23.16	4.1	43.6%	0.03
NL12	4.46	8.8	23.5%	0.03	**NL63**	111.8	4.7	2.0%	0.10
NL13	9.23	4.0	21.8%	0.03	**NL64**	4.3	1.5	57.4%	0.05
NL14	24.59	17.0	3.9%	0.10	**NL65**	6.5	0.5	54.6%	0.02
NL15	16.75	3.9	21.9%	0.03	**NL66**	34.97	11.6	8.7%	0.09
NL16	24.42	2.9	25.3%	0.03	**NL67**	33.77	2.1	52.5%	0.02
NL17	40.82	2.8	47.3%	0.03	**NL68**	10.06	15.4	10.8%	0.09
NL18	19.46	7.6	1.8%	0.05	**NL69**	44.8	9.4	1.0%	0.10
NL19	34.32	1.7	36.4%	0.03	**NL70**	37.28	2.9	4.1%	0.10
NL20	12.46	1.6	30.5%	0.03	**NL71**	22.9	10.1	21.9%	0.03
NL21	26.65	1.6	39.4%	0.03	**NL72**	17.61	1.4	3.3%	0.10
NL22	29.43	17.0	12.0%	0.03	**NL73**	47.74	4.3	34.7%	0.03
NL23	54.9	14.3	18.7%	0.03	**NL74**	31.82	2.8	2.2%	0.03
NL24	44.88	3.8	10.1%	0.03	**NL75**	58.83	8.5	1.7%	0.10
NL25	35.63	3.2	18.2%	0.03	**NL76**	25.41	1.0	4.9%	0.03
NL26	16.97	7.7	11.8%	0.03	**NL77**	56.19	5.4	41.0%	0.03
NL27	50.62	5.4	30.2%	0.03	**NL78**	81.81	3.5	2.6%	0.10
NL28	28.88	1.5	34.3%	0.03	**NL79**	32.7	13.7	47.7%	0.03
NL29	35.78	0.5	34.8%	0.03	**NL80**	36.65	5.6	1.6%	0.07
NL30	60.41	0.6	24.7%	0.03	**NL81**	62.29	9.2	1.0%	0.10
NL31	18.07	0.4	25.8%	0.03	**NL82**	98.86	4.1	3.2%	0.10
NL32	112.12	4.5	2.2%	0.10	**NL83**	68.5	4.6	4.7%	0.07
NL33	37.58	15.6	49.4%	0.03	**NL84**	8.89	13.1	45.2%	0.03
NL34	39.26	1.6	46.3%	0.03	**NL85**	5.67	5.1	27.0%	0.03
NL35	116.65	4.9	1.4%	0.10	**NL86**	16.51	1.1	11.4%	0.03
NL36	62.31	12.4	4.8%	0.10	**NL87**	345.16	5.1	16.2%	0.04
NL37	32.64	11.6	49.2%	0.03	**NL88**	44.64	1.9	19.2%	0.03
NL38	29.64	14.8	1.0%	0.10	**NL89**	33.47	3.6	38.1%	0.03
NL39	161.76	5.9	6.2%	0.07	**NL90**	97.36	9.4	11.0%	0.05
NL40	80.76	7.6	1.0%	0.10	**NL91**	89.82	8.1	34.6%	0.03
NL41	126.11	7.9	3.1%	0.10	**NL92**	30.44	5.1	53.9%	0.02
NL42	74.73	0.4	29.5%	0.03	**NL93**	106.53	2.0	46.7%	0.03
NL43	10.86	2.1	48.1%	0.03	**NL94**	56.12	3.8	14.9%	0.03
NL44	149.52	4.4	1.6%	0.10	**NL95**	242.31	2.3	37.7%	0.03
NL45	6.98	1.0	48.3%	0.03	**NL96**	154.3	7.7	4.1%	0.07
NL46	44.02	4.9	1.0%	0.10	**NL97**	144.61	3.8	27.8%	0.03
NL47	6.48	4.4	49.7%	0.03	**NL98**	75.21	5.0	47.1%	0.03
NL48	39.19	7.8	2.6%	0.10	**NL99**	67.08	11.2	36.4%	0.03
NL49	14.91	2.5	51.3%	0.02	**NL100**	24.18	5.9	32.2%	0.03
NL50	51.54	1.8	41.1%	0.03	**NL101**	40.37	6.8	38.9%	0.03
NL51	37.89	7.4	3.4%	0.10					



Title: **RAFTS Model Sub-catchment Layout - Revised**

Figure: **4-1**

Rev: **A**

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4.1.2 Rainfall Data

Rainfall information is the primary input and driver of the hydrological model which simulates the catchment's response in generating surface run-off. Rainfall characteristics for both historical and design events are described by:

- Rainfall depth – the depth of rainfall occurring across a catchment surface over a defined period (e.g. 270mm in 36hours or average intensity 7.5mm/hr); and
- Temporal pattern – describes the distribution of rainfall depth at a certain time interval over the duration of the rainfall event.

Both of these properties may vary spatially across the catchment during any given event and between different events.

The procedure for defining these properties is different for historical and design events. For historical events, the recorded hyetographs at continuous rainfall gauges provide the observed rainfall depth and temporal pattern (refer Section 2.2.4 for rainfall gauge locations). The rainfall inputs for the historical calibration/validation events are discussed in further detail in Section 5.

For design events, rainfall depths are most commonly determined by the estimation of intensity-frequency-duration (IFD) design rainfall curves for the catchment. Standard procedures for derivation of these curves are defined in AR&R (2001). Similarly AR&R (2001) defines standard temporal patterns for use in design flood estimation.

4.1.3 Rainfall Losses

The antecedent catchment condition reflecting the degree of wetness of the catchment prior to a major rainfall event directly influences the magnitude and rate of runoff. The initial loss-continuing loss model has been adopted during the hydrological modelling process. The initial loss component represents a depth of rainfall effectively lost from the system and not contributing to runoff and simulates the wetting up of the catchment to a saturated condition. The continuing loss represents the rainfall lost through soil infiltration once the catchment is saturated and is applied as a constant rate (mm/hr) for the duration of the runoff event.

The rainfall loss parameters for the historical calibration/validation events and design events are discussed in further detail in Section 5 and Section 6 respectively.

4.2 Hydraulic Model

BMT WBM has applied the fully 2D software modelling package TUFLOW. TUFLOW was developed in-house at BMT WBM and has been used extensively for over fifteen years on a commercial basis by BMT WBM. TUFLOW has the capability to simulate the dynamic interaction of in-bank flows in open channels, major underground drainage systems, and overland flows through complex overland flowpaths using a linked 2D / 1D flood modelling approach. TUFLOW is specifically orientated towards establishing flow and inundation patterns in coastal waters, estuaries, rivers, floodplains and urban areas where the flow behaviour is essentially 2D in nature and cannot or would be awkward to represent using a 1D model, and accordingly is well suited to model the conditions in the Narrabeen Lagoon catchment.

The influence of entrance conditions on flood behaviour has been investigated utilising morphologic routines in the TUFLOW software. This model functionality enables the integration of scouring processes at the sand berm which can be important for the determination of representative design flood conditions.

4.2.1 Model Configuration

Consideration needs to be given to the following elements in constructing the model:

- topographical data coverage and resolution (e.g. LiDAR data);
- location of recorded data (e.g. levels/flows for calibration);
- location of controlling features (e.g. dams, levees, bridges);
- catchment specific factors (e.g. lagoon entrance); and
- computational limitations.

With consideration to the available survey information and local topographical and hydraulic controls, a linked 1D/2D model was developed extending from the Lagoon entrance in North Narrabeen at the downstream limit, to the head of the catchment.

The floodplain area modelled within the 2D domain comprises a total area of approximately 55km^2 which includes the Narrabeen Lagoon catchment in its entirety.

A TUFLOW 2D model grid resolution of 6m was adopted for Narrabeen Lagoon. It should be noted that TUFLOW samples elevation points at the cell centres, mid-sides and corners, so a 6m cell size results in DEM elevations being sampled every 3m. This resolution was selected to give the necessary detail required for accurate representation of floodplain, channel and lagoon entrance topography, key floodplain obstructions such as buildings and road/structure embankments and to keep simulation times within acceptable limits considering the size of model domain. Smaller channels and culverts are represented using 1D elements linked to the 2D floodplain domain.

4.2.2 Topography

The ability of the model to provide an accurate representation of the flood behaviour of the catchment ultimately depends upon the quality of the underlying topographic data. For the Narrabeen Lagoon catchment, a high resolution DEM was derived from a combination of the following data sets (refer to Section 2.2.6 for further details):

- LiDAR survey data;
- Narrabeen Lagoon bathymetry survey data; and
- Ground survey data.

The ground surface elevation for the TUFLOW model grid points are sampled directly from the DEM. Local modifications to modelled ground surface levels have been made where appropriate to represent key floodplain restrictions such as through the presence of embankments or obstructions such as solid walls or fences.

4.2.3 Lagoon Entrance

The ability to model morphological changes in the Lagoon entrance during a flood event is critical for this study, as it incorporates changes to the effectiveness of the Lagoon entrance in conveying water out of the Lagoon during the flood event. The changing entrance shape as the entrance scour develops affects peak water levels in the Lagoon during a flood.

The Van Rijn formulation of sand transport is generally accepted as being currently the most feasible and accurate method for estimating sand transport. However, it must be noted that sand transport is a complex interaction of processes that is still not fully understood. In order to account for these uncertainties, it is necessary to make approximations related to a number of the process interactions. Although these approximations are unavoidable, the Van Rijn method is still considered appropriate and has been combined with the TUFLOW hydraulic model to achieve realistic time-varying entrance shoal and berm levels and the accompanying simulated flood discharges.

The model allows the integration of scouring processes at the Lagoon entrance in terms of cross-sectional conveyance capacity. The scouring rate is based on inter-related parameters: flood flows, initial water levels, downstream ocean water levels and, of greatest importance, the original lagoon entrance/berm geometry.

4.2.4 Structures

There are numerous bridge and culvert crossings over the main channels within the model extents as detailed in Table 4-2 (refer to Figure 4-2 for locations). These structures vary in terms of construction type and configuration, with varying degrees of influence on local hydraulic behaviour. All major structures listed in Table 4-2 were incorporated into the hydraulic model. Incorporation of these major hydraulic structures provides for simulation of the hydraulic losses associated with these structures and their influence on peak water levels within the catchment. The structures are represented as either a 2D flow constriction element or a1D structure dependent on their relative size with consideration of the model grid resolution.

In addition to the major hydraulic structures presented in Table 4-2, a number of smaller hydraulic structures were also incorporated into the hydraulic model. These smaller structures included key stormwater drainage culverts and access road culverts.

For this study the stormwater infrastructure network was not modelled. The study focuses on mainstream flooding of Narrabeen Lagoon and its main tributaries, and accordingly, at this catchment scale, modelling of the detail of the general stormwater drainage network is not required.

4.2.5 Hydraulic Roughness

The development of the TUFLOW model requires the assignment of different hydraulic roughness (Manning's 'n') zones. These zones are delineated from aerial photography and cadastral data (refer Section 2.2) identifying different land-uses (eg. forest, cleared land, roads, urban areas, etc) for modelling the variation in flow resistance.

Table 4-2 Major Hydraulic Structures within Model Area

ID	Location	Structure Type
S1	Ocean Street (Narrabeen Lagoon)	Bridge (approx 65m span)
S2	Pittwater Road (Mullet Creek)	Bridge (approx 18m span)
S3	Pittwater Road (Narrabeen Lagoon)	Bridge (approx 51m span)
S4	Wakehurst Parkway (Deep Creek)	Bridge (approx 43m span)
S5	Wakehurst Parkway (Middle Creek)	Bridge (approx 40m span)
S6	Wakehurst Parkway (Middle Creek)	Culvert (2 x 1.5m pipe)
S7	Sydney Water Access Rd (Middle Creek)	Culvert (3 x 1.5m pipe)
S8	Wakehurst Parkway (Middle Creek)	Bridge (approx 23m span)
S9	Wakehurst Parkway (Middle Creek)	Bridge (approx 15m span)
S10	Wakehurst Parkway (Middle Creek)	Culvert (2 x 1.8m pipe)
S11	Dreadnought Road (Middle Creek)	Culvert (2 x 4.3m x 1.8m box)
S12	Dreadnought Road (Middle Creek)	Culvert (2 x 1.5m pipe)
S13	Toronto Avenue (South Creek)	Bridge (approx 12m span)
S14	Carcoola Road (South Creek)	Culvert (5 x 3.3m x 1.8m box)
S15	Willandra Road (South Creek)	Culvert (2 x 3m x 1.5m box)
S16	Akira Circuit (South Creek)	Culvert (4 x 1.35m pipe)
S17	McIntosh Road (South Creek)	Culvert (2 x 1.8m pipe)
S18	Willandra Road (Lower) (South Creek)	Culvert (1 x 3m x 1.5m box + 1 x 0.75m pipe)
S19	Willandra Bungalows Retirement Community (Wheeler Creek)	Bridge (approx 15m span)
S20	Little Willandra Road (Wheeler Creek)	Culvert (2 x 2.7m x 1.6m box + 1 x 2.7m x 1.8m box)
S21	Pittwater Road (Nareen Creek)	Culvert (8m x 1.7m box)
S22	Pittwater Road (Nareen Creek)	Culvert (7.1m x 1.5m box)
S23	Narroy Road (Nareen Creek)	Culvert (2 x 3.4m x 1.2m box)
S24	Jacksons Road (Mullet Creek)	Culvert (3 x 2.4m x 2.4m box)
S25	Garden Street (Mullet Creek)	Culvert (4 x 1.8m pipe)
S26	Jacksons Road (Narrabeen Creek)	Culvert (3 x 2.45m x 2.45m box)
S27	Boondah Road (Narrabeen Creek)	Culvert (3 x 1.05m pipe)
S28	Macpherson Street (Narrabeen Creek)	Culvert (3 x 1.2m pipe)
S29	Ponderosa Parade (Narrabeen Creek)	Culvert (2 x 1.8m pipe)
S30	Jubilee Avenue (Narrabeen Creek)	Bridge (approx 14m span)
S31	Garden Street (Fern Creek)	Culvert (1.8m x 3m box)
S32	Ingleside Road (Mullet Creek)	Culvert (3.4m x 0.9m box)
S33	Powder Works Road (Mullet Creek)	Culvert (3 x 1.8m pipe)

The following cadastral data (in both cases most recent data supplied by The Councils) was used to delineate the Manning's 'n'; surface roughness zones:

- Pittwater LGA – 2010 cadastre; and
- Warringah LGA – 2011 cadastre.

The aerial photography used to delineate the Manning's 'n' surface roughness zones was dependent upon the time period of the calibration/validation event (for example the 1998 aerial photography was used for the April 1998 calibration event). The most recent aerial photography available was used delineate the Manning's 'n' surface roughness zones for the design events.

A combination of the following aerial photography was used to delineate the Manning's 'n' surface roughness zones:

- Warringah LGA - 1998 Aerial Photography;
- Pittwater LGA – 2007 Aerial Photography;
- Warringah LGA – 2008 Aerial Photography;
- Warringah LGA – 2009 Aerial Photography;
- Narrabeen Lagoon Catchment Google Imagery; and
- Narrabeen Lagoon Catchment NearMap Imagery.

The base land use map used to assign the different hydraulic roughness zones for the design flood events is shown in Figure 4-3. In addition to the land use zones shown in Figure 4-3, all buildings within the previously mapped PMF extent were also represented as a Manning's 'n' surface roughness zone. The land use map adopted for the calibration and validation events was altered where appropriate to account for development changes that have occurred within the catchment over the past 15 years, in particular the significant development that occurred within the Warriewood Valley between the April 1998 validation event and present day design events.

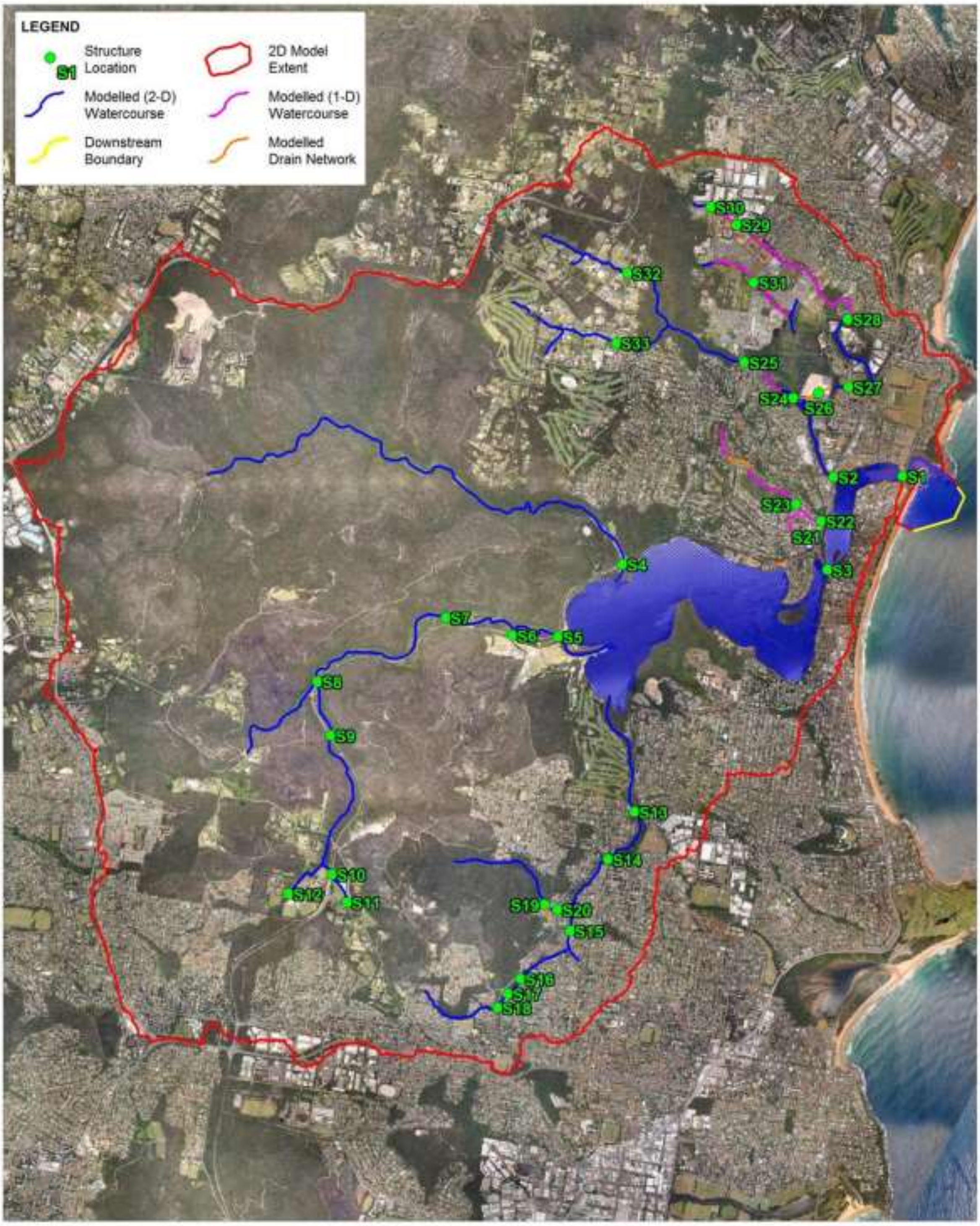
The hydraulic roughness is one of the principal calibration parameters within the hydraulic model and has a major influence on flow routing and flood levels. During the model calibration process the Manning's 'n' surface roughness values are adjusted locally (within reasonable bounds) to provide best fit for peak water level profiles. The degree of variability largely reflects the degree of channel vegetation, channel size and sinuosity.

4.2.6 Boundary Conditions

The model boundary conditions are derived as follows:

- Inflow – the catchment runoff is determined through the hydrological model and is applied to the TUFLOW model as flow vs. time inputs. These are applied at major sub-catchment inflow points and along the modelled watercourses; and
- Downstream Water Level – the downstream model limit corresponds to the tidal water level of the Tasman Sea. A water level time series has been applied at this location for the duration of the modelled events.

The adopted water levels for the downstream boundary condition for the calibration and design events are discussed in Section 5 and Section 6 respectively. The layout of the 2D hydraulic model is shown in Figure 4-2.



Title: **Linked 1D/2D TUFLOW Model Layout**

Figure: **4-2**

Rev: **A**

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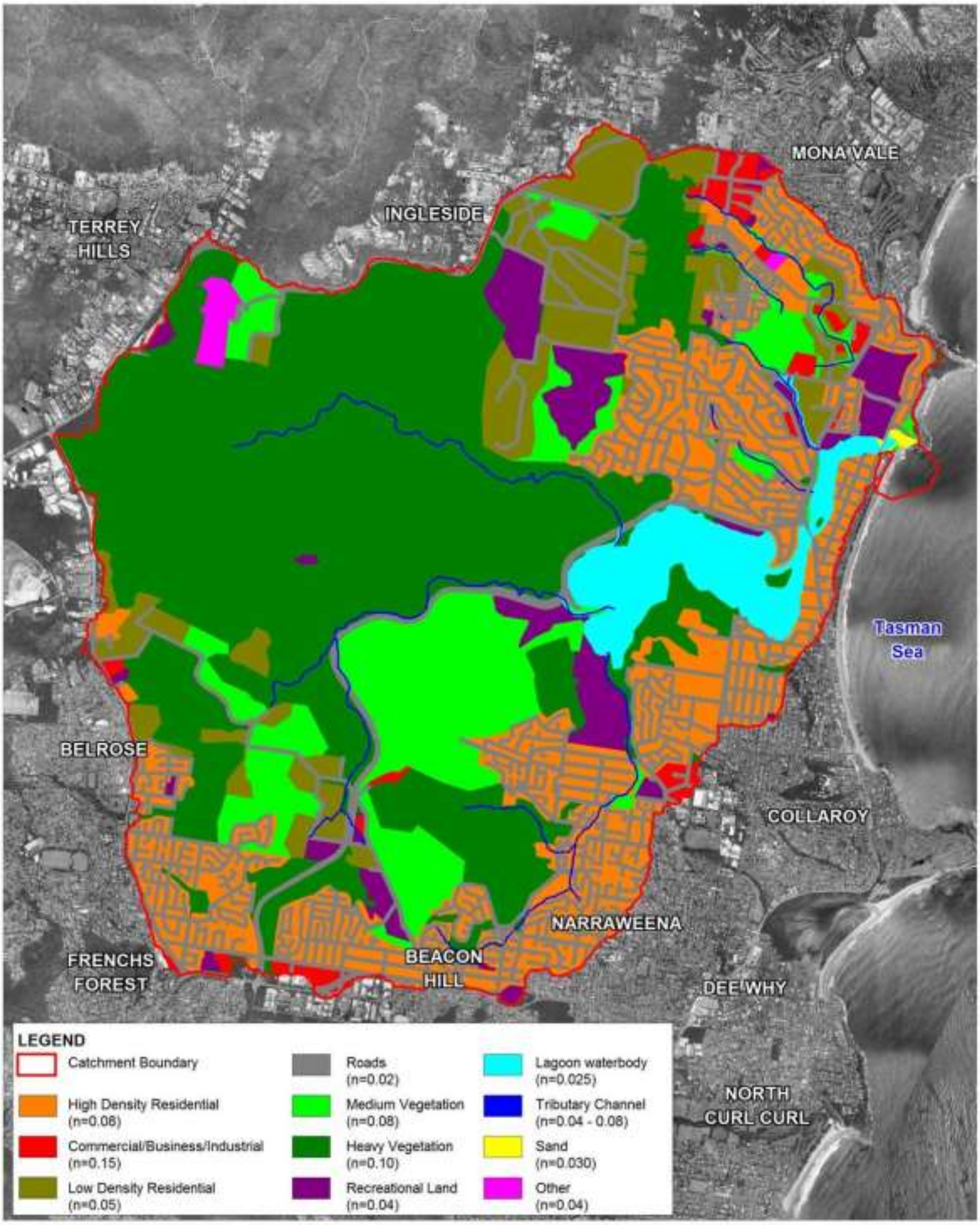

Title:
Land Use Map (and typical Manning's 'n' values)

Figure: **4-3**

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5 MODEL CALIBRATION AND VALIDATION

5.1 Selection of Calibration Events

The selection of suitable historical events for calibration and validation of flood models is largely dependent on the availability of relevant historical flood information. Ideally the calibration and validation process should cover a range of flood magnitudes to demonstrate the suitability of a model for the range of design events to be considered.

Review of the available rainfall and water level data for the Narrabeen Lagoon catchment highlighted three flood events with sufficient data to support a calibration process – the April 1998, August 1998 and March 2011 event. The April 1998 event has been selected as the primary calibration event due to the fact that it resulted in the highest recorded Lagoon water levels since the installation of the MHL water level gauges. Due to data availability, the March 2011 and August 1998 events have been used for model validation. It should be noted that the existing water level gauges do not directly provide flow information (i.e. not flow gauging stations). Accordingly direct calibration of model flows cannot be undertaken.

The majority of the photographs and other anecdotal reports of flooding received from the community through the questionnaire returns largely related to flooding in the lower end of the system around the Lagoon foreshore, particularly for the March 2011 event. The information received does not add significant additional calibration data given the majority of photographs/reports can be correlated to the Lagoon water level data from the existing gauges.

The March 1942 and May 1974 events are noted with the highest recorded water levels in Narrabeen Lagoon. These events however have not been adopted for calibration purposes given the limited data availability for March 1942 event and the May 1974 being predominantly a storm surge event.

5.2 April 1998 Model Calibration

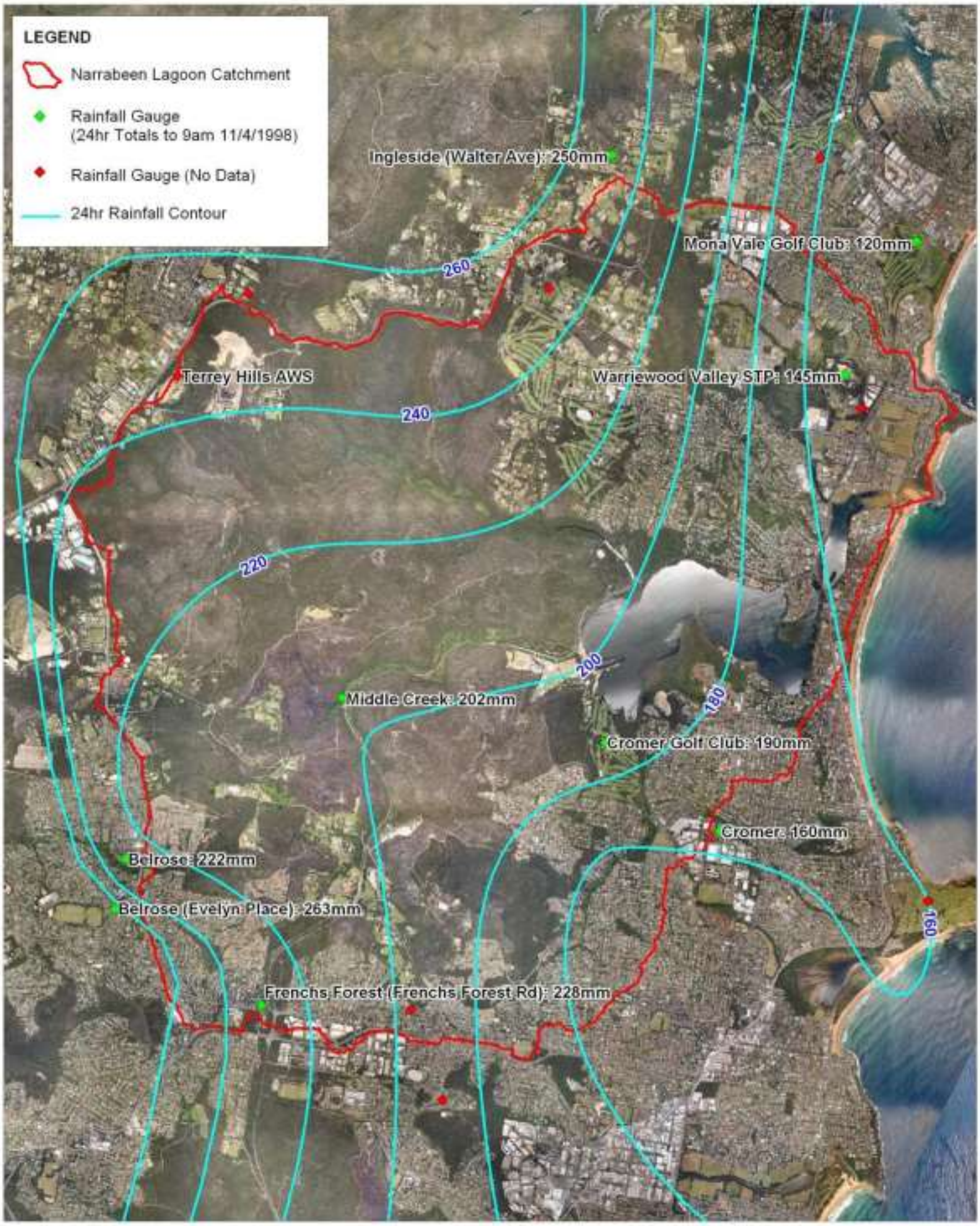
5.2.1 Calibration Data

5.2.1.1 Rainfall Data

There were nine active rainfall gauges within or in close proximity to the Narrabeen Lagoon catchment for the April 1998 event. Three of these gauges were continuous read gauges operated by MHL, one gauge was a continuous read gauge operated by Sydney Water, with the remaining five gauges being daily read gauges operated by BoM.

The recorded daily totals (for the 24 hours to 9am) for the period 9am April 10th – 11th 1998 are summarised inTable 5-1. The adopted rainfall distribution for the April 1998 event is shown in Figure 5-1.

The recorded hyetographs at the active continuous rainfall gauges within the Narrabeen lagoon catchment or in the near vicinity are shown in Figure 5-2. The hyetograph period shown is from 9:00am 10th April to 9:00am 11th April 1998.



Title: **April 1998 Rainfall Distribution**

Figure: **5-1**

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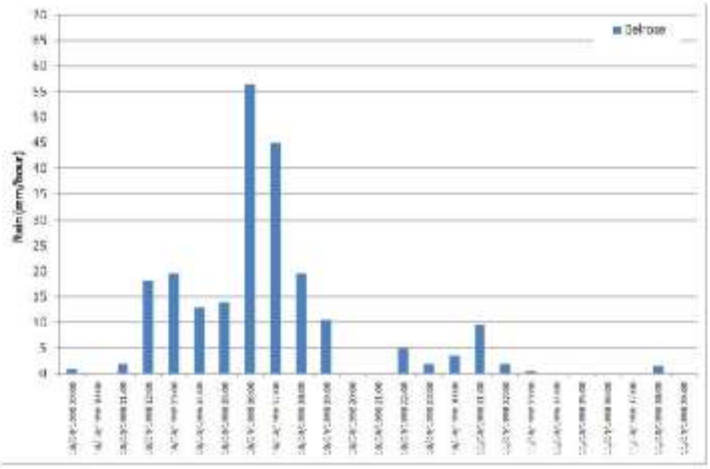
Table 5-1Recorded Rainfall April 1998 Event

Gauge Location	Operator	24 hr Total (to 9am 10/04/98) (mm)	24 hr Total (to 9am 11/04/98) (mm)
Middle Creek	MHL	38	202
Cromer	MHL	31	160
Belrose	MHL	30	222
Warriewood Valley STP	Sydney Water	42	145
Ingleside	BoM	48	250
Cromer Golf Club	BoM	35	190
Mona Vale Golf Club	BoM	40	120
Frenchs Forest Rd	BoM	32	228
Belrose (Evelyn Place)	BoM	30	263



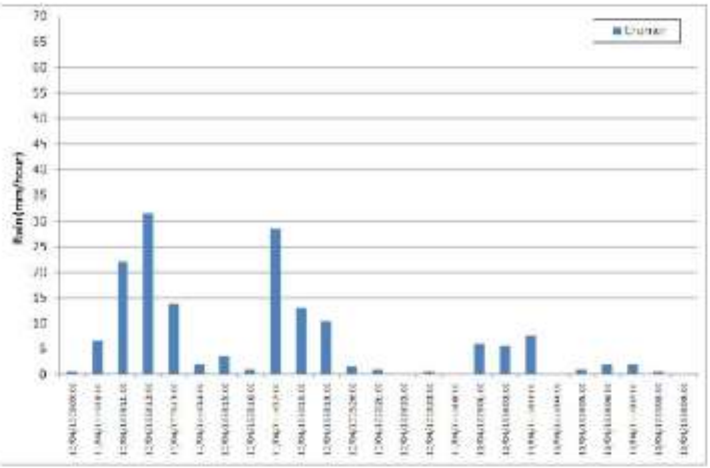


Figure 5-2 April 1998 Recorded Rainfall

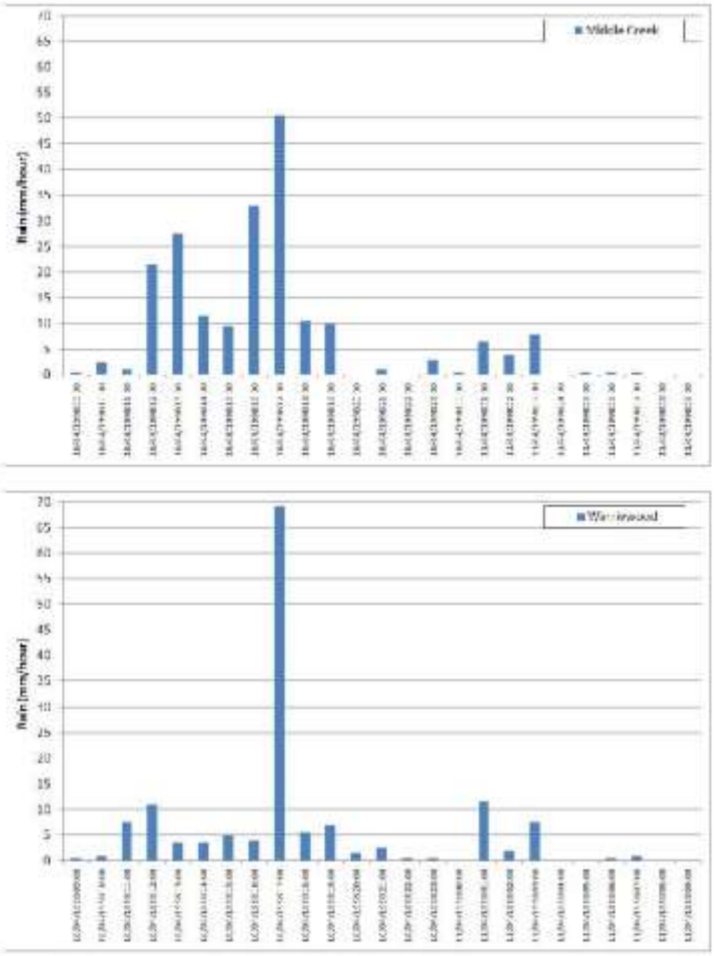


Figure 5-2 April 1998 Recorded Rainfall

To gain an appreciation of the relative intensity of the April 1998 event, the recorded rainfall depths at the Middle Creek MHL continuous read rainfall gauge for various storm durations were compared with the design IFD data for the Narrabeen Lagoon catchment as shown in Figure 5-3. The April 1998 event generally tracks above the design 5% AEP (20-year ARI) rainfall depth for the duration of the event, and above the 10% AEP (10-year ARI) event for the 6 to10 hour durations. For the Middle Creek continuous read rainfall gauge the following comparisons to design rainfall depths can be made for the April 1998 event:

- 6-hour duration – 146mm recorded compared with 148mm design 5% AEP;
- 9-hour duration – 175mm recorded compared with 175mm design 5% AEP;
- 12-hour duration – 179mm recorded compared with 194mm design 5% AEP;
- 18-hour duration – 201mm recorded compared with 198mm design 10% AEP; and
- 24-hour duration – 203mm recorded compared with 221mm design 10% AEP.

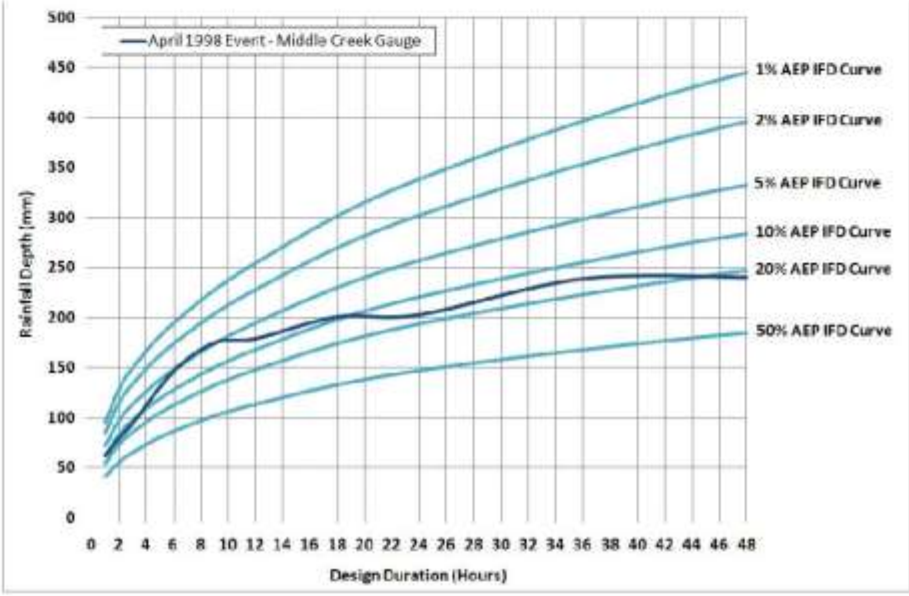


Figure 5-3 Comparison of April 1998 Rainfall with IFD Relationships

5.2.1.2 Water Level Data

There were three active water level gauges operating within the Narrabeen Lagoon catchment during the April 1998 event – Middle Creek (on the Middle Creek tributary), Pittwater Road Bridge (Narrabeen Lagoon) and Ocean Street Bridge (Narrabeen Lagoon).

The recorded water level time series at each gauge location for the April 1998 event is shown in Figure 5-4. The time series shown includes the initial response at the onset of the event, the peak water levels and the recession for some 20-hours after the flood peak.

For the start of the simulation period as shown in Figure 5-4, the water level in Narrabeen Lagoon (as recorded at the gauges) is approximately 0.46m AHD. Initial water levels in the model have been set to this level for the event simulation.

5.2.2 Rainfall Losses

Typical design loss rates applicable for NSW catchments east of the western slopes are initial loss of 10 to 35 mm and continuing loss of 2.5mm/hr (AR&R, 2001). For historical events however, the initial loss is indicative of the catchment wetness and any rainfall that fell prior to the modelled storm burst.

Initial rainfall losses of 10mm, 20mm and 30mm have been simulated for the April 1998 event. An initial loss of 30mm was found to provide the best fit to the observed hydrological behaviour in the Narrabeen Lagoon catchment for the April 1998 event.

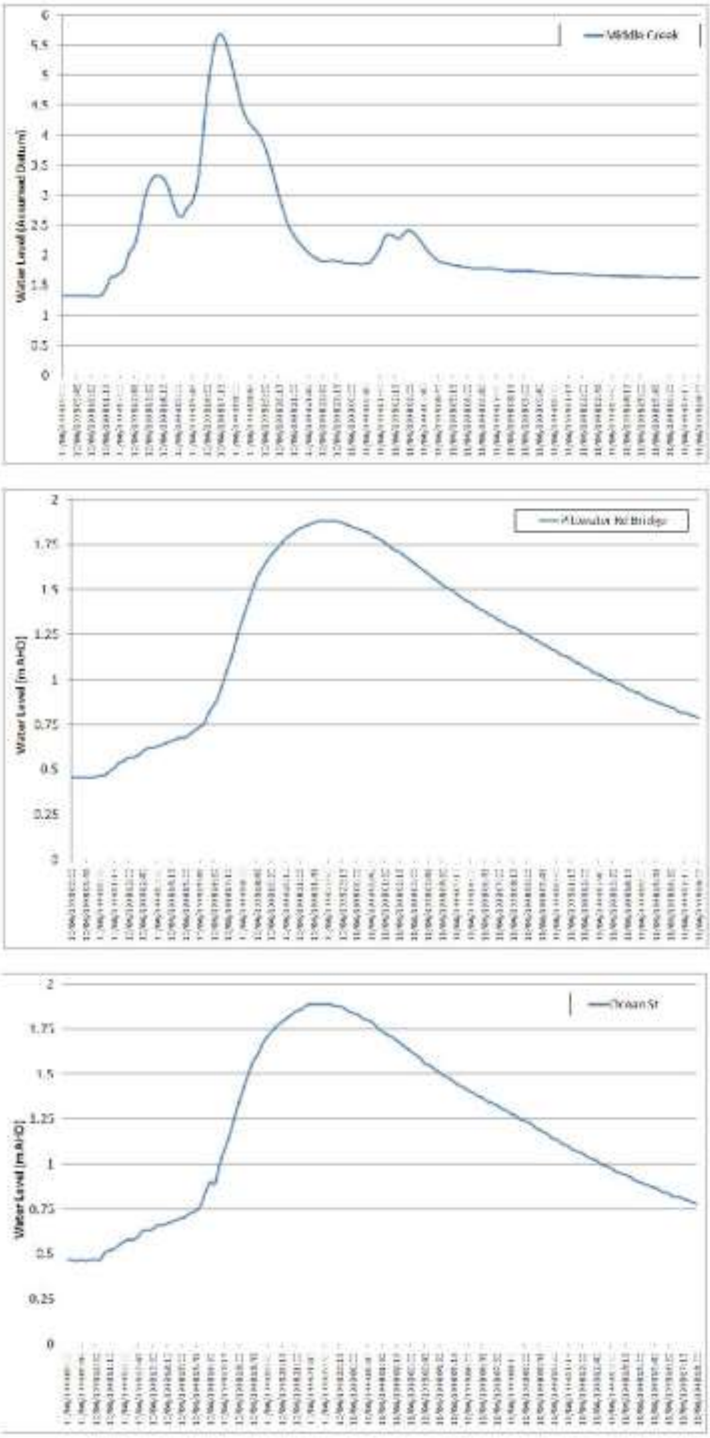


Figure 5-4 April 1998 Recorded Water Levels

5.2.3 Downstream Boundary Conditions

Ocean tide (water level) data was available for the April 1998 event from a continuous tide gauge maintained by MHL at Middle Head. This water level data is considered to be representative of the ocean water levels at the Narrabeen Lagoon entrance and as such was used as the downstream boundary for the April 1998 event. The relationship between recorded ocean water levels and recorded rainfall for the April 1998 event is shown in Figure 5-5.

