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Review of Hewitts Creek Flood Study Final Report

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Review of Hewitts Creek Flood Study Final Report

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Title :	Review of Hewitts Creek Flood Study –Final Report
Author :	Paul Dunne and Darren Lyons
Synopsis :	Final report for the Review of Hewitts Creek Flood Study. The report covers the data collection process, community consultation, development of computer models, establishment of design flood behaviour and flood mapping.

REVISION/CHECKING HISTORY

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EXECUTIVE SUMMARY

Introduction

The review of Hewitts Creek Flood Study has been prepared for Wollongong City Council (Council) to define the existing flood behaviour in the Hewitts Creek study area and consider the influence of potential climate change on future flood behaviour.

The review updates the previous Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a), to account for the various recent changes within the study area and take advantage of innovations and improvements in computer flood modelling. The study provides a holistic assessment of historic, current and future flood risk and establishes the basis for the subsequent Floodplain Risk Management Study and Plan.

Flood risk has been assessed through the establishment of appropriate numerical models. The study has produced information on flood flows, velocities, levels and extents for a range of flood event magnitudes under existing catchment and floodplain conditions and considering the influence of potential climate change on future flood behaviour. Specifically, the study incorporates:

- 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 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 hydrologic and hydraulic models;
- Determination of design flood conditions for a range of design events - including the 20% Annual Exceedance Probability (AEP), 10% AEP, 5% AEP, 2% AEP, 1% AEP, 0.5% AEP, 0.2% AEP and Probable Maximum Flood (PMF);
- Examination of potential impact of climate change using the latest guidelines for the 1% AEP design event; and
- Presentation of study methodology, results and findings in a comprehensive report incorporating detailed flood mapping.

Figure ES-1 and ES-2 show the indicative extents, depths and elevations for the 1% AEP event and PMF.

Catchment Description

The Hewitts Creek study area includes the catchments of Slacky, Tramway, Woodlands, Hewitts and Thomas Gibson Creeks. The combined catchments drain an area of approximately 8.1km^2 and extend from the Illawarra Escarpment in the west to Thirroul Beach, McCauley's Beach and Bulli Beach in the east, where they discharge into the Tasman Sea.

The upper (western) areas of the study area are dominated by the Illawarra Escarpment which falls steeply from 400-500m AHD to approximately 250 m AHD. These steep upper reaches of the catchments are heavily vegetated. The middle portions of the catchments extends from the base of the Illawarra Escarpment to the Illawarra Railway, at approximately 15m AHD, and the land is more gently graded with residential developments being the dominant land use. From east of the Illawarra Railway to the coast, the land is generally quite flat with a mixture of residential and retail developments and parkland.

Historical Flooding

The Hewitts Creek study area has a history of flooding with the most recent significant flood event having occurred on 17 August 1998. An extensive record of historical flood levels and anecdotal evidence was captured following this flood event. Other flood events which occurred in the study area for which flood level data is available include events in April 1988, June 1991 and February 2013.

Following the August 1998 flood event, a significant amount of data on observed flood levels was captured in the study area from flood marks left by the flood. At that time, Council also issued questionnaires to residents in flood affected areas to gain further knowledge on the flood heights, flood mechanisms and damages to private and commercial property. In addition to the extensive survey of levels and information for the 1998 flood event, surveyed flood levels have also been provided by Council for the 1988, 1991 and 2013 flood events. The extent of these surveyed levels is significantly less than the data available for the 1998 flood event.

This observed flood information, coupled with recorded rainfall data, gauged water levels and recorded tidal data provided the data necessary for calibration and validating of the hydrological and hydraulic model.

Community Consultation

Community consultation undertaken during the study has aimed to collect information on historical flooding and previous flood experience, and inform the community about the development of the flood study. The key element of the consultation process involved the distribution of an information newsletter and questionnaire relating to historical flooding. The community were asked to provide relevant historical flood information, including dates of previous flood events, photographs, observed flood depths and descriptions of flood behaviour within the study area.

A total of 186 responses were received by post, email and via the online questionnaire. Of the 186 responses received, 82 identified flooding as an issue at their property and/or on their street.

The Draft Review of Hewitts Creek Flood Study was placed on public exhibition from 13 October 2014 to 10 November 2014 with two community information sessions held during the exhibition period. A total of 59 written responses were received from the community providing feedback on the draft Flood Study report.

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 a Flood Study, a hydrologic model and a hydraulic model are developed.

The WBNM (Watershed Bounded Network Model) hydrologic model has been selected for this study to simulate the catchment rainfall-runoff relationships. The model has been developed from the WBNM model developed as part of the 2002 Flood Study. The WBNM model schematisation and parameters have been updated to ensure that the level of detail is sufficient for modelling the required flooding mechanisms within the 2D model representing current day conditions in the study area.

With consideration to the available survey information and local topographical and hydraulic controls, a fully two - dimensional (2D) hydraulic model has been developed for the study area extending from the foothills of the Illawarra Escarpment to the Tasman Sea. The upstream limit of the 2D model corresponds with the western extent of the residential and commercial development within the study area. This model simulates flood depths, extents and velocities utilising the TUFLOW 2D software developed by BMT WBM. This 2D modelling approach is suited to model the complex interaction between channels and floodplains and converging and diverging of flows through structures and urban environments.

The channel and floodplain topography is defined using a hydraulic model grid resolution of 2m. The model grid has been developed from a high resolution digital elevation model (DEM) derived from LiDAR survey, ground survey data and “Works as Executed” drawings. This detailed model grid provides for greater accuracy in predicting flows and water levels and the interaction of in-channel and floodplain areas compared with previous studies.

Model Calibration and Validation

The APRIL 1988, August 1998 and February 2013 events have been selected for model calibration and validation. The August 1998 flood has been used as the principal calibration event, given the availability and completeness of rainfall data, tidal data and historical flood levels and anecdotal evidence on observed flood mechanisms. The August 1998 event is the largest of the three flood events and resulted in significant out of bank flooding across the study area. The use of this larger flood event allows calibration of the hydraulic model to both in-bank and out of bank flows and provides confidence in the model results for the less frequent flood event range. The February 2013 event has been chosen to allow validation of the hydraulic model to be used for the design model simulations (i.e. incorporating changes to the study area since the 1998 calibration event).

The calibration and validation results indicate that the TUFLOW model results correlates well with the vast majority of the observed flood marks and flood mechanisms. The developed hydrological and hydraulic models are thus considered to provide a sound representation of the flooding behaviour of the catchment.

Design Event Modelling and Output

The developed hydrological and hydraulic models have been applied to derive design flood conditions within the Hewitts Creek study area. 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 (AR&R) (Pilgrim, 2001). A range of storm durations using standard Australian Rainfall and Runoff temporal patterns, were modelled. The design results represent the maximum envelope of all the durations assessed for the given design event frequency.

The design events considered in this study include the 20% AEP (5-year Annual Return Interval (ARI)), 10% AEP (10-year ARI), 5% AEP (20-year ARI), 2% AEP (50-year ARI), 1% AEP (100-year ARI) 0.5% AEP (200-year ARI), 0.2% AEP (500-year ARI) and Probable Maximum Flood (PMF) events. The model results for the design events considered have been presented in a detailed flood mapping series for the catchment. The maps present the peak value across all scenarios for each design event simulated. Maps have been produced showing water level, water depth and velocity. Provisional flood hazard categories, hydraulic categories, flood emergency response classification and preliminary residential flood planning area and levels are derived from the hydrodynamic model results and are also mapped. The mapping outputs are presented in Appendix D.

Climate Change

On 8 September 2012, the NSW Government announced its Stage One Coastal Management Reforms which no longer recommends 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. Council's adopted sea level rise projections are 0.4m for 2050 and 0.9m for 2100 which are in line with the NSW Chief Scientist and Engineer's Report (NSW Government, 2012). Given that there is currently significant uncertainty around rainfall projections as a result of climate change, increases in rainfall intensities have been assessed as part of sensitivity tests.