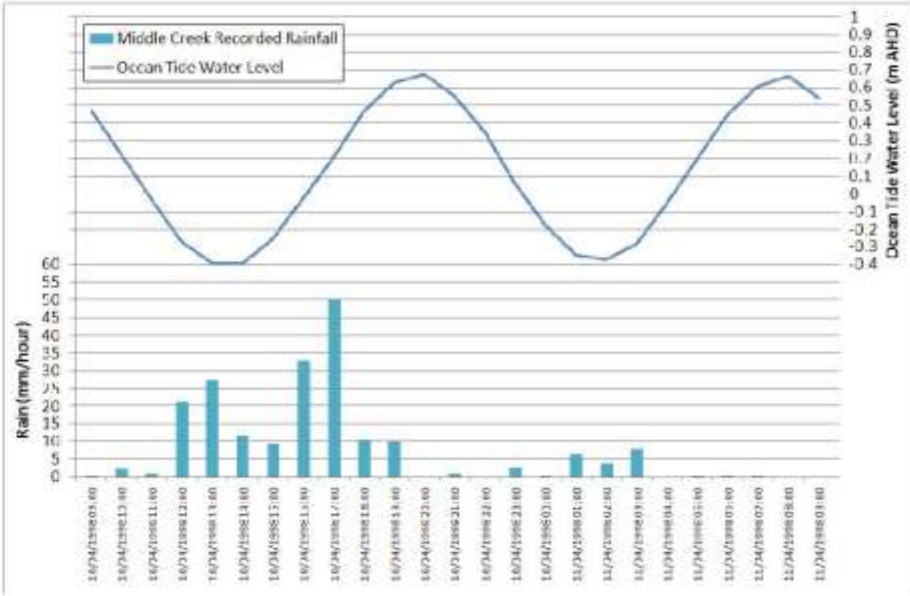


Figure 5-5 April 1998 Recorded Tidal Water Level

5.2.4 Lagoon Entrance Bathymetry

The modelled bathymetry of the Lagoon entrance can significantly impact on the response of modelled Lagoon levels to catchment inflows and tides. Ideally, for full calibration of the entrance dynamics, bathymetric survey data of the entrance before and after the event would be available. However, this data was not available for the April 1998 calibration event (nor was it available for the August 1998 or March 2011 validation events).

Inspection of the available aerial photography of the Narrabeen Lagoon entrance (shown in Figure 5-6), shows that the entrance is typically semi-shoaled, with a channel running along the northern rock wall before flowing across the berm and into the Tasman Sea. Figure 5-6 also shows the mass of sand that is gradually deposited downstream of the Ocean St Bridge and the channel that forms along the southern shoreline of the Lagoon to enable flow through the Ocean St Bridge structure.

Title:
Narrabeen Lagoon Entrance Aerial Photography

Figure: 5-6

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The February 2005, July 2006 (pre-dredge) and August 2011 (pre-dredge) bathymetric survey data is shown in Figure 5-7. A comparison of the three surveys shows the February 2005 survey represents a relatively open Lagoon condition, the August 2011 survey represents a semi-shoaled entrance condition and the July 2006 survey represents a relatively closed entrance condition. In the absence of event specific survey data, the semi-shoaled August 2011 Lagoon entrance condition was adopted for the calibration and validation events. The semi-shoaled entrance condition was considered representative of the average long term entrance condition for the Narrabeen Lagoon.

It is acknowledged that configuration of entrance channel shoals is highly dynamic in response to coastal processes. Furthermore, the Councils undertake periodic maintenance dredging of the entrance channel. Comparisons between pre and post dredge bathymetric surveys (shown in Figure 5-8) show the changes that occur within the Lagoon entrance as a result of dredging works. These dredging works have the potential to significantly change the flood behaviour of the Narrabeen Lagoon. Sensitivity testing of the Lagoon entrance condition has been undertaken using the 2006 post-dredge bathymetric survey data (see Section 7.7 for further discussion of sensitivity tests).

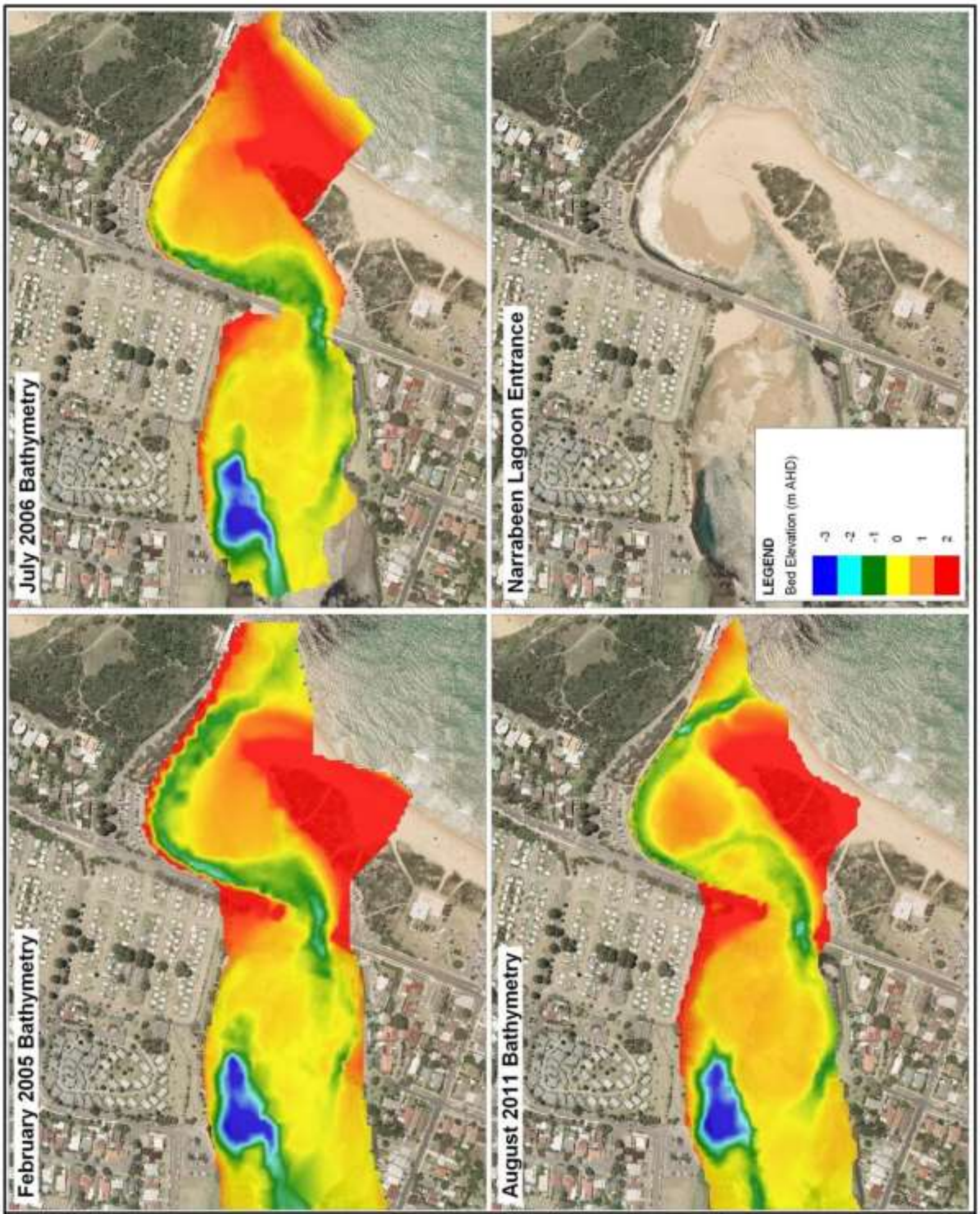
5.2.5 Adopted Model Parameters

The model calibration centred around the adjustment of the sub-catchment PERN values, Bx storage coefficient factor and rainfall loss values (hydrological model parameters) and the Manning's 'n' values for the floodplain and channel (hydraulic model parameters).

The final parameter values adopted, as shown in Table 5-2 were found to give a good result in representing the hydrological and hydraulic behaviour in the Narrabeen Lagoon catchment for the April 1998 event.

Table 5-2 April 1998 Model Parameters

Parameter	Value	Comment
Initial Loss (mm): pervious area impervious area	 30 5	The 30mm initial loss provided the best fit for initial catchment response and total storm volumes with respect to available data for the 1998 event.
Continuing Loss (mm/hr): pervious area impervious area	 2.5 0	As recommended in AR&R (2001).
Storage coefficient factor Bx	1.0	Rafts software default value found appropriate
PERN (roughness value for hydrological model)	0.015 -0.10	Variable adjusted dependent on surface coverage – e.g. 0.015 for hardstand/impervious areas to 0.10 for forested catchment.
Manning's 'n' roughness value for hydraulic model (lagoon and tributaries)	0.04 -0.06	Variable adjusted locally (within reasonable bounds) to provide best fit for peak water level profiles. Variability largely reflects degree of channel vegetation, channel size and sinuosity.
Manning's 'n' roughness value for hydraulic model (floodplain)	0.02 – 0.20	Variable adjusted locally (within reasonable bounds) to provide best fit for peak water level profiles. Variability largely reflects land use on the floodplain (cleared, forested, roads, urban lots)



Title:
Narrabeen Lagoon Entrance Bathymetry

Figure: **5-7**
Rev: **A**

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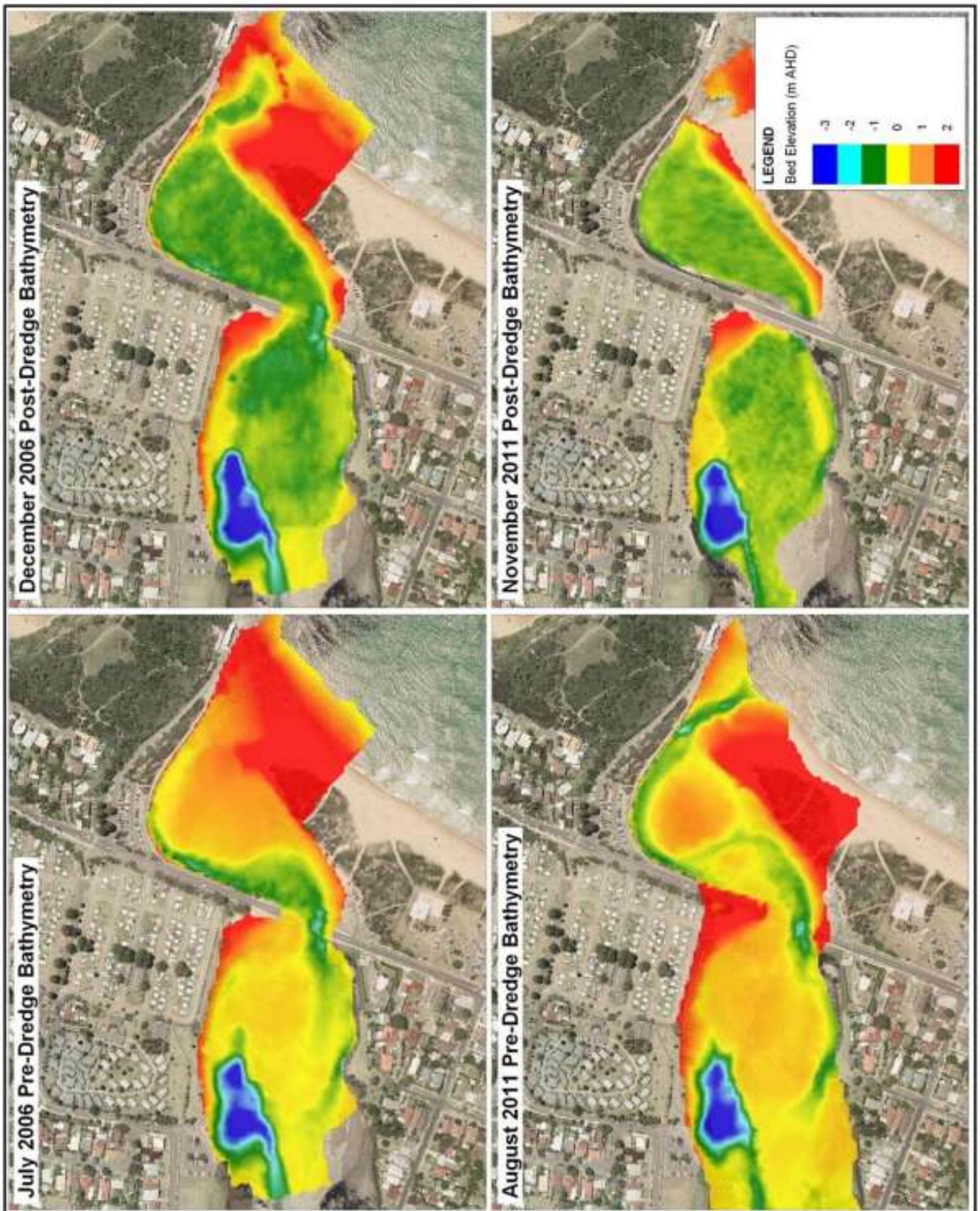

Title:
Narrabeen Lagoon Pre and Post Dredge Entrance Bathymetry

Figure: **5-8**

Rev: **A**

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5.2.6 Observed and Simulated Flood Conditions April 1998

Calibration data for the April 1998 event includes available water level time series at the Middle Creek, Pittwater Road and Ocean Street gauges; and a series of water level calibration points defined in previous flood studies completed in the catchment.

None of the water level gauges are flow gauging stations, such that a direct flow calibration is not possible. However, given the large storage associated with the body of the Lagoon, the water level time series provides for a simplified flow calibration on the basis of rates of rise and total flood volumes generated.

A comparison of recorded and simulated water level profiles in Narrabeen Lagoon for the April 1998 event are shown in Figure 5-9 and Figure 5-10 for the Ocean Street and Pittwater Road gauges respectively. The simulated results show that a good model calibration has been achieved for a number of aspects of the simulated catchment flood behaviour:

- Catchment runoff response – the relative timing of the observed and simulated water level hydrographs show an excellent agreement throughout the simulated event. This shows the catchment runoff processes are being well simulated including the initial catchment response from the wetting-up period (incorporating rainfall losses) and the general rise of water levels in the Lagoon indicating a good simulation of the relative timing of the main tributary inflows.
- Peak flood levels – the peak flood levels show a good agreement. There is some slight discrepancy in the peak level at Ocean Street and Pittwater Road being slightly higher than recorded. The simulated results do show a slight water level gradient at the peak of the event being generated in the modelled condition which is not evident in the recorded levels.
- Total flood volumes – the area under the water level time series graph is indicative of the total flood volume for the event. As evident in the observed vs. simulated comparisons, both water level profiles generally track the same for the duration of the event, and accordingly the total volumes would appear to be in good agreement. The adopted rainfall depth distribution and the modelled initial and continuing loss parameters provide for a good representation of total runoff volume generated from the catchment.

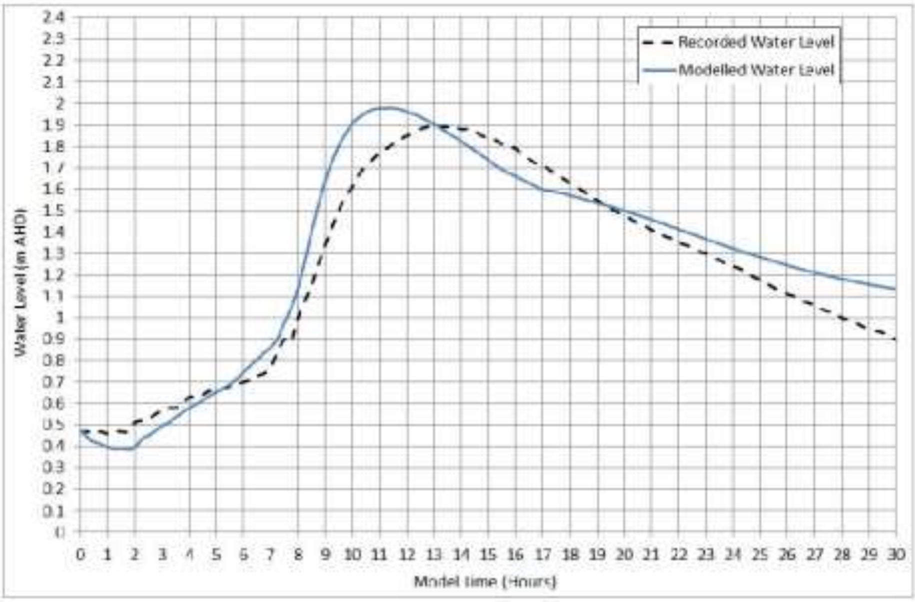


Figure 5-9 Ocean Street Water Level Calibration – April 1998

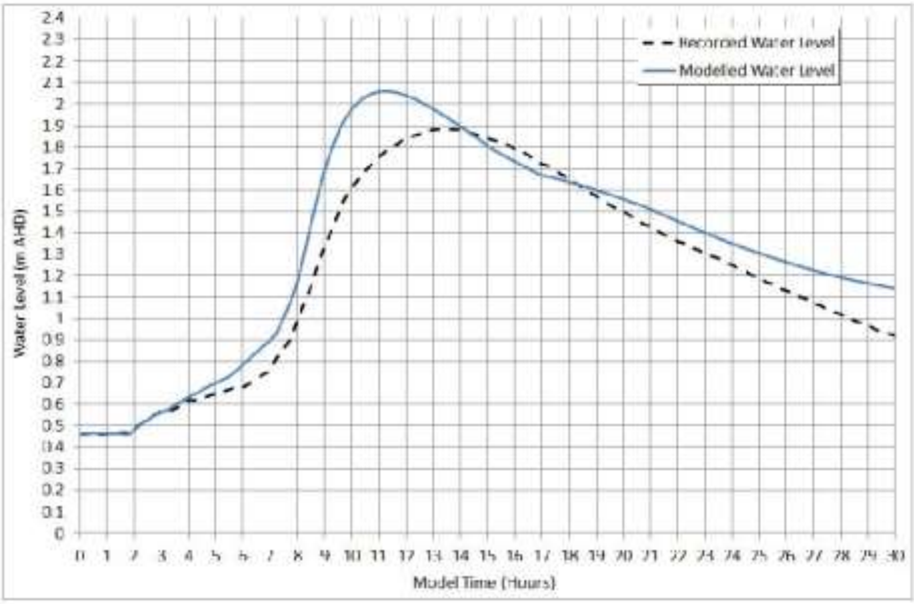


Figure 5-10 Pittwater Road Bridge Water Level Calibration – April 1998

The comparison of recorded and simulated water levels at the Middle Creek gauge is shown in Figure 5-11. The simulation of the absolute peak water level at this site is similar to that achieved at the Lagoon gauges. In contrast to the Lagoon body where water levels are a function of the total volumes entering the system and the stage-volume relationship of the Lagoon, the water levels at the Middle Creek gauge are driven by local hydraulic controls of the creek and are also much more sensitive to the timing of rainfall bursts. Nevertheless, the simulated profile presented in Figure 5-11 shows a good result from the perspective of the simulated hydrological conditions. The recorded water level profile shows two distinct peaks which are also shown in the modelled results. Both the timing and relative magnitude of the modelled peaks show a good match to the observed conditions. Accordingly, it can be taken that the models are performing reasonably well in simulating the catchment response to rainfall.

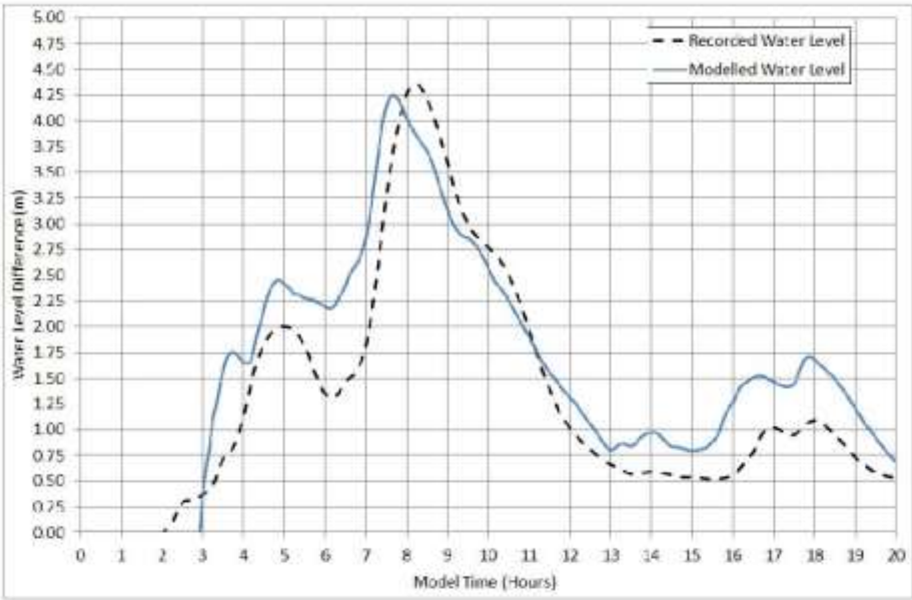
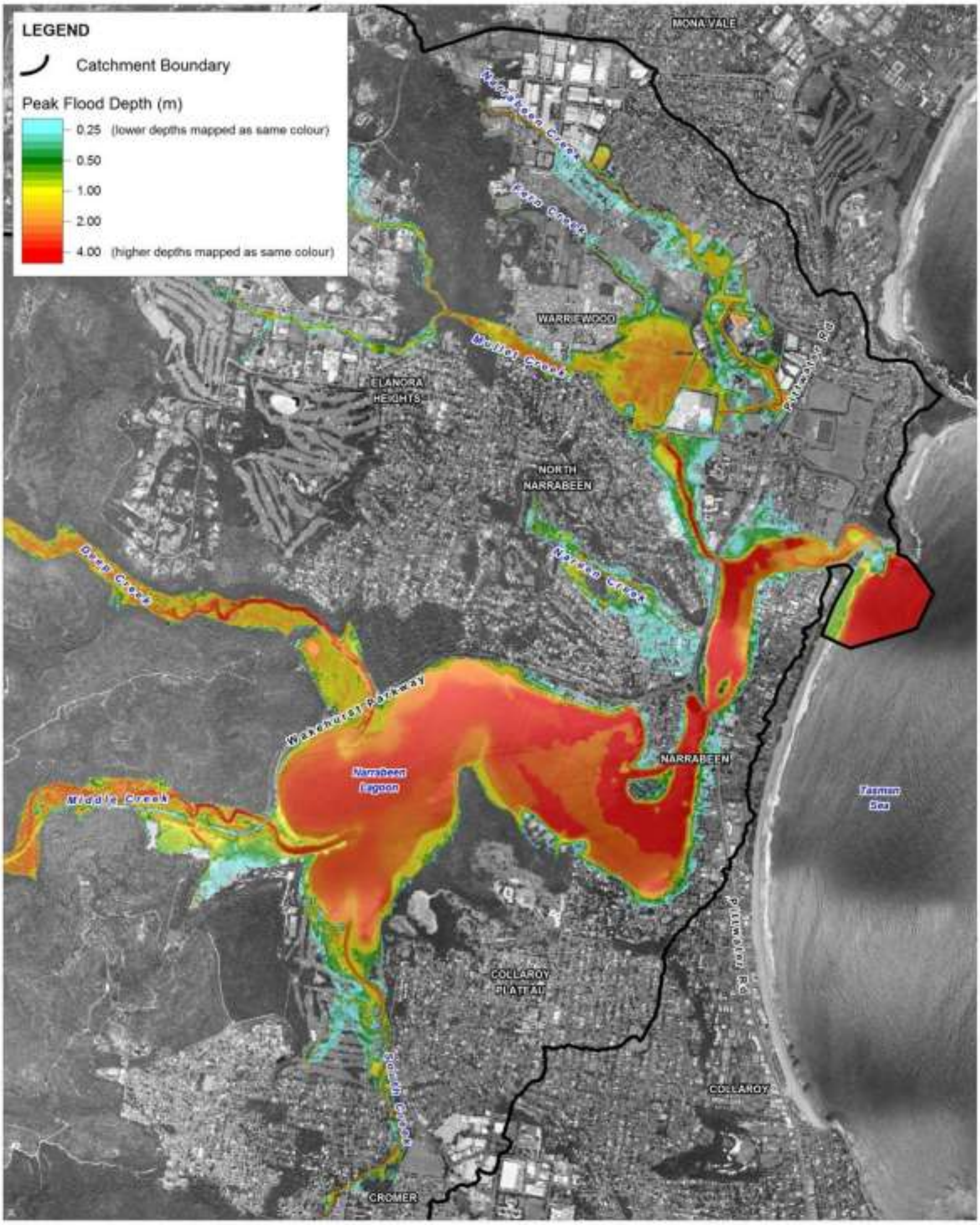


Figure 5-11 Middle Creek Water Level Calibration – April 1998

There are a number of uncertainties in the simulated hydrological conditions, not in the least the assumed spatial and temporal distribution of rainfall which may have a significant influence on the catchment generated runoff. Overall the simulated catchment response is considered a good representation of the observed conditions. The deviations in the timing, shape and peak levels of simulated hydrographs from observed conditions are within acceptable bounds considering uncertainties in the data such as spatial and temporal variations in rainfall across the catchment.

In terms of the catchment wide response, the simulated inundation extent for the April 1998 event is shown in Figure 5-12. The simulated conditions indicate that out-of-bank flooding is relatively minor in the upper catchment areas of Middle Creek, South Creek and Deep Creek with the floodwaters generally confined to the within the main creek alignments.

The major inundation occurs around the Lagoon foreshore area as a result of elevated Lagoon water levels and in the major flood storage area of the Warriewood Wetlands.



Title: **April 1998 Simulated Peak Flood Inundation**

Figure: 5-12

Rev: A

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5.3 March 2011 Model Validation

The March 2011 flood has been used as a model validation event, given the availability of rainfall and water level data as well as information provided during the community consultation process (e.g. photographs).

5.3.1 Validation Data

5.3.1.1 Rainfall Data

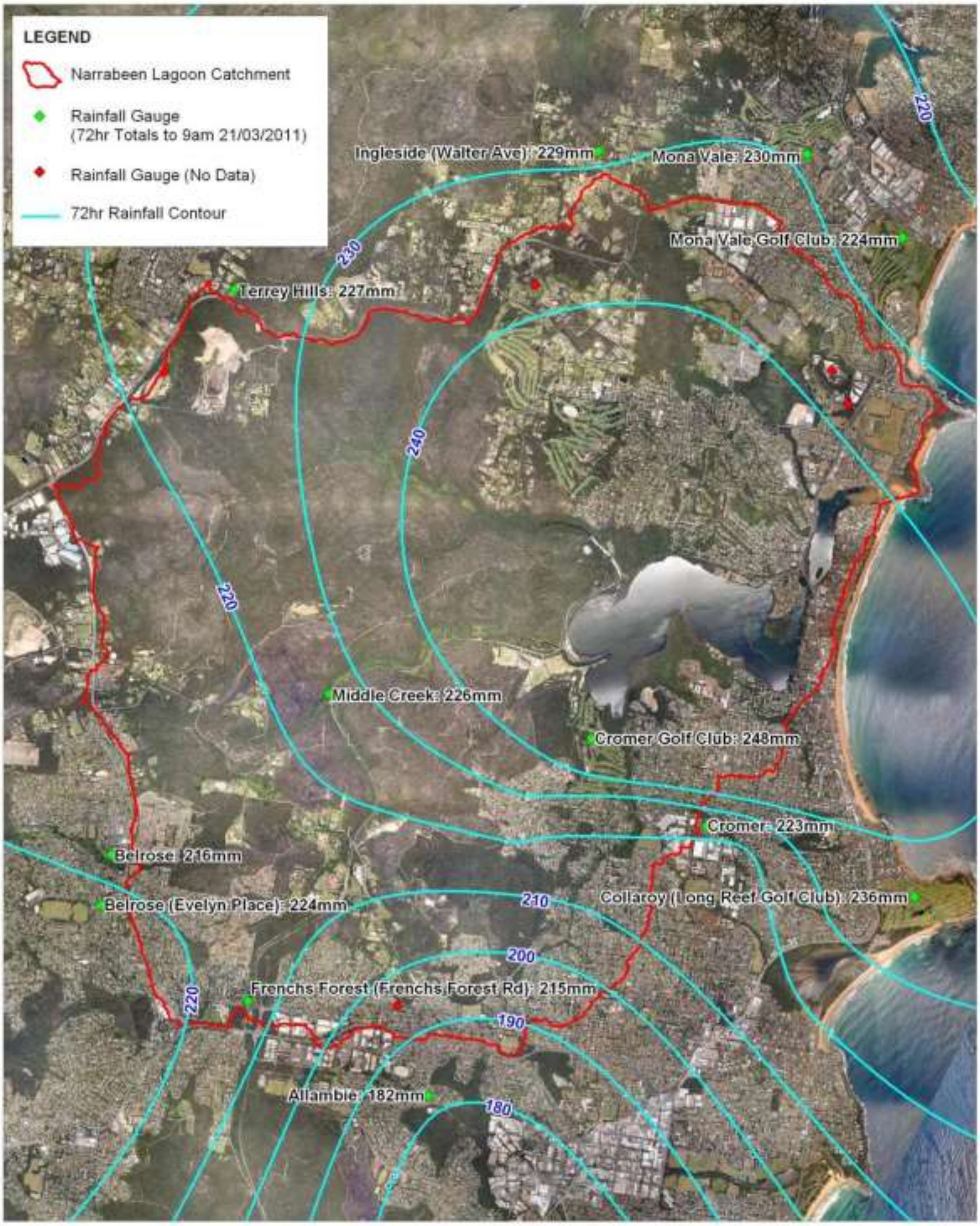
There were twelve active rainfall gauges within or in close proximity to the Narrabeen Lagoon catchment for the March 2011 event. Five of these gauges were continuous read gauges operated by MHL with the remaining seven gauges being daily read gauges operated by BoM. The recorded daily totals (for the 24 hours to 9am) from March 19th – 21st 2011 for the twelve active rainfall gauges are summarised in Table 5-3 (the recorded rainfall at Ingleside BoM gauge was in the form of a 3-day total from 9am 19/3/2011 to 9am 21/3/2011).

Table 5-3 Recorded Rainfall March 2011 Event

Gauge Location	Operator	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)
Middle Creek	MHL	46	135	45	226
Cromer	MHL	62	121	40	223
Belrose	MHL	60	121	35	216
Mona Vale	MHL	82	107	41	230
Allambie	MHL	45	100	37	182
Terrey Hills	BoM	61	126	40	227
Cromer Golf Club	BoM	61	122	65	248
Mona Vale Golf Club	BoM	71	106	47	224
Frenchs Forrest Rd	BoM	56	119	40	215
Belrose (Evelyn Place)	BoM	57	137	30	224
Collaroy (Long Reef Golf Club)	BoM	79	115	42	236
Ingleside	BoM	229			229

As shown in Table 5-3, there was extensive rainfall across the local area over a 3-day recording period. The majority of the rain fell in the 24-hours to 9:00am on the 20th March, however, this was preceded by substantial falls recorded on the 19th March, and followed by further substantial falls recorded on the 21st March. The combined 72-hour totals across the catchment were typically in excess of 220mm, with the Cromer Golf Club gauge recording the highest 3-day total of some 248mm.

The daily rainfall totals for both the continuous and daily read gauges were used to derive a spatial distribution of rainfall across the Narrabeen Lagoon catchment. The estimated rainfall distribution for the March 2011 event is shown in Figure 5-13.



Title:
March 2011 Rainfall Distribution

Figure: **5-13**

Rev: **A**

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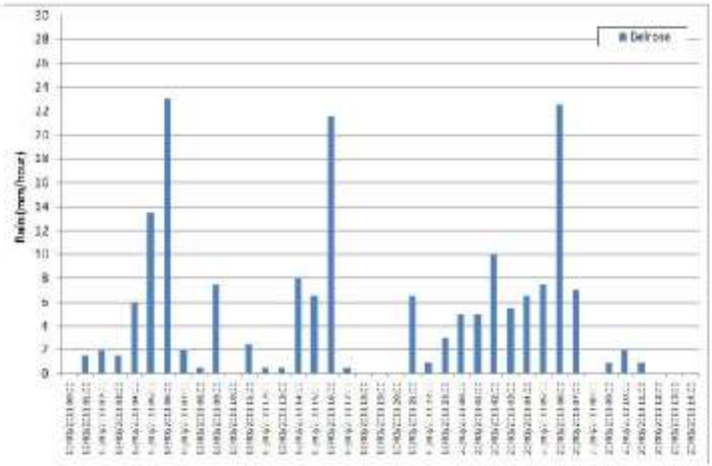
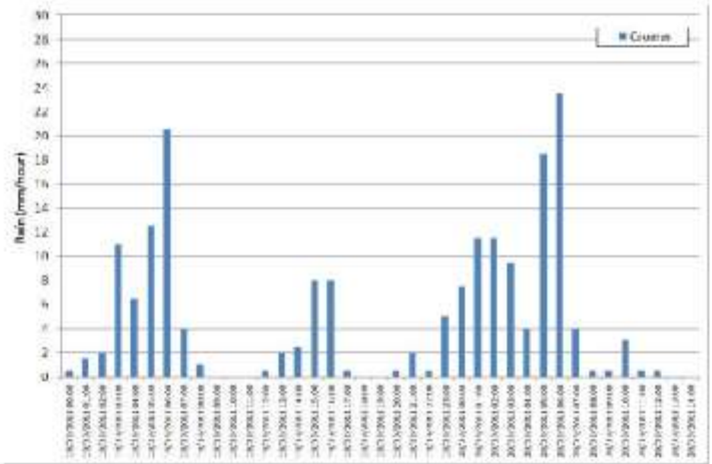
The recorded hyetographs at the continuous read rainfall gauges within the Narrabeen Lagoon catchment or in the near vicinity are shown in Figure 5-14. The hyetograph period shown is from 12:00am 19th March to 2:00pm 20th March 2011, corresponding the period of the main rainfall resulting in the peak flood levels attained in Narrabeen Lagoon.

As evidenced in the recorded hyetographs, there is some variability across the gauges in terms of the relative intensities and rainfall depths across the period. Typically however, all continuous read gauges show that the rainfall generally fell within three distinct bursts.





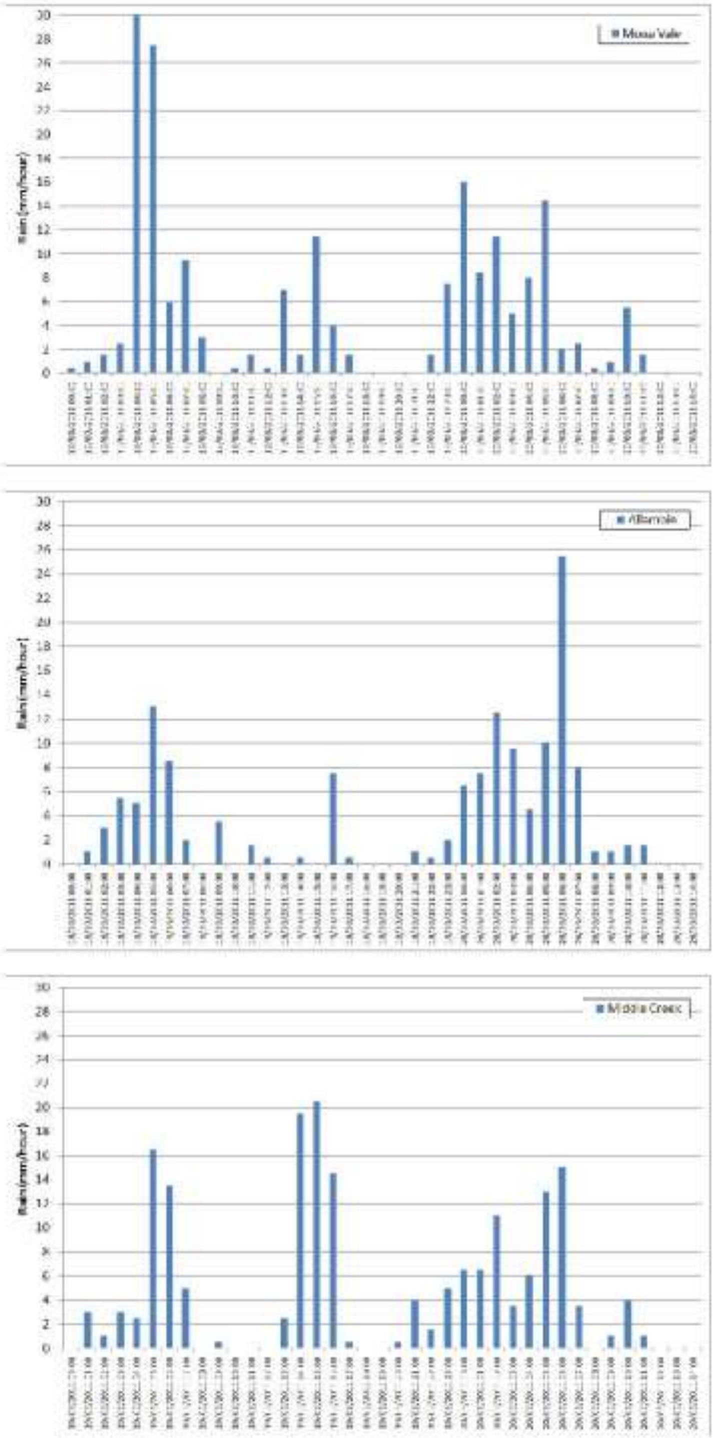


Figure 5-14 March 2011 Recorded Rainfall

To gain an appreciation of the relative intensity of the March 2011 event, the recorded rainfall depths at the Middle Creek MHL continuous read rainfall gauge for various storm durations were compared with the design IFD data for the Narrabeen Lagoon catchment as shown in Figure 5-15. The March 2011 event generally tracks the design 50% AEP (2-year ARI) rainfall depth for the duration of the event. For the Middle Creek continuous read rainfall gauge the following comparisons to design rainfall depths can be made for the March 2011 event:

- 12-hour duration –93mm recorded compared with 113mm design 50% AEP;
- 18-hour duration –131mm recorded compared with 133mm design 50% AEP;
- 24-hour duration –140mm recorded compared with 147mm design 50% AEP;
- 36-hour duration –185mm recorded compared with 168mm design 50% AEP; and
- 48-hour duration –190mm recorded compared with 185mm design 50% AEP.

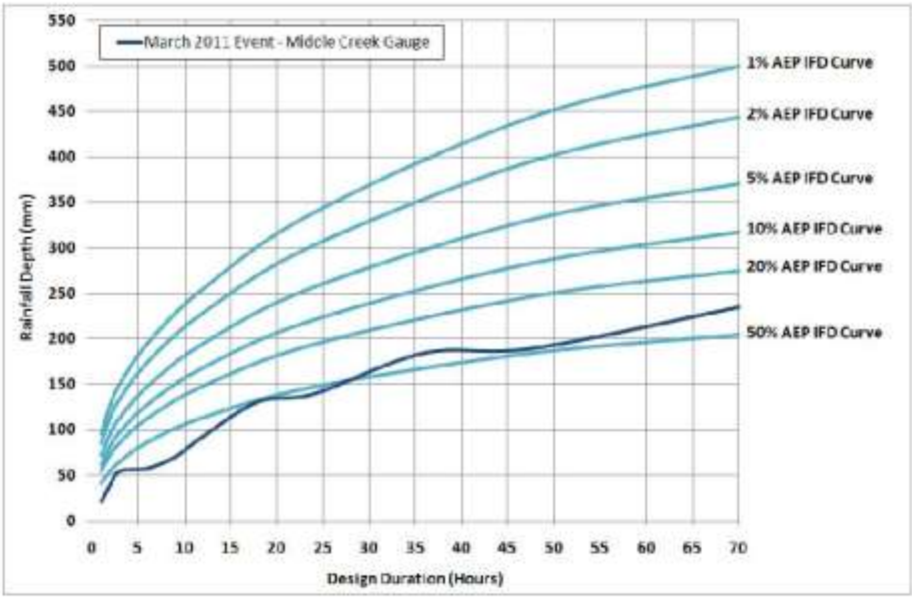


Figure 5-15 Comparison of March 2011 Rainfall with IFD Relationships

5.3.1.2 Water Level Data

There were three active water level gauges operating within the Narrabeen Lagoon catchment during the March 2011 event – Middle Creek (on the Middle Creek tributary), Pittwater Road Bridge (Narrabeen Lagoon) and Ocean Street Bridge (Narrabeen Lagoon).

The recorded water level time series at each gauge location for the March 2011 event is shown in Figure 5-16. The time series shown covers a period of some 3-days. As noted in the rainfall analysis, three separate significant rainfall periods occurred during the event. The timing of these rainfall bursts resulted in a gradual rise in water levels in the lagoon over a period of some 36-hours from the initial response to the peak water level condition in the lagoon. A further 36-hour period showing the recession of the event is also included in Figure 5-16.

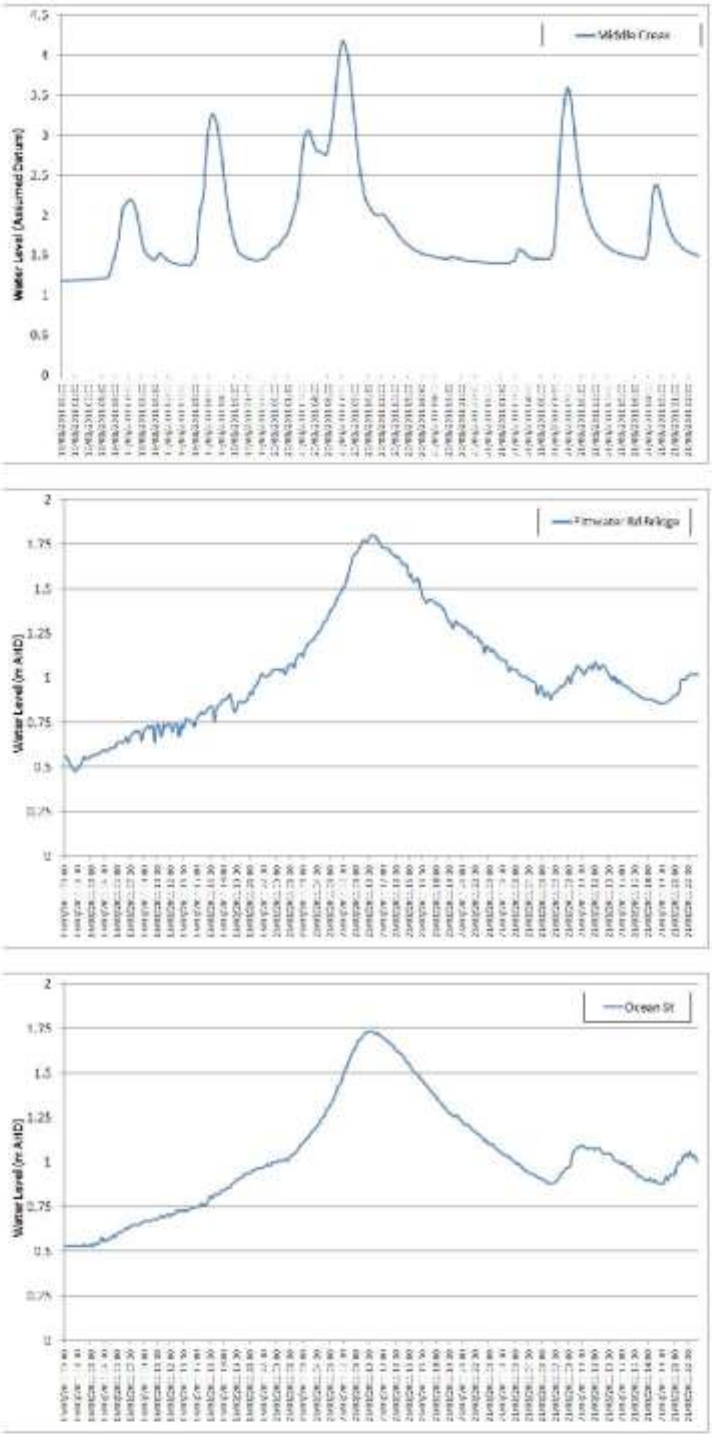


Figure 5-16 March 2011 Recorded Water Levels

5.3.2 Downstream Boundary Conditions

Ocean tide (water level) data was available for the March 2011 event from a continuous tide gauge maintained by MHL at Middle Head. This water level data is considered to be representative of the ocean water levels at the Narrabeen Lagoon entrance and as such was used as the downstream boundary for the March 2011 event. The relationship between recorded ocean water levels and recorded rainfall for the March 2011 event is shown in Figure 5-17.