The model results for the sea level rise projections have been translated into 0.4m and 0.9m flood planning levels and areas, provided as flood planning maps in Appendix D. Impacts on flood levels and areas resulting from projected sea level rise is confined to the downstream reaches of the study area. These impacts are relatively low for both the 0.4m and 0.9m sea level rise. Future planning and floodplain risk management in the catchment will need to take due consideration of the increasing flood risk under possible sea level rise conditions.

Sensitivity Testing

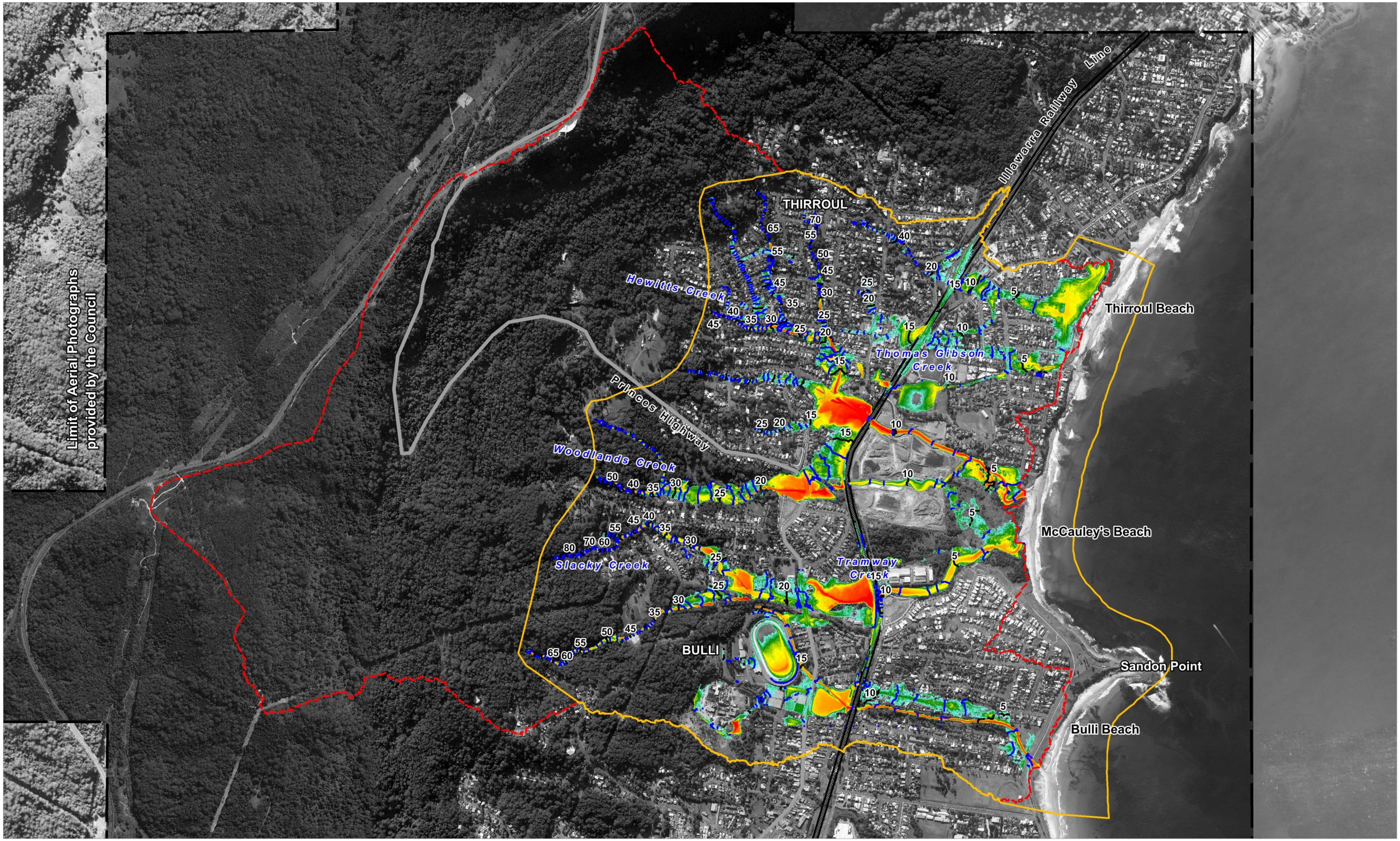
A series of sensitivity tests have been undertaken on the modelled flood behaviour of the Hewitts Creek study area. The tests provide a basis for determining the relative sensitivity of modelling results to adopted parameter values. The tests undertaken included:

- WBNM Lag Parameter;
- Rainfall intensity;
- Hydraulic roughness; and
- Channel sedimentation.