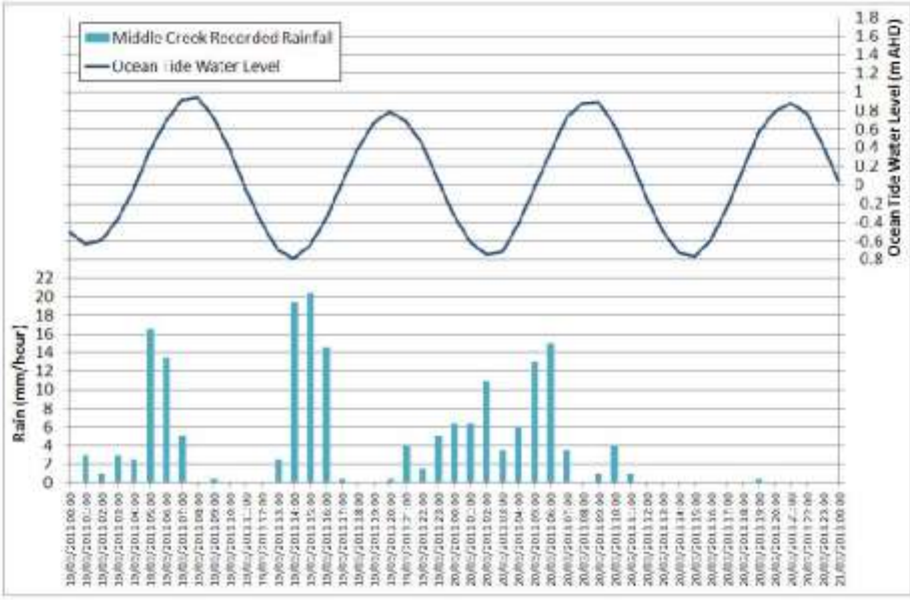


Figure 5-17 March 2011 Recorded Tidal Water Level

5.3.3 Observed and Simulated Flood Conditions March 2011

Similar to the April 1998 event, validation data for the catchment is limited to the available water level time series at the Middle Creek, Pittwater Road and Ocean Street gauges. A comparison of recorded and simulated water level profiles in Narrabeen Lagoon for the March 2011 event are shown in Figure 5-18 and Figure 5-19 for the Ocean Street and Pittwater Road gauges respectively. The simulated results generally show a reasonable comparison between the recorded and simulated profiles. Some of key the aspects of the simulated catchment flood behaviour include:

- Catchment runoff response – similar to the reported calibration for the April 1998 event, the relative timing of the observed and simulated water level hydrographs show an excellent agreement throughout the simulated event. This shows the catchment runoff processes are being well simulated including the initial catchment response from the wetting-up period (incorporating rainfall losses) and the general rise of water levels in the Lagoon indicating a good simulation of the relative timing of the main tributary inflows.
- Peak flood levels – the peak Lagoon flood levels are underestimated in the model simulation of the order of 0.1m. Throughout the initial part of the event, the water levels are typically well simulated. The major discrepancy in water levels arises near the peak of the event. The

under-prediction of this event can be attributed to the adopted rainfall distribution across the catchment does not quite match the actual rainfall that fell particularly in the last rainfall burst. This under-prediction highlights the uncertainty in establishing a continuous rainfall distribution across the catchment using point values recorded at a limited number of gauge locations.

It is appropriate to compare the recorded and observed water levels at the Middle Creek gauge as shown in Figure 5-20. As noted in the discussion of the April 1998 event calibration (refer Section 5.2.6), the influence of local hydraulic controls on the simulated results provides for discrepancy between the absolute water levels in comparison to recorded data. However, similar to the April 1998 event, the catchment response in terms of timing is well simulated. This is particularly evident when comparing the timing of the rise and falls associated with the three distinct peaks recorded at the Middle Creek gauge (refer Section 5.3.1.2). What is evident however, is a discrepancy between the relative magnitude of each of the peaks. The recorded condition shows an escalation in the magnitude of each successive peak. The simulated condition also shows an escalation in the magnitude of the each successive peak but underestimates the final peak level. This underestimation can be partly attributed to the adopted rainfall patterns with reference to the recorded hyetographs shown in Figure 5-14.

- Total flood volumes – the simulated water level time series at the Lagoon gauges show an under-prediction towards the peak of the event. As a result, the total area under the water level hydrograph being indicative of total peak runoff volumes is under-predicted. This apparent under-prediction in volume can also be described by the similar affects discussed in comparing the peak water levels. The simulated discharge from the Lagoon at the peak event may be too efficient resulting in a more rapid than expected recession – it is noted the peak coincided with a high tide condition, such that the entrance hydrodynamics can have a major influence on lagoon storage. It is also expected that there is some under prediction in runoff volumes directly from the adopted rainfall distribution which can be somewhat subjective based on discrete point gauge data.

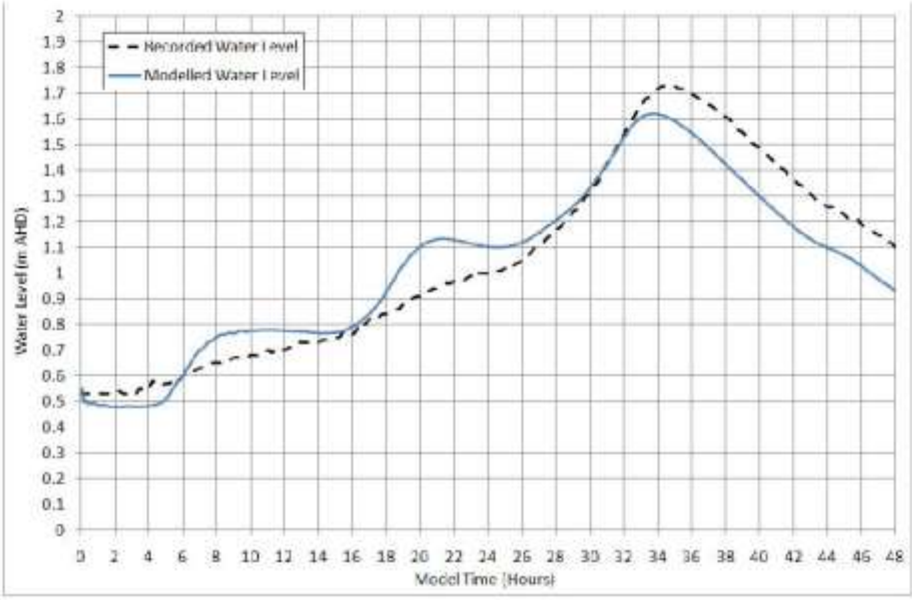


Figure 5-18 Ocean Street Water Level Validation – March 2011

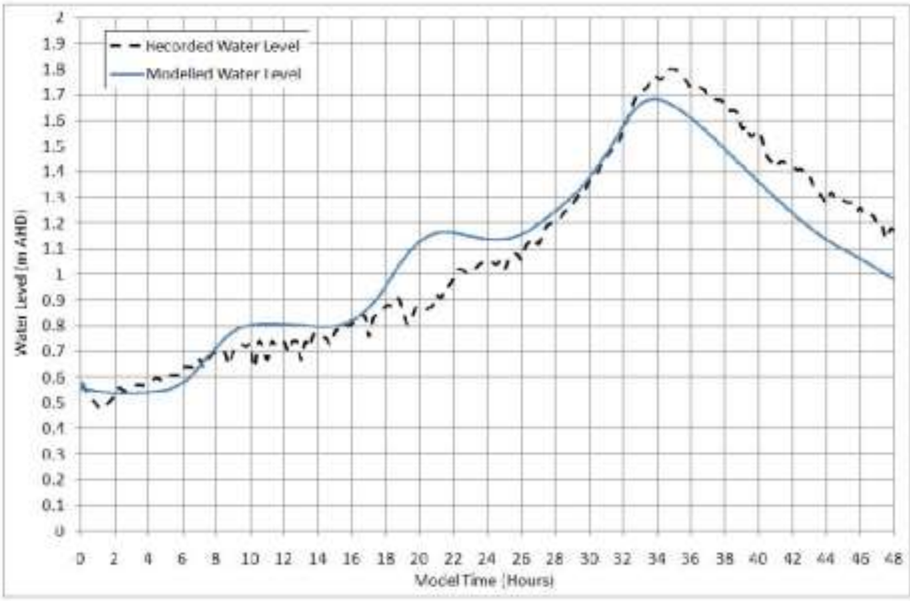


Figure 5-19 Pittwater Road Bridge Water Level Validation – March 2011

The recorded rainfall hyetograph at the Middle Creek gauge generally shows a rainfall distribution consisting of three fairly even rainfall bursts. In comparison, many of the other stations show a hyetograph weighted towards the third main rainfall burst. The simulated water level profile shown in Figure 5-20 is reflective of the Middle Creek rainfall hyetograph with three fairly similar peaks. If more of the catchment was simulated with a rainfall distribution weighted toward the latter part of the event, the simulated water level response would perhaps better represent the recorded condition.

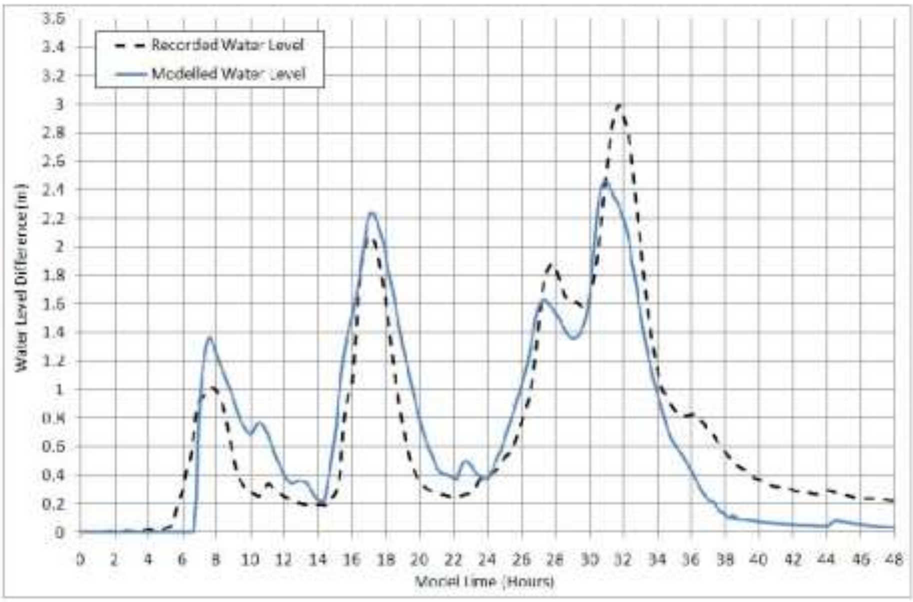
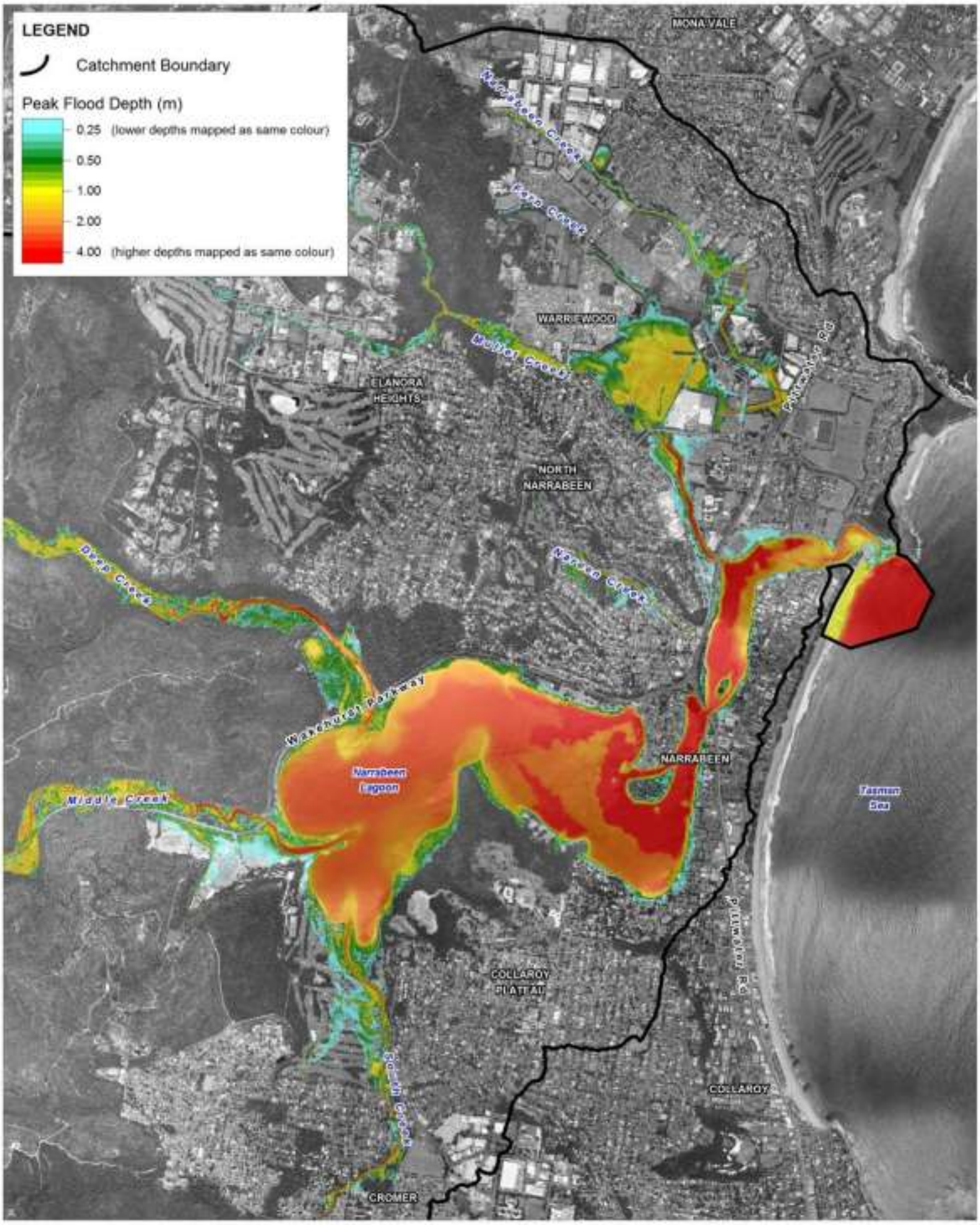


Figure 5-20 Middle Creek Water Level Validation – March 2011

Similar to the 1998 calibration event, there are a number of uncertainties in the simulated hydrological conditions, not in the least the assumed spatial and temporal distribution of rainfall which may have a significant influence on the catchment generated runoff. Overall the simulated catchment response is considered a good representation of the observed conditions. The deviations in the timing, shape and peak levels of simulated hydrographs from observed conditions are within acceptable bounds considering uncertainties in the data such as spatial and temporal variations in rainfall across the catchment.

In terms of the catchment wide response, the simulated inundation extent for the March 2011 event is shown in Figure 5-21. The simulated conditions indicate that out-of-bank flooding is relatively minor in the upper catchment areas of Middle Creek, South Creek and Deep Creek with the floodwaters generally confined to the within the main creek alignments.

The major inundation occurs around the Lagoon foreshore area as a result of elevated water levels and in the major flood storage area of the Warriewood Wetlands.



Title:
March 2011 Simulated Peak Flood Inundation

Figure: 5-21

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5.4 August 1998 Model Validation

The August 1998 flood has been used as a model validation event, given the availability of additional water level data for Mullet Creek, Fern Creek and Narrabeen Creek that was not available for the April 1998 or March 2011 flood events (refer Section 2.2.2).

5.4.1 Validation Data

5.4.1.1 Rainfall Data

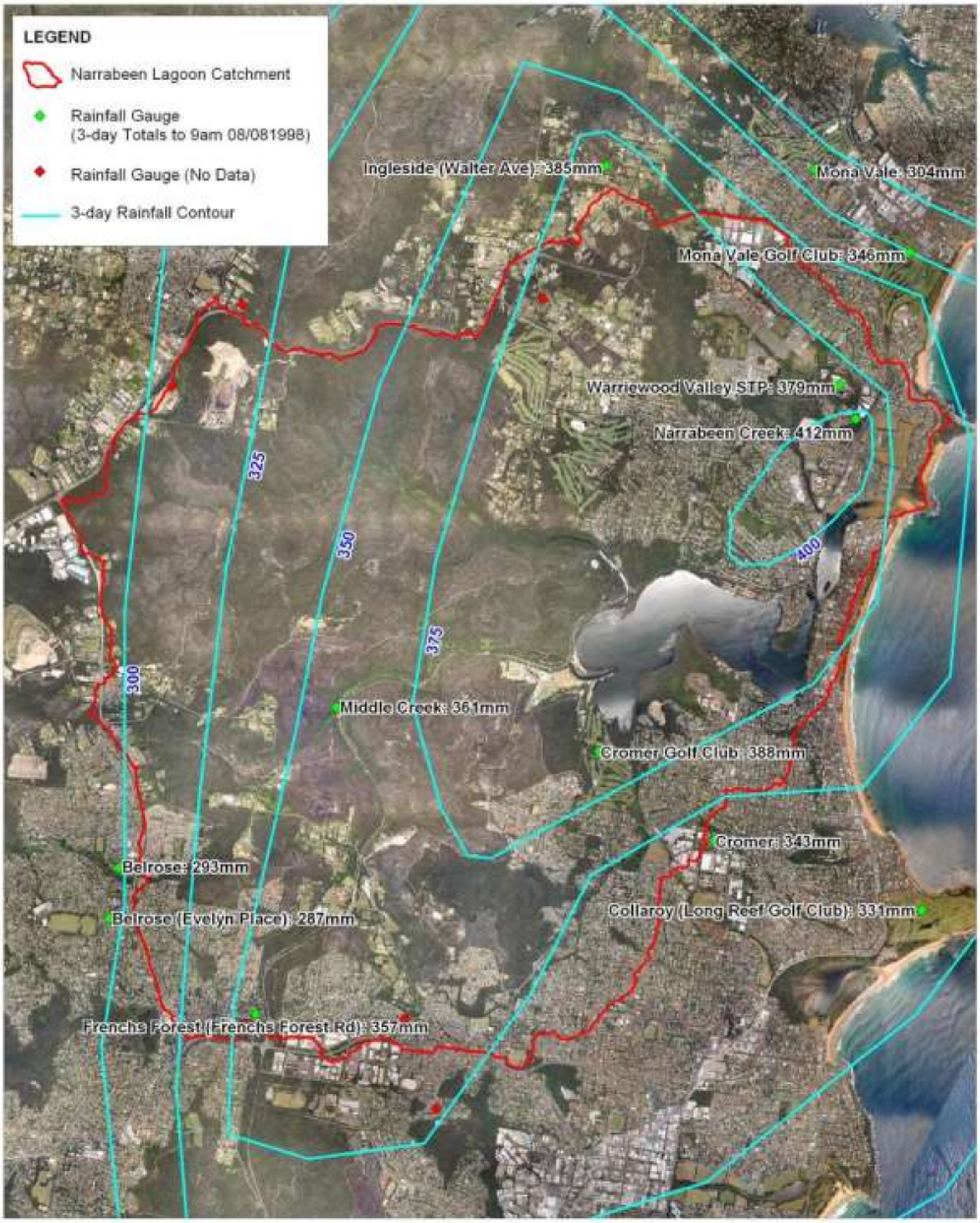
There were twelve active rainfall gauges within or in close proximity to the Narrabeen Lagoon catchment for the August 1998 event. Six of these gauges were continuous read gauges (five operated by MHL and one by Sydney Water), with the remaining six gauges being daily read gauges operated by BoM. The recorded daily totals (for the 24 hours to 9am) from 6th – 8th August 1998 for the eleven active rainfall gauges are summarised in Table 5-4.

Table 5-4 Recorded Rainfall August 1998 Event

Gauge Location	Operator	24 hr Total (to 9am 06/08/98) (mm)	24 hr Total (to 9am 07/08/98) (mm)	24 hr Total (to 9am 08/08/98) (mm)	72 hr Total (to 9am 08/08/98) (mm)
Middle Creek	MHL	89	111	161	361
Cromer	MHL	78	141	124	343
Belrose	MHL	73	89	131	293
Mona Vale	MHL	91	111	102	304
Narrabeen Creek	MHL	112	153	147	412
Warriewood Valley STP	Sydney Water	101	144	134	379
Ingleside (Walter Ave)	BoM	132	126	127	385
Cromer Golf Club	BoM	88	133	167	388
Mona Vale Golf Club	BoM	94	131	121	346
Frenchs Forrest Rd	BoM	79	115	163	357
Belrose (Evelyn Place)	BoM	82	85	120	287
Collaroy (Long Reef Golf Club)	BoM	58	149	124	331

As shown in Table 5-4, there was extensive rainfall across the local area over a 3-day recording period. The combined 3-day totals across the catchment were typically in excess of 300mm, with the Narrabeen Creek gauge recording the highest 3-day total of some 412mm.

The daily rainfall totals for both the continuous and daily read gauges were used to derive a spatial distribution of rainfall across the Narrabeen Lagoon catchment. The estimated rainfall distribution for the August 1998 event is shown in Figure 5-22.



Title:
August 1998 Rainfall Distribution

Figure: 5-22

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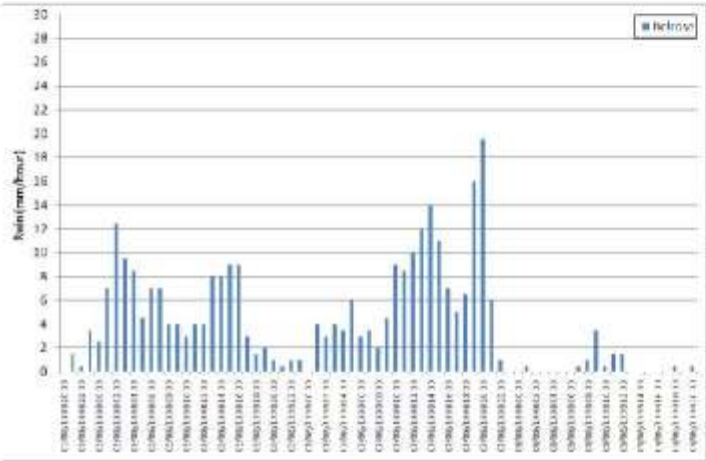
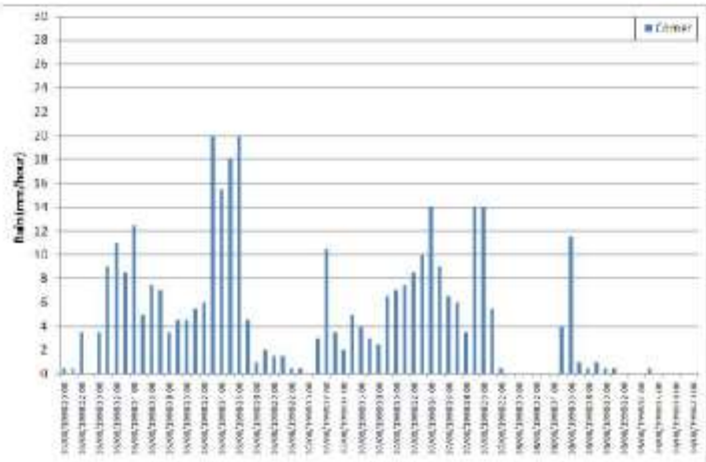
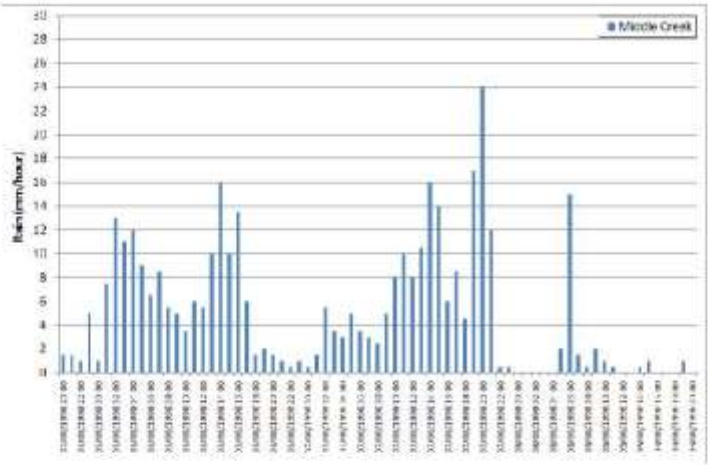
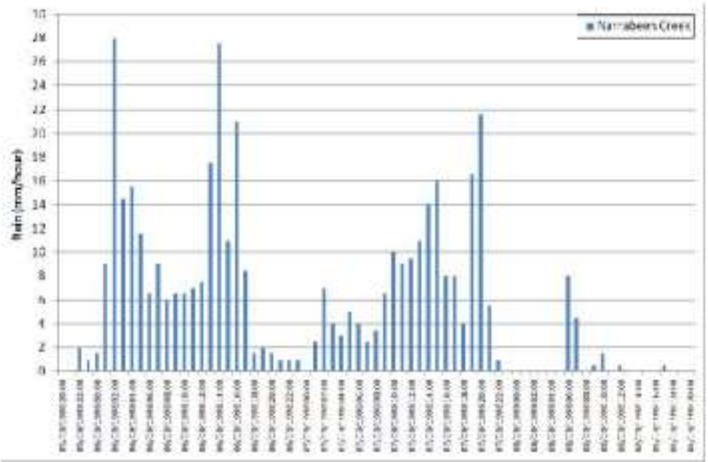
The recorded hyetographs at the continuous read rainfall gauges within the Narrabeen lagoon catchment or in the near vicinity are shown in Figure 5-23. The hyetograph period shown is from 8:00pm 5[th] August to 8:00pm 8[th] August 1998, corresponding to the period of the main rainfall resulting in the peak flood levels attained in Narrabeen Lagoon.

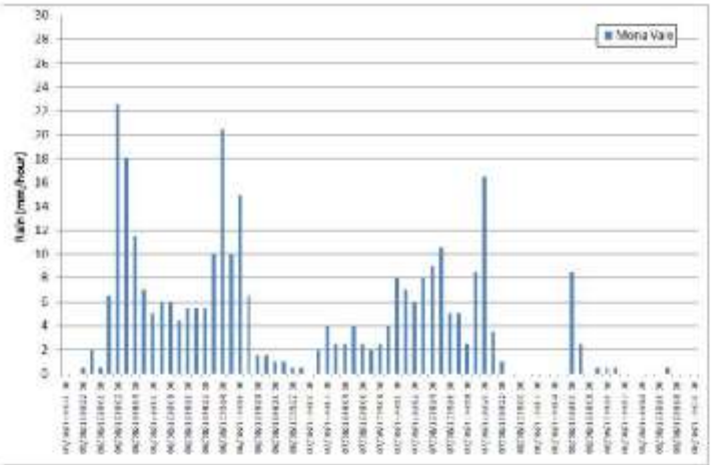
As evidenced in the recorded hyetographs, there is some variability across the gauges in terms of the relative intensities and rainfall depths across the period. Typically however, all continuous read gauges show that the rainfall generally fell within two distinct burst followed by a third smaller burst.






Middle Creek
Rain (mm/hour)


Narrabeen Creek
Rain (mm/hour)


Mona Vale
Rain (mm/hour)

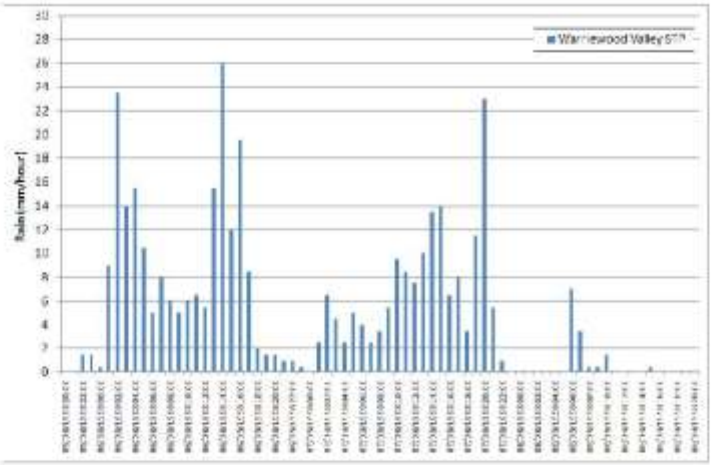


Figure 5-23 August 1998 Recorded Rainfall

To gain an appreciation of the relative intensity of the August 1998 event, the recorded rainfall depths at both the Middle Creek and Narrabeen Creek MHL continuous read rainfall gauges for various storm durations were compared with the design IFD data for the Narrabeen Lagoon catchment as shown in Figure 5-15. In comparison to the short duration April 1998 calibration event, the August 1998 was a longer duration event spread across a 2-3 day period.

For the Middle Creek continuous read rainfall gauge the following comparisons to design rainfall depths can be made for the August 1998 event:

- 24-hour duration – 173mm recorded compared with 194mm design 20% AEP;
- 48-hour duration – 335mm recorded compared with 332mm design 5% AEP; and
- 72-hour duration – 364mm recorded compared with 374mm design 5% AEP.

For the Narrabeen Creek continuous read rainfall gauge the following comparisons to design rainfall depths can be made for the August 1998 event:

- 24-hour duration – 224mm recorded compared with 221mm design 10% AEP;
- 48-hour duration – 397mm recorded compared with 396mm design 2% AEP; and
- 72-hour duration – 414mm recorded compared with 447mm design 2% AEP.

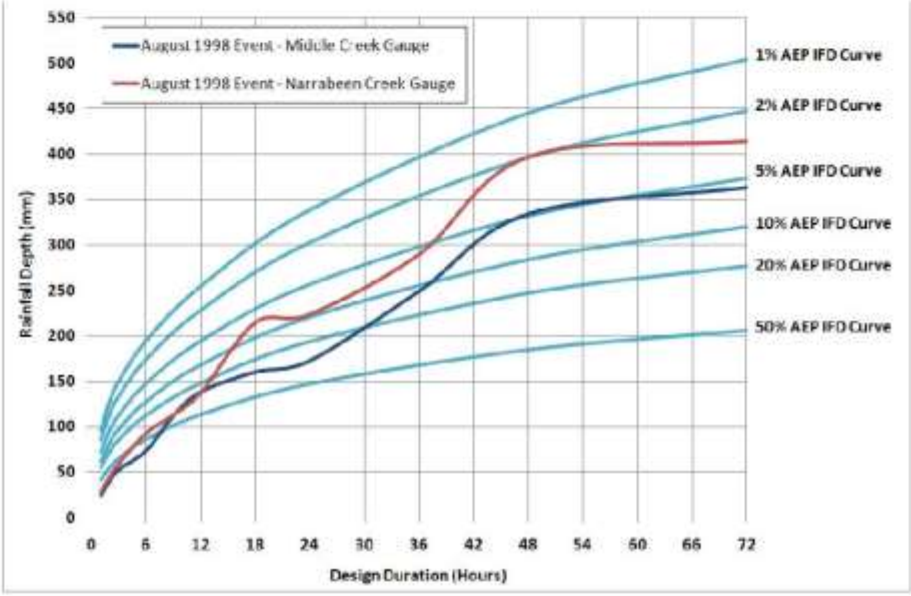
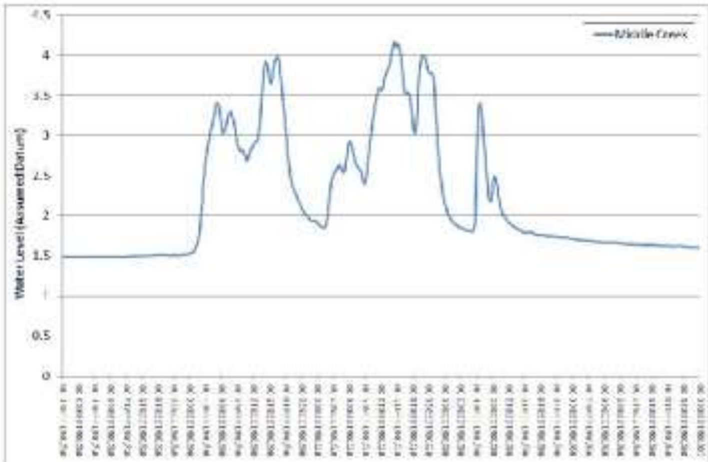


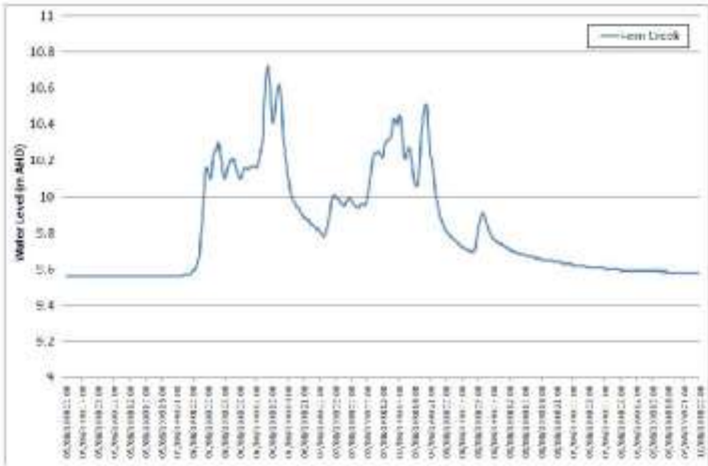
Figure 5-24 Comparison of August 1998 Rainfall with IFD Relationships

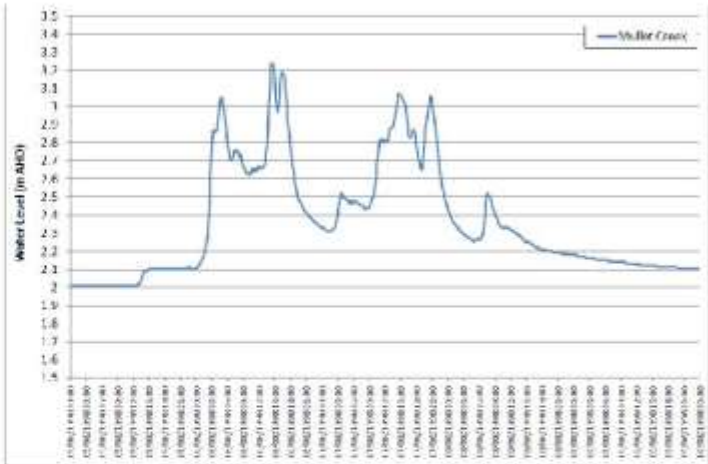
5.4.1.2 Water Level Data

There were six active water level gauges operating within the Narrabeen Lagoon catchment during the August 1998 event – Middle Creek (on the Middle Creek tributary), Fern Creek (on the Fern Creek tributary), Narrabeen Creek (on the Narrabeen Creek tributary), Mullet Creek (on the Mullet Creek tributary), Pittwater Road Bridge (Narrabeen Lagoon) and Ocean Street Bridge (Narrabeen Lagoon).

The recorded water level time series at each gauge location for the August 1998 event are shown in Figure 5-25. The time series shown covers a period of some 5-days. As noted in the rainfall analysis, three separate significant rainfall periods occurred during the event. The timing of these rainfall bursts resulted in fluctuating water levels in the lagoon and its tributaries over a period of some 48-72-hours.


Middle Creek
Water Level (Assumed Datum)


Water Level (m AHD)


Mullet Creek
Water Level (m AHD)

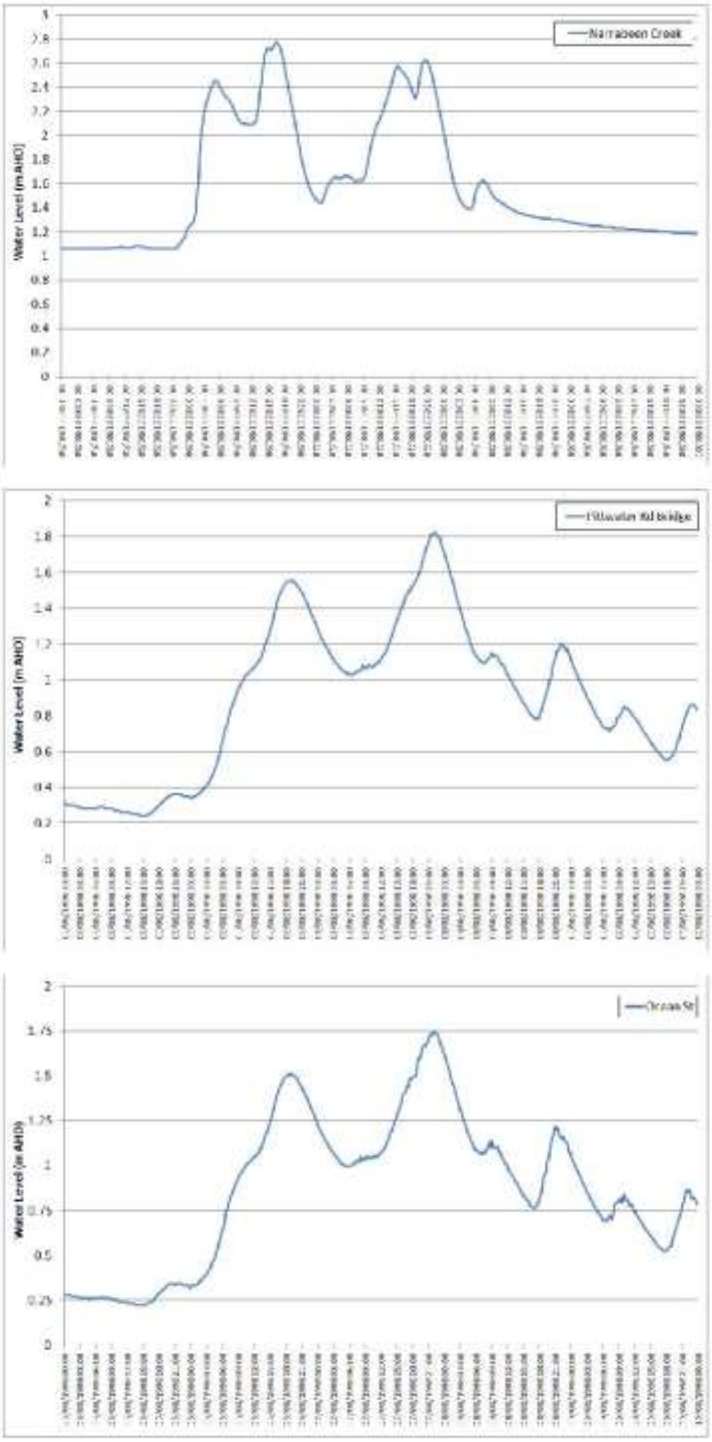


Figure 5-25 August 1998 Recorded Water Levels

5.4.2 Downstream Boundary Conditions

Ocean tide (water level) data was available for the August 1998 event from a continuous tide gauge maintained by MHL at Middle Head. This water level data is considered to be representative of the ocean water levels at the Narrabeen Lagoon entrance and as such was used as the downstream boundary for the August 1998 event. The relationship between recorded ocean water levels and recorded rainfall for the August 1998 event is shown in Figure 5-26.

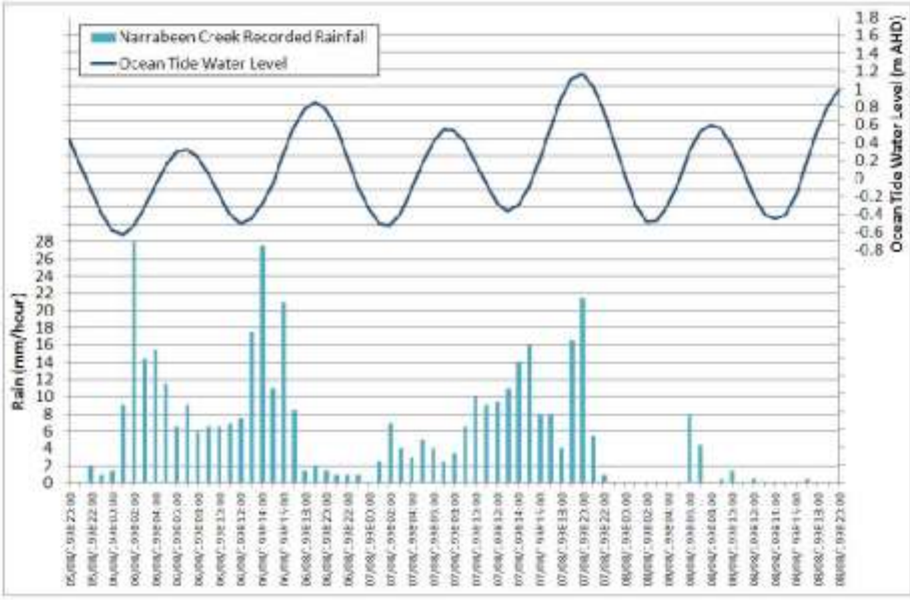


Figure 5-26 August 1998 Recorded Tidal Water Level

5.4.3 Observed and Simulated Flood Conditions August 1998

In addition to the gauge data available for Middle Creek, Pittwater Road, Ocean Street, further calibration data for the August 1998 is available from the water level time series at the Fern Creek, Narrabeen Creek and Mullet Creek gauges in the Warriewood Valley catchment. These additional stations have a relatively short period of operation, however were active for this event. None of these however are flow gauging stations, such that a direct flow calibration is not possible.

A comparison of recorded and simulated water level profiles in the Narrabeen Lagoon catchment for the August 1998 event is shown in Figure 5-27 to Figure 5-32. The simulated results show that a good model calibration has been achieved for a number of aspects of the simulated catchment flood behaviour:

- Catchment runoff response – the relative timing of the observed and simulated water level hydrographs show an excellent agreement throughout the simulated event. This shows the catchment runoff processes are being well simulated including the initial catchment response from the wetting-up period (incorporating rainfall losses) and the general rise of water levels in the Lagoon indicating a good simulation of the relative timing of the main tributary inflows.

The additional gauges in the Warriewood Valley show a very rapid response to rainfall which has been reproduced well by the models.