Results are shown to be generally insensitive to the values adopted for deriving the design flood levels and extents for the WBNM Lag Parameter, hydraulic roughness and channel sedimentation tests. Higher sensitivity was exhibited for changes to the rainfall intensity.

Conclusions

The primary objective of the Review of Hewitts Creek Flood Study has been to define the flood behaviour in the Hewitts Creek study area through the establishment of appropriate numerical models. The principal outcome of the flood study is the understanding of flood behaviour in the catchment and in particular the design flood level information that will be used to set appropriate flood planning levels. The flood study will form the basis for the subsequent floodplain risk management activities, being the next stage of the floodplain management process. Accordingly, the adoption of the flood study and predicted design flood levels is recommended.



LEGEND

TUFLOW Model Boundary

Catchment Boundary

Peak Flood Depth (m)
4.00
2.00
1.00
0.50
0.15

5m Water Level Contour (m AHD)
Water Level (m AHD)

1m water Level Contour (m AHD)

Title:
Review of Hewitts Creek Flood Study
Maximum Flood Depths and Water Levels: 1% AEP Event

Figure: **ES-1**

Rev: **0**

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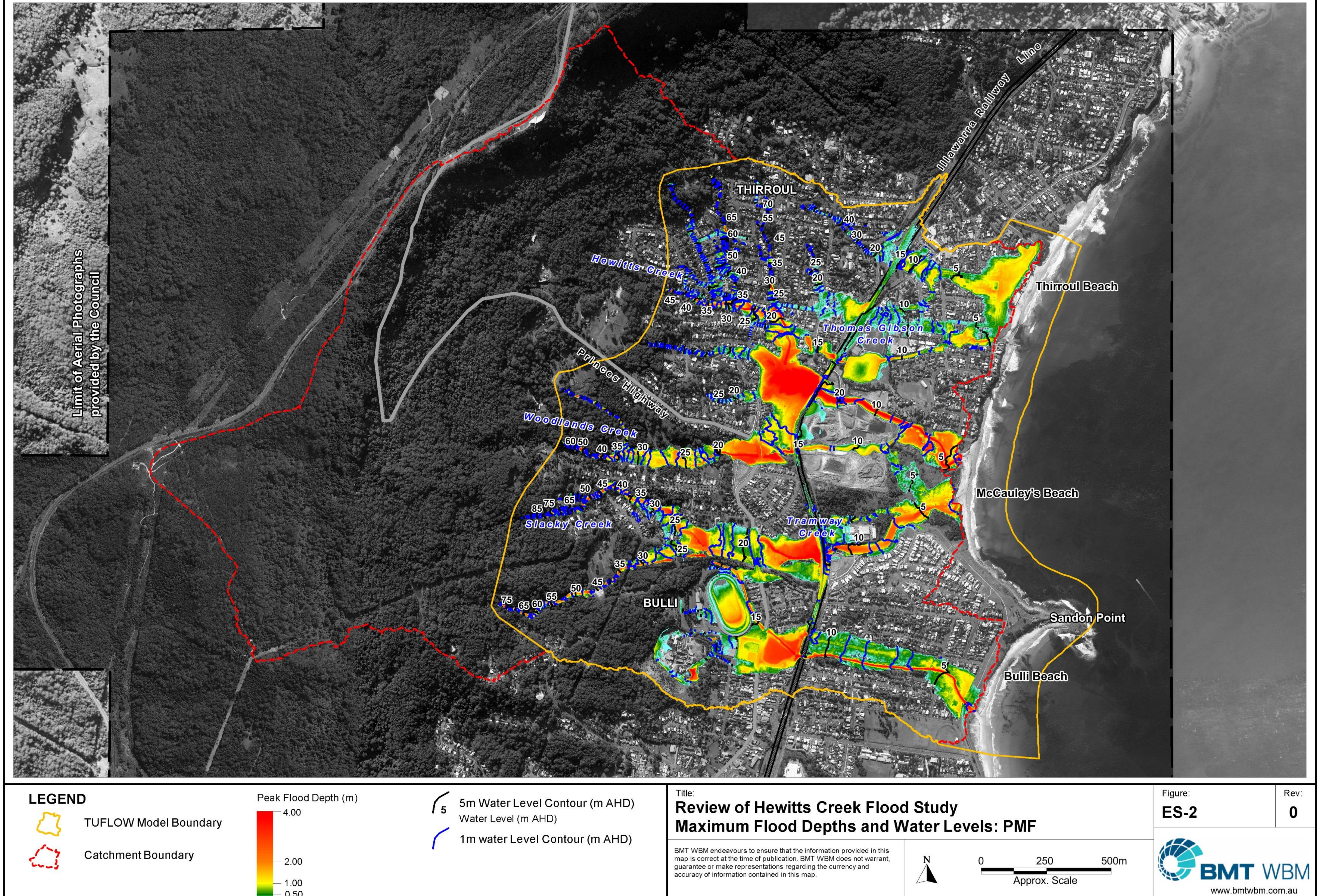