- Peak flood levels – the peak flood levels generally show a good agreement. The multiple peaks, particularly of the highly dynamic Warriewood Valley gauges are also simulated well.
- Total flood volumes – the area under the water level time series graph is indicative of the total flood volume for the event. As evident in the observed vs. simulated comparisons, each water level profile generally tracks the same for the duration of the event, and accordingly the total volumes would appear to be in good agreement. The adopted rainfall depth distribution and the modelled initial and continuing loss parameters provide for a good representation of total runoff volume generated from the catchment.

Similar to the April 1998 and March 2011 events, there are a number of uncertainties in the simulated hydrological conditions, not in the least the assumed spatial and temporal distribution of rainfall which may have a significant influence on the catchment generated runoff. Overall the simulated catchment response is considered a very good representation of the observed conditions. The deviations in the timing, shape and peak levels of simulated hydrographs from observed conditions are within acceptable bounds considering uncertainties in the data such as spatial and temporal variations in rainfall across the catchment.

In terms of the catchment wide response, the simulated inundation extent for the August 1998 event is shown in Figure 5-33. The simulated conditions indicate that out-of-bank flooding is relatively minor in the upper catchment areas of Middle Creek, South Creek and Deep Creek with the floodwaters generally confined to the within the main creek alignments. Widespread inundation is largely limited to the mid to lower catchment largely around the Lagoon foreshore and within the Warriewood Wetlands.

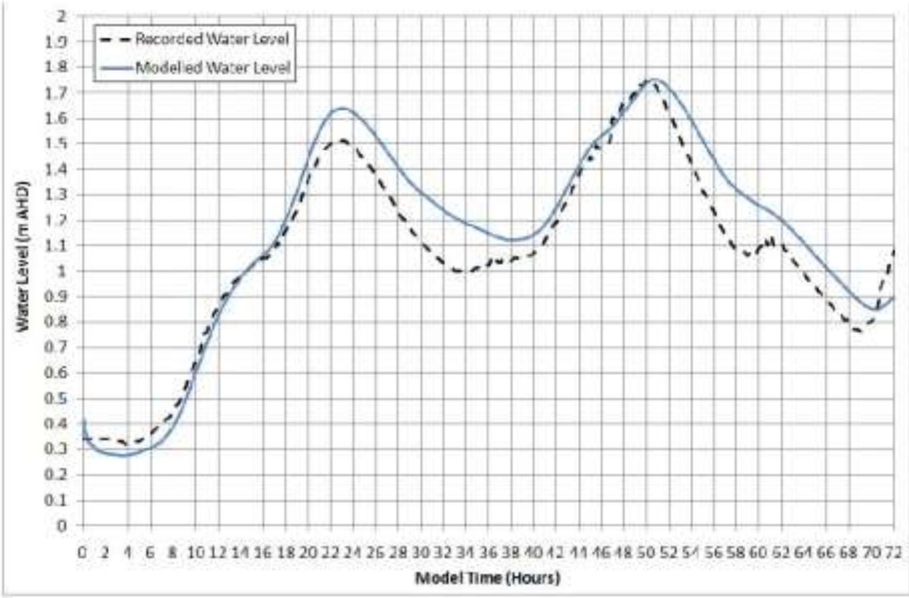


Figure 5-27 Ocean Street Water Level Validation – August 1998

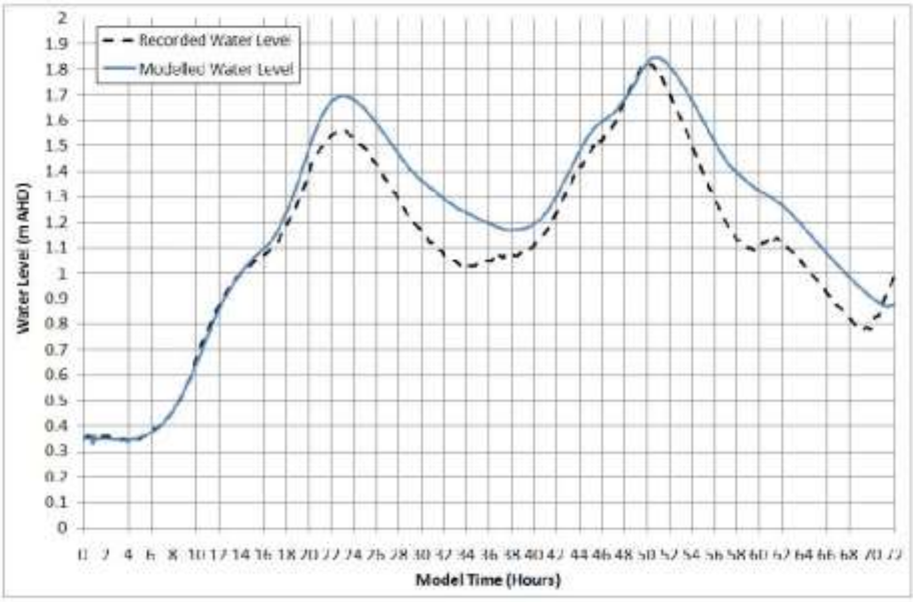


Figure 5-28 Pittwater Road Bridge Water Level Validation – August 1998

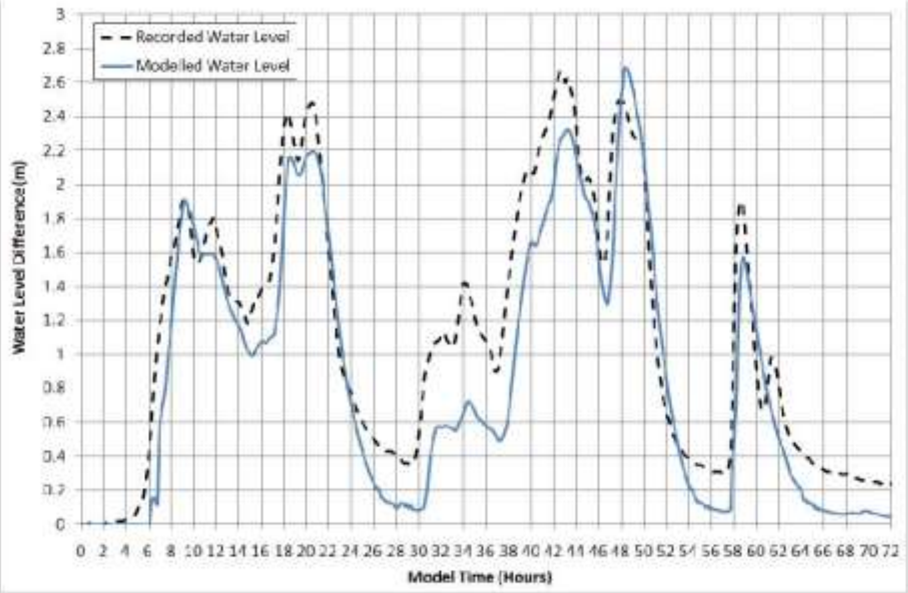


Figure 5-29 Middle Creek Water Level Validation – August 1998

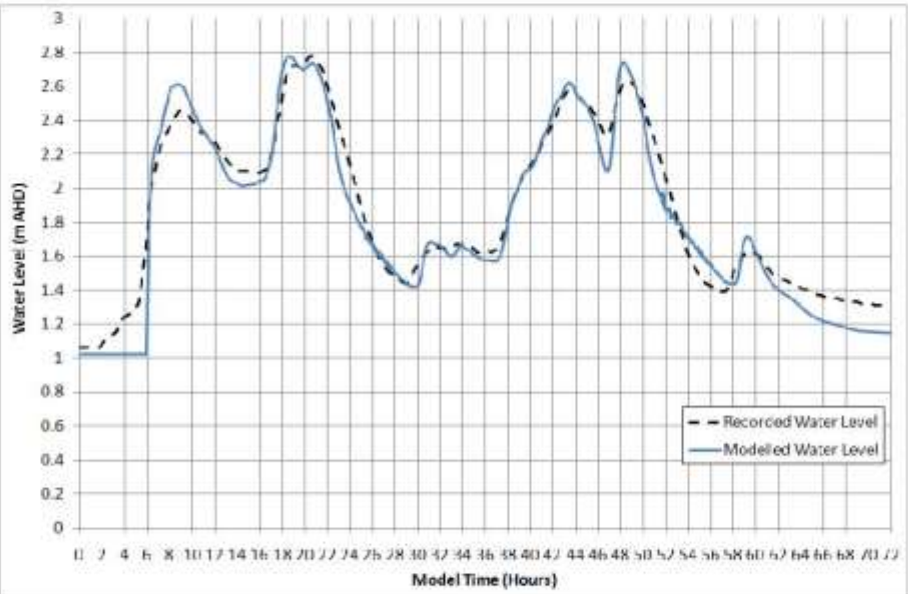


Figure 5-30 Narrabeen Creek Water Level Validation – August 1998

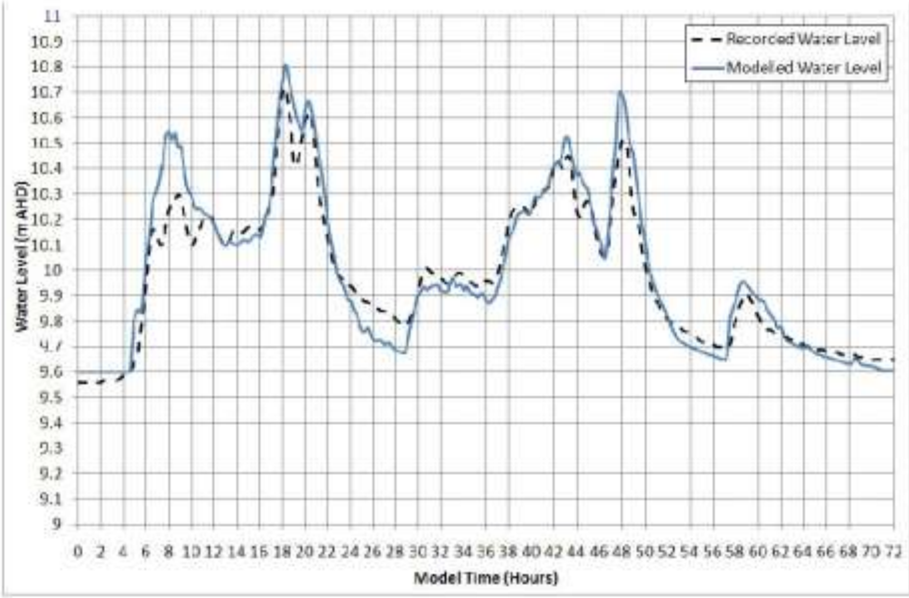


Figure 5-31 Fern Creek Water Level Validation – August 1998

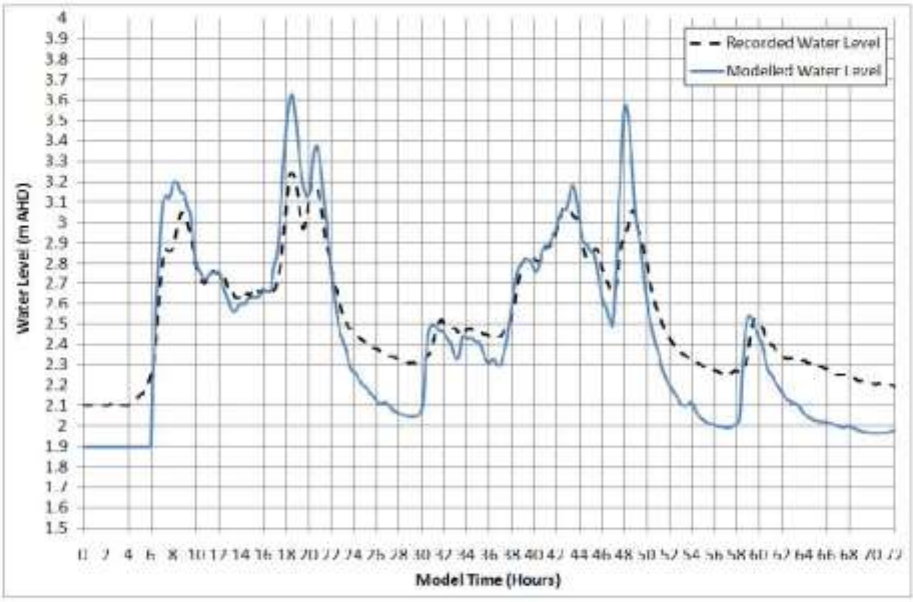
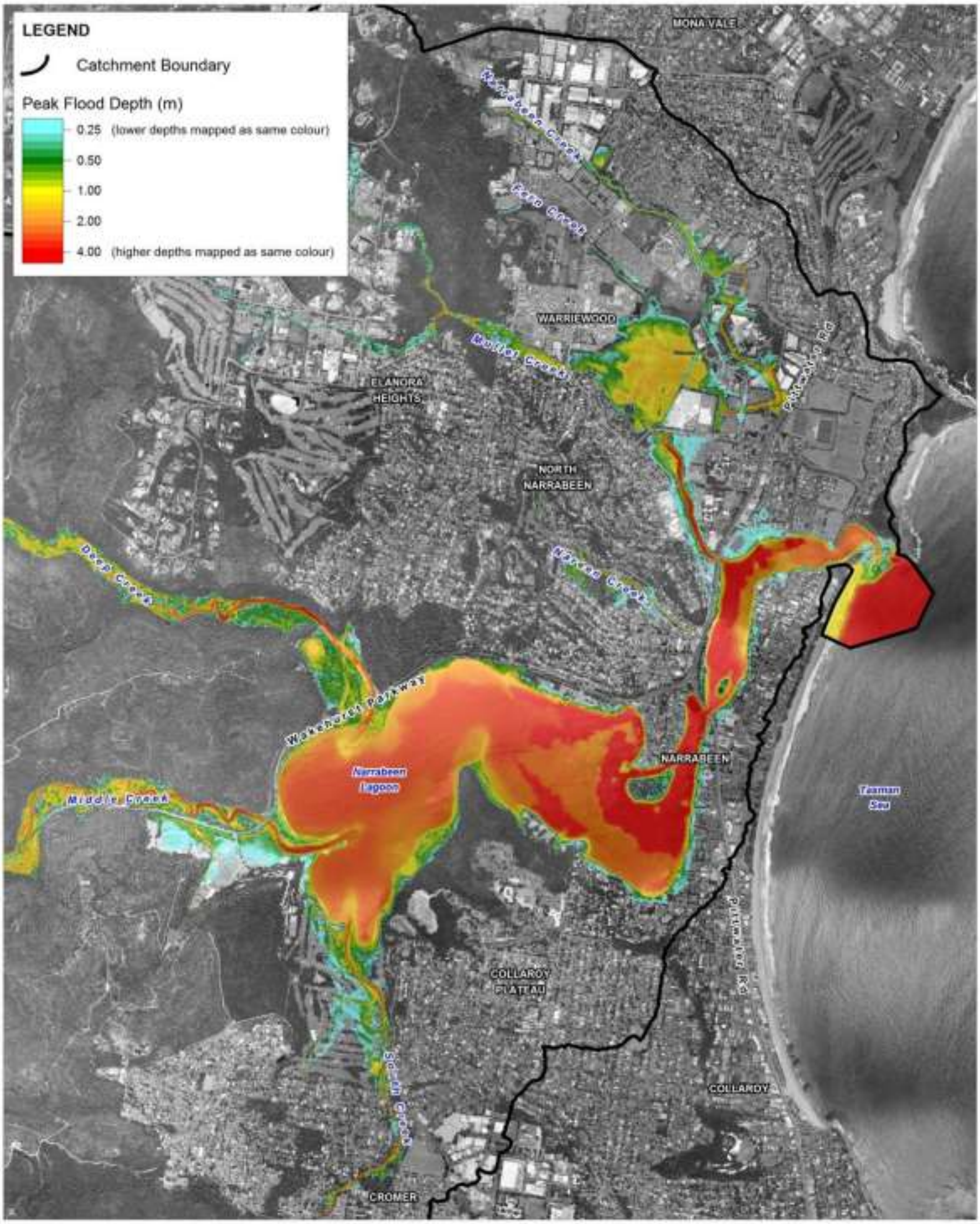


Figure 5-32 Mullet Creek Water Level Validation – August 1998



Title:
August 1998 Simulated Peak Flood Inundation

Figure: 5-33

Rev: A

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5.5 Determination of Design Model Parameters

In calibrating the models emphasis is generally placed on reaching agreement between recorded and simulated flood conditions with respect to peak water levels and relative timing of occurrence.

The model calibration achieved reasonable agreement in regards to observed conditions within the Narrabeen Lagoon catchment for the principal calibration event of April 1998 and validation events of March 2011 and August 1998. The final model parameter values adopted, as shown in Table 5-2, have been maintained (as per the calibration events) for design event simulation.

Given the limited amount of calibration data available, it is important to acknowledge the limitation of the calibration process undertaken. All of the parameters have been kept within normal bounds generally considered for a catchment study of this nature. Further consideration has been given to sensitivity testing of key model parameters on design flood conditions as presented in Section 7.7.

6 DESIGN FLOOD CONDITIONS

Design floods are hypothetical floods used for floodplain risk management. They are based on having a probability of occurrence specified either as:

- Annual Exceedance Probability (AEP) expressed as a percentage; or
- Average Recurrence Interval (ARI) expressed in years.

This report uses the AEP terminology. Refer to Table 6-1 for a definition of AEP and the ARI equivalent.

Table 6-1 Design Flood Terminology

AEP[1]	ARI[2]	Comments
Probable Maximum Flood (PMF)		A hypothetical flood or combination of floods which represent an extreme scenario.
0.1%	1,000 years	A hypothetical flood or combination of floods likely to occur on average once every 1,000 years or with a 0.1% probability of occurring in any given year
0.2%	500 years	As for the 0.1% AEP flood but with a 0.2% probability or 500 year return period
0.5%	200 years	As for the 0.1% AEP flood but with a 0.5% probability or 200 year return period
1%	100 years	As for the 0.1% AEP flood but with a 1% probability or 100 year return period.
2%	50 years	As for the 0.1% AEP flood but with a 2% probability or 50 year return period.
5%	20 years	As for the 0.1% AEP flood but with a 5% probability or 20 year return period.
10%	10 years	As for the 0.1% AEP flood but with a 10% probability or 10 year return period.
20%	Approx. 5 years	As for the 0.1% AEP flood but with a 20% probability or 5 year return period.
50%	Approx. 2years	As for the 0.1% AEP flood but with a 50% probability or 2 year return period.

1 Annual Exceedance Probability (%)
2 Average Recurrence Interval (years)

The design events simulated include the PMF event, 0.1%, 0.2%, 0.5%, 1%, 2%, 5%, 10%, 20% and 50% AEP events for catchment derived flooding and the 0.5%, 1%, 2%, 5%. 10% and 20% AEP events for ocean derived flooding. The 1% AEP flood is generally used as the standard flood for land use planning and control.

In determining the design floods it is necessary to take into account:

- Design rainfall parameters (rainfall depth, temporal pattern and spatial distribution). These inputs drive the hydrological model from which design flow hydrographs will be extracted as inputs to the hydraulic model;

- Design Lagoon entrance condition and berm geometry. Consideration was given to both open and closed Lagoon entrance conditions;
- Design downstream ocean boundary levels. A fully scoured entrance condition will provide for the critical case for ocean flooding, whilst for closed condition and intermediate scouring, coincident catchment and tidal conditions may dictate flooding; and
- Design initial Lagoon water level.

In determining the design floods it is necessary to take into account the critical storm duration of the catchment (small catchments are more prone to flooding during short duration storms while for large catchments longer durations will be more critical).

6.1 Design Rainfall

Design rainfall parameters are derived from standard procedures defined in AR&R (2001) which are based on statistical analysis of recorded rainfall data across Australia. The derivation of location specific design rainfall parameters (e.g. rainfall depth and temporal pattern) for Narrabeen Lagoon is presented below.

6.1.1 Rainfall Depths

Design rainfall depth is based on the generation of intensity-frequency-duration (IFD) design rainfall curves utilising the procedures outlined in AR&R (2001). These curves provide rainfall depths for various design magnitudes and for durations from 5 minutes to 72 hours.

Table 6-2 shows the average design rainfall intensities based on AR&R adopted for the modelled events specific to Narrabeen Lagoon.

The Probable Maximum Precipitation (PMP) is used in deriving the Probable Maximum Flood (PMF) event. The theoretical definition of the PMP is "the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of year" (AR&R, 2001). The ARI of a PMP/PMF event ranges between 10^4 and 10^7 years and is beyond the "credible limit of extrapolation". That is, it is not possible to use rainfall depths determined for the more frequent events (1% AEP and less) to extrapolate the PMP. The PMP has been estimated using the Generalised Short Duration Method (GSDM) derived by the Bureau of Meteorology. Durations of up to 6-hours have been considered for the PMP in accordance with the GSDM.

Table 6-2 Average Design Rainfall Intensities (mm/hr)

Duration (hours)	Design Event Frequency (AEP)									
	50%	20%	10%	5%	2%	1%	0.5%	0.2%	0.1%	PMP
0.5	60.3	78.5	89.3	103.0	122.0	136.0	149.2	168.3	183.2	380.0
1	41.3	54.3	62.0	72.0	85.3	95.4	107.2	121.6	132.8	280.0
1.5	33.0	42.5	48.5	57.0	67.5	77.0	84.2	95.4	104.1	240.0
2	27.6	36.4	41.5	48.3	57.2	64.0	70.7	80.0	87.3	210.0
3	21.7	28.5	32.5	37.7	44.6	49.9	55.1	62.3	68.0	170.0
6	14.4	18.7	21.3	24.6	29.0	32.4	35.9	40.6	44.2	113.0
9	11.1	14.5	16.6	19.2	22.4	25.3	28.0	31.6	34.4	n/a
12	9.5	12.3	14.0	16.2	19.0	21.2	23.4	26.4	28.8	n/a
18	7.3	9.6	10.9	12.7	14.8	16.6	18.6	21.0	22.9	n/a
24	6.1	8.1	9.2	10.7	12.6	14.1	15.7	17.8	19.4	n/a
48	3.9	5.1	5.9	6.9	8.3	9.3	10.3	11.7	12.8	n/a
72	2.9	3.8	4.4	5.2	6.2	7.0	7.8	8.9	9.8	n/a

6.1.2 Temporal Patterns

The IFD data presented in Table 6-2 provides for the average intensity that occurs over a given storm duration. Temporal patterns are required to define what percentage of the total rainfall depth occurs over a given time interval throughout the storm duration. The temporal patterns adopted in the current study are based on the standard patterns presented in AR&R (2001).

The same temporal pattern has been applied across the whole catchment. This assumes that the design rainfall occurs simultaneously across each of the modelled sub-catchments. The direction of a storm and relative timing of rainfall across the catchment may be determined for historical events if sufficient data exists, however, from a design perspective the same pattern across the catchment is generally adopted.

6.1.3 Rainfall Losses

The rainfall loss parameters adopted for the design floods were similar to those used in the hydrological model calibration and validation. For the initial and continuing rainfall losses, values of 10mm and 2.5mm/h were used for pervious areas and 2mm and 0mm/hr for impervious areas. These are consistent with the recommended ranges for design event losses in AR&R (2001).

6.1.4 Critical Duration

A series of model runs were carried out in order to identify the critical storm durations for the catchment. The critical storm durations required to produce the maximum peak water levels in Narrabeen Lagoon were found to be the storm durations of between 9 to 24 hours. These durations are similar to the events experienced in April 1998 and March 2011. Higher up the tributary catchments, shorter duration events typically 90-minute – 2-hour durations provide for peak flood level conditions.

For the PMF event, the critical duration for the broader Lagoon area is the 5-hour duration with the 0.5 and 1-hour events typically the critical duration for the local flooding in the upper tributaries.

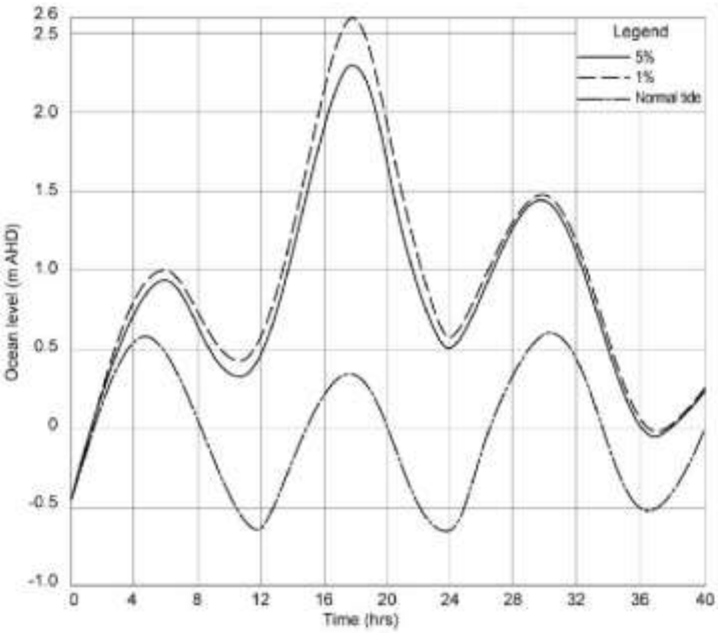
The design flood mapping adopts an "envelope" approach such that peak flood levels throughout the catchment are represented, considering the difference in critical duration throughout the catchment.

6.2 Design Ocean Boundary

Design ocean boundaries for use in flood risk assessments are recommended by the *Flood Risk Management Guide: Incorporating sea level rise benchmarks in flood risk assessments* (DECCW, 2010). The design ocean boundaries from this document are presented in Figure 6-1. The recommended normal ocean boundary, representative of a mean neap tide condition has been adopted for the catchment derived flood events. For the ocean derived flood events, the elevated ocean boundaries based on frequency analysis of peak water levels have been adopted.

6.2.1 Catchment Derived Flood Events

The adopted tidal boundary for catchment derived flood events was based on the normal tide recommendation and is shown in Figure 6-2. The timing of the 0.6m AHD peak water level was adjusted to coincide with the peak catchment inflow.



Source: Figure 7.1, Appendix A, Draft Flood Risk Management Guide (DECCW, 2009)

Figure 6-1 DECCW Recommended Design Ocean Boundaries

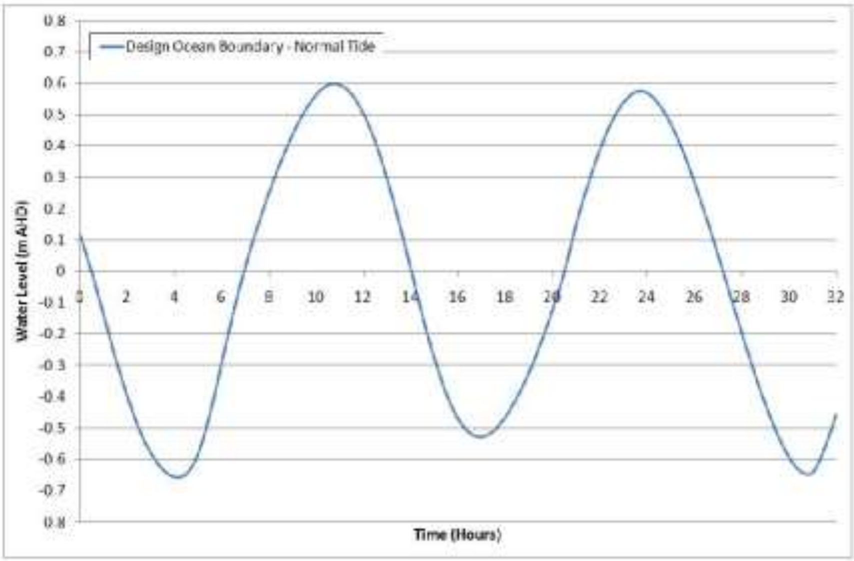


Figure 6-2 Design Ocean Boundary – Normal Tide

6.2.2 Ocean Derived Flood Events

The adopted tidal boundary for ocean derived flood events was based on the elevated tide recommendation in the *Flood Risk Management Guide: Incorporating sea level rise benchmarks in flood risk assessments* (DECCW, 2010). These levels include the following considerations:

- Barometric pressure set up of the ocean surface due to the low atmospheric pressure of the storm;
- Wind set up due to strong winds during the storm "piling" water upon the coastline;
- Astronomical tide, particularly the Higher High Water Solstice Springs (HHWSS); and
- Wave set up.

Adopted peak ocean boundary water levels for various magnitude storm events are shown in Figure 6-3 with peak levels summarised in Table 6-3.

Table 6-3 Design Peak Ocean Water Levels

Event Magnitude	Water Level (m)
20% AEP	1.9
5% AEP	2.25
2% AEP	2.45
1% AEP	2.60
0.5% AEP	2.75

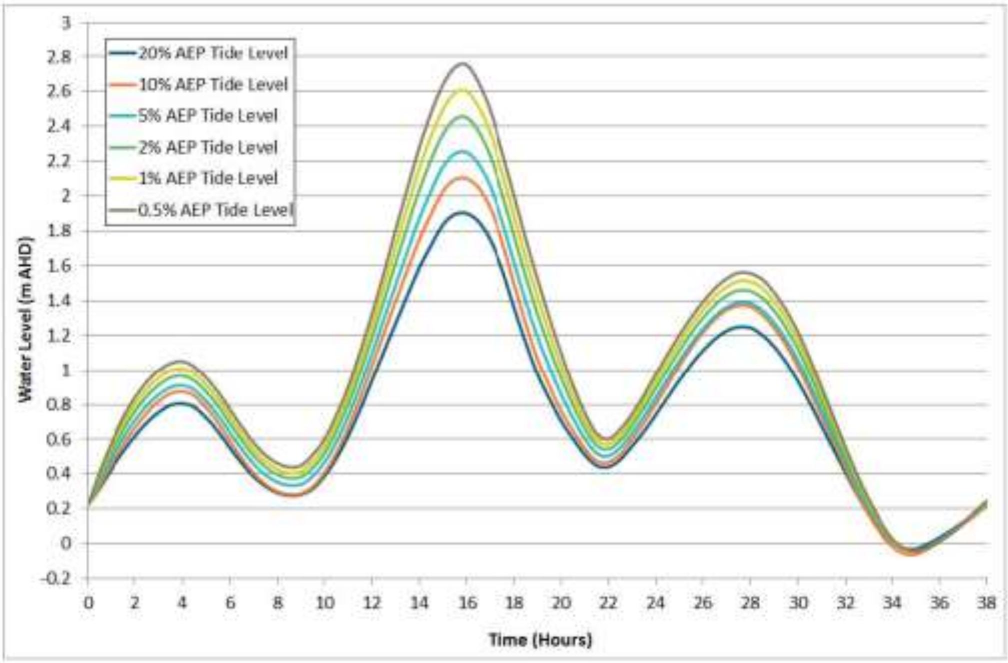


Figure 6-3 Design Ocean Boundary – Elevated Tide

6.3 Design Lagoon Entrance Condition and Berm Geometry

As stated in Section 2.1.2, the Narrabeen Lagoon entrance opening is subject to forces that act to close the entrance (waves, tides and wind) and those that act to maintain an open entrance (flood flows and dredging), which results in the Lagoon being defined as an intermittently closed and open Lake/Lagoon (ICOLL).

The entrance of Narrabeen Lagoon is artificially opened to mitigate flooding of nearby residential and commercial areas. Routine entrance clearance dredging has been carried out within the lagoon flood tide delta approximately every four years since 1975, which has kept the entrance mostly open since that time. In addition at the entrance of the Lagoon lies a shallow rock shelf (Figure 6-4) that is located currently around mid-tide level, and acts as a control on the tidal hydraulics of the lagoon.

Figure 6-4 Narrabeen Lagoon entrance and rock shelf

The entrance channel to Narrabeen Lagoon is predominantly open to the ocean due to mass sand clearance works undertaken by The Councils, approximately every four years. Even so, the entrance condition at Narrabeen Lagoon is possibly the most significant control on flood water levels within the lower catchment for lower design events.

The height of the entrance berm level and the presence of the shallow rock shelf will influence how high lagoon water levels need to reach before natural breakout and discharge to the ocean is initiated. The relativity between the rate of entrance scour (and thus discharge from the lake) and the rate of catchment runoff flowing into the Lagoon system will determine how high lagoon water levels reach in excess of the entrance berm level. Elevated ocean water levels may also penetrate into the lagoon, through overtopping of the entrance berm (Figure 6-5) and restrict outflow.

The conditions of the entrance, including the entrance berm level, are a function of active coastal processes (wave and sediment transport). Consequently, for ICOLLs, an assessment of lagoon flood conditions requires consideration of adjacent coastal conditions as discussed in Section 6.2.

Figure 6-5 Waves overtopping into Narrabeen Lagoon

6.3.1 Catchment Derived Flood Events

The Lagoon entrance bathymetry (with the exception of the entrance berm level) for the catchment derived flood events was obtained from the 2011 pre-dredge bathymetric survey (as adopted for the calibration and validation events). The entrance berm level adopted for the catchment derived flood events is 1.3m AHD.

The 1.3m AHD entrance berm level corresponds to the level in the Lagoon that triggers a mechanical breakout to be initiated as outlined in the Lagoon Entrance Management Operational Management Standard (Warringah Council, 2012). Using this data provides for a largely closed entrance and represents the worst case entrance condition for a catchment derived flood event.

The adopted model bathymetry for the Lagoon entrance representing a closed condition is shown in Figure 6-6.

6.3.2 Ocean Derived Flood Events

The Lagoon entrance bathymetry (including entrance berm level) for the ocean derived flood events was obtained from the 2005 bathymetric survey (refer Section 5.2.4). The Lagoon entrance condition for the ocean derived flood events is shown in Figure 6-6. Using this data provides for a largely unrestricted entrance condition, as recommended for use in ocean derived flood events by Appendix A of the Flood Risk Management Guide (DECCW, 2010).

6.4 Design Initial Water Levels

Initial water levels in Narrabeen Lagoon for design flood events have been derived based on a combination of water levels defined in the Narrabeen Lagoon Entrance Management OMS and analysis of available water level records from two water level gauges located in Narrabeen Lagoon.

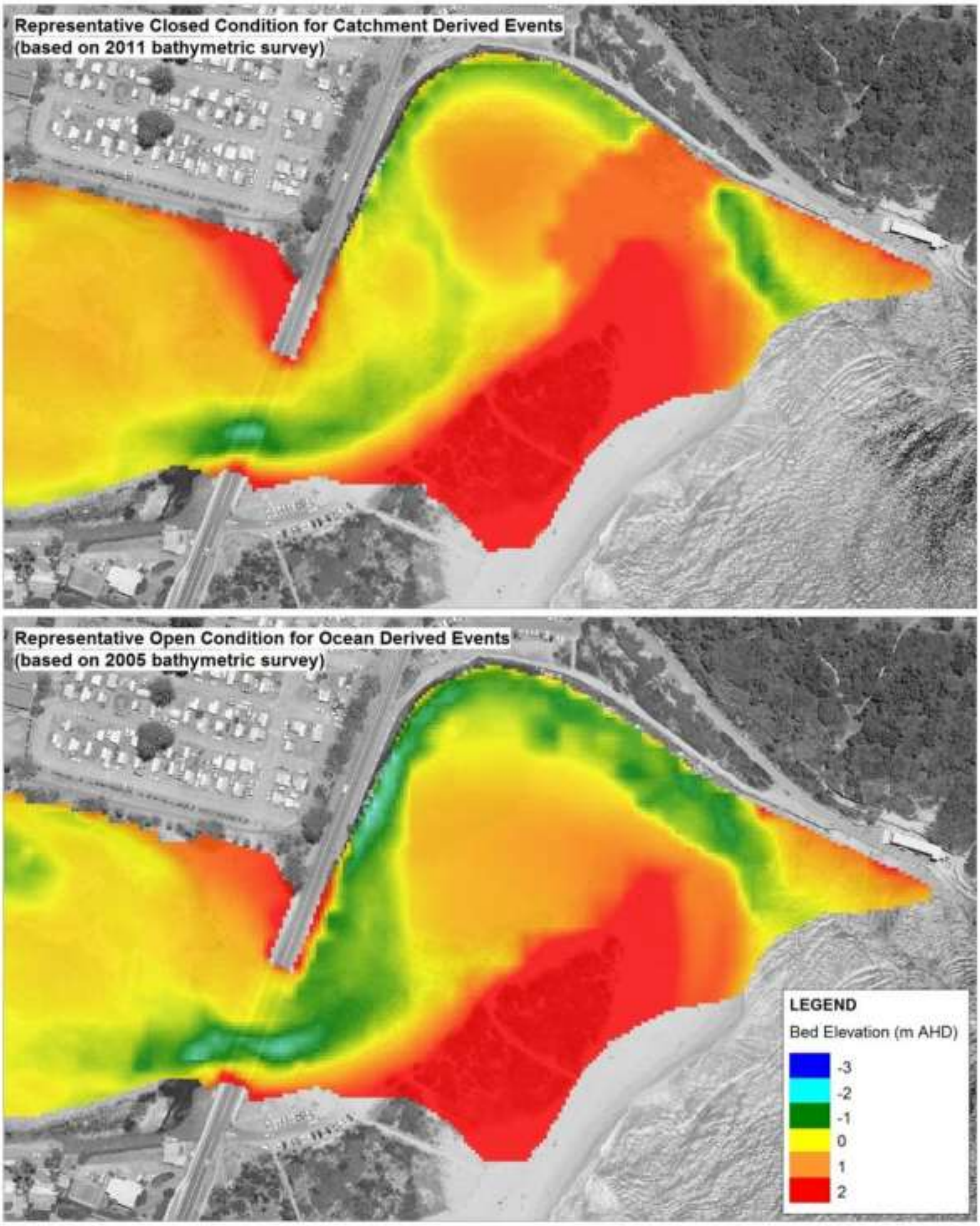
6.4.1 Catchment Derived Flood Events

The initial water level in Narrabeen lagoon adopted for catchment derived flood events is 1.3m AHD. This water level corresponds to the adopted closed berm height (i.e. assuming Lagoon is full to this level) and represents the level in the Narrabeen Lagoon Entrance Management OMS at which a mechanical Lagoon breakout is initiated. An initial water level of 1.3m AHD therefore provides for the worst case initial water level for a catchment derived flood event.

This initial water level is considered conservative, however, the design storm burst can occur during a period of heavy rainfall, and the entrance may not have had time to be opened either mechanically or naturally by the flood waters.

6.4.2 Ocean Derived Flood Events

The initial water level in Narrabeen lagoon for the ocean derived flood events is based on a nominal tidal condition. The initial water level in Narrabeen Lagoon was set to 0.23m AHD which equates to the water level at time zero for the adopted ocean tide time series (refer Section 6.2 and Figure 6-3).



Title:
Design Lagoon Entrance Condition

Figure: **6-6**

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Approx. Scale

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6.5 Modelled Design Events

In consultation with The Councils a suite of design event scenarios were defined that are most suitable for future floodplain risk management in Narrabeen Lagoon. Consideration was given to design flood events driven by both catchment and ocean processes. The potential impact of climate change on flood behaviour within Narrabeen Lagoon is presented in Section 8.

6.5.1 Catchment Derived Flood Events

A range of design events were defined to model the behaviour of catchment derived flooding within the Narrabeen Lagoon catchment including the 50% AEP, 20% AEP, 10% AEP, 5% AEP, 2% AEP, 1% AEP, 0.5% AEP, 0.2% AEP, 0.1% AEP and PMF events. The catchment derived flood events were based on the following:

- Design rainfall parameters derived from standard procedures defined in AR&R (2001);
- Normal ocean boundary as recommended in Appendix A of the Draft Flood Risk Management Guide (DECCW, 2009);
- Lagoon entrance bathymetry based on 2011 pre-dredge bathymetric survey with the berm height set to 1.3m AHD; and
- Initial water level of 1.3m AHD.

6.5.2 Ocean Derived Flood Events

A range of design events were defined to model the behaviour of ocean derived flooding within the Narrabeen Lagoon catchment including the 20% AEP, 10% AEP, 5% AEP, 2% AEP, 1% AEP and 0.5% AEP events. The ocean derived flood events were based on the following:

- No catchment rainfall;
- Elevated ocean boundary as recommended in Appendix A of the Draft Flood Risk Management Guide (DECCW, 2009);
- Lagoon entrance bathymetry based on 2005 bathymetric survey; and
- Initial water level of 0.2m AHD.

6.5.3 Joint Catchment and Ocean Derived Flood Events

Model simulations were undertaken considering the coincidence of catchment and ocean flooding conditions consistent with the recommendations of the Flood Risk Management Guide (DECCW, 2009). These simulations were undertaken for the 1% AEP event using:

- 1% AEP catchment rainfall with 5% AEP design ocean condition; and
- 5% AEP catchment rainfall with 1% AEP design ocean condition.

The results of the above simulations were then compared to the design flood results for the 1% AEP catchment and 1% AEP ocean derived events in order to assess the influence of joint catchment and ocean design events on design flood levels. Different meteorological conditions drive the catchment and ocean flooding, such that a combined 1% AEP catchment event combined with a 1% AEP ocean event represents an extremely rare occurrence.

7 DESIGN FLOOD RESULTS

A range of design flood conditions were modelled, the results of which are presented and discussed below. The simulated design events included the 50% AEP, 20% AEP, 10% AEP, 5% AEP, 2% AEP, 1% AEP, 0.5% AEP, 0.2% AEP, 0.1% AEP and PMF events for catchment derived flooding and the 20% AEP, 10% AEP, 5% AEP, 2% AEP, 1% AEP and 0.5% events for ocean derived flooding. A series of design flood maps for selected events are provided in Appendix A.

7.1 Peak Flood Conditions

7.1.1 Catchment Derived Flood Events

The design flood results are presented in a flood mapping series in Appendix A. For the simulated design events including the 20% AEP, 10% AEP, 5% AEP, 2% AEP, 1% AEP, 0.5% AEP, 0.2% AEP, 0.1% AEP and PMF events, a map of peak flood level, depth and velocity is presented covering the modelled area.

Predicted flood levels at 17 selected locations are shown in Table 7-1 for the full range of design event magnitudes considered. The locations of reported flood levels are shown in Figure 7-1.

7.1.2 Ocean Derived Flood Events

The design flood results are presented in a flood mapping series in Appendix A. For the simulated design events including the 20% AEP, 10% AEP, 5% AEP, 2% AEP, 1% AEP and 0.5% AEP events, a map of peak flood level, depth and velocity is presented covering the modelled area.

Predicted flood levels at selected locations are shown in Table 7-2 for the full range of design event magnitudes considered. All events are modelled with an open entrance condition (refer Section 5.2.4). For lower order events that occur during a closed entrance condition the berm may offer some form of flood protection. However, for large ocean derived events the entrance berm would be overtopped or in some cases destroyed.

7.1.3 Joint Catchment and Ocean Derived Flood Events

Predicted peak flood levels at selected locations for the coincident catchment and ocean flooding scenarios are shown in Table 7-3. The coincident flooding scenarios presented include:

- 1% AEP catchment rainfall with 5% AEP design ocean condition; and
- 5% AEP catchment rainfall with 1% AEP design ocean condition.

Table 7-1 Modelled Peak Flood Levels for Catchment Derived Design Events

Location	Modelled Peak Flood Level (m AHD)									
	50% AEP	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP	0.1% AEP	PMF
US Ocean St Bridge	2.2	2.4	2.6	2.6	2.7	2.9	3.0	3.2	3.3	4.7
US Pittwater Rd Bridge (Narrabeen Lagoon)	2.2	2.4	2.6	2.7	2.8	3.0	3.1	3.3	3.4	5.0
US Pittwater Rd Bridge (Mullet Creek)	2.2	2.4	2.6	2.7	2.8	2.9	3.1	3.3	3.4	4.9
US Jackson Rd Culvert (Mullet Creek)	2.5	2.5	2.7	2.8	2.9	3.0	3.2	3.3	3.4	4.9
US Garden St Culvert (Mullet Creek)	3.9	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.7	5.3
US Garden St Culvert (Fern Creek)	10.9	11.2	11.3	11.6	11.8	11.9	12.0	12.1	12.2	12.5
US Macpherson St Culvert (Narrabeen Creek)	2.9	3.0	3.1	3.2	3.3	3.3	3.4	3.5	3.6	4.9
Narrabeen RSL Carpark (Nareen Creek)	5.2	5.4	5.5	5.6	5.7	5.8	5.9	5.9	6.0	6.3
US Narroy Rd Culvert (Nareen Creek)	2.2	2.4	2.6	2.7	2.8	3.0	3.1	3.3	3.4	4.9
US Pittwater Rd Culvert (Nareen Creek)	2.2	2.4	2.6	2.7	2.8	3.0	3.1	3.3	3.4	4.9
US Deep Creek Bridge	2.2	2.5	2.6	2.7	2.9	3.0	3.2	3.3	3.5	5.0
US Middle Creek Bridge 1	2.2	2.5	2.6	2.7	2.9	3.0	3.2	3.3	3.5	5.0
US Middle Creek Bridge 2	8.1	8.5	8.8	9.1	9.5	9.8	10.0	10.2	10.4	12.0
US Middle Creek Bridge 3	10.1	10.6	10.9	11.1	11.5	11.7	11.9	12.1	12.3	14.0
US Toronto Ave Bridge (South Creek)	4.3	4.3	4.4	4.5	4.8	5.0	5.2	5.3	5.4	6.3
US Carcoola Rd Culvert (South Creek)	6.1	6.3	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.8
US Willandra Rd Culvert (South Creek)	12.7	12.9	12.9	13.0	13.1	13.1	13.2	13.3	13.3	13.9

Title:
Design Event Peak Flood Level Reporting Locations

Figure: 7-1

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Table 7-2 Modelled Peak Flood Levels for Ocean Derived Design Events

Location	Modelled Peak Flood Level (m AHD)					
	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP
US Ocean St Bridge	1.3	1.4	1.6	1.8	1.9	2.0
US Pittwater Rd Bridge (Narrabeen Lagoon)	1.3	1.4	1.6	1.7	1.9	2.0
US Pittwater Rd Bridge (Mullet Creek)	1.3	1.4	1.6	1.7	1.9	2.0
US Jackson Rd Culvert (Mullet Creek)	1.3	1.4	1.5	1.7	1.8	2.0
US Macpherson St Culvert (Narrabeen Creek)	-	-	1.5	1.7	1.8	2.0
US Narroy Rd Culvert (Nareen Creek)	1.2	1.4	1.5	1.7	1.9	2.0
US Deep Creek Bridge	1.3	1.4	1.6	1.8	1.9	2.0
US Middle Creek Bridge 1	1.3	1.4	1.6	1.8	1.9	2.0
US Toronto Ave Bridge (South Creek)	1.3	1.4	1.6	1.8	1.9	2.0

Table 7-3 Modelled Peak Flood Levels for Joint Design Events

Location	Modelled Peak Flood Level (m AHD)			
	1% AEP 9-hour Catchment Event	1% AEP Ocean Event	1% AEP Catchment + 5% AEP Ocean	5% AEP Catchment + 1% AEP Ocean
US Ocean St Bridge	2.9	1.9	3.0	2.6
US Pittwater Rd Bridge (Narrabeen Lagoon)	3.0	1.9	3.0	2.6
US Pittwater Rd Bridge (Mullet Creek)	2.9	1.9	3.0	2.6
US Jackson Rd Culvert (Mullet Creek)	3.0	1.8	3.0	2.7
US Garden St Culvert (Mullet Creek)	4.2	-	4.2	4.1
US Garden St Culvert (Fern Creek)	11.5	-	11.5	11.2
US Macpherson St Culvert (Narrabeen Creek)	3.3	1.8	3.3	3.2
Narrabeen RSL Carpark (Nareen Creek)	5.3	-	5.3	5.2
US Narroy Rd Culvert (Nareen Creek)	2.9	1.9	3.0	2.6
US Pittwater Rd Culvert (Nareen Creek)	2.9	1.9	3.0	2.6
US Deep Creek Bridge	3.0	1.9	3.1	2.6
US Middle Creek Bridge 1	3.0	1.9	3.1	2.6
US Middle Creek Bridge 2	9.5	-	9.5	9.0
US Middle Creek Bridge 3	11.2	-	11.2	10.9
US Toronto Ave Bridge (South Creek)	4.7	1.9	4.7	4.2
US Carcoola Rd Culvert (South Creek)	6.3	-	6.4	6.3
US Willandra Rd Culvert (South Creek)	12.9	-	12.9	12.8

7.2 Design Flood Hydrographs

A range of storm durations were modelled in order to identify the critical storm duration for design event flooding in the catchment. Design durations considered included the 0.5-hour 1-hour, 1.5-hour, 2-hour, 3-hour, 4.5-hour, 6-hour, 9-hour, 12-hour, 18-hour and 24-hour durations.

Outputs from the model simulations indicate that the maximum peak inflows to Narrabeen Lagoon are generally derived when using a storm duration of between 9 to 24 hours. Note there are only minor differences in peak levels in the Lagoon between the 9 to 24 hour durations. In the upper reaches of some of the tributary catchments, the 2-hour duration provided for the highest peak flows.

A plot of the water level response at the location on Narrabeen Creek upstream of Macpherson Street provides a good representation of general flood response in the catchment. Figure 7-2 shows the simulated water level time series at Macpherson Street for the 1% AEP 2-hour and 9-hour storm durations. This location is approximately at the limit of where the influence of Narrabeen Lagoon flooding ends and the local catchment flood condition becomes the dominant flooding condition. This is further illustrated in Figure 7-3 showing a plot of the critical duration for the 1% AEP event across the lower part of the catchment. Within the broader Lagoon and the lower reaches of the tributary channels, the longer 9-18 hour duration events provide for the peak flood water levels in the system. Macpherson Street on the Narrabeen Creek tributary represents the approximate limit where the shorter duration 2-hour event for local flooding becomes the critical duration.

Figure 7-2 shows the flood peak for the 2-hour and 9-hour durations to be almost the same level at Macpherson Street. The 2-hour duration water level profile is largely driven by the local flooding generated in the Narrabeen Creek catchment. The relatively small catchment provides for a rapid water level response to rainfall, with peak flood conditions being reached within an hour.

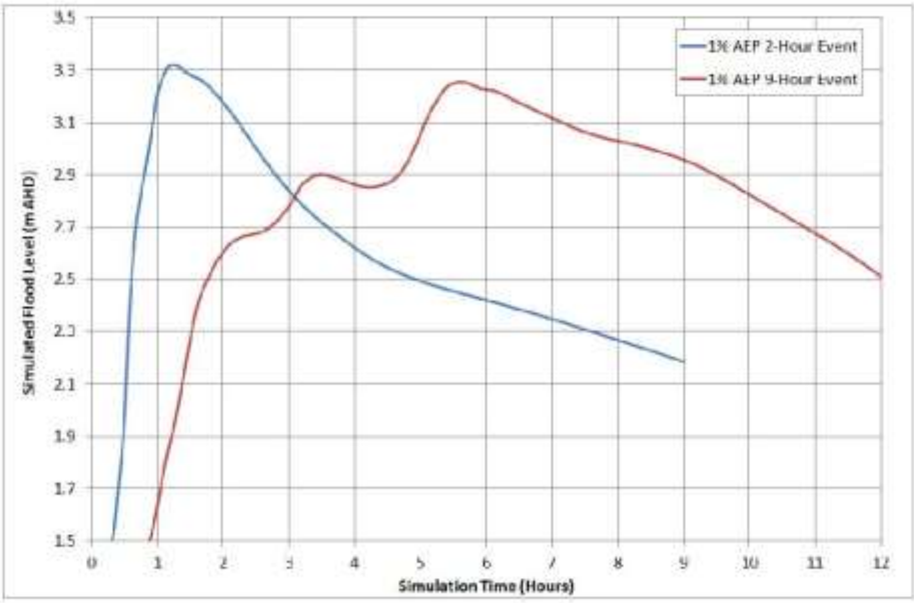
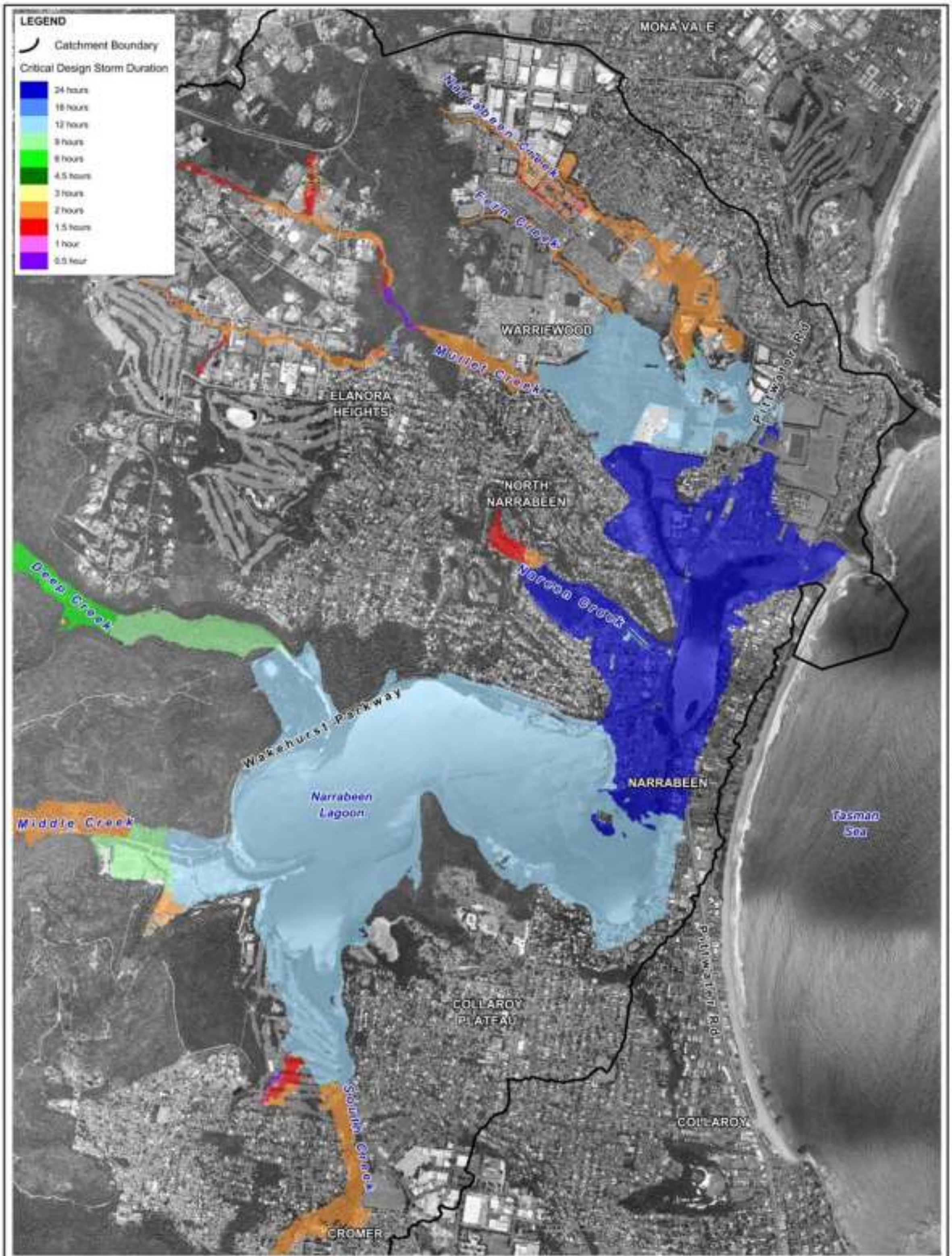


Figure 7-2 Simulated Water Level Response at Macpherson Street, Narrabeen Creek



Title: Crtitical Design Storm Duration - 1% AEP Catchment Event

Figure: 7-3

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The 1% AEP 9-hour water level time series shown in Figure 7-2 represents significantly longer storm duration with a greater overall runoff volume compared to the 2-hour design event. The plot shows a dual peak with the local catchment contribution peaking at around 4-hours before the higher peak at around 6-hours. This later peak represents the peak flood condition being reached in the broader Narrabeen Lagoon. Further upstream within Narrabeen Creek, there is less influence from the Lagoon flood level in which short duration event local catchment flooding becomes the clear dominant flooding mechanism. This type of flood behaviour is similar on the other small tributaries where the critical durations in the upper reaches are relatively short as shown in Figure 7-3.

The rapid water level rise as seen in Figure 7-2 has implications for floodplain risk management and emergency response given the potential for limited available warning time before the onset of peak flood conditions. Critical durations are similar for most of the other design event return periods. For the PMF event, the critical duration for the broader Lagoon area is the 5-hour duration with the 0.5 and 1-hour events typically the critical duration for the local flooding in the upper tributaries.

The simulated 1% AEP 9-hour duration hydrographs for each of the main tributaries at the confluence with Narrabeen Lagoon and the Lagoon hydrograph at the Ocean Street Bridge are shown in Figure 7-4. Also shown for reference is the combined inflows to the Lagoon from the tributary catchments. The significant effect of the storage on attenuating flows through the Lagoon is evident in comparing the combined inflow hydrograph to the Ocean Street hydrograph. This attenuating effect results in lower peak discharge to the ocean, however also provides for a lag of some 2 to 3 hours between the peak inflows to the Lagoon and the actual peak flood condition in the main body of the Lagoon. The Lagoon response for the 9-hour duration design event is similar to the conditions observed in the April 1998 event.

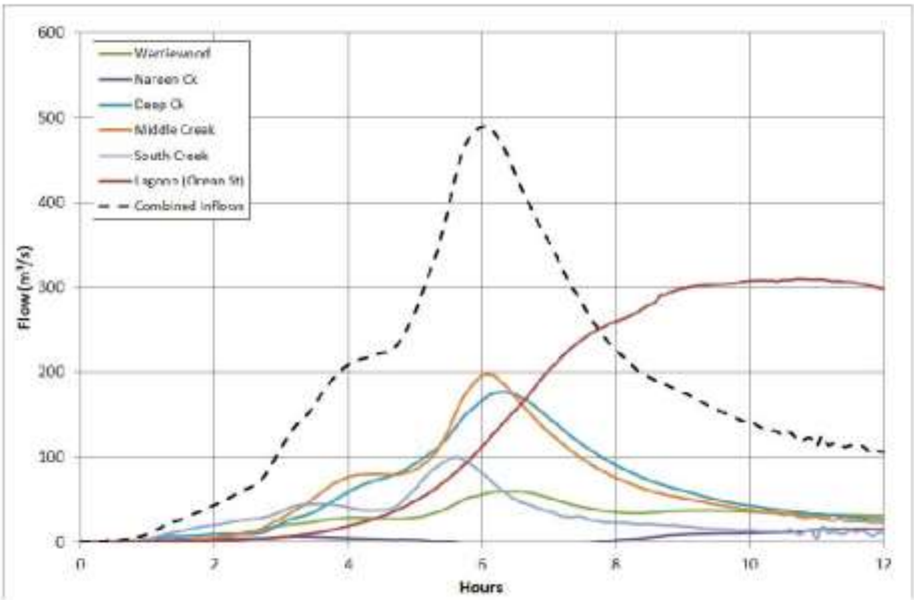


Figure 7-4 Sub-catchment Contributions to Narrabeen Lagoon (1% AEP 9-hour Event)

The rates of rise of the hydrographs are to some degree dependent on the adopted temporal patterns across the range of design storm event durations (refer to Section 6.1.2). However, the response shown in Figure 7-4 with a rapid rise in flow over 1 to 2 hours is generally typical of the catchment response. Even shorter response times may be apparent in the upper reaches of the catchments.

The main contributions to flows in Narrabeen Lagoon obviously come from the largest sub-catchments being the Deep Creek and Middle Creek tributaries. A summary of the design peak flows from each tributary for the 1% AEP event are summarised in Table 7-4. Shown for comparison in the table are the peak discharges from previous studies including the 1990 Narrabeen Lagoon Flood Study and the more recent flood studies completed for individual sub-catchments.

Table 7-4 Design Peak Tributary Flows (1% AEP Event)

Sub-catchment	Peak 1% AEP Flow (m^3/s)		
	Current Study	Narrabeen Lagoon Flood Study (PWD, 1990)	Recent Flood Study (see notes)
Warriewood Valley (Mullet, Fern and Narrabeen Creeks)	60 (157)	130	60[a]
Nareen Creek	17	42	24[b]
Deep Creek	177	190	n/a
Middle Creek	212	167	196[c]
South Creek	129	101	121[d]

a) Warriewood Valley Flood Study (Lawson & Treloar, 2005)

b) Nareen Creek Flood Study (Cardno Lawson Treloar, 2005)

c) Middle Creek Flood Modelling (DHI, 2009)

d) South Creek Flood Study (Webb, McKeown & Associates, 2006)

Note: The bracketed value for the current study represents the combined peak flow of the combined Mullet/Fern/Narrabeen Ck tributaries upstream of Warriewood Wetland.

In general the simulated peak flows from the current study compare reasonably well to peak flows from the other completed studies. There is consistency between the current study and the 2005 study by Lawson and Treloar for the Warriewood sub-catchment. This value represents the flow downstream of Warriewood Wetlands, which is highly attenuated in comparison to the peak flows from the upstream tributaries. The bracketed value represents the combined peak inflows from the tributaries upstream of Warriewood Wetlands, noting that this value compares more favourably with the PWD (1990) study. The PWD (1990) study value also represents an "un-attenuated" flow from the hydrological model, without the influence of the significant Warriewood Wetland and Narrabeen Lagoon storage effects. It is noted that the current study also predicts higher flows from the Narrabeen, Fern and Mullet Creek tributaries upstream of Warriewood Wetlands in comparison to Lawson and Treloar (2005).

For the simulated 1% AEP design event the combined peak inflow into Narrabeen Lagoon is 490m^3/s. The relative inflows for other selected design event magnitudes are shown in Figure 7-5 for comparison.

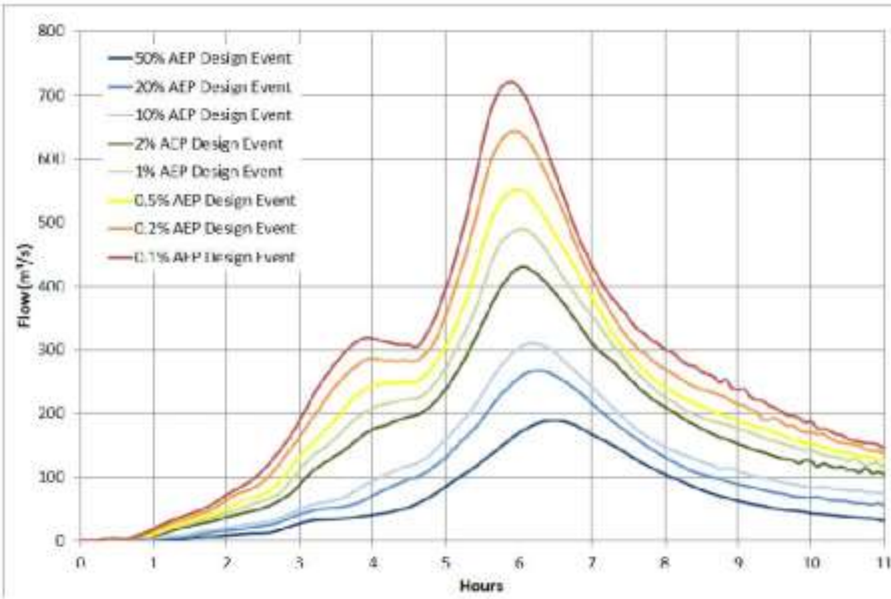


Figure 7-5 Combined Inflows to Narrabeen Lagoon for Sample Design Events

7.3 Design Flood Behaviour

The design flood mapping in Appendix A presents the peak design flood condition throughout the catchment, giving the peak flood extents, depth and velocity distributions. Further discussion on the general nature of flooding within each of the main sub-catchments of Narrabeen Lagoon is provided below.

7.3.1 Narrabeen Lagoon Entrance

The main Lagoon waterbody represents a significant flood storage area at the downstream end of the catchment. As discussed in Section 7.2, the Lagoon receives significant flood flows from each of its tributary catchments. These inflows are highly attenuated through the flood storage provided in the Lagoon and the control of outflow through the entrance channel.

The simulated design flood conditions have assumed a relatively shoaled entrance condition at the beginning of the flood event, and a corresponding high initial Lagoon water level. As floodwaters are conveyed from the tributary catchments through the Lagoon water body, overtopping of the entrance berm initiates scour, with a continual widening and deepening of the entrance channel as flow increases. The flood levels attained in the Lagoon are a function of the volume of floodwater entering from the tributary catchments and the discharge through the entrance channel to the ocean.

The model simulations provide for significant scour of the entrance through the flood event from the initial shoaled condition. In general, the entrance channel deepens considerably with removal of the entrance shoals under high flow conditions also. The model provides for entrance scour in order to simulate the berm breaching process and thereby the influence on flood conveyance. The extent of scour or erosion, particularly in the PMF event is expected to extend to up to the base of the stabilised dune at Birdwood Park.

Figure 7-6 shows an example of the simulated evolution of the entrance scour under flood condition. The model scenario shown is for the 1% AEP 9-hour design flood event incorporating a heavily shoaled initial condition at the entrance, with the adopted minimum berm height of 1.3m AHD. At this level the entrance is closed. The overtopping of the berm initiates outflow through the entrance in response to catchment inflows. On the initial rising limb of the hydrograph, the entrance remains largely constrained with the Lagoon body and entrance water levels rising commensurately. As catchment inflows increase and induce scour of the entrance, the outflow hydrograph rises rapidly. Under the high flow conditions a significant water level gradient from the Lagoon to the entrance is generated. Water levels in the Lagoon and entrance channel would continue to fall through the hydrograph recession until the tidal exchange is reinstated through the scoured (open) entrance.

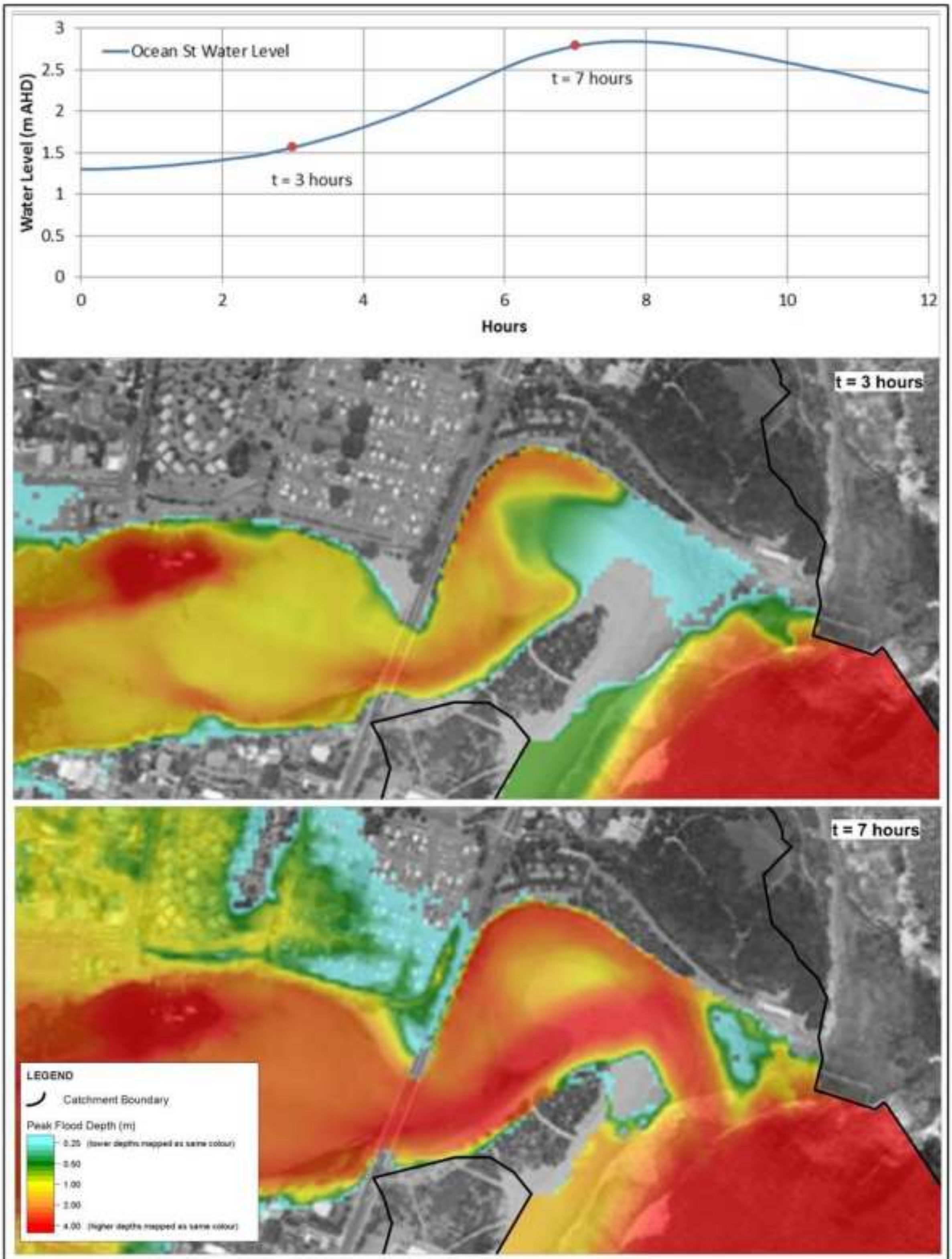
The results presented show in general terms the simulation of flood behaviour at the entrance of Narrabeen Lagoon for a catchment flood event initiating an entrance breakout. The application of the morphological model within the flood study context is not intended to define the exact evolution of the entrance channel in terms of definitive erosion and sedimentation zones and the final entrance shape and bathymetry. What is important however is that the models provide for an appropriate representation of the total conveyance of the entrance, and simulate the changing capacity as the flood wave propagates through the system.

Comparison of pre- and post-breakout bathymetric survey, although typically unavailable within reasonable periods of a given event, can provide the opportunity to validate the models in respect to the shape and position of the scoured channel. Collection of such survey data may be considered in future entrance breakout events.

7.3.2 Narrabeen Lagoon and Foreshores

Typically in flood conditions, the peak water level in the Lagoon is similar across the entire waterbody with very little water level gradient. The foreshore inundation accordingly can be tied to a representative Lagoon water level. At the downstream end of the Lagoon, small flood water level gradients are generated from Pittwater Road bridge through to the entrance.

Figure 7-7 shows examples of the relative response of water level in Narrabeen Lagoon for the 1% AEP design event of various storm durations. As the Narrabeen Lagoon storage has a significant influence on design flood conditions, longer duration (volume driven) events are typically more critical in terms of peak flood level in the Lagoon. The 9-hour, 18-hour and 24-hour events resulted in similar peak flood levels in Narrabeen Lagoon, albeit with different response in terms of timing and volume of flow.



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Narrabeen Lagoon Flood Study - Peak Flood Depths: 1% AEP Catchment Derived Event	7-6	A

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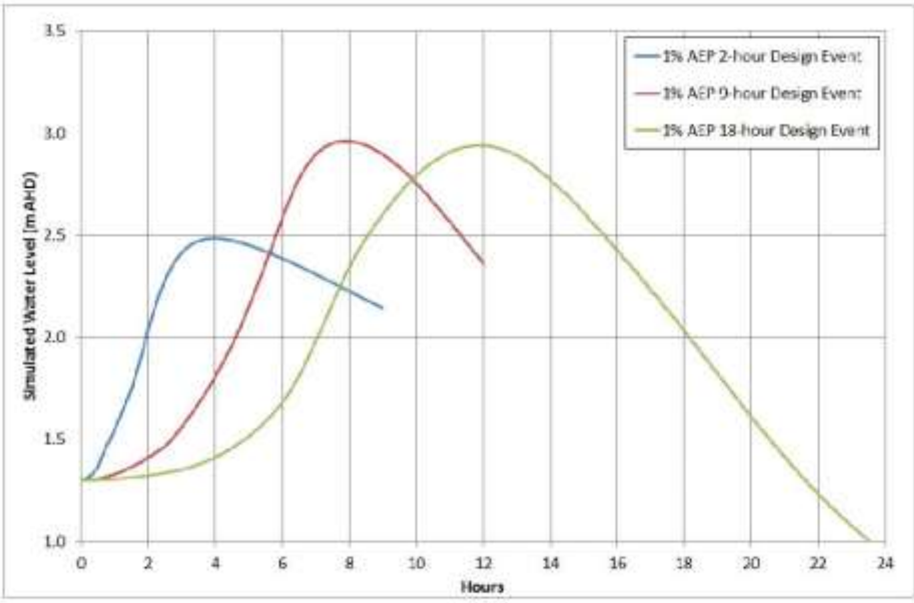
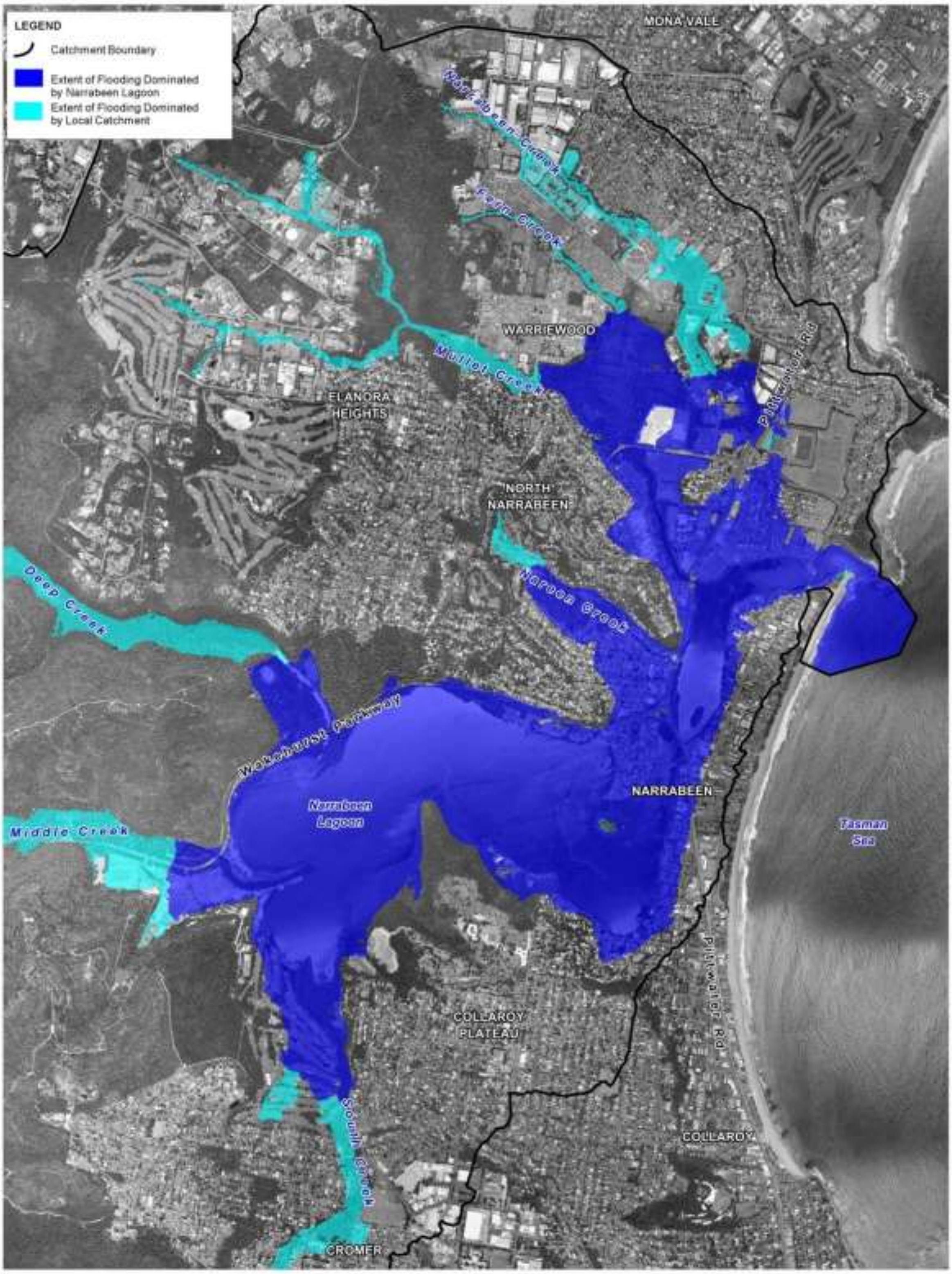


Figure 7-7 Simulated Water Level Response in Narrabeen Lagoon

The 9-hour design event provides for close to critical peak flood level condition, but also represents a very rapid rise in flood water level in the Lagoon. This rapid rise in flood level has significant implications in terms of flood emergency response. Properties may be subject to inundation without significant flood warning time (e.g. 6 hours) which may limit the opportunity for an effective coordinated flood emergency response. Key access routes are likely to cut by floodwaters prior to the peak flood levels being reached.

The 2-hour design event, characterised by very high intensity short duration rainfall, does not generate sufficient flood volumes throughout the catchment to raise Narrabeen Lagoon flood levels to the design peak conditions under longer duration events. However, the Lagoon levels attained are still high enough for inundation of lower foreshore areas. As shown, this may occur within a matter of hours, again providing limitations on effective flood warning and response. The shorter duration events are also the more critical events for the upper reaches of the catchments.

Figure 7-8 shows the approximate extent of the influence of Narrabeen Lagoon flood levels. The figure provides for the approximate delineation between the floodplain area dominated by the peak Narrabeen Lagoon flood condition and the area dominated by the local catchment peak flood condition. As noted, a large proportion of the lower catchment is dominated by the Narrabeen Lagoon peak flood level.



Title:
Extent of Narrabeen Lagoon Influence on Peak 1% AEP Flood Levels

Figure: 7-8 | Rev: A

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7.3.3 Warriewood Valley (Mullet, Fern and Narrabeen Creeks)

This catchment has the highest density of urbanisation, particularly within the extent of the defined flood prone land (up to the PMF extent).

In the upper reaches of Narrabeen Creek and Mullet Creek, flooding is generally confined to the channel with limited overbank flows. In the upper reaches of these channels, the contributing catchment area is relatively small and with the combination of recent in-stream works to increase/maintain channel capacity, floodwaters even in major events are largely conveyed in-bank. Accordingly, the development that has taken place to date is largely free from extensive inundation. The capacity of the existing culvert at Ponderosa Parade on Narrabeen Creek may be exceeded in events in excess of the 10% AEP event. Once floodwaters overtop the road, some flow bypasses the creek channel and is conveyed along Macpherson Street.

Typical peak flood level profiles along Narrabeen Creek are shown in Figure 7-9. Peak flood levels in the lower tributaries are dominated by the Narrabeen Lagoon water level. The limit of the Lagoon water level influence on Narrabeen Creek is approximately around the Macpherson Street bridge up to the 1% AEP condition. Upstream of this location, peak flood levels are driven by local channel capacity and catchment flows, whereas for downstream, peak flood levels are driven by the flooding in Narrabeen Lagoon.

In the middle reaches of the catchment, the Warriewood Wetlands represent a significant storage area with Mullet and Fern Creeks draining directly into the wetlands. Outflow from the wetlands is controlled by the culverts under Jacksons Road. The wetlands are relatively low-lying and accordingly subject to extensive inundation in major flooding. The Wetlands however only have a minor influence on design peak flood conditions. The flood storage provided by the Wetlands is relatively small in comparison to the overall flood volumes generated by the contributing catchments. Moreover, peak levels in the Wetlands are driven by the flood condition in the broader Narrabeen Lagoon such that Wetland storage has minimal influence on the peak flood level.

Centro Warriewood Shopping Centre is located adjacent to the wetlands, however is constructed on elevated ground. It is understood that the shopping centre floor levels are of the order of 3.0m AHD, which is approximately at the 1%AEP event level. There are however some lower lying areas of the centre such as loading docks and car-park areas which would be subject to inundation in major flood events. Access to the shopping centre is via Jacksons Road which has a low point adjacent to the centre of around 2.5m AHD. This would be the critical level in terms of emergency flood egress for the shopping centre.

Typical peak flood level profiles along Mullet Creek are shown in Figure 7-10. As for Narrabeen Creek, peak flood levels in the lower reaches of Mullet Creek are dominated by the Lagoon flooding conditions as indicated by the flat water level profile extending upstream from the confluence. The Lagoon flooding influence on peak flood levels extends to the Garden Street crossing of Mullet Creek, upstream of the wetlands.

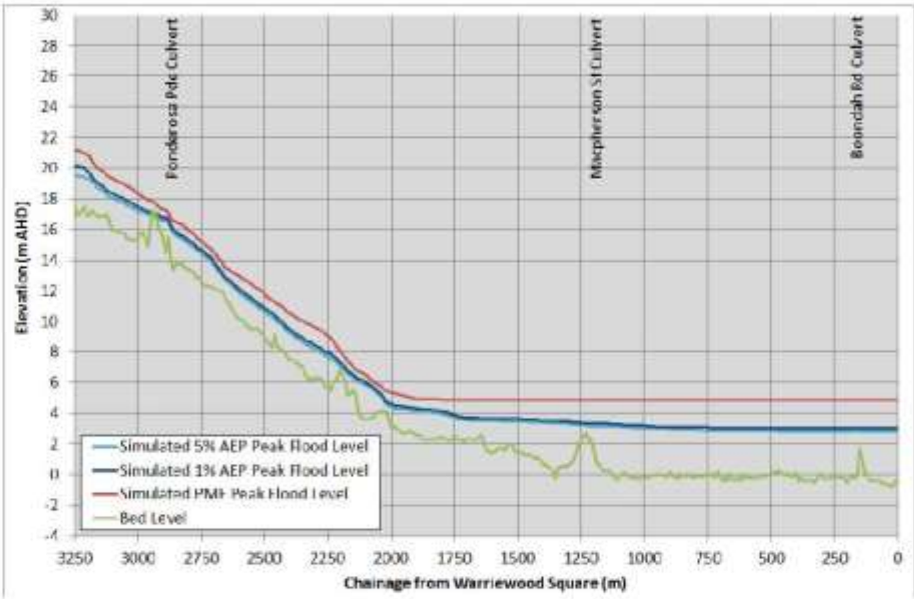


Figure 7-9 Peak Flood Water Level Profile for Narrabeen Creek

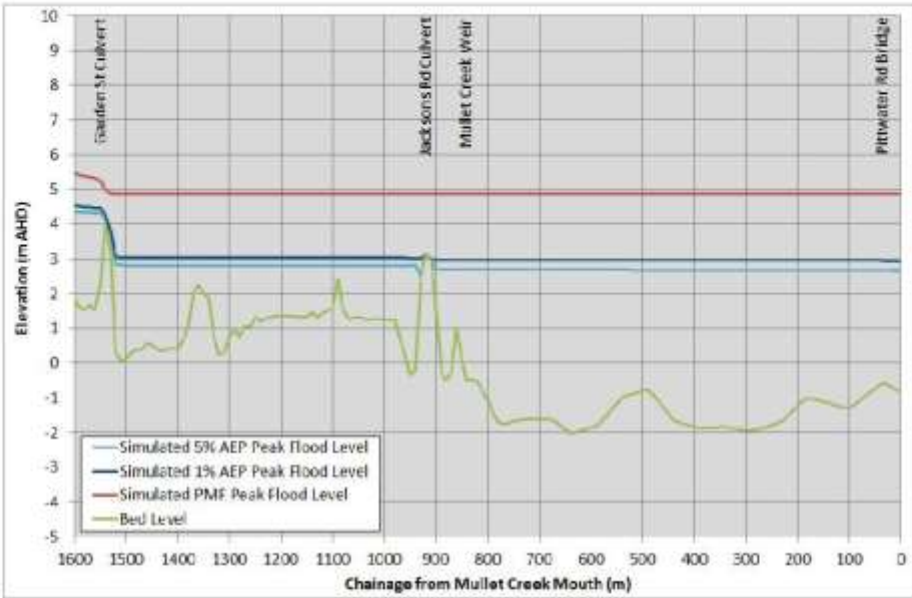


Figure 7-10 Peak Flood Water Level Profile for Mullet Creek

In the lower reaches of Mullet Creek, the Garden Street area is affected by flooding. A significant proportion of this land, which is largely fully occupied by existing development, is at 2.0m AHD or below. Accordingly, some of this area would be subject to significant inundation in a major flood event, and also potentially subject to more frequent inundation for lower order events ~20% AEP.

7.3.4 Nareen Creek

Nareen Creek is a relatively small catchment, however it is fully developed with the exception of Narroy Park. The creek channel is small and accordingly limited in capacity. Whilst the local catchment poses some risks from flash flooding, the flooding from Narrabeen Lagoon provides for the dominant flood condition in terms of peak flood levels. The floodplain of Nareen Creek is relatively low-lying at around 2.0-2.4m AHD for the developed areas downstream of Narroy Park. Flooding in this locality will be dominated by the conditions in Narrabeen Lagoon, including the peak flood levels reached and their relative timing in response to rainfall. Nevertheless, the lower parts of the catchment are still susceptible to the flash flooding risks associated with shorter durations.

7.3.5 Deep Creek

The Deep Creek catchment is essentially undeveloped and accordingly there is limited existing development subject to flood risk. The Wakehurst Parkway traverses Deep Creek near its confluence with the Lagoon. The Deep Creek bridge is a relatively high level crossing with a deck level of the order of 3.5m AHD. However, the western approach does dip to a low point of around 2.5m AHD approximately 200m west of the main channel. Given the design flood levels of the Lagoon, the Wakehurst Parkway may be expected to be inundated at this location in significant flood events.

7.3.6 Middle Creek

The Middle Creek catchment provides a substantial contribution of flood flow to Narrabeen Lagoon. However, as with Deep Creek, the majority of the Middle Creek catchment is undeveloped. There is some urban development at the very top of the catchment around Frenchs Forest and Oxford Falls, however, there is little development affected by mainstream flooding of Middle Creek. The Wakehurst Parkway runs adjacent to Middle Creek for the majority of its length with multiple bridge crossings.