Title:

Review of Hewitts Creek Flood Study
Maximum Flood Depths and Water Levels: PMF

Figure: ES-2

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CONTENTS

LIST OF FIGURES

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LIST OF TABLES

GLOSSARY

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)
calibration	The adjustment of model configuration 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.
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 vollume 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, and inundate floodplains 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.
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 Development 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 (FPL)	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 source	The source of the floodwaters.
flood storage	Floodplain area that is important for the temporary storage of floodwaters during a flood.
floodway	A flow path (sometimes artificial) that carries significant volumes of floodwaters during a flood.
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	Relating to water flow in rivers, estuaries and coastal systems; in particular, the evaluation of flow parameters such as water level and velocity
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 distribution of ranfall 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.
isohyet	Equal rainfall contour.
morphological	Pertaining to geomorphology.
peak flood level, flow or velocity	The maximum flood level, flow or velocity that occurs during a flood event.
Pluviographmeter (pluviograph)	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.
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 Review of the Hewitts Creek Flood Study has been prepared for Wollongong City Council to define the existing flood behaviour in the Hewitts Creek catchments and consider the influence of potential climate change on future flood behaviour.

This study will update the previous Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a), providing a holistic assessment of historic, current and future flood risk and establish the basis for the subsequent Floodplain Risk Management Study and Plan.

The study is being prepared to meet the objectives of the NSW State Government's Flood Prone Land Policy. This project has been conducted under the State Assisted Floodplain Management Program and received State financial support.

The study is being undertaken in a staged approach as outlined below:

- Stage 1 - Collection, compilation and review of available information and initial community consultation;
- Stage 2 - Hydrological analysis;
- Stage 3 - Hydraulic modeling;
- Stage 4 - Climate change analysis; and
- Stage 5 - Final reporting.

1.1 Study Location

The Hewitts Creek study area includes the catchments of Slacky, Tramway, Woodlands, Hewitts and Thomas Gibson Creeks which are located on a narrow strip of land to the north of Wollongong (refer to Figure 1-1, Study Locality and Figure 2-1, The Study Area). The combined catchments cover an area of approximately 8.1 km^2 and drain to the Tasman Sea.

Title:

Study Locality

Figure: 1-1

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Approx. Scale

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1.2 Study Background

As with many of the catchments flowing east from the Illawarra Escarpment, the Hewitts Creek study area has a history of flooding. An analysis of flooding occurring within the Wollongong region from 1945 to 2002, based on rainfall records and newspaper articles, has been compiled by Davidson (1981) and Forbes Rigby (2002). The analysis indicates a total of 34 events in the region ranging in nature from minor (i.e. flooding resulting in road closure) to extreme (i.e. significant damage to properties with life threatening conditions). The last extreme flood event occurred in 1998 which resulted in extensive flooding and significant damage to a number of properties. The August 1998 event generally equates to a 100 year Average Recurrence Interval (ARI). Since 2002, there have been a number of smaller flood events in the region including March 2011, February 2012 and February 2013. These events generally equate to a 1 year ARI.

The Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a) and Hewitts Creek Floodplain Risk Management Study and Plan (Forbes Rigby Pty Ltd., 2002b) have previously been completed to define and manage the flood behaviour of the Hewitts Creek catchments. This review will update the previous Flood Study to account for changes in the study area over the subsequent years and take advantage of innovations and improvements in computer flood modelling and available datasets. This study will define the nature and extent of flooding which will establish the basis for the subsequent Floodplain Risk Management Study and Plan.

1.3 The Floodplain Management Process

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

The implementation of the Flood Prone Land Policy culminates in the preparation and implementation of a Floodplain Management Plan in accordance with the Floodplain Management Process (see Figure 1-2) outlined in the Floodplain Development Manual. Periodic reviews of Floodplain Management Plans form part of the Floodplain Management Process.

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

The Policy provides for technical and financial support by the NSW State Government through the five sequential steps as shown in Figure 1-2.

As part of this study, steps 1 and 2 of this process have been undertaken to provide an understanding of existing and future flood behaviour within the Hewitts Creek study area.

Floodplain risk management considers the consequences of flooding on the community and aims to develop appropriate floodplain management measures to minimise and mitigate the impact of flooding. This incorporates the existing flood risk associated with current development, and future flood risk associated with future development and changes in land use.

Figure 1-2 Steps of the Floodplain Management Process

1.3.1 The Hewitts Creek Floodplain Risk Management Committee

The floodplain management process for this study is overseen by the Hewitts Creek Floodplain Risk Management Committee which was established by Council. The committee has broad representation including councillors, council staff, state Government agencies, stakeholder groups and community representatives.

1.4 The Need for a Review of the Hewitts Creek Flood Study

There are a number of drivers which necessitate a review of the Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a) including:

- The effect of increasing rainfall and ocean levels as a result of Climate Change;
- The availability of additional detailed ground survey data;

- Advances in modelling technology (use of two –dimensional (2D) modelling);
- The implementation of some flood mitigation measures recommended in the Hewitts Creek Floodplain Risk Management Study and Plan (Forbes Rigby Pty Ltd., 2002b) since the completion of the 2002 studies;
- Residential and commercial developments which have been built in the catchment since the completion of the 2002 studies; and
- The availability of additional information from flood events after the completion of the 2002 studies.

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 (DECC, 2009) that adopted sea level rise planning benchmarks to ensure consistent consideration of sea level rise in coastal areas of NSW. These planning benchmarks provided 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 recommends 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' (NSW Government, 2012).

The NSW Chief Scientist and Engineer's Report (NSW Government, 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.

Council's adopted sea level rise projections are 0.4m for 2050 and 0.9m for 2100 and are in line with the NSW Chief Scientist and Engineer's Report (NSW Government, 2012). These sea level rise benchmarks have been adopted for various flood studies and the Coastal Zone Study adopted by

Council. For the Hewitts Creek study area, rising sea levels are expected to increase the frequency, severity and duration of flooding along low lying areas of the coastal region in the study area. Future planning will need to take due consideration of this increased flood risk. Further information on the impact of sea level rise for planning consideration is provided in Section 9 - Climate Change Analysis.

In 2007 the NSW State 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%. When combined with the influence of the Illawarra Escarpment, increased rainfall intensities will translate into increased fluvial flood inundation in the Hewitts Creek study area.

In consultation with Council 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 intensities have been undertaken. The results of these sensitivity tests are discussed in Section 10 – Sensitivity Tests.

1.4.2 LiDAR Data

LiDAR survey provides complete coverage of the study area and has been provided by Council. The LiDAR data was captured in May 2005 by AAM Hatch and has been supplied with a stated vertical accuracy +/- 0.15m @ 68% confidence and horizontal accuracy +/- 0.55m @ 68% confidence.