The Middle Creek channel and floodplain is relatively narrow and well confined through the upper and middle reaches. It is not until near the confluence with the Lagoon that the floodplain widens and flattens, thereby providing for more extensive areas of inundation in times of flood. The Sydney Academy of Sport and Recreation is located on the right bank of Middle Creek some 500m upstream of the confluence with the Lagoon. The majority of the land occupied by the site is at around 2.0-2.2m AHD. Accordingly, significant inundation of the site may occur even for relatively low order flood events ~20% AEP.

7.3.7 South Creek

The South Creek catchment is extensively urbanised, including adjacent to the main channel along its full length. The channel and floodplain, however, are relatively narrow and steep such that there is no extensive or broad scale inundation in the upper and middle reaches particularly. There are numerous road crossings and culverts forming local hydraulic controls.

Typical peak flood level profiles along South Creek are shown in Figure 7-11. The influence of Narrabeen Lagoon flood levels extends to approximately a few hundred metres downstream of Toronto Avenue. Upstream of this location the local catchment flows and channel/floodplain capacity control peak flood water level conditions. The most significant area of inundation along South Creek however is downstream of Toronto Avenue. This inundation is largely confined to the Cromer golf course which occupies the floodplain area on the left bank of South Creek near the Lagoon confluence.

A number of the road crossings over South Creek are overtopped in major flood events. In the majority of these cases the bridge/culvert crossing is at the low point in the road such that floodwaters overtopping the road immediately re-enter the creek channel downstream, thereby having limited effect on adjacent properties. For Alkira Circuit however, once the culvert capacity is exceeded and road overtopping occurs, flow would be conveyed down Alkira Circuit effectively by-passing the creek channel. The by-pass flow eventually re-enters the South Creek channel via overland flow through properties along Alkira Circuit. It should be noted that the current study is not at a resolution to address the local overland flow issue and resolve the flow depth and velocity conditions through the affected properties on Alkira Circuit.

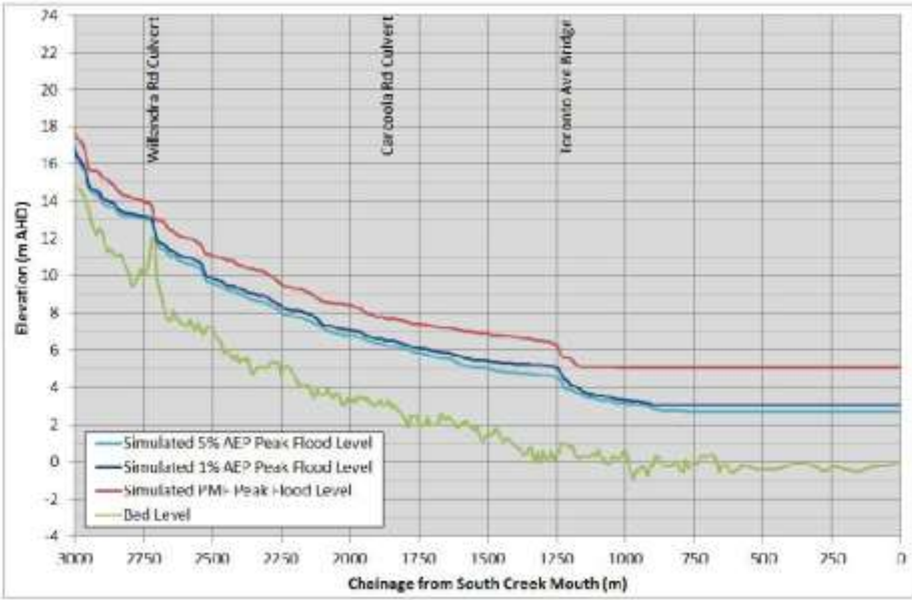


Figure 7-11 Peak Flood Water Level Profile for South Creek

7.4 Comparison with Previous Studies

A comparison of the peak flood levels from the current study with those of the previous flood studies undertaken within the Narrabeen Lagoon catchment for several key locations is presented in Table 7-5. Comparison of the simulated flood extents for the 1% AEP and PMF events is also shown in Figure 7-12 and Figure 7-13.

The peak flood level comparisons shown in Table 7-5 indicate that the peak flood levels in the lower catchment and main body of Narrabeen Lagoon for the current study are greater in the lower reaches then the previously modelled peak flood levels. There is also some variation between flood levels in the mid-catchment reaches of the main tributary alignments. The variation in the peak flood levels between the current study and previous flood studies may be attributed to the following factors:

- Differences in modelling approach and software;

- Differences in topographical data sets;
- Improved model calibration and use of historical data;
- Changes to hydraulic structures;
- Catchment land use changes.

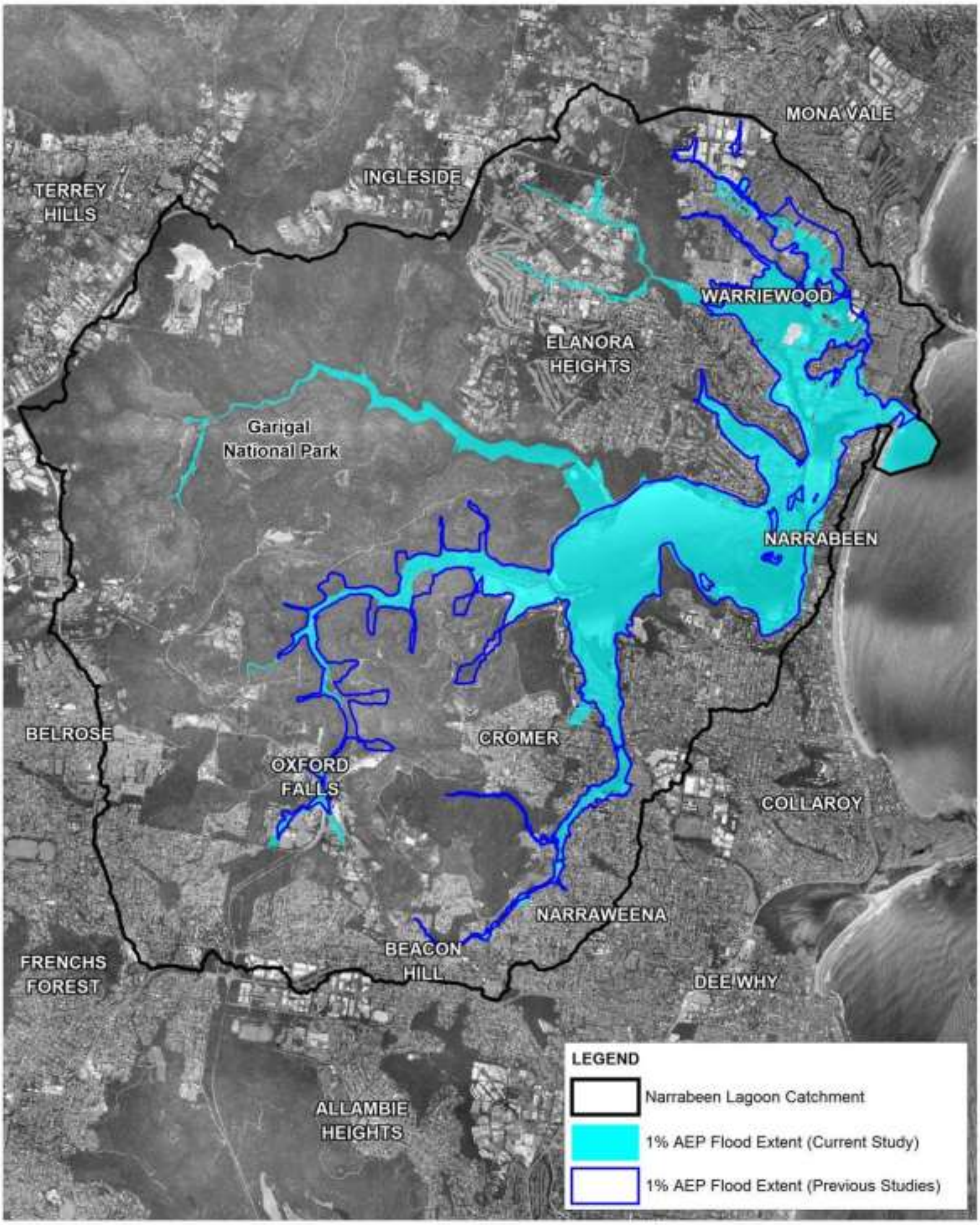
Generally the water levels simulated between the current study and previous studies are of a similar order with typical variations less than 0.3m (typical of order of accuracies expected through a model calibration process).

Table 7-5 Comparison of 1% AEP Peak Flood Levels to Previous Flood Studies

Location	1% AEP Peak Flood Levels (m AHD)	
	Current Study	Previous Flood Study (see notes)
US Ocean St Bridge	2.9	2.7[a]
US Pittwater Rd Bridge (Narrabeen Lagoon)	3.0	2.9[a]
Mullet Creek Confluence	3.0	2.7[a]
US Jackson Rd Culvert (Mullet Creek)	3.0	3.0[a]
US Garden St Culvert (Mullet Creek)	4.5	3.9[b]
US Garden St Culvert (Fern Creek)	11.9	11.8[b]
US Macpherson St Culvert (Narrabeen Creek)	3.3	3.3[b]
Narrabeen RSL Carpark (Nareen Creek)	5.8	5.8[c]
US Deep Creek Bridge	3.0	2.9[a]
US Middle Creek Bridge 1	3.0	3.2[a]
US Toronto Ave Bridge (South Creek)	5.0	4.9[a] & 5.2[e]
US Carcoola Rd Culvert (South Creek)	6.6	7.7[a] & 6.9[e]
US Willandra Rd Culvert (South Creek)	13.1	13.6[a] & 13.2[e]

a) Narrabeen Lagoon Flood Study (PWD, 1990)
b) Warriewood Valley Flood Study (Lawson & Treloar, 2005)
c) Nareen Creek Flood Study (Cardno Lawson Treloar, 2005)
d) Middle Creek Flood Modelling (DHI, 2009)
e) South Creek Flood Study (Webb, McKeown & Associates, 2006)

Of the peak flood level comparisons shown in Table 7-5, the most significant difference from previous studies is at the Garden Street culvert on Mullet Creek. This difference is largely derived from an increase in design flows for the current study in comparison to the previous Warriewood Flood Study. The previous Warriewood Flood Study had significantly higher continuing losses for the duration of the design events, thereby lower peak flows were generated. As noted in Section 6.1.3, the design rainfall losses adopted in the current study are consistent with the recommended ranges for design event losses in AR&R (2001). The appropriateness of the adopted design flow conditions have been further confirmed through cross checks of peak flow estimates based on the Rational Method. Further information on the Rational Method is included in Appendix C.



Title:
1% AEP Design Event – Flood Extent Comparison

Figure: 7-12

Rev: A

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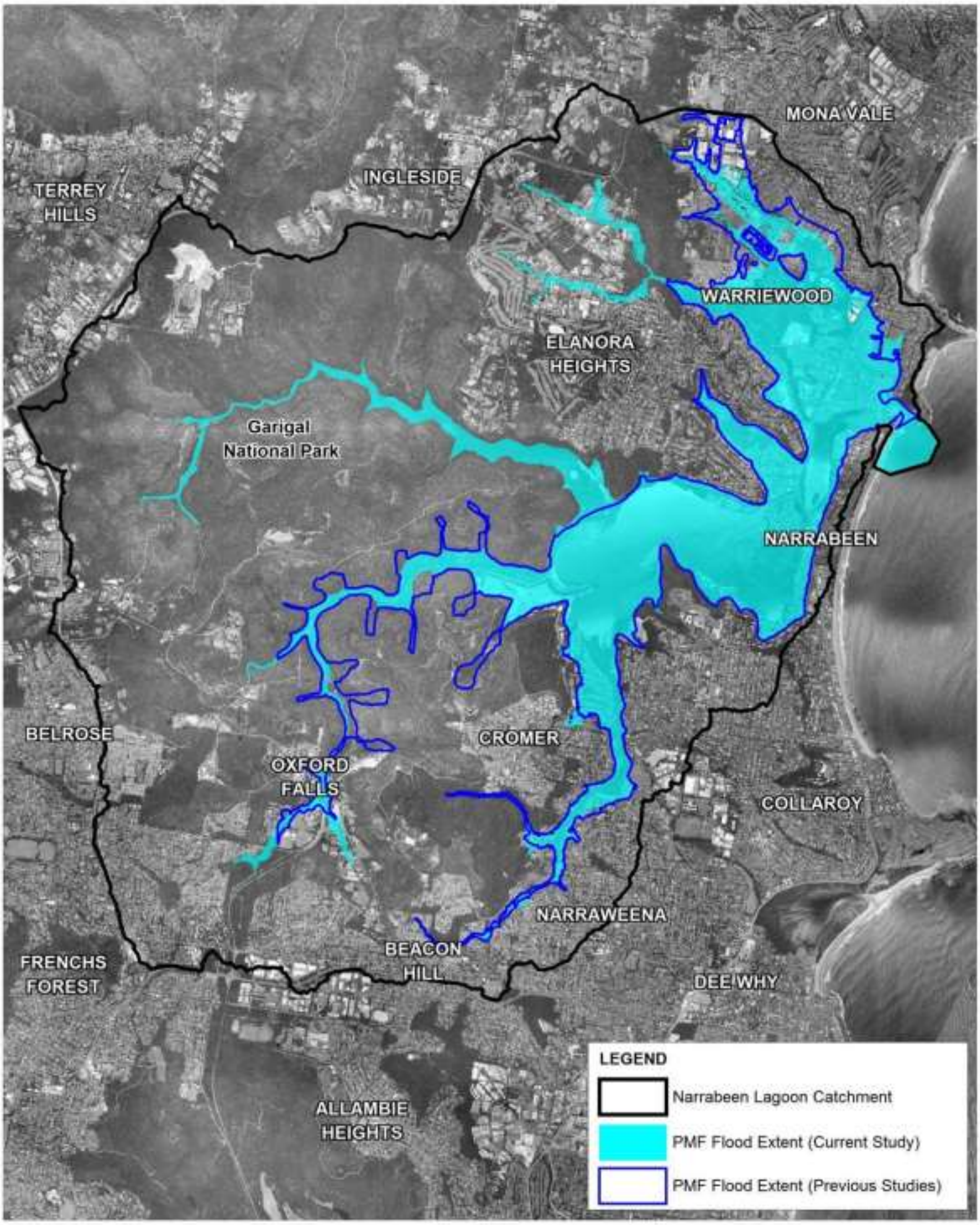

Title:
PMF Design Event – Flood Extent Comparison

Figure: 7-13

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7.5 Hydraulic Categories

There are no prescriptive methods for determining what parts of the floodplain constitute floodways, flood storages and flood fringes. Descriptions of these terms within the Floodplain Development Manual (NSW Government, 2005) are essentially qualitative in nature. Of particular difficulty is the fact that a definition of flood behaviour and associated impacts is likely to vary from one floodplain to another depending on the circumstances and nature of flooding within the catchment.

The hydraulic categories as defined in the Floodplain Development Manual (NSW Government, 2005) are:

Floodway - Areas that convey a significant portion of the flow. These are areas that, even if partially blocked, would cause a significant increase in flood levels or a significant redistribution of flood flows, which may adversely affect other areas.

Flood Storage - Areas that are important in the temporary storage of the floodwater during the passage of the flood. If the area is substantially removed by levees or fill it will result in elevated water levels and/or elevated discharges. Flood Storage areas, if completely blocked would cause peak flood levels to increase by 0.1m and/or would cause the peak discharge to increase by more than 10%.

Flood Fringe - Remaining area of flood prone land, after Floodway and Flood Storage areas have been defined. Blockage or filling of this area will not have any significant effect on the flood pattern or flood levels.

A number of approaches were considered when attempting to define hydraulic categories across the Narrabeen Lagoon catchment. Approaches to define hydraulic categories that were considered for this assessment included partitioning the floodplain based on:

- Peak flood velocity;
- Peak flood depth;
- Peak velocity * depth (sometimes referred to as unit discharge);
- Cumulative volume conveyed during the flood event; and
- Combinations of the above.

The definition of hydraulic categories that was considered to best fit the application within the Narrabeen Lagoon catchment, was based on a combination of velocity*depth and depth parameters. The adopted hydraulic categorisation is defined in Table 7-6.

Preliminary hydraulic category mapping for the 20% AEP, 5% AEP, 1% AEP and PMF design events is included in Appendix A. It is also noted that mapping associated with the flood hydraulic categories may be amended in the future (e.g. a change from floodway to flood storage), at a local or property scale, subject to appropriate analysis that demonstrates no additional impacts to upstream, downstream or adjacent properties. From the definitions provided in the Floodplain Development Manual, it should be noted that filling would generally only be permissible in flood fringe areas. Filling would generally not be permitted in Floodways or Flood Storage Areas.

Table 7-6 Hydraulic Categories

Floodway	Velocity * Depth > 0.5	Areas and flowpaths where a significant proportion of floodwaters are conveyed (including all bank-to-bank creek sections).
Flood Storage	Velocity * Depth < 0.5 and Depth > 0.5 metres	Areas where floodwaters accumulate before being conveyed downstream. These areas are important for detention and attenuation of flood peaks.
Flood Fringe	Velocity * Depth < 0.5 and Depth < 0.5 metres	Areas that are low-velocity backwaters within the floodplain. Filling of these areas generally has little consequence to overall flood behaviour.

7.6 Provisional Hazard Classifications

The NSW Government's Floodplain Development Manual (2005) defines flood hazard categories as follows:

High hazard – possible danger to personal safety; evacuation by trucks is difficult; able-bodied adults would have difficulty in wading to safety; potential for significant structural damage to buildings; and

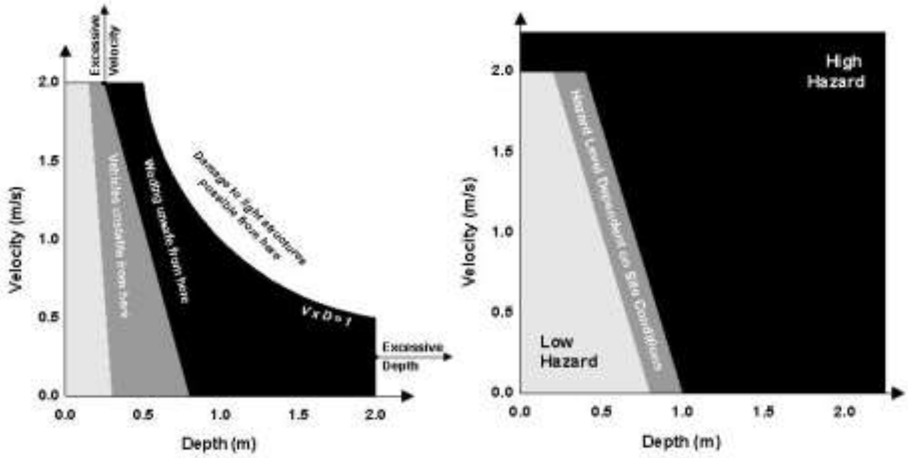
Low hazard – should it be necessary, trucks could evacuate people and their possessions; able-bodied adults would have little difficulty in wading to safety.

The key factors influencing flood hazard or risk are:

* Size of the Flood
* Rate of Rise - Effective Warning Time
* Community Awareness
* Flood Depth and Velocity
* Duration of Inundation
* Obstructions to Flow
* Access and Evacuation

The provisional flood hazard is often determined on the basis of the predicted flood depth and velocity. This is conveniently done through the analysis of flood model results. A high flood depth will cause a hazardous situation while a low depth may only cause an inconvenience. High flood velocities are dangerous and may cause structural damage while low velocities have no major threat.

Figures L1 and L2 in the Floodplain Development Manual (NSW Government, 2005) are used to determine provisional hazard classification within flood liable land. These figures are reproduced in Figure 7-14.



Velocity Depth Relationships **Provisional Hazard Categories**

Figure 7-14 Provisional Flood Hazard Categorisation

The provisional hydraulic hazard is included in the mapping series provided in Appendix A for the 20% AEP, 5% AEP, 1% AEP and PMF events.

7.7 Sensitivity Tests

A number of sensitivity tests have been undertaken on the modelled flood behaviour in the Narrabeen Lagoon catchment. In defining sensitivity tests, consideration is given to the most appropriate tests taking into account catchment properties and simulated design flood behaviour. The tests undertaken have included:

- increased hydraulic roughness;
- structure blockage;
- Lagoon entrance condition; and
- design rainfall losses.

The rationalisation for each of these sensitivity tests along with adopted model configuration/parameters and results are summarised in the following sections. The impact of the sensitivity tests on the standard design 1% AEP flood condition (9-hour duration) is also presented in Appendix A as a series of peak water level afflux diagrams.

7.7.1 Hydraulic Roughness

Sensitivity tests on the hydraulic roughness (Manning's 'n') were undertaken by applying a 25% decrease and a 25% increase in the adopted values for the baseline design conditions. Whilst a calibration process has been undertaken with respect to available data, and adopted design parameters are within typical ranges, the inherent variability/uncertainty in hydraulic roughness warrants consideration of the relative impact on adopted design flood conditions.

The sensitivity tests have been undertaken for the 1% AEP catchment rainfall event (9 hour duration). The results of the sensitivty tests on hydraulic roughness for the 1% AEP design event are summarised in Table 7-7. The change in peak flood level conditions from the adopted design base case is also shown as afflux diagrams in Appendix A.

Table 7-7 Peak 1% AEP Flood Levels for Hydraulic Roughness Sensitivity Tests

Location	Peak Design Flood Level (m AHD)		
	Base	25% Decrease	25% Increase
US Ocean St Bridge	2.9	2.8 (-0.1)	2.9 (0.0)
US Pittwater Rd Bridge (Narrabeen Lagoon)	3.0	2.9 (-0.1)	3.0 (0.0)
US Pittwater Rd Bridge (Mullet Creek)	2.9	2.9 (0.0)	3.0 (+0.1)
US Jackson Rd Culvert (Mullet Creek)	3.0	3.0 (0.0)	3.0 (0.0)
US Garden St Culvert (Mullet Creek)	4.2	4.2 (0.0)	4.2 (0.0)
US Garden St Culvert (Fern Creek)	11.5	11.5 (0.0)	11.5 (0.0)
US Macpherson St Culvert (Narrabeen Creek)	3.3	3.2 (-0.1)	3.3 (0.0)
Narrabeen RSL Carpark (Nareen Creek)	5.3	5.3 (0.0)	5.3 (0.0)
US Narroy Rd Culvert (Nareen Creek)	2.9	2.9 (0.0)	3.0 (+0.1)
US Pittwater Rd Culvert (Nareen Creek)	2.9	2.9 (0.0)	3.0 (+0.1)
US Deep Creek Bridge	3.0	3.0 (0.0)	3.0 (0.0)
US Middle Creek Bridge 1	3.0	2.9 (-0.1)	3.0 (0.0)
US Middle Creek Bridge 2	9.5	9.1 (-0.4)	9.8 (+0.3)
US Middle Creek Bridge 3	11.2	11.0 (-0.2)	11.4 (+0.2)
US Toronto Ave Bridge (South Creek)	4.7	4.6 (-0.1)	4.8 (+0.2)
US Carcoola Rd Culvert (South Creek)	6.3	6.2 (-0.1)	6.5 (+0.2)
US Willandra Rd Culvert (South Creek)	12.9	12.9 (0.0)	12.9 (0.0)

Note: Bracketed value is change in peak flood level from base design conditions

The model simulation results show minor reductions in peak flood level (generally < 0.1m) for reduced hydraulic roughness in the lower catchment and main body of Narrabeen Lagoon. The main areas affected are the steeper upper to mid catchment regions of the main tributary alignments, particularly Middle Creek and South Creek. The decrease in roughness has minimal influence on inundation extents in overbank areas.

Similarly, minor increases in peak flood level in the lower catchment and main body of Narrabeen Lagoon (generally < 0.1m) are simulated for the increased hydraulic roughness conditions applied in the sensitivity test. Again, the principal areas affected are steeper upper to mid catchment regions of the main tributary alignments with only minor changes to the flood inundation extents.

7.7.2 Structure Blockage

Structure blockages have the potential to substantially increase the magnitude and extent of property inundation through local increases in water level, redistribution of flows on the floodplain, and activation of additional flow paths. A sensitivity test on the design flood conditions has been undertaken to account for the potential for structure blockage. The following blockage assumptions were applied to structures across all watercourses for the 1% AEP catchment rainfall event (9 hour duration):

- 100% blockage for structures with a major diagonal opening width less than 6m;
- 25% bottom up blockage for structures with a major diagonal opening width greater than 6m. For bridge structures involving piers or bracings, the major diagonal length is defined as the clear diagonal opening between piers/bracings, not the width of the channel at the cross-section; and
- 100% blockage for handrails over structures where overtopping occurs.

The change in peak water levels with the assumed blockage conditions is summarised at key locations (generally corresponding to the structure locations) in Table 7-8. Mapping of the extents of the simulated afflux is included in Appendix A for the 1% AEP catchment rainfall event (9 hour duration). Table 7-8 shows the simulated peak flood level with no structure blockage, along with the change from the assumed structure blockage flood conditions shown in brackets.

Table 7-8 Peak 1% AEP Flood Levels for Structure Blockage Sensitivity Tests

Location	Peak Design Flood Level (m AHD)	
	Base	Blockage
US Ocean St Bridge	2.9	2.9 (0.0)
US Pittwater Rd Bridge (Narrabeen Lagoon)	3.0	3.0 (0.0)
US Pittwater Rd Bridge (Mullet Creek)	2.9	2.9 (0.0)
US Jackson Rd Culvert (Mullet Creek)	3.0	3.2 (+0.2)
US Garden St Culvert (Mullet Creek)	4.2	4.5 (+0.3)
US Garden St Culvert (Fern Creek)	11.5	12.1 (+0.6)
US Macpherson St Culvert (Narrabeen Creek)	3.3	3.4 (+0.1)
Narrabeen RSL Carpark (Nareen Creek)	5.3	5.6 (+0.3)
US Narroy Rd Culvert (Nareen Creek)	2.9	2.9 (0.0)
US Pittwater Rd Culvert (Nareen Creek)	2.9	2.9 (0.0)
US Deep Creek Bridge	3.0	3.0 (0.0)
US Middle Creek Bridge 1	3.0	3.0 (0.0)
US Middle Creek Bridge 2	9.5	9.6 (+0.1)
US Middle Creek Bridge 3	11.2	11.3 (+0.1)
US Toronto Ave Bridge (South Creek)	4.7	5.5 (+0.8)
US Carcoola Rd Culvert (South Creek)	6.3	6.4 (+0.1)
US Willandra Rd Culvert (South Creek)	12.9	13.2 (+0.3)

Note: Bracketed value is change in peak flood level from standard design conditions

As shown in Table 7-8 and the afflux mapping in Appendix A, the assumed blockage condition has minimal impact on flood conditions in the lower catchment and main body of Narrabeen Lagoon. In this regard, the assumed blockage condition does not change the broader flooding behaviour in the lower catchment.

7.7.3 Lagoon Entrance Condition

The Narrabeen Lagoon entrance condition is highly dynamic with potential for significant variation in the degree of shoaling and the height of the entrance berm and subsequent impact on design flood behaviour. The catchment flood scenarios adopted a 1.3m AHD berm height at the entrance for the baseline conditions. Sensitivity tests on the berm condition have been undertaken for the 1% AEP catchment rainfall event (9 hour duration) and 1% AEP ocean driven event. These sensitivity tests include:

- A higher berm height of 2m AHD - this berm height is representative of the height to which the berm may build over a sustained period of relatively low catchment rainfall and high coastal storm activity (assumes no manual breakout of the Lagoon); and
- A fully open channel condition such that the entrance conveyance is not constrained. The adopted condition utilises a post-dredged channel condition from the 2006 post-dredge bathymetry survey.

Table 7-9 Peak 1% AEP Flood Levels for Lagoon Entrance Condition Sensitivity Tests (Higher Initial Berm Height)

Location	Peak Design Flood Level (m AHD)			
	Base (1.3m Berm) 1% AEP Catchment	2m Berm 1% AEP Catchment	Base (1.3m Berm) 1% AEP Catchment + 5% AEP Ocean	2m Berm 1% AEP Catchment + 5% AEP Ocean
US Ocean St Bridge	2.9	3.1 (+0.2)	3.0	3.2 (+0.2)
US Pittwater Rd Bridge (Narrabeen Lagoon)	3.0	3.2 (+0.2)	3.0	3.2 (+0.2)
US Pittwater Rd Bridge (Mullet Creek)	2.9	3.2 (+0.3)	3.0	3.2 (+0.2)
US Jackson Rd Culvert (Mullet Creek)	3.0	3.2 (+0.2)	3.0	3.2 (+0.2)
US Garden St Culvert (Mullet Creek)	4.2	4.2 (0.0)	4.2	4.2 (0.0)
US Garden St Culvert (Fern Creek)	11.5	11.5 (0.0)	11.5	11.5 (0.0)
US Macpherson St Culvert (Narrabeen Creek)	3.3	3.3 (0.0)	3.3	3.3 (0.0)
Narrabeen RSL Carpark (Nareen Creek)	5.3	5.3 (0.0)	5.3	5.3 (0.0)
US Narroy Rd Culvert (Nareen Creek)	2.9	3.2 (+0.3)	3.0	3.2 (+0.2)
US Pittwater Rd Culvert (Nareen Creek)	2.9	3.2 (+0.3)	3.0	3.2 (+0.2)
US Deep Creek Bridge	3.0	3.2 (+0.2)	3.1	3.2 (+0.1)
US Middle Creek Bridge 1	3.0	3.2 (+0.2)	3.1	3.2 (+0.1)
US Middle Creek Bridge 2	9.5	9.5 (0.0)	9.5	9.5 (0.0)
US Middle Creek Bridge 3	11.2	11.2 (0.0)	11.2	11.2 (0.0)
US Toronto Ave Bridge (South Creek)	4.7	4.7 (0.0)	4.7	4.7 (0.0)
US Carcoola Rd Culvert (South Creek)	6.3	6.4 (+0.1)	6.4	6.4 (0.0)
US Willandra Rd Culvert (South Creek)	12.9	12.9 (0.0)	12.9	12.9 (0.0)

Note: Bracketed value is change in peak flood level from standard design conditions

The results of the sensitivity tests on higher initial berm height and lower initial berm height for the 1% AEP design event are summarised in Table 7-9 and Table 7-10 respectively. The entrance condition is shown to have some effect on peak flood levels, particularly around the Lagoon. Higher berm conditions provide for higher peak flood levels for catchments events, conversely for ocean events, an open condition provides for higher peak levels in the Lagoon. In upstream areas where typical 1% AEP flood levels are in excess of 3.5m AHD, there is minimal influence on peak flood levels. In the Lagoon area, it can be seen that higher berm levels equate to higher peak flood levels for catchment events, however, the magnitude of the increase is somewhat limited by the expected scour throughout the flood event that naturally breaks open the berm. The fully open entrance condition provides for some reduction in peak levels in Narrabeen Lagoon, with minimal influence however on the tributary channels.

Table 7-10 Peak 1% AEP Flood Levels for Lagoon Entrance Condition Sensitivity Tests (Lower Initial Berm Height)

Location	Peak Design Flood Level (m AHD)					
	Base 1% AEP Catchment	Fully Open 1% AEP Catchment	Base 1% AEP Catchment + 5% AEP Ocean	Fully Open 1% AEP Catchment + 5% AEP Ocean	Base 1% AEP Ocean	Fully Open 1% AEP Ocean
US Ocean St Bridge	2.9	2.4 (-0.5)	3.0	2.7 (-0.3)	1.9	2.0 (+0.1)
US Pittwater Rd Bridge (Narrabeen Lagoon)	3.0	2.6 (-0.4)	3.0	2.7 (-0.3)	1.9	2.0 (+0.1)
US Pittwater Rd Bridge (Mullet Creek)	2.9	2.5 (-0.4)	3.0	2.7 (-0.3)	1.9	2.0 (+0.1)
US Jackson Rd Culvert (Mullet Creek)	3.0	2.9 (-0.1)	3.0	2.9 (-0.1)	1.8	2.0 (+0.2)
US Garden St Culvert (Mullet Creek)	4.2	4.2 (0.0)	4.2	4.2 (0.0)	-	-
US Garden St Culvert (Fern Creek)	11.5	11.5 (0.0)	11.5	11.5 (0.0)	-	-
US Macpherson St Culvert (Narrabeen Creek)	3.3	3.3 (0.0)	3.3	3.3 (0.0)	1.8	1.9 (+0.1)
Narrabeen RSL Carpark (Nareen Creek)	5.3	5.3 (0.0)	5.3	5.3 (0.0)	-	-
US Narroy Rd Culvert (Nareen Creek)	2.9	2.5 (-0.4)	3.0	2.7 (-0.3)	1.9	2.0 (+0.1)
US Pittwater Rd Culvert (Nareen Creek)	2.9	2.5 (-0.4)	3.0	2.7 (-0.3)	1.9	2.0 (+0.1)
US Deep Creek Bridge	3.0	2.7 (-0.3)	3.1	2.8 (-0.3)	1.9	2.0 (+0.1)
US Middle Creek Bridge 1	3.0	2.7 (-0.3)	3.1	2.8 (-0.3)	1.9	2.0 (+0.1)
US Middle Creek Bridge 2	9.5	9.5 (0.0)	9.5	9.5 (0.0)	-	-
US Middle Creek Bridge 3	11.2	11.2 (0.0)	11.2	11.2 (0.0)	-	-
US Toronto Ave Bridge (South Creek)	4.7	4.7 (0.0)	4.7	4.7 (0.0)	1.9	2.0 (+0.1)
US Carcoola Rd Culvert (South Creek)	6.3	6.3 (0.0)	6.4	6.3 (-0.1)	-	-
US Willandra Rd Culvert (South Creek)	12.9	12.9 (0.0)	12.9	12.9 (0.0)	-	-

Note: Bracketed value is change in peak flood level from standard design conditions

7.7.4 Rainfall Losses

The hydrological model parameters adopted for the design floods were similar to those used in the hydrological model calibration and validation. For the initial and continuing rainfall losses, values of 10mm and 2.5mm/hr were used for pervious areas and 2mm and 0mm/hr for impervious areas. These are consistent with the recommended ranges for design event losses in AR&R (2001). Rainfall losses are to some degree dependent on antecedent catchment conditions which vary between dry and wet conditions.

Sensitivity tests on the adopted rainfall losses have been undertaken for the 1% AEP catchment rainfall event (9 hour duration). These sensitivity tests provide for:

- Higher rainfall losses of 30mm initial loss and 2.5mm/hr continuing loss for previous surfaces; and
- Lower rainfall losses of 0mm initial loss and 0mm/hr continuing loss for previous surfaces

As shown in Table 7-11 and the afflux mapping in Appendix A, the assumed design rainfall losses only has minor impact on 1% AEP catchment flood conditions in the catchment.

Table 7-11 Peak 1% AEP Flood Levels for Design Rainfall Loss Sensitivity Tests

Location	Peak Design Flood Level (m AHD)		
	Base	Increased Losses	Decreased Losses
US Ocean St Bridge	2.9	2.8 (-0.1)	3.0 (+0.1)
US Pittwater Rd Bridge (Narrabeen Lagoon)	3.0	2.9 (-0.1)	3.1 (+0.1)
US Pittwater Rd Bridge (Mullet Creek)	2.9	2.9 (0.0)	3.1 (+0.2)
US Jackson Rd Culvert (Mullet Creek)	3.0	2.9 (-0.1)	3.1 (+0.1)
US Garden St Culvert (Mullet Creek)	4.2	4.2 (0.0)	4.2 (0.0)
US Garden St Culvert (Fern Creek)	11.5	11.5 (0.0)	11.5 (0.0)
US Macpherson St Culvert (Narrabeen Creek)	3.3	3.3 (0.0)	3.3 (0.0)
Narrabeen RSL Carpark (Nareen Creek)	5.3	5.3 (0.0)	5.3 (0.0)
US Narroy Rd Culvert (Nareen Creek)	2.9	2.9 (0.0)	3.1 (+0.2)
US Pittwater Rd Culvert (Nareen Creek)	2.9	2.9 (0.0)	3.1 (+0.2)
US Deep Creek Bridge	3.0	2.9 (-0.1)	3.1 (+0.1)
US Middle Creek Bridge 1	3.0	2.9 (-0.1)	3.1 (+0.1)
US Middle Creek Bridge 2	9.5	9.5 (0.0)	9.5 (0.0)
US Middle Creek Bridge 3	11.2	11.2 (0.0)	11.2 (0.0)
US Toronto Ave Bridge (South Creek)	4.7	4.7 (0.0)	4.7 (0.0)
US Carcoola Rd Culvert (South Creek)	6.3	6.3 (0.0)	6.4 (+0.1)
US Willandra Rd Culvert (South Creek)	12.9	12.9 (0.0)	12.9 (0.0)

Note: Bracketed value is change in peak flood level from base design conditions

7.7.5 On-site Detention Policy

The Warriewood Valley in particular has had significant urban development since the late 1990's. Incorporated into the development controls for this urban intensification were provisions for on-site detention.

The regional detention basins constructed as part of the developments have been incorporated within the existing models. However, the property scale measures such as on-site detention features, air space within rain water tanks, infiltration pits and swales were conservatively considered to be ineffective as detention devices within the hydrological modelling. This is related to uncertainties associated with their long-term performance as well as their functionality in rare and extreme events.

A further sensitivity test has been undertaken to assess the potential cumulative impact of OSD provisions at a regional scale within the Warriewood Valley. It is not possible to discretely model the OSD provisions at each property. However, in the case of Warriewood Valley, the OSD policy provisions have for provided specific detention volume targets relative to developed area (i.e. m^3 of storage per hectare development). This storage volume can be simply represented in the existing models by an additional reduction in effective rainfall from the catchment. Based on the on-site detention volume targets for Warriewood Valley, the cumulative OSD provisions are estimated to provide for the additional storage of an equivalent of 50mm of catchment rainfall.

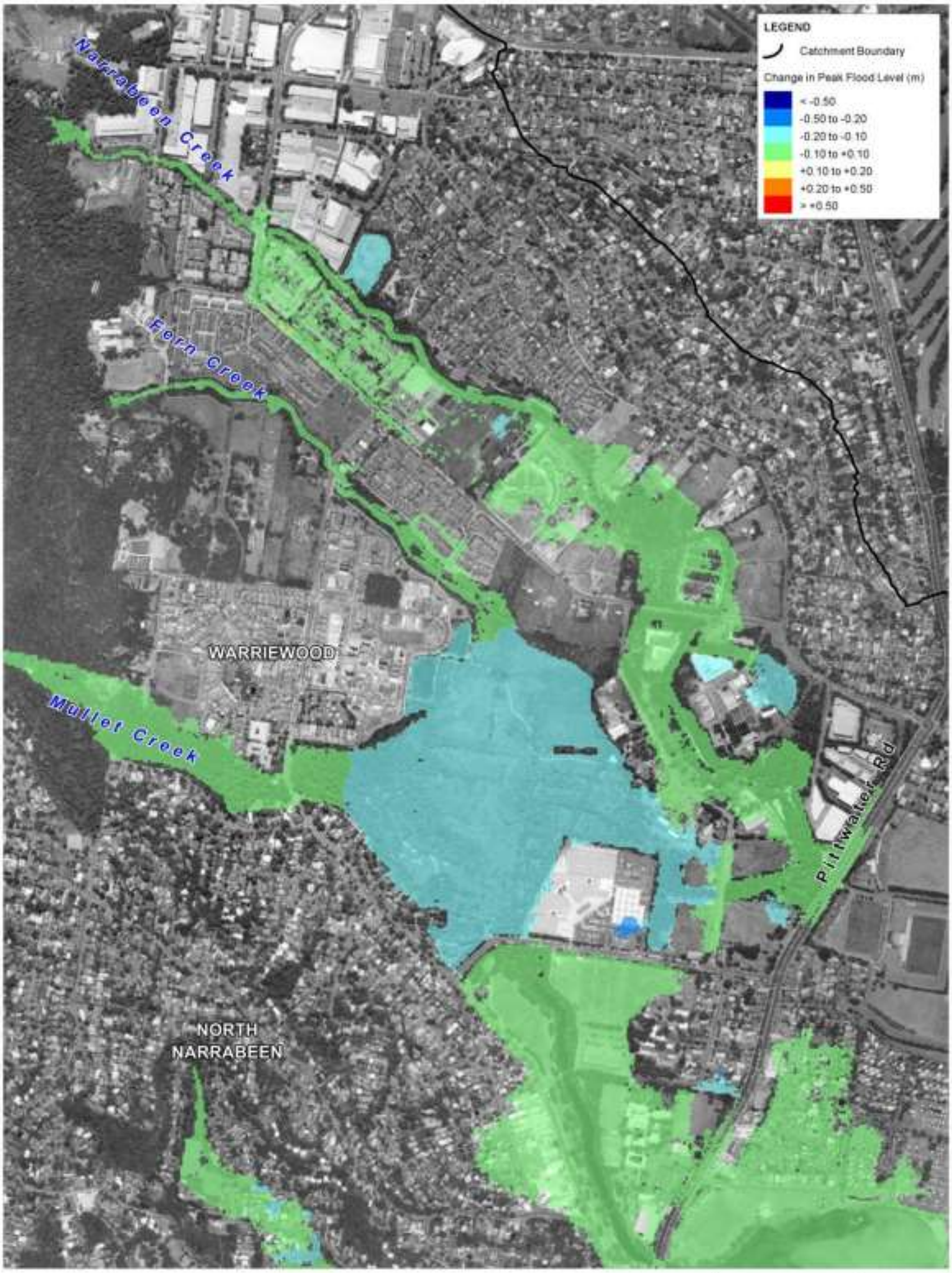
A model simulation was undertaken for the 1% AEP 2-hour duration event with an initial loss for the developed areas (including impervious area) of 50mm. The change in peak flood level for this simulation compared to the baseline 1% AEP condition is shown in Figure 7-15. The impact of the additional OSD provision on the 1% AEP is relatively modest in terms of changes in the peak flood level. The largest reductions can be seen in the broader Warriewood Wetland area which is significant temporary flood storage. The OSD provisions provide for an overall reduction in total runoff volume and accordingly results in lower volumes discharging to the Wetlands.

7.8 Flood Planning Levels

Land use planning and development controls are key mechanisms by which The Councils can manage flood-affected areas within the study area. Such mechanisms will influence future development (and redevelopment) and therefore the benefits will accrue gradually over time. Without comprehensive floodplain planning, existing problems may be exacerbated and opportunities to reduce flood risks may be lost.

The Flood Planning Level (FPL) is the level below which a Council places restrictions on development due to the hazard of flooding. Traditionally, floodplain planning has usually been based on the 1% AEP flood level + 0.5m freeboard.

Council's adopted FPLs and flood related development controls are specified in existing Development Control Plans. Further information can be found in the Narrabeen Lagoon Flood Study - Flood Planning Levels Report (September 2013).