The filtered ground data has been converted into a 1m resolution digital elevation model (DEM) using terrain modelling software (MapInfo Vertical Mapper). The filtered data removes features such as vegetation and buildings to provide a representation of the natural surface.

1.4.3 Modelling Techniques

The overland flow regime in urban environments is characterised by inundation of urban areas with interconnecting and varying flow paths. Out-of-bank flows from creeks can occur as a result of blockage of waterways including culverts and bridges. The direction of out of bank flows is heavily influenced by the floodplain characteristics. Road networks often convey a considerable proportion of floodwaters due to the hydraulic efficiency of the road surface compared to developed areas which are often blocked by fences, buildings and other structures).

The hydraulic model needs to be capable of defining the location of these out-of-bank flows and the direction floodwaters will take once it leaves the creek system. This complex flooding environment is not well represented by a 1D modelling approach as the watercourses do not have a constrained flow path (i.e. narrow watercourse corridor) and the out-of-bank flows typically do not flow parallel to the watercourse corridor. Given the urban nature of the study area and the known overland flow issues between sub-catchments, a 2D modelling approach is being applied for the Hewitts Creek study area.

The LiDAR data has been used to inform the development of the ground surface in the TUFLOW hydraulic model as discussed in Section 6.5.2.

1.4.4 Flood Mitigation Measures and Recent Development Works

Since the completion of the 2002 studies, there have been a number of flood mitigations measures from the Floodplain Risk Management Study and Plan which have been implemented in the study area. A number of housing developments have also taken place in the catchment. Table 1-1 lists the changes which have occurred since the completion of the 2002 studies.

Table 1-1 Development and Flood Mitigation Measures Implemented in the Study Area

Location	Details of changes to study area
Black Diamond Place, Bulli	Modifications to detention basin adjacent to Slacky Creek
Old Bulli Mine Dam, Bulli	Embankment upgrade works and creek rehabilitation on a tributary of Slacky Creek
Princes Highway and Lawrence Hargrave Drive, Thirroul	Construction of a bridge and associated road works on/adjacent to Woodlands Creek
Princes Highway, Bulli	Voluntary purchase of two properties adjacent to Tramway Creek
Sandon Point, Bulli	New residential development adjacent to Tramway Creek
51 George Street, Thirroul	New footbridge over Hewitts Creek
Lachlan Street, Thirroul	Improvements to existing culvert on Hewitts Creek
McCauley Beach, Bulli/ Thirroul	New residential development adjacent to Hewitts and Woodland Creeks
McCauley Street, Thirroul	New residential development adjacent to Thomas Gibson Creek
Wrexham Road and Lawrence Hargrave Drive, Thirroul	New residential development adjacent to Thomas Gibson Creek
The Esplanade, Thirroul	New overland flow path adjacent to Flanagan’s Creek
Blackhall Street, Bulli	New footbridge at Blackhall Street on Slacky Creek

1.5 Study Objectives

The primary objective of the current Flood Study is to define the flood behaviour under historical, existing and future conditions in the Hewitts Creek study area through the establishment of appropriate numerical models. The study provides information on flood levels and depths, velocities, flows, hydraulic categories and provisional hazard categories. Specifically, the study incorporates:

- 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 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), 0.2%, 0.5%, 1%, 2%, 5%, 10% and 20% AEP events;
- Application of culvert and bridge blockages based on Wollongong City Councils Conduit Blockage Policy (Wollongong City Council, 2009);

- Development of a series of flood inundation maps showing the predicted flood inundation extents for the range of design events considered. These flood inundation maps illustrate the change in the footprint of flood affected areas with increasing flood event magnitude and climate change scenarios;

- Flood emergency response classification of communities for the full range of flood events;

- Determination of preliminary residential flood planning level and flood planning area (based upon the 1% AEP plus a 0.5m freeboard) for current conditions and incorporating Councils adopted sea level rise projections; and

- Examination of potential impacts of climate change using the latest guidelines

The models and results produced in this Flood Study are intended to:

- Outline the flood behaviour within the study area to aid in strategic land use management planning; and

- Form the basis for a subsequent floodplain risk management study where detailed assessment of floodplain risk management measures will be undertaken. The recommended measures will form part of the Floodplain Risk Management Plan.