Title:
Narrabeen Lagoon Flood Study - Change in Peak Flood Level OSD (1% AEP Catchment Event)

Figure: X
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7.9 Model Uncertainties and Limitations

There are a number of inherent uncertainties and limitations with the modelling of environmental phenomena such as flooding. Some of the key considerations include:

- The dynamic nature of the entrance berm has a significant impact on flood levels within Narrabeen Lagoon and the surrounding floodplain areas. The resultant flooding from catchment runoff of a given magnitude will vary depending on the entrance conditions at the onset of the event. The design conditions modelled are based on the assumption of a maximum berm height condition of 1.3m AHD in line with the existing entrance management policy;
- The modelled flood behaviour is driven by the model topography, derived primarily from the LiDAR dataset and channel cross section survey. Local topographic features that have not been captured by these datasets may have a local influence on flood behaviour and differ to that which has been modelled;
- The study is focused on mainstream flooding and has not explicitly modelled stormwater drainage network or overland flow flooding conditions;
- The land use in the catchment will change through time and changes in vegetation within the channel and on the floodplain may impact on the local flood conditions.

The Flood Study has established existing design flood conditions to provide the basis for subsequent analysis of floodplain risk management options. Outcomes of the Floodplain Risk Management Study, which is the next stage of the floodplain risk management process, may provide for changes in adopted design flood levels particularly considering modifications to existing entrance management policies and implications of other potential climate change scenarios.

8 CLIMATE CHANGE ANALYSIS

In 2009, the NSW Government incorporated consideration of potential climate change impacts into relevant planning instruments. The NSW Sea Level Rise Policy Statement (DECCW, 2009) was prepared to support consistent adaptation to projected sea level rise impacts. The policy statement incorporated sea level rise planning benchmarks for use in assessing potential impacts of sea level rise in coastal areas, as well as in flood risk and coastal hazard assessments. The benchmarks were a projected rise in sea level, relative to the 1990 mean sea level, of 0.4 metres by 2050 and 0.9 metres by 2100.

Recently, the NSW Government announced its Stage One Coastal Management Reforms (September, 2012). As part of these reforms, the NSW Government no longer recommends state-wide sea level rise benchmarks for use by local councils, but instead provides councils with the flexibility to consider local conditions when determining future hazards within their LGA.

Accordingly, it is recommended by the NSW Government that councils should consider information on historical and projected future sea level rise that is widely accepted by scientific opinion. This may include information in the NSW Chief Scientist and Engineer's Report entitled 'Assessment of the Science behind the NSW Government's Sea Level Rise Planning Benchmarks' (2012).

The NSW Chief Scientist and Engineer's Report (2012) acknowledges the evolving nature of climate science, which is expected to provide a clearer picture of the changing sea levels into the future. The report identified that:

- The science behind sea level rise benchmarks from the 2009 NSW Sea level Rise Policy Statement was adequate;
- Historically, sea levels have been rising since the early 1880's;
- There is considerable variability in the projections for future sea level rise; and
- The science behind the future sea level rise projections is continually evolving and improving.

As the majority of analysis and modelling tasks associated with this current Flood Study were completed prior to the announcement of the NSW Government's Coastal Management Reforms in September 2012, the potential impacts of sea level rise have been based on sea level rise projections from the 2009 NSW Sea Level Rise Policy Statement. Given that the Chief Scientist and Engineer's Report finds the science behind these sea level rise projections adequate, as discussed in Section 1.4.1, it was agreed between The Councils and BMT WBM that the potential impacts of sea level rise for the Narrabeen Lagoon catchment were based on the best available information at hand during preparation of this report.

Worsening coastal flooding impacts as a consequence of sea level rise in lowland areas such as around Narrabeen Lagoon are of particular concern for the future. Regional climate change studies (e.g. CSIRO, 2004) indicate that aside from sea level rise, there may also be an increase in the maximum intensity of extreme rainfall events. This may include increased frequency, duration and height of flooding and consequently increased number of emergency evacuations and associated property and infrastructure damage.

The NSW Floodplain Development Manual (DIPNR, 2005) requires consideration of climate change in the preparation of Floodplain Risk Management Studies and Plans, with further guidance provided in:

- Floodplain Risk Management Guideline – Practical Consideration of Climate Change (DECC, 2007); and
- Flood Risk Management Guide – Incorporating Sea Level Rise Benchmarks in Flood Risk Assessments (DECCW, 2010).

Key elements of future climate change (e.g. sea level rise, rainfall intensity) have been assessed in the Narrabeen Lagoon catchment for consideration in the ongoing floodplain risk management.

8.1 Potential Climate Change Impacts

The impacts of future climate change are likely to lead to a wide range of environmental responses in coastal lagoons such as Narrabeen Lagoon. These are likely to manifest throughout the physical, chemical and ecological processes that drive local estuarine ecosystems.

The following changes in the physical characteristics of the Narrabeen Lagoon system have potential influence on the flood behaviour of the system and implications for medium and long term floodplain management:

- Increase in ocean boundary water level – sea level projections provide for a direct increase in tidal and storm surge water level conditions;
- Increase in entrance berm height – typical entrance berm levels are expected to increase upward and move landward in response to sea level rise;
- Increase in initial Lagoon water level – linked to both the ocean water levels and berm heights; and
- Increase in rainfall intensity – the frequency and severity of extreme rainfall events is expected to increase.

The model configuration and assumptions adopted for each of these potential climate change impacts are discussed in the following sections.

8.1.1 Ocean Water Level

As discussed in Section 1.4.1, the sea level rise planning benchmarks provided in the NSW Sea Level Rise Policy Statement (DECCW, 2009) have been adopted for this Flood Study.

The benchmarks are a projected rise in sea level, relative to the 1990 mean sea level, of 0.4 metres by 2050 and 0.9 metres by 2100 (DECCW, 2009). Based on these guidelines, design ocean boundary conditions were raised by 0.4 m and 0.9 m to assess the potential impact of sea level rise on flood behaviour in the Narrabeen Lagoon catchment for the year 2050 and 2100 respectively.

The ocean water level boundary conditions for present day flood conditions were discussed in Section 6.2. The sea level rise allowances provide for direct increases in these ocean water levels.

Table 8-1 presents a summary of adopted peak ocean water levels for a range of design events for existing water level conditions and the 2050 and 2100 sea level rise benchmarks.

Table 8-1 Design Peak Ocean Water Levels Incorporating Sea Level Rise

Event Magnitude	Water Level (m AHD)		
	Existing	2050 (+0.4 m)	2100 (+0.9 m)
20% AEP	1.9	2.3	2.8
5% AEP	2.25	2.65	3.15
2% AEP	2.45	2.85	3.35
1% AEP	2.60	3.0	3.5
0.5% AEP	2.75	3.15	3.65

8.1.2 Entrance Berm Conditions

A change in entrance berm processes is likely to result from the projected sea level rise and changes to coastal storm intensity. From this change, a net upward shift in typical berm heights at the entrance may be expected, and therefore flood water levels will need to reach a higher level before inducing a natural breakout to the ocean (Haines and Thom, 2007). The entrance berm is also expected to shift landwards in association with sea level rise.

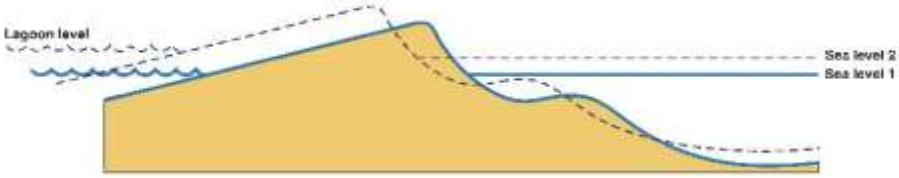


Figure 8-1 Shoreline response to increasing sea level (Hanslow *et al.*, 2000)

There are no government guidelines concerning the impact of future climatic change of entrance berm geometries.

The adopted berm height conditions for design events were discussed in Section 6.3. For catchment derived flooding, a typically shoaled entrance at an approximate level of 1.3m AHD was adopted. The 1.3m AHD entrance berm level corresponds to the water level in the Lagoon that triggers a mechanical. breakout to be initiated as outlined in the Narrabeen Lagoon Entrance Management Operational Management Standard (OMS).

Current entrance management policies were largely adopted to protect existing low-lying development from inundation. With gradual sea level rise, current trigger levels will eventually be reached by normal tidal variability such that opening the entrance at existing levels will not be possible. The impact of sea level rise on current entrance management would in fact be seen much sooner, with the effectiveness of artificial breakouts gradually diminishing as high tailwater conditions limit the formation of an effective scour channel. The trigger level for future entrance openings is recommended to be a significant focus of the subsequent Floodplain Risk Management Study.

For the purpose of this Study, a berm height increase of 0.4m and 0.9m has been adopted for the 2050 and 2100 benchmarks respectively. This increase has been applied to the adopted 1.3m AHD shoaled entrance condition for existing conditions. This provides for a berm height of 1.7m AHD and 2.2m AHD for the 2050 and 2100 benchmarks respectively.

8.1.3 Initial Lagoon Water Levels

Typical initial water levels in the Lagoon are a function of the natural tidal variability and condition of the entrance channel. For catchment flooding conditions, a closed entrance condition has been simulated as typically providing for higher flood water level conditions. In periods of entrance closure, water levels in the Lagoon may build to a level of the order of 1.3m AHD before a mechanical opening is triggered. In line with the assumptions discussed above regarding increasing entrance berm levels with sea level rise, corresponding increases in initial Lagoon water levels have been adopted. Accordingly, initial Lagoon water levels of 1.7m AHD and 2.2m AHD have been adopted for the 2050 and 2100 benchmarks respectively.

For ocean derived flooding, an open entrance condition is assumed, such that Lagoon water levels are driven by the ocean tidal condition. Initial Lagoon water levels therefore reflect the relative ocean tide level at the start of the simulation period. For future flooding conditions, these levels incorporate the sea level rise allowances as discussed in Section 8.1.1.

8.1.4 Design Rainfall Intensity

Current research predicts that a likely outcome of future climatic change will be an increase in flood producing rainfall intensities. Climate Change in New South Wales (CSIRO, 2007) provides projected increases in 2.5% AEP 24h duration rainfall depths for Sydney Metropolitan catchments of up to 12% and 10%, for the years 2030 and 2070 respectively.

The NSW Government has also released a guideline (DECC, 2007) for Practical Consideration of Climate Change in the floodplain management process that advocates consideration of increased design rainfall intensities of up to 30%. In line with this guidance note, additional tests incorporating 10%, 20% and 30% increases in design rainfall have been undertaken.

8.2 Climate Change Model Conditions

A range of design event simulations have been undertaken incorporating combinations of increases in ocean water levels, berm heights, initial Lagoon levels and rainfall intensities. A summary of the modelled scenarios for the 1% AEP design event condition is provided in Table 8-2.

Similar combinations have also been modelled for the nominal 5% AEP design event condition.

The modelled scenarios incorporate a full range of combinations of the impacts of:

- increases in rainfall intensity of 10% 20% and 30%; and
- sea level rise allowance of 0.4m and 0.9m.

In considering the sea level rise impacts, the modelled scenarios incorporate the appropriate increases in ocean water level, berm height and initial lagoon water levels (dependent on berm condition) as discussed in Sections 8.1.1, 8.1.2 and 8.1.3 respectively.

As shown in Table 8-2, the impacts of the climate changes scenarios have been simulated for both catchment derived and ocean derived flooding conditions. Joint catchment and ocean flooding scenarios have also been simulated corresponding to the combinations assessed for existing conditions as discussed in Section 7.1.3.

As per the modelling of existing conditions, the climate change scenarios for catchment derived flooding use a closed berm condition, whilst for ocean derived events an open entrance condition is adopted. As discussed, these entrance conditions provide for the worst case condition for each of the flooding mechanisms. Given that catchment derived flooding is the dominant mechanism in terms of peak flood levels for the broader Narrabeen Lagoon catchment, a closed berm condition has also been adopted for the simulation of the joint catchment and ocean event scenarios.

Table 8-2 Summary of Design Model Runs for Climate Change Considerations

Catchment Events
1% AEP 9-hour duration +10% rainfall increase (closed entrance)
1% AEP 9-hour duration +20% rainfall increase (closed entrance)
1% AEP 9-hour duration +30% rainfall increase (closed entrance)
1% AEP 9-hour duration +0.4m sea level rise (closed entrance)
1% AEP 9-hour duration +0.9m sea level rise (closed entrance)
1% AEP 9-hour duration +10% rainfall increase + 0.4m sea level rise (closed entrance)
1% AEP 9-hour duration + 20% rainfall increase + 0.4m sea level rise (closed entrance)
1% AEP 9-hour duration +30% rainfall increase + 0.4m sea level rise (closed entrance)
1% AEP 9-hour duration +10% rainfall increase + 0.9m sea level rise (closed entrance)
1% AEP 9-hour duration + 20% rainfall increase + 0.9m sea level rise (closed entrance)
1% AEP 9-hour duration +30% rainfall increase + 0.9m sea level rise (closed entrance)
Ocean Events
1% AEP ocean event + 0.4m sea level rise (open entrance)
1% AEP ocean event + 0.9m sea level rise (open entrance)
Coincident Events
1% AEP 9-hour duration +10% rainfall increase + 5% AEP ocean event (closed entrance)
1% AEP 9-hour duration +20% rainfall increase + 5% AEP ocean event (closed entrance)
1% AEP 9-hour duration +30% rainfall increase + 5% AEP ocean event (closed entrance)
1% AEP 9-hour duration + 5% AEP ocean event + 0.4m sea level rise (closed entrance)
1% AEP 9-hour duration + 5% AEP ocean event +0.9m sea level rise (closed entrance)
1% AEP 9-hour duration +10% rainfall increase + 5% AEP ocean event +0.4m sea level rise (closed entrance)
1% AEP 9-hour duration + 20% rainfall increase + 5% AEP ocean event + 0.4m sea level rise (closed entrance)
1% AEP 9-hour duration +30% rainfall increase + 5% AEP ocean event + 0.4m sea level rise (closed entrance)
1% AEP 9-hour duration +10% rainfall increase + 5% AEP ocean event + 0.9m sea level rise (closed entrance)
1% AEP 9-hour duration + 20% rainfall increase + 5% AEP ocean event + 0.9m sea level rise (closed entrance)
1% AEP 9-hour duration +30% rainfall increase + 5% AEP ocean event + 0.9m sea level rise (closed entrance)

8.3 Climate Change Results

The potential impacts of future climate change were considered for a range of design event scenarios as defined in Table 8-2. The impact of potential climate change scenarios on the 5% AEP and 1% AEP design flood condition is presented in Appendix A as a series of maps showing increase in peak flood inundation extents from the baseline (existing) conditions. Further discussion on relative increases from existing peak flood levels is provided hereunder.

The modelled peak flood levels for the catchment derived flooding considering increases in design rainfall and sea level in isolation are presented in Table 8-3. The selected reporting locations were previously presented in Figure 7-1. The most significant climate change impact for Narrabeen Lagoon will be from the predicted increase in berm height, which is in line with the 0.4m and 0.9m sea level rise benchmarks for 2050 and 2100. This impact can be observed in Table 8-3 for the locations typically within or around the foreshore of the Lagoon. Typical increases in flood level around the Lagoon are 0.3m and 0.6m for the simulated 2050 and 2100 berm height levels. The berm height conditions only affect the lower catchment, with upstream locations along the tributary channels unaffected by berm height conditions.

The upstream areas are more so impacted by increases in rainfall intensities. For increases in rainfall intensity from 10% up to 30%, peak flood level increases of between 0.1m to 0.5m are typical, depending on the nature of the channel or creek section. These increases are of similar order when comparing the difference between the existing 1% and 0.5% AEP peak flood levels as reported in Table 7-1.

Table 8-4 shows the combined impacts of increased rainfall intensity and sea level rise for various combinations. Broadly speaking, the impact in the lower Narrabeen Lagoon catchment is a summation of the individual influence of increased rainfall intensity and sea level rise as shown in Table 8-3. For example, a 20% increase in rainfall intensity provides for approximately a 0.2m increase in peak Lagoon flood levels, whilst a 0.4m sea level rise provides for a similar 0.2m increase. The combined impact of 20% rainfall increase and 0.4m sea levels rise on the exiting 1% AEP flood level as shown in Table 8-4 is generally around 0.4m. In the upper tributary areas, beyond the influence of the general Lagoon flooding height, there is no impact associated with sea level rise, such that the combined scenario is representative of the impact of rainfall increase only.

The combined 30% increase in rainfall and 0.9m sea level rise represents the most severe of the climate change scenarios modelled. The most significant impacts are from sea level rise and affect the broader Lagoon area and accordingly for property located on these lower foreshore areas. For this scenario, increases of up to 0.9m would be realised above the existing 1% AEP design flood level. As mentioned above, the upper reaches of the tributary channels beyond the influence of the broader Lagoon flooding are not affected by the sea level rise component but do however have increased flood levels in association with the rainfall intensity increases.

Table 8-3 Modelled Peak Flood Levels for Catchment Derived Climate Change Events

Location	Modelled Peak Flood Level (m AHD)					
	Existing 1% AEP	+ 10% Rainfall	+ 20% Rainfall	+30% Rainfall	+ 0.4m SLR	+ 0.9m SLR
US Ocean St Bridge	2.9	3.0 (+0.1)	3.1 (+0.2)	3.2 (+0.3)	3.2 (+0.3)	3.5 (+0.6)
US Pittwater Rd Bridge (Narrabeen Lagoon)	3.0	3.1 (+0.1)	3.2 (+0.2)	3.3 (+0.3)	3.2 (+0.2)	3.5 (+0.5)
US Pittwater Rd Bridge (Mullet Creek)	2.9	3.1 (+0.2)	3.2 (+0.3)	3.3 (+0.4)	3.2 (+0.3)	3.5 (+0.6)
US Jackson Rd Culvert (Mullet Creek)	3.0	3.1 (+0.1)	3.2 (+0.2)	3.3 (+0.3)	3.2 (+0.2)	3.5 (+0.5)
US Garden St Culvert (Mullet Creek)	4.2	4.3 (+0.1)	4.3 (+0.1)	4.4 (+0.2)	4.2 (0.0)	4.2 (0.0)
US Garden St Culvert (Fern Creek)	11.5	11.6 (+0.1)	11.7 (+0.2)	11.7 (+0.2)	11.5 (0.0)	11.5 (0.0)
US Macpherson St Culvert (Narrabeen Creek)	3.3	3.3 (0.0)	3.4 (+0.1)	3.5 (+0.2)	3.3 (0.0)	3.5 (+0.2)
Narrabeen RSL Carpark (Nareen Creek)	5.3	5.4 (+0.1)	5.4 (+0.1)	5.4 (+0.1)	5.3 (0.0)	5.3 (0.0)
US Narroy Rd Culvert (Nareen Creek)	2.9	3.1 (+0.2)	3.2 (+0.3)	3.3 (+0.4)	3.2 (+0.3)	3.5 (+0.6)
US Pittwater Rd Culvert (Nareen Creek)	2.9	3.1 (+0.2)	3.2 (+0.3)	3.3 (+0.4)	3.2 (+0.3)	3.5 (+0.6)
US Deep Creek Bridge	3.0	3.1 (+0.1)	3.2 (+0.2)	3.3 (+0.3)	3.2 (+0.2)	3.6 (+0.6)
US Middle Creek Bridge 1	3.0	3.1 (+0.1)	3.2 (+0.2)	3.3 (+0.3)	3.2 (+0.2)	3.6 (+0.6)
US Middle Creek Bridge 2	9.5	9.6 (+0.1)	9.9 (+0.4)	10.0 (+0.5)	9.5 (0.0)	9.5 (0.0)
US Middle Creek Bridge 3	11.2	11.3 (+0.1)	11.5 (+0.3)	11.6 (+0.4)	11.2 (0.0)	11.2 (0.0)
US Toronto Ave Bridge (South Creek)	4.7	4.8 (+0.1)	4.9 (+0.2)	5.0 (+0.3)	4.7 (0.0)	4.8 (+0.1)
US Carcoola Rd Culvert (South Creek)	6.3	6.4 (+0.1)	6.5 (+0.2)	6.5 (+0.2)	6.3 (0.0)	6.4 (+0.1)
US Willandra Rd Culvert (South Creek)	12.9	12.9 (0.0)	12.9 (0.0)	13.0 (+0.1)	12.9 (0.0)	12.9 (0.0)

Note: Bracketed value is change in peak flood level from standard design conditions

Table 8-4 Modelled Peak Flood Levels for Catchment Derived Climate Change Events

Location	Modelled Peak Flood Level (m AHD)						
	Existing 1% AEP	+0.4m SLR + 10% Rainfall	+0.4m SLR + 20% Rainfall	+0.4m SLR + 30% Rainfall	+0.9m SLR + 10% Rainfall	+0.9m SLR + 20% Rainfall	+0.9m SLR + 30% Rainfall
US Ocean St Bridge	2.9	3.3 (+0.4)	3.3 (+0.4)	3.4 (+0.5)	3.6 (+0.7)	3.6 (+0.7)	3.7 (+0.8)
US Pittwater Rd Bridge (Narrabeen Lagoon)	3.0	3.3 (+0.3)	3.4 (+0.4)	3.5 (+0.5)	3.6 (+0.6)	3.7 (+0.7)	3.8 (+0.8)
US Pittwater Rd Bridge (Mullet Creek)	2.9	3.3 (+0.4)	3.4 (+0.5)	3.5 (+0.6)	3.6 (+0.7)	3.7 (+0.8)	3.8 (+0.9)
US Jackson Rd Culvert (Mullet Creek)	3.0	3.3 (+0.3)	3.4 (+0.4)	3.5 (+0.5)	3.6 (+0.6)	3.7 (+0.7)	3.8 (+0.8)
US Garden St Culvert (Mullet Creek)	4.2	4.3 (+0.1)	4.3 (+0.1)	4.4 (+0.2)	4.3 (+0.1)	4.3 (+0.1)	4.4 (+0.2)
US Garden St Culvert (Fern Creek)	11.5	11.6 (+0.1)	11.7 (+0.2)	11.7 (+0.2)	11.6 (+0.1)	11.7 (+0.2)	11.7 (+0.2)
US Macpherson St Culvert (Narrabeen Creek)	3.3	3.4 (+0.1)	3.4 (+0.1)	3.5 (+0.2)	3.6 (+0.3)	3.7 (+0.4)	3.8 (+0.5)
Narrabeen RSL Carpark (Nareen Creek)	5.3	5.4 (+0.1)	5.4 (+0.1)	5.4 (+0.1)	5.4 (+0.1)	5.4 (+0.1)	5.5 (+0.2)
US Narroy Rd Culvert (Nareen Creek)	2.9	3.3 (+0.4)	3.4 (+0.5)	3.5 (+0.6)	3.6 (+0.7)	3.7 (+0.8)	3.8 (+0.9)
US Pittwater Rd Culvert (Nareen Creek)	2.9	3.3 (+0.4)	3.4 (+0.5)	3.5 (+0.6)	3.6 (+0.7)	3.7 (+0.8)	3.8 (+0.9)
US Deep Creek Bridge	3.0	3.4 (+0.4)	3.5 (+0.5)	3.6 (+0.6)	3.7 (+0.7)	3.7 (+0.7)	3.8 (+0.8)
US Middle Creek Bridge 1	3.0	3.3 (+0.3)	3.4 (+0.4)	3.5 (+0.5)	3.6 (+0.6)	3.7 (+0.7)	3.8 (+0.8)
US Middle Creek Bridge 2	9.5	9.6 (+0.1)	9.9 (+0.4)	10.0 (+0.5)	9.6 (+0.1)	9.9 (+0.4)	10.0 (+0.5)
US Middle Creek Bridge 3	11.2	11.3 (+0.1)	11.5 (+0.3)	11.6 (+0.4)	11.3 (+0.1)	11.5 (+0.3)	11.6 (+0.4)
US Toronto Ave Bridge (South Creek)	4.7	4.8 (+0.1)	4.9 (+0.2)	5.0 (+0.3)	4.9 (+0.2)	4.9 (+0.2)	5.1 (+0.4)
US Carcoola Rd Culvert (South Creek)	6.3	6.4 (+0.1)	6.5 (+0.2)	6.5 (+0.2)	6.4 (+0.1)	6.5 (+0.2)	6.5 (+0.2)
US Willandra Rd Culvert (South Creek)	12.9	12.9 (0.0)	12.9 (0.0)	13.0 (+0.1)	12.9 (0.0)	12.9 (0.0)	13.0 (+0.1)

Note: Bracketed value is change in peak flood level from standard design conditions

Table 8-3 and Table 8-4 show the sensitivity of the 1% AEP design flood condition to potential climate change scenarios. The relative impacts on other design event magnitudes show similar characteristics in terms of increases in peak flood levels and area of influence. Additional inundation mapping for the 5% AEP design events under various climate change scenarios is included in Appendix A.

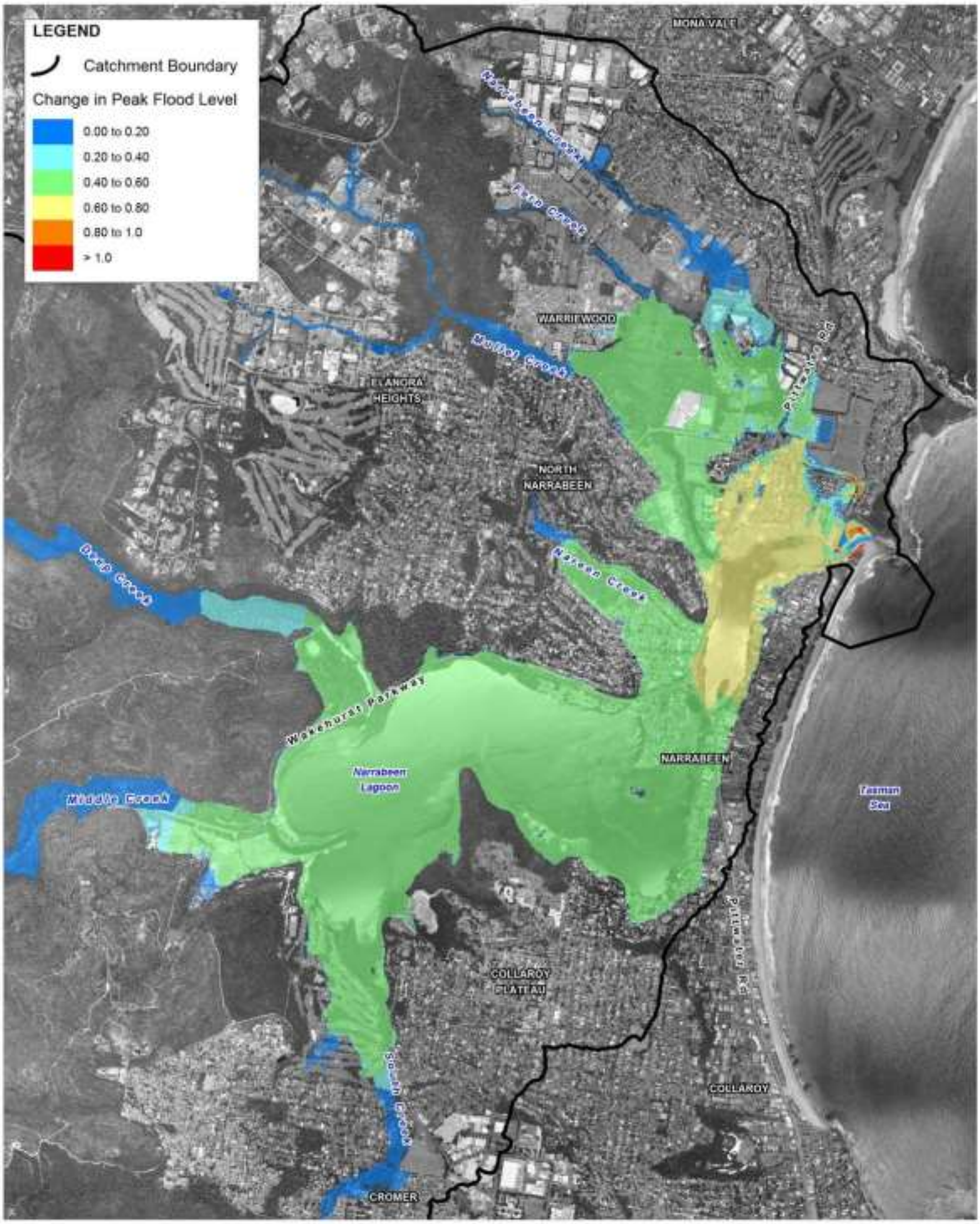
The climate change impacts on ocean derived flooding conditions are summarised in Table 8-5. These simulations are for a pure ocean flooding condition without additional rainfall inputs from the catchment. Accordingly, only locations within the Lagoon foreshores are shown with upper catchment locations excluded. As with ocean flooding results for existing conditions, there is a significant attenuation of the ocean surge through the entrance channel. For example, for the peak 2100 condition, the ocean peak level of 3.5m AHD attenuates to approximately 3.0m AHD in the Lagoon.

Table 8-5 Modelled Peak Flood Levels for Ocean Derived Climate Change Events

Location	Modelled Peak Flood Level (m AHD)		
	Existing 1% AEP	1% AEP + 2050 SLR (+0.4 m)	1% AEP + 2100 SLR (+0.9 m)
US Ocean St Bridge	1.9	2.4 (+0.5)	3.0 (1.1)
US Pittwater Rd Bridge (Narrabeen Lagoon)	1.9	2.4 (+0.5)	3.0 (1.1)
US Pittwater Rd Bridge (Mullet Creek)	1.9	2.3 (+0.4)	3.0 (1.1)
US Jackson Rd Culvert (Mullet Creek)	1.8	2.3 (+0.5)	3.0 (1.2)
US Macpherson St Culvert (Narrabeen Creek)	1.8	2.3 (+0.5)	3.0 (1.2)
US Narroy Rd Culvert (Nareen Creek)	1.9	2.3 (+0.4)	3.0 (1.1)
US Deep Creek Bridge	1.9	2.4 (+0.5)	3.0 (1.1)
US Middle Creek Bridge 1	1.9	2.4 (+0.5)	3.0 (1.1)
US Toronto Ave Bridge (South Creek)	1.9	2.4 (+0.5)	3.0 (+1.1)

Comparing the peak levels for catchment and ocean derived flooding under climate change scenarios, the catchment flooding scenarios remain the dominant flooding mechanism for Narrabeen Lagoon.

The results of the climate change analysis highlight the sensitivity of the peak flood level conditions in Narrabeen Lagoon to potential impacts of climate change. Future planning and floodplain risk management in the catchment will need to take due consideration of the increase in flood risk under possible future climate conditions. The most significant impacts of climate change are associated with sea level rise and the corresponding increases in ocean water levels and entrance berm heights. Figure 8-2 shows the increase in flood level under a 0.9m sea level rise from the existing peak 1% AEP catchment flood level. The area of influence is significant, encompassing the entire Lagoon and foreshore areas and extending a short distance up the tributary channels.



Title: **Peak 1% AEP Flood Level Increase with 0.9m Sea Level Rise**

Figure: **8-2**

Rev: **A**

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9 CONCLUSION

The objective of the Flood Study has been to undertake a detailed flooding assessment of the Narrabeen Lagoon catchment and establish models as necessary for accurate flood level prediction. Central to this is the development of appropriate hydrological and hydraulic models.

The study program provided for a staged approach in undertaking the Flood Study, incorporating.

STAGE 1 – Data Compilation and Initial Community Consultation

STAGE 2 – Hydrological modelling

STAGE 3 – Hydraulic modelling

STAGE 4 – Climate Change Analysis

STAGE 5 – Draft Flood Study and Public Exhibition

Interim reports at these stages were produced within the study duration, culminating in the Draft Flood Study which was placed on Public Exhibition. During the public exhibition period, comment was invited from the public and incorporated into the Final Report where appropriate (refer to Section 3.6).

The Final Report provides full documentation of the Flood Study incorporating all interim stages. In completing the flood study, the following activities have been undertaken:

- Compilation and review of existing information pertinent to the study and acquisition of additional data including survey as required;
- A community consultation and participation program that included the identification of local flooding concerns, collection of information on historical flood behaviour and engagement of the community in the on-going floodplain management process;
- Development and calibration of appropriate hydrological and hydraulic models;
- Determination of design flood conditions for a range of design events including the Probable Maximum Flood (PMF), 0.1%, 0.2%, 0.5%, 1%, 2%, 5%, 10%, 20% and 50% AEP events for catchment derived flooding and the 0.5%, 1%, 2%, 5%, 10% and 20% AEP events for ocean derived flooding; and
- Assessment of the potential impact of climate change using the latest guidelines.

The key study outputs include design flood mapping incorporating peak flood inundation extent, flood depth, flood velocity and flood hazard for the full range of return period magnitudes assessed. This report and the mapping outputs help to define the flood behaviour in the Narrabeen Lagoon catchment and establish the basis for subsequent floodplain management activities.

Provided below is a summary of the key findings of the Flood Study, in particular some of the important considerations for future floodplain risk management in the catchment:

- The design flood conditions documented in the report typically provide for a small increase in previously adopted design flood conditions for Narrabeen Lagoon. The main contributing factor to this change is the way the entrance condition has been modelled. In addition to advances in the software to simulate entrance breakout response, the initial conditions in respect to berm elevations and initial water levels in the Lagoon have been represented more conservatively in the current study.

- Longer duration events (9-36 hours) typically provide for the worst case flooding conditions in Narrabeen Lagoon. With the Lagoon waterbody being a significant flood storage, events of longer duration are required to generate sufficient flood runoff volumes from the catchment to elevate Lagoon water levels. In the lower reaches of all the tributary catchments, flood levels are dominated by the Lagoon flooding conditions. However, the shorter duration events (~2 hours) still provide for significant flooding in the lower reaches of local catchments. The peak flood water level in the Lagoon extends a significant distance up the tributary channels. In the upper reaches of the tributary catchments, shorter duration events of the order of 2-hours provide the critical flood condition in terms of peak flood water level.

- The rise in flood water levels can be relatively fast from the catchment's response to rainfall. Even for the longer duration events providing for the highest peak flood water levels in the Lagoon, the main period of rise in Lagoon water level can occur over a few hours. The April 1988 flood event (used for model calibration in the current study) is an example of such a response in the catchment. Flood levels in the tributary catchments may also rise significantly faster owing to the shorter critical durations in these catchments. This potential rapid inundation has implications for flood warning and emergency response, particularly in flood situations where property and access roads may be quickly inundated.

- Catchment derived flooding events represent the dominant flooding mechanism in Narrabeen Lagoon. Whilst some ocean flooding scenarios will provide for inundation of some foreshore areas, the extent and severity of flooding is significantly less than the corresponding catchment derived event magnitude. The entrance condition has some influence on catchment flood behaviour with higher entrance berm levels providing for higher peak flood levels. The existing entrance management policy provides for manual breakout of the Lagoon entrance at defined trigger levels in preparation for imminent flooding. Irrespective of the successful implementation of a manual entrance breakout, significant flood inundation may be expected during major catchment flood events.

- There are a number of areas within the Narrabeen Lagoon catchment which represent the most significant flood risk exposure to existing property. The worst affected areas are typically in the lower parts of the catchment and most severely impacted on by major flooding in Narrabeen Lagoon. These areas include the foreshore areas of the Lagoon (e.g. Lakeside Park, Wimbledon Avenue, west of Lagoon Street) and the low-lying floodplain areas adjacent to Nareen Creek (e.g. Gondola Road, Nareen Parade) and Mullet Creek (e.g. Garden Street, Warraba Road).

- Peak design flood water levels are expected to progressively increase as the impacts of climate change manifest. For the Narrabeen Lagoon catchment, potential sea level rise will provide for a worsening of existing flood conditions through higher ocean water levels (tide and storm surge), higher entrance berm and higher initial water levels in the Lagoon. Robust land use planning and development policies will be required to ensure future flood risks are not unduly exacerbated in light of predicted flood behaviour under potential climate change scenarios.

- Warringah Council's existing Entrance Management OMS is to open the entrance at a defined trigger water level (currently 1.3m AHD). With potential sea level rise, normal tide levels in the Lagoon will approach and eventually exceed the current trigger levels. Future openings would need to be at significantly higher trigger levels to be effective. Low-lying land currently impacted by flooding may also be subject to regular (or permanent) tidal inundation at some time in the future.

10 REFERENCES

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APPENDIX A: DESIGN FLOOD MAPPING

Refer to Mapping Compendium

APPENDIX B: CONSULTATION MATERIAL

- Media Release
- Manly Daily Advertisement
- Community Newsletter
- Community Questionnaire
- Public Exhibition Media Release
- Public Exhibition Manly Daily Advertisements
- Public Exhibition Brochure

Warringah Council

Media Release

August , 2011

Flood Studies for Narrabeen and Manly Lagoons

Warringah Council is seeking the community's assistance with its flood studies for Manly and Narrabeen Lagoon catchments.

"If you have information or photos of flooding around these lagoons or in their catchments, we would love to hear from you," said Warringah Mayor Michael Regan.

Warringah Council, in partnership with Manly and Pittwater Councils, is undertaking detailed flood studies of the Manly and Narrabeen Lagoon catchments to improve our understanding of flood behaviour and identify problem areas.

The aim of the studies is to:

- define existing flood behaviour
- help identify flooding problem areas in Manly and Narrabeen Lagoon catchments
- assess the impacts of climate change

The studies will also identify the impact sea level rise and rainfall intensity will have on the flood behaviour of the catchments.

"The studies will help improve council's planning and management, such as setting flood levels for development control and improving flood emergency responses.

"You can help by posting information and photos of flooding on the websites set up specifically for the Narrabeen Lagoon and Manly Lagoon flood studies," said Mayor Regan.

For more information visit warringah.nsw.gov.au

Information provided is strictly confidential and will only be used for the study.

For more information please contact the **Communications Team** on 9942 2221 or media@warringah.nsw.gov.au


Flood Study
Send us your flooding photos
Help your local councils to improve flood management in Manly and Narrabeen
The information gathered from your photos will help in verifying flood predictions and managing risks to our community.
To help or find out more visit
gis.wbmpl.com.au/narrabeenlagoon
gis.wbmpl.com.au/manlylagoon
or call 9942 2381.
Warringah Council
MANLY COUNCIL
PITTWATER COUNCIL

Narrabeen Lagoon Flood Study

Community Newsletter September 2011

What is the study about?

Warringah and Pittwater Councils are carrying out a flood study to understand flood risks in the Narrabeen Lagoon catchment.

This includes the areas draining to Narrabeen Creek, Mullet Creek, Deep Creek, Middle Creek, Snake Creek, South Creek and Narrabeen Lagoon.

This study will update previous studies on the individual streams and provide a holistic assessment of flooding within the catchment. The study is being prepared to meet the objectives of the NSW State Government's Flood Policy.

Who is responsible?

Warringah Council is working in partnership with Pittwater Council.

Narrabeen Lagoon Floodplain Risk Management Working Group / Community Committee will oversee the study, providing regular input and feedback on key outcomes. The Committee has a broad representation including Councillors, Council Staff, State Government Department representatives, stakeholder groups and community representatives .

BMT WBM, an independent company specialising in flooding and floodplain risk management, will undertake the study.

The NSW Office of Environment and Heritage is providing financial and technical assistance.

Potential Flood Risks

Flooding in Narrabeen Lagoon comes from three general sources: significant catchment rainfall, oceanic inundation (tide and storm surge) and low-level, persistent flooding from backed up lake water when the lake entrance is closed.

The Flood Study will assess flooding behaviour in the catchment to identify the critical or worst case flood conditions for a range of flood events for both catchment and ocean flooding.

For different locations within the catchment, and for different size flood events, the dominant flooding mechanism can vary, being either catchment rainfall or ocean flooding.

The condition of the entrance may have a significant influence on flood behaviour in Narrabeen Lagoon. For catchment flooding, an effective open entrance provides for lower flood levels in comparison to a heavily shoaled or closed entrance. However, generally for ocean flooding, an open entrance condition will provide worst case conditions, through greater penetration of ocean water into the estuary under storm surge (ocean flooding) conditions.

As part of the current study, we are investigating a range of entrance conditions, both open and in various states of closure to assess the impact on flooding (under current conditions and future conditions considering potential sea level rise). Accordingly there will be some quantification of potential changes in flood conditions for various entrance states for both catchment and ocean flooding. From the floodplain risk management perspective, we need to look at a range of events from frequent "nuisance" type flooding to extreme events with significant inundation and high flood risk exposure of property and people.

Warringah Council

PITTWATER COUNCIL

BMT WBM

Climate Change

The primary impacts of climate change in coastal areas are likely to result from sea level rise, which, coupled with storms, may lead to increased coastal erosion, tidal inundation and flooding.

The NSW Government recently adopted sea level rise planning benchmarks to ensure consistent consideration of sea level rise in coastal areas of NSW. These planning benchmarks are an increase above 1990 mean sea levels of 40cm by 2050 and 90cm by 2100.

For Narrabeen Lagoon, rising sea level is expected to increase the frequency, severity and duration of flooding. This is particularly the case when the entrance is open, with potentially more ocean water flowing through the entrance and into the main body of the Lagoon.

Projected sea level rise will also result in higher sand levels at the entrance when it is closed. This means that lake levels will need to be even higher in the future in order to initiate effective break-out channels.

Another potential impact of climate change to be investigated is an increase in design rainfall intensities, which may result in increased flood flows and volumes in the catchment.

During the course of the study, the changes to flood inundation patterns under climate change scenarios will be identified to determine the increased flood risk.

Wave penetration into Lagoon, 2006

Key Study Outputs

The main objective of the study is to characterise the flooding behaviour in the catchment detailing appropriate flood water level, depth and velocity distributions across the floodplain for historical and hypothetical flood event conditions.

By assessing a range of flood magnitudes, both the severity and frequency of potential flooding for individual properties can be ascertained.

Detailed computer models are developed specifically for the catchment to simulate flood behaviour. Historical flood information such as rainfall depths, peak water levels, flooded property details etc, are used to ensure the computer models are representative of the real catchment behaviour.

Flood maps across the catchment will be produced using the model results which will show the predicted extent of flooding .

The flood study results will be used to provide more effective flood planning in the catchment and will assist Councils in:

•Setting appropriate levels for development control;

•Identifying potential works to reduce existing flooding; and

•Improving flood emergency response and recovery.

Historical entrance opening

Community input

Community involvement in managing flood risks is essential to improve the decision making process, to identify local concerns and values, and to inform the community about the consequences of flooding and potential management options. The success of the flood planning in the Narrabeen Lagoon catchment hinges on the community's input and acceptance of the proposals.

There are a number of ways you can be involved in the study:

•Please take a few minutes of your time to complete and return the questionnaire. This will greatly assist in collating people's knowledge and experience about previous flooding history and existing flood problem areas.

•A community information session is planned at a later stage following assessment of available floodplain management options and to collect people's ideas and opinions before coming up with the recommended plan.

•A website has been established to keep the community informed on the study progress. The website has further information on flooding in Narrabeen Lagoon and will be updated throughout the study as new information becomes available. Community members will also be able to post their views and comments on the website so they can be considered during the course of the study.

Study timetable

Comprehensive flood studies of this nature take some time to complete, incorporating detailed technical analysis, community consultation activities, study documentation and review processes.

Set out below is an indicative timetable which the project will follow, with key project stages/milestones and their proposed completion dates.

STAGE 1 – Data Compilation and Initial Community Consultation

Completion by September 2011

STAGE 2 – Hydrological modelling

Completion by October 2011

STAGE 3 – Hydraulic modelling

Completion by April 2012

STAGE 4 – Climate Change Analysis

Completion by August 2012

STAGE 5 – Draft Flood Study and Public Exhibition

Completion by October 2012

The completion of the study will see the adoption by Council of the Final Flood Study Report following appropriate review and feedback from stakeholders.

Narrabeen Lagoon entrance following opening

Want more information?

For more information about the Narrabeen Lagoon Flood Study , please contact:

Warringah Council
Ms Deborah Millener
Floodplain Management Officer
Ph 9942 2111

BMT WBM (Consultant)
Mr Darren Lyons
Project Manager
Ph 4940 8882

Website:
http://gis.wbmpl.com.au/NarrabeenLagoon/

Flooding in Narrabeen, April 1927

Wheeler Park, March 2011

Important Terms

Catchment flooding: is the inundation of land due to significant rainfall in the catchment. The runoff generated from the catchment flows into Narrabeen Lagoon from local streams.

Ocean flooding: is the inundation of land by sea water and results from one or a combination of storm surge, wave set-up and tidal conditions.

Low-level persistent flooding: is the inundation of land due to elevated lake levels in periods of entrance closure, with lake water level fluctuations due to local catchment rainfall and lake evaporation.

ICOLLs: Intermittently Closed and Open Lakes and Lagoons (such as Narrabeen Lagoon) are separated from the ocean by a sand beach barrier or berm. This entrance barrier forms and breaks down depending on the movement and redistribution of sand and sediments by waves, tides, flood flows and winds. ICOLLs open and close to the ocean ***naturally*** in a constant but ***irregular*** cycle.

Natural breakout: Following heavy rainfall, water levels in the ICOLL rise and may eventually spill over the entrance sand berm and with sufficient force can scour an entrance channel through the beach and reopen the ICOLL to the ocean.

Artificial opening: Artificial breaching of the entrance barrier is undertaken to 'drain' the ICOLL to the ocean and lower water levels to relieve flooding of foreshore development and infrastructure or avoid the likely threat of flooding which would occur before the ICOLL entrance opens naturally.

Narrabeen Lagoon Flood Study
Community Questionnaire September 2011

Your views and experiences are important to the study

Warringah Council (in partnership with Pittwater Council) is undertaking a detailed flood study of the Narrabeen Lagoon catchment to help identify flooding problem areas. We are seeking the community's help by collecting information on any flooding or drainage problems that you may have experienced in the past. Please take a minute or two to read through these questions and provide responses wherever you can. Please return this form to Warringah Council in the enclosed envelope (no stamp required). All information provided is confidential and used only for the purposes of the study.

Contact and Property Details

Name:..

Address:...

Phone or email:..

Please tick your type of property :

☐ House ☐ Unit/Flat/Apartment

☐ Business ☐ Other (please specify)

....

How long have you been at this property?

.... Years

Please keep me informed on study progress?

☐ Yes ☐ No

Previous Flooding Experience

Have you ever experienced flooding at this property?

☐ Yes ☐ No

If yes, what dates or years did this happen?

....

....

Do you think your property could be flooded in the future?

☐ Yes ☐ No

Previous Flooding Experience

Are you able to indicate the depth that flood waters reached on your property or elsewhere such as roads?

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A map is provided on the back, please mark up your property or known flooding areas. Additional space is provided to add other comments.

Photographs and Video

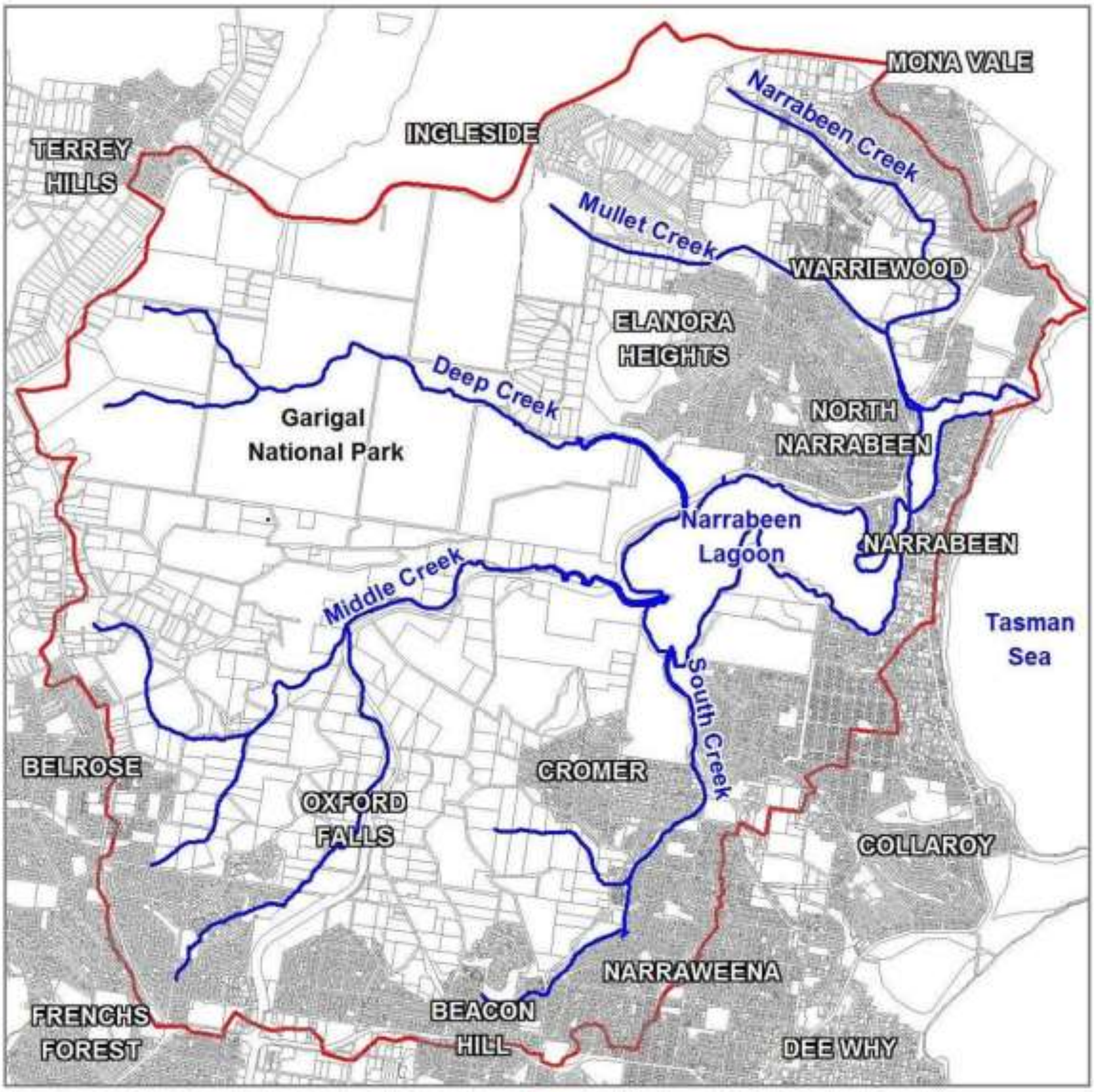
Do you have any photographs or video of flooding that you are willing to share with Council?

☐ Yes ☐ No

Photographs and video can be returned with the questionnaire or emailed to:

Darren.Lyons@bmtwbm.com.au

Warringah Council PITTWATER COUNCIL BMT WBM



Please provide any additional comments or information that you think will help the study

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THANK YOU FOR YOUR ASSISTANCE IN COMPLETING THE SURVEY. PLEASE PROVIDE ANY ADDTIONAL INFORMATION YOU FEEL IS RELEVANT TO THE STUDY

Media Release - Draft Narrabeen Lagoon Flood Study

Friday, July 12, 2013

Draft Narrabeen Lagoon Flood Study

Warringah and Pittwater Councils are exhibiting the Draft Narrabeen Lagoon Flood Study and you are invited to have your say.

The final Draft Narrabeen Lagoon Flood Study will update the 1990 flood study and define current and future flood behaviour of the catchment, which extends as far as Mona Vale to the north, Belrose to the west and Beacon Hill to the south.

The draft study, which is being prepared to meet the objectives of the NSW State Government's Flood Prone Land Policy, will establish the basis for subsequent floodplain management activities and is on public exhibition until Monday 12 August.

Under the State Policy, NSW Local Governments are responsible for identifying and managing the risk to life and property from flooding.

One of the most important steps in this process is increasing our community's awareness of flooding so that people are better able to understand and plan for the flood risks they face.

For most people, there will be no immediate change to their situation.

However, property owners who are planning redevelopment of their property may need to take some additional steps as part of the consent process because flood-related development controls will apply. For example, the construction of new buildings will need to be set at or above the Flood Planning Level (1 in 100 year flood plus 0.5m) and out of flood danger.

Community Information Sessions are being held during the public exhibition to give people whose properties may be affected by the study the chance to have a 15-minute, one-on-one talk with Council Officers. The information sessions will be held on:

Saturday 20, Friday 26, Tuesday 30 July, 9.30am – 5pm

Coastal Environment Centre, Pelican Way, Lake Park Rd, North Narrabeen

Monday 22 July, 9.30am – 5pm

Tramshed Arts and Community Centre, 1395A Pittwater Rd, Narrabeen

Bookings essential on:

Warringah Council area: Valerie Tulk on 9942 2111 or valerie.tulk@warringah.nsw.gov.au

Pittwater Council area: Debbi Millener on 9970 1111 or floodplain@pittwater.nsw.gov.au

The Draft Narrabeen Lagoon Flood Study is on public exhibition at warringah.nsw.gov.au; pittwater.nsw.gov.au; Warringah Council Chambers, Pittwater Council Offices, and Council libraries.

This study has been prepared for Warringah and Pittwater Councils with financial assistance from the NSW and Commonwealth Governments through the Natural Disaster Resilience Program.

Manly Daily Notices – Public Exhibition

PUBLIC EXHIBITIONS
Draft Narrabeen Lagoon Flood Study
Warringah and Pittwater Councils have prepared the Draft Narrabeen Lagoon Flood Study to define current and future flood behaviour and you are invited to have your say. Exhibition period 13 July – 12 August.

Community information sessions
20, 26, 30 July, 9.30am – 5pm
Coastal Environment Centre
(off Lake Park Rd, North Narrabeen)

22 July, 9.30am – 5pm
Tramshed - Lakeview Room
(Pittwater Rd, Narrabeen)

Bookings essential
Warringah Council area: Valerie Tulk on 9942 2111 or valerie.tulk@warringah.nsw.gov.au

Pittwater Council area: Debbi Millener on 9970 1111 or floodplain@pittwater.nsw.gov.au

The above draft and accompanying documents are available at warringah.nsw.gov.au, Civic Centre, pittwater.nsw.gov.au, Pittwater Council Offices and Council libraries. Submissions are invited in writing to Warringah Council, 725 Pittwater Rd, Dee Why NSW 2099 or council@warringah.nsw.gov.au or; Pittwater Council, PO Box 882, Mona Vale NSW 1660 or pittwater_council@pittwater.nsw.gov.au marked 'Draft Narrabeen Lagoon Flood Study'.

Manly Daily 13th and 20th July 2013

PITTWATER/WARRINGAH

Have your say on flood study

PITTWATER and Warringah Councils are exhibiting the Draft Narrabeen Lagoon Flood Study and you are invited to have your say.

The draft study, which is being prepared to meet the objectives of the NSW State Government's Flood Prone Land Policy, will establish the basis for subsequent flood management activities and will be put on public exhibition until Monday, August 12.

For more information on how to view the study and be a part of associated information sessions, phone Debbi Millener on 9970 1208.

Manly Daily 17th July 2013

COMMUNITY GUIDE TO NARRABEEN LAGOON FLOOD STUDY JULY 2013

WARRINGAH COUNCIL

Introduction

Warringah and Pittwater Councils are carrying out a flood study to understand flood risks in the Narrabeen Lagoon catchment. The study includes areas draining to Narrabeen Lagoon such as South Creek, Middle Creek, Deep Creek, Mullet Creek and Narrabeen Creek. This study updates the 1990 Narrabeen Lagoon Flood Study as well as flood studies for individual creeks, and provides a holistic assessment of flooding within the catchment.

The Draft Narrabeen Lagoon Flood Study is on public exhibition from Monday 15 July to 12 August and you are invited to have your say.

Flooding in the Narrabeen Lagoon Catchment

The main aim of the study is to define current and future flood behaviour in the Narrabeen Lagoon catchment.

Flooding in Narrabeen Lagoon comes from two main sources:

1. significant catchment rainfall
2. oceanic inundation (tide and storm surge)

Floodplain Risk Management Process

Under the NSW Government's Flood Prone Land Policy, councils have the primary responsibility for managing flood prone areas, with financial and technical support provided by the State Government.

Floodplain risk management considers the consequences of flooding on the community and aims to develop appropriate actions to minimise and mitigate the impacts of flooding. The Flood Prone Land Policy specifies a staged approach to the floodplain management process:

What happens next?

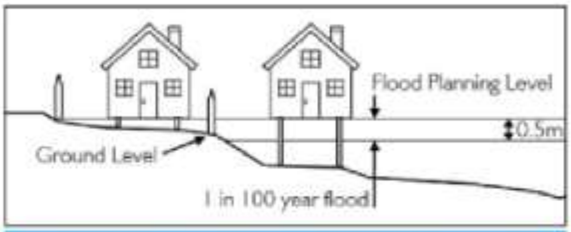
After the public exhibition of the Draft Narrabeen Lagoon Flood Study, all comments will be reviewed and final amendments made to the study. Once adopted by both Warringah and Pittwater Councils, the study will be used in the preparation of the Narrabeen Lagoon Floodplain Risk Management Study and Plan.

The Floodplain Risk Management Study will outline what can be done to manage flooding in the Narrabeen Lagoon catchment through the identification, assessment and comparison of various risk management options.

The Floodplain Risk Management Plan will contain several management measures and strategies. These will help guide and coordinate the responsibilities of government and the community in undertaking flood management works and initiatives. Preferred options will be publicly exhibited and subject to revision in light of community response.

How am I affected?

The Flood Study Map shows the extent of flood prone land, which is defined as the area affected by the Probable Maximum Flood (PMF, i.e. the largest flood that could conceivably occur). Properties affected by the Flood Planning Level, i.e. the 1 in 100 year flood plus 0.5m freeboard, (see image and explanation in FAQs below) are shaded on the map.



New buildings need to be above the Flood Planning Level

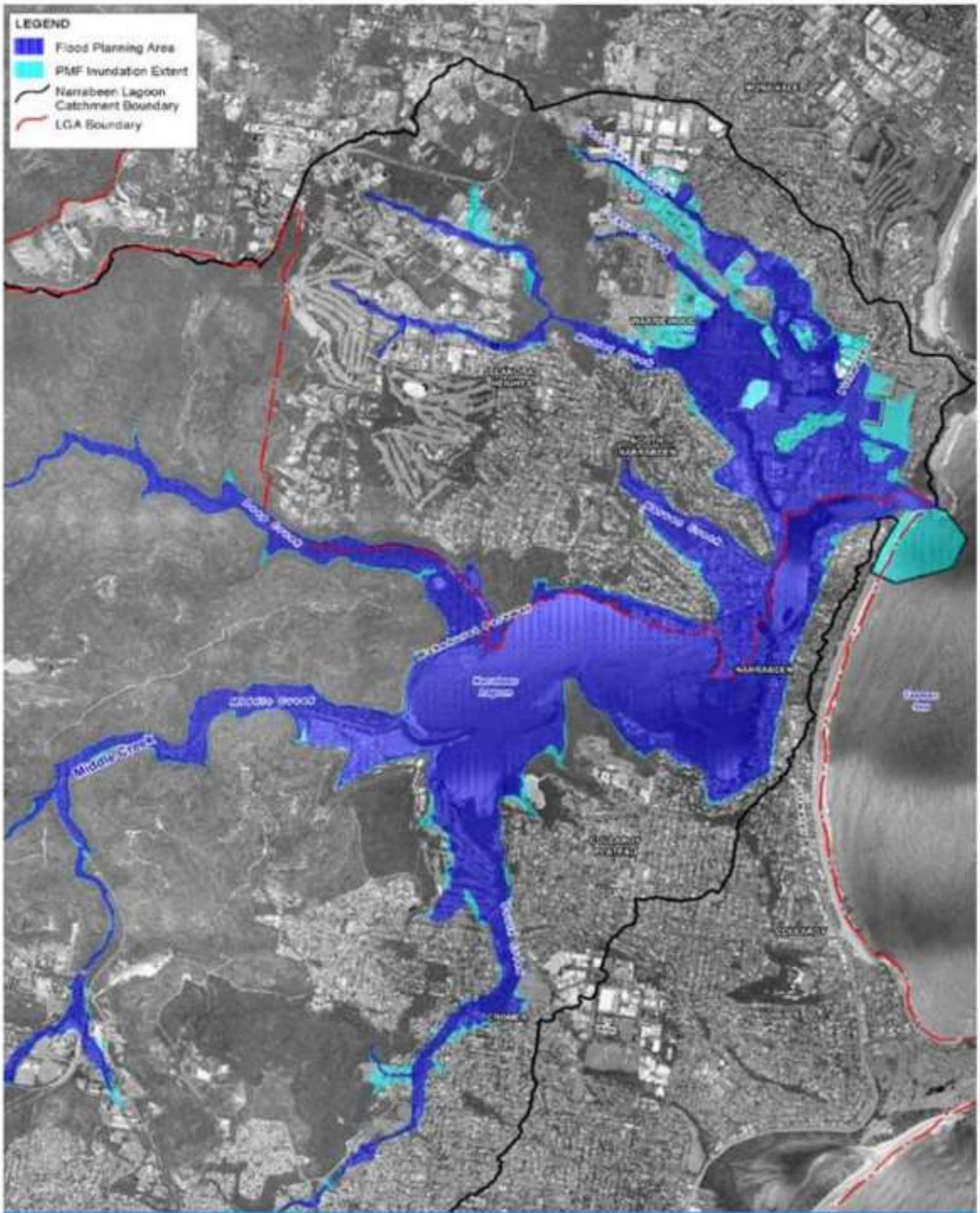
Certain flood related development controls may apply to flood prone properties. For instance, residential properties affected by the Flood Planning Level may be subject to minimum floor level requirements. For further information visit warringah.nsw.gov.au or pittwater.nsw.gov.au.

Community Input

Community involvement in managing flood risks is essential for:

- raising awareness in the community about the potential for flooding in the catchment
- improving the decision making process
- identifying local concerns and values

As part of the community consultation, the Draft Narrabeen Lagoon Flood Study will be on public exhibition from Monday 15 July to Monday 12 August, 2013. You are invited to participate in the study by providing comment on the draft report, available from warringah.nsw.gov.au, pittwater.nsw.gov.au, Warringah Council Chambers and Pittwater Council offices and libraries.



WARRINGAH.NSW.GOV.AU

What can I do?

To make a submission on the Draft Narrabeen Lagoon Flood Study, write to the General Manager of your local Council marked
'Submission – Draft Narrabeen Lagoon Flood Study':

Warringah Council
725 Pittwater Road
Dee Why
NSW 2099
or email council@warringah.nsw.gov.au

Pittwater Council
PO Box 882
Mona Vale
NSW 1660
or email pittwater_council@pittwater.nsw.gov.au

Submissions close Monday, 12 August, 2013.

One-on-one community information sessions

Saturday 20th, Friday 26th, Tuesday 30th July
9.30am - 5pm
Coastal Environment Centre, Pelican Way, Lake Park Road
North Narrabeen

Monday 22nd July
9.30am - 5pm
Tramshed Arts & Community Centre, 1395A Pittwater Road, Narrabeen

BOOKINGS ARE ESSENTIAL:

Warringah Council area:	Pittwater Council area:
Valerie Tulk 9942 2111 or valerie.tulk@warringah.nsw.gov.au	Debbi Millener 9970 1111 or floodplain@pittwater.nsw.gov.au

March 2011 - Narrabeen

April 2009 - Wakehurst Parkway

Frequently Asked Questions

Why does Council study flooding?

NSW Local Governments have responsibility for identifying and then managing the risk to life and property from flooding, and have a duty of care to disclose this information to the community. Local Governments must act in accordance with the NSW Flood Prone Land Policy, which aims to reduce the impact of flooding and flood liability on individual owners and occupiers of flood prone property. One of the most important steps in this process is increasing our community's awareness of flooding so that people are better able to understand and plan for the flood risks they face.

What areas are included in the Draft Narrabeen Lagoon Flood Study?

Narrabeen Lagoon is fed primarily by South Creek, Middle Creek, Deep Creek, Mullet Creek and Narrabeen Creek. As a result the study area extends to include parts of Mona Vale in the north, Belrose in the west and Beacon Hill in the south.

Which areas could be flooded?

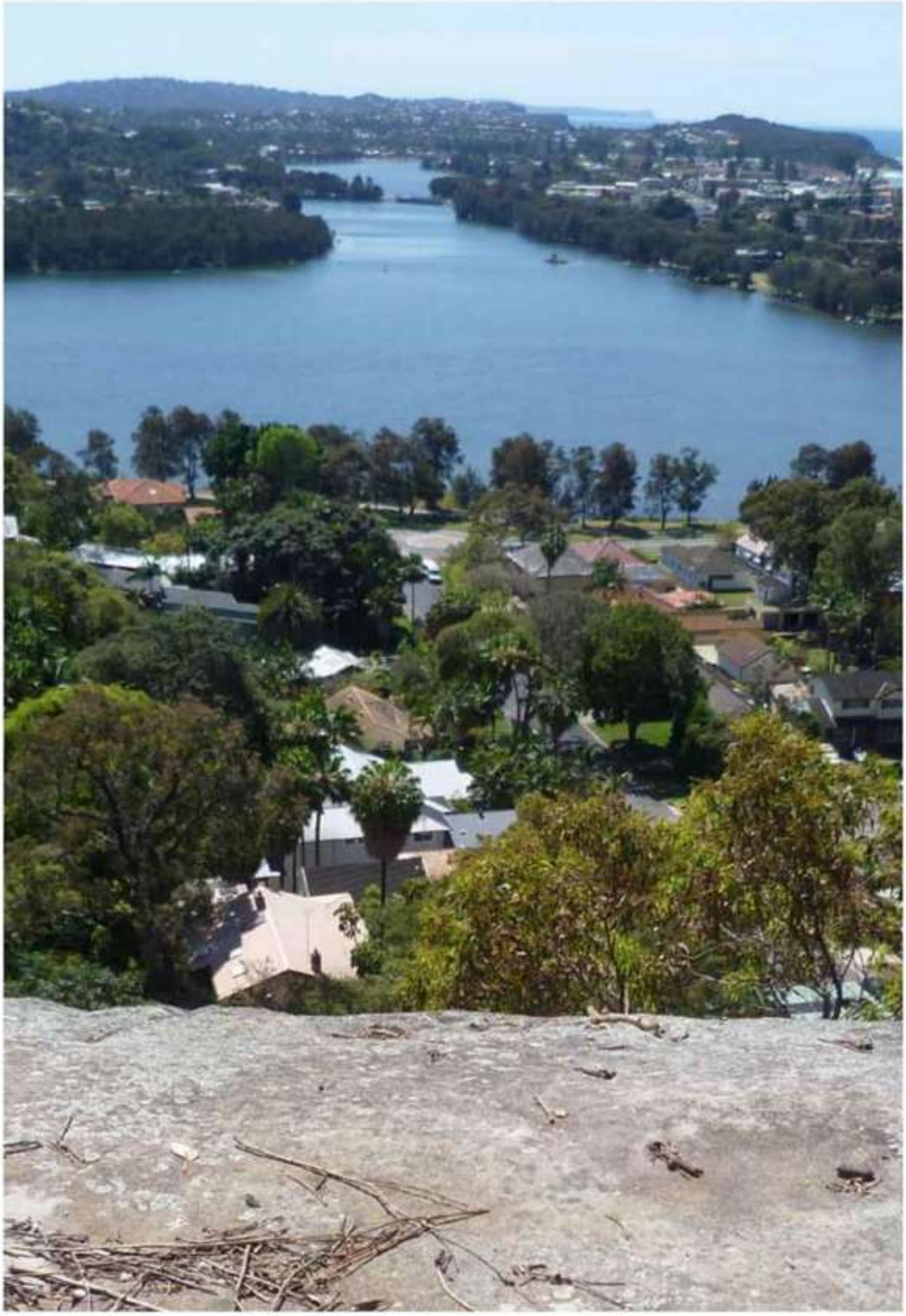
The Draft Narrabeen Lagoon Flood Study map shows land that would be affected by the Probable Maximum Flood (i.e. the largest flood that could conceivably occur). Properties affected by the Flood Planning Level (i.e. the 1 in 100 year flood plus 0.5m freeboard) are also shaded on the map.

What is a 1 in 100 year flood?

A 1 in 100 year flood occurs on average once every 100 years, i.e. there is a 1% chance of a flood of this size occurring at a particular location in any given year. This does not mean that if a location floods one year, it will definitely not flood for the next 99 years. Nor, if it has not flooded for 99 years that it will necessarily flood the next year. Some parts of Australia have received a couple of 1 in 100 year floods within a decade of each other.

What is Freeboard?

Freeboard is included in the Flood Planning Level as a buffer, to account for factors such as wind, waves, unforeseen blockages, other localised hydraulic effects and uncertainties in the modelling and determination of flood levels. Freeboard is typically 0.5m above a flood level.



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My property was never classified as 'flood prone' or 'flood liable' before. Now it is. Why?

The flood levels from this draft flood study are slightly higher in some areas than those previously adopted for the 1990 Narrabeen Lagoon Flood Study. The main reasons for this difference include more advanced models and calibration data, better understanding of entrance conditions, improved surveys and changes in land use.

What are councils doing to manage flood risk?

Councils prepare flood studies and plans according to the NSW Government's Floodplain Development Manual (2005), and implement associated recommendations with the financial and technical assistance of NSW Government through its Flood Prone Land Policy. Land use planning through development controls is one of the most effective means of managing flood risk in the catchment. Additional flood mitigation measures in the catchment currently include: the management of the Narrabeen Lagoon entrance, implementing a flood warning network and raising flood awareness in the community.

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Council's primary responsibility is to identify and then manage the risk to life and property from flooding, and has a duty of care to disclose this information to the community. The Draft Narrabeen Lagoon Flood Study represents significant advances since previous flood studies in the catchment and is a public document, which all members of the community, including insurance companies, are able to access.

What can I do to prepare in case of a flood?

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Where can I find out about Council's flood related development controls?

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Further information

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WARRINGAH COUNCIL | PITTWATER COUNCIL | NSW Office of Environment & Heritage | Australian Government

This project is supported by the NSW and Commonwealth Governments through the Natural Disaster Resilience Program

COMMUNITY GUIDE TO NARRABEEN LAGOON FLOOD STUDY JULY 2013

PITTWATER COUNCIL

Introduction

Warringah and Pittwater Councils are carrying out a flood study to understand flood risks in the Narrabeen Lagoon catchment. The study includes areas draining to Narrabeen Lagoon such as Mullet Creek, Narrabeen Creek, South Creek, Middle Creek and Deep Creek. This study updates the 1990 Narrabeen Lagoon Flood Study as well as flood studies for individual creeks, and provides a holistic assessment of flooding within the catchment. The Draft Narrabeen Lagoon Flood Study is on public exhibition from Monday 15 July to 12 August and you are invited to have your say.

Flooding in the Narrabeen Lagoon Catchment

The main aim of the study is to define current and future flood behaviour in the Narrabeen Lagoon catchment.

Flooding in Narrabeen Lagoon comes from two main sources:

1. significant catchment rainfall
2. oceanic inundation (tide and storm surge)

Floodplain Risk Management Process

Under the NSW Government's Flood Prone Land Policy, councils have the primary responsibility for managing flood prone areas, with financial and technical support provided by the State Government.

Floodplain risk management considers the consequences of flooding on the community and aims to develop appropriate actions to minimise and mitigate the impacts of flooding. The Flood Prone Land Policy specifies a staged approach to the floodplain management process:

What happens next?

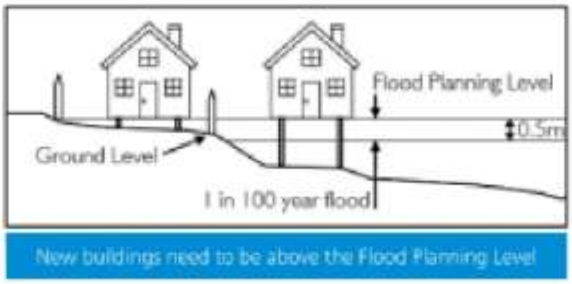
After the public exhibition of the Draft Narrabeen Lagoon Flood Study, all comments will be reviewed and final amendments made to the study. Once adopted by both Pittwater and Warringah Councils, the study will be used in the preparation of the Narrabeen Lagoon Floodplain Risk Management Study and Plan.

The Floodplain Risk Management Study will outline what can be done to manage flooding in the Narrabeen Lagoon catchment through the identification, assessment and comparison of various risk management options.

The Floodplain Risk Management Plan will contain several management measures and strategies. These will help guide and coordinate the responsibilities of government and the community in undertaking flood management works and initiatives. Preferred options will be publicly exhibited and subject to revision in light of community response.

How am I affected?

The Flood Study Map shows the extent of flood prone land, which is defined as the area affected by the Probable Maximum Flood (PMF, i.e. the largest flood that could conceivably occur). Properties affected by the Flood Planning Level, i.e. the 1 in 100 year flood plus 0.5m freeboard, (see image and explanation in FAQs below) are shaded on the map.



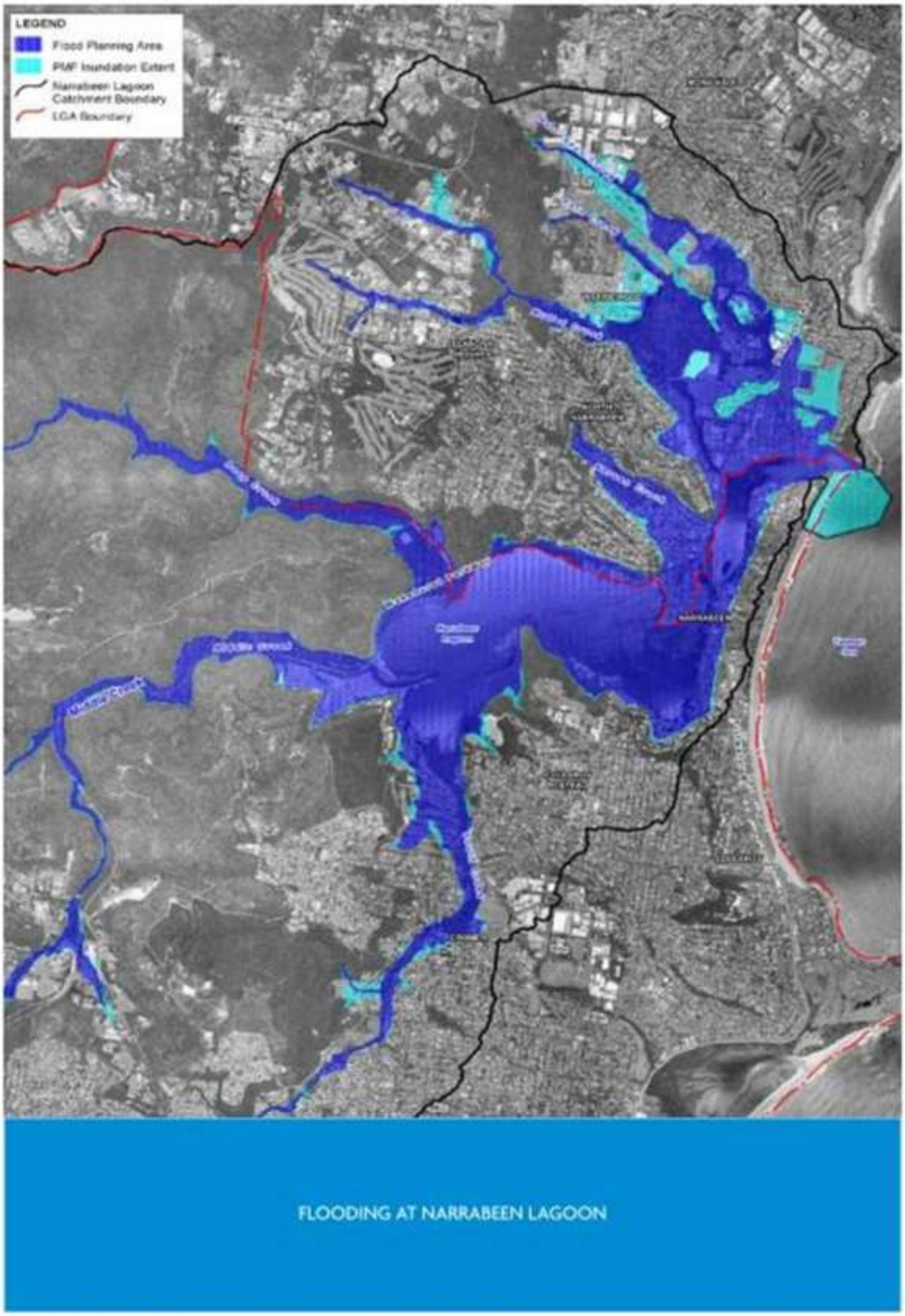
Certain flood related development controls may apply to flood prone properties. For instance, residential properties affected by the Flood Planning Level may be subject to minimum floor level requirements. For further information visit pittwater.nsw.gov.au.

Community Input

Community involvement in managing flood risks is essential for:

- raising awareness in the community about the potential for flooding in the catchment
- improving the decision making process
- identifying local concerns and values

As part of the community consultation, the Draft Narrabeen Lagoon Flood Study will be on public exhibition from Monday 15 July to Monday 12 August, 2013. You are invited to participate in the study by providing comment on the draft report, available from pittwater.nsw.gov.au, or customer service centres, libraries at 1 Park Street, Mona Vale, 59A Old Barrenjoey Road, Avalon and the Coastal Enviroment Centre.


LEGEND
Flood Planning Area
PMF Inundation Extent
Narrabeen Lagoon Catchment Boundary
LGA Boundary
FLOODING AT NARRABEEN LAGOON

What can I do?

To make a submission on the Draft Narrabeen Lagoon Flood Study, write to the General Manager of your local Council marked
'Submission – Draft Narrabeen Lagoon Flood Study':

Pittwater Council
PO Box 882
Mona Vale
NSW 1660
or email pittwater_council@pittwater.nsw.gov.au

Warringah Council
725 Pittwater Road
Dee Why
NSW 2099
or email council@warringah.nsw.gov.au

Submissions close Monday, 12 August, 2013.

One-on-one community information sessions

Saturday 20th, Friday 26th, Tuesday 30th July
9.30am - 5pm
Coastal Environment Centre, Pelican Way, Lake Park Road
North Narrabeen

Monday 22nd July
9.30am - 5pm
Tramshed Arts & Community Centre, 1395A Pittwater Road, Narrabeen

BOOKINGS ARE ESSENTIAL:

Pittwater Council area:	Warringah Council area:
Debbi Millener 9970 1111 or floodplain@ pittwater.nsw.gov.au	Valerie Tulk 9942 2111 or valerie.tulk@ warringah.nsw.gov.au

March 2011 - Narrabeen

April 2009 - Wakehurst Parkway

Frequently Asked Questions

Why does Council study flooding?

NSW Local Governments have responsibility for identifying and then managing the risk to life and property from flooding, and have a duty of care to disclose this information to the community. Local Governments must act in accordance with the NSW Flood Prone Land Policy, which aims to reduce the impact of flooding and flood liability on individual owners and occupiers of flood prone property. One of the most important steps in this process is increasing our community's awareness of flooding so that people are better able to understand and plan for the flood risks they face.

What areas are included in the Draft Narrabeen Lagoon Flood Study?

Narrabeen Lagoon is fed primarily by South Creek, Middle Creek, Deep Creek, Mullet Creek and Narrabeen Creek. As a result the study area extends to include parts of Mona Vale in the north, Belrose in the west and Beacon Hill in the south.

Which areas could be flooded?

The Draft Narrabeen Lagoon Flood Study map shows land that would be affected by the Probable Maximum Flood (i.e. the largest flood that could conceivably occur). Properties affected by the Flood Planning Level (i.e. the 1 in 100 year flood plus 0.5m freeboard) are also shaded on the map.

What is a 1 in 100 year flood?

A 1 in 100 year flood occurs on average once every 100 years, i.e. there is a 1% chance of a flood of this size occurring at a particular location in any given year. This does not mean that if a location floods one year, it will definitely not flood for the next 99 years. Nor, if it has not flooded for 99 years that it will necessarily flood the next year. Some parts of Australia have received a couple of 1 in 100 year floods within a decade of each other.

What is Freeboard?

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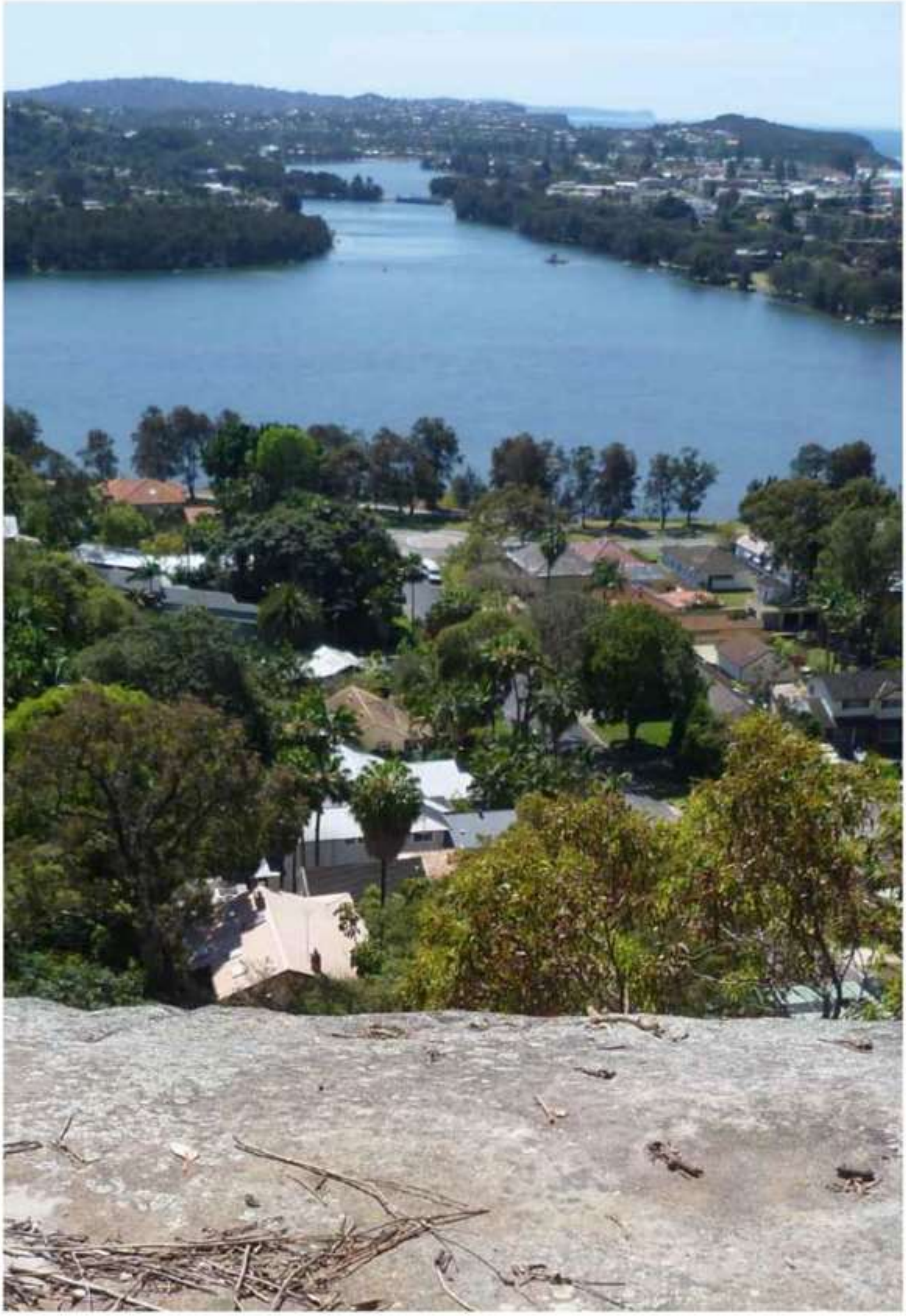

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APPENDIX C: RATIONAL METHOD CROSS CHECKS

The Rational Method is a simplistic technique used to estimate a design peak discharge volume from a small to medium sized catchment for a given design storm event. The Rational Method recommended for use in eastern New South Wales is the probabilistic rational method (AR&R, 2001). The probabilistic Rational Method is based on data from 308 gauged catchments and is applicable to catchment areas of up to 250km^2. Further information on the probabilistic Rational Method can be found in AR&R (2001).

The probabilistic Rational Method has been used in the current study as a means to cross check the design peak discharge values estimated by the TUFLOW hydraulic model. Table C-1 provides the parameter values adopted for the probabilistic Rational Method calculations as well as the estimated design peak flow values for the three tributaries upstream of Warriewood Wetlands (namely Mullet Creek, Narrabeen Creek and Fern Creek).

Table C-1 Probabilistic Rational Method Calculation

Parameter	Mullet Ck (U/S Garden St)	Narrabeen Ck (U/S Ponderosa Pde)	Fern Ck (U/S Warriewood Wetlands)
Catchment Area (ha)	368 ha	93 ha	61 ha
Critical Duration (t_c)	1.0 hrs	0.75 hrs	0.5
Design Rainfall Intensity ($^{100}I_{tc}$)	95.4 mm/h	112.0 mm/h	136.0 mm/h
C_{10} (10% AEP runoff coefficient)	0.75	0.75	0.75
FF_{100} (frequency factor)	1.39	1.39	1.39
C_{100} (1% AEP runoff coefficient)	1.04	1.04	1.04
Q_{100} (peak 1%AEP discharge)	101.7 m^3/s	30.3 m^3/s	24.0 m^3/s

Table C-2 shows a comparison between the design discharge values extracted from the TUFLOW model developed in the current study, the probabilistic Rational Method estimate and the design discharge value presented in the Warriewood Valley Flood Study (Lawson and Treloar, 2005) for the three tributaries upstream of Warriewood Wetlands. There is a good correlation between the design discharge values extracted from the TUFLOW model and the probabilistic Rational Method, however, these values are higher than the corresponding estimated flow condition reported in Warriewood Valley Flood Study. This difference in design discharge volumes between the current and previous study results in a significant difference in design flood water levels (as discussed in Section 7.4 in the main body of the report).

Table C-2 Comparison of Estimated Peak Design 1% AEP Discharge

Extent	Current Study (TUFLOW model)	Rational Method	Warriewood Valley Flood Study
Mullet Ck (U/S Garden St)	103.8	101.7	44.3
Narrabeen Ck (U/S Ponderosa Pde)	34.5	30.3	12.5
Fern Ck (U/S Warriewood Wetlands)	16.7	24.0	7.3