A review of the models and model results from the Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a) has been undertaken to inform the development of models as part of the current Flood Study (refer to Section 6) and provide a basis for comparison between the current Flood Study results and the 2002 Flood Study results (refer to Section 7 and 8).

1.6 About This Report

This report documents steps 1 and 2 of the Floodplain Management Process comprising the following sections:

Section 1 introduces the study.

Section 2 provides an overview of the study area.

Section 3 discusses the available data.

Section 4 outlines the community consultation program undertaken.

Section 5 details the additional survey information required.

Section 6 details the development of the hydrological and hydraulic models.

Section 7 summarises the hydrological and hydraulic model calibration and validation.

Section 8 details the design flood results and associated flood mapping.

Section 9 details the sea level rise analysis.

Section 10 details the sensitivity testing conducted.

2 STUDY AREA

2.1 Catchment Description

The Hewitts Creek study area includes the catchments of Slacky, Tramway, Woodlands, Hewitts and Thomas Gibson Creeks as shown in Figure 2-1. The combined catchments drain an area of approximately 8.1 km^2. The western portions of the catchments are dominated by the Illawarra Escarpment. Heavy rain on the steep slopes of the escarpment leads to rapid flooding in the creeks, which all drain to the Tasman Sea.

Slacky Creek has a catchment area of approximately 2.9km^2 and is located at the southern extent of the study area. The main channel reach of the creek extends from National Avenue at the base of the escarpment to Bulli Beach. Upstream of the coal haulage embankment (just upstream of Bulli Raceway), a tributary extends south westwards to the base of the escarpment. The removal of a storage reservoir embankment and creek rehabilitation works were recently completed on this tributary as part of the Old Bulli Mine Dam embankment upgrade works.

The catchment of Tramway Creek is bounded by Woodlands Creek to the north and Slacky Creek to the south and has an area of approximately 0.3km^2. The main channel of Tramway Creek extends from Princes Highway to the ocean outfall at McCauley’s Beach.

The main channel reach of Woodlands Creek extends eastwards from Yenda Avenue at the base of the escarpment to the coastal region and has an area of approximately 1.6km^2. The Woodlands Creek channel forms a tributary of Hewitts Creek approximately 0.3km upstream of McCauley’s Beach.

The Hewitts Creek catchment has an area of approximately 2.2 km^2. The main creek runs from the base of the escarpment at George Street to the outlet at McCauley’s Beach. Two tributaries of Hewitts Creek extend northwards from George Street to Fords Road and Nardoo Crescent respectively. Recent works as part of the McCauley’s Beach residential development has resulted in significant engineering works (widening and re-profiling of the channel and floodplain) along both Hewitts Creek and Woodlands Creek downstream of the Illawarra Railway.

Thomas Gibson Creek has a catchment area of approximately 0.9 km^2 and is located at the north-western extent of the study area. The main open channel reach of Thomas Gibson Creek is located in the southern part of this catchment and extends from Lawrence Hargrave Drive (just west of the Illawarra Railway) to Thirroul Beach. The remainder of the creeks within the Thomas Gibson Creek catchment are mainly culverted with some short open channel reaches. These creeks discharge through a single outfall at Thirroul Beach approximately 40m north of the main open channel reach.

Coastal sediment processes result in the natural build-up of sand and sediment at the outlet of the creeks at Bulli Beach, McCauley’s Beach and Thirroul Beach, and may result in closure of the ocean entrance. Currently, there is no entrance management policy in place to manage the sediment build-up on the entrance of the creeks in the study area.

Figure 2-2 shows the topography of the study area. The upper areas of the catchments are dominated by the Illawarra Escarpment which falls steeply from 400-500m AHD to approximately 250 m AHD. These steep upper reaches of the catchments are heavily vegetated. The middle portions of the catchments extends from the base of the Illawarra Escarpment to the Illawarra Railway, at approximately 15m AHD, and are more gently graded with residential developments being the dominant land use. From east of the railway line to the coast, the land is generally quite flat with a mixture of residential and retail developments.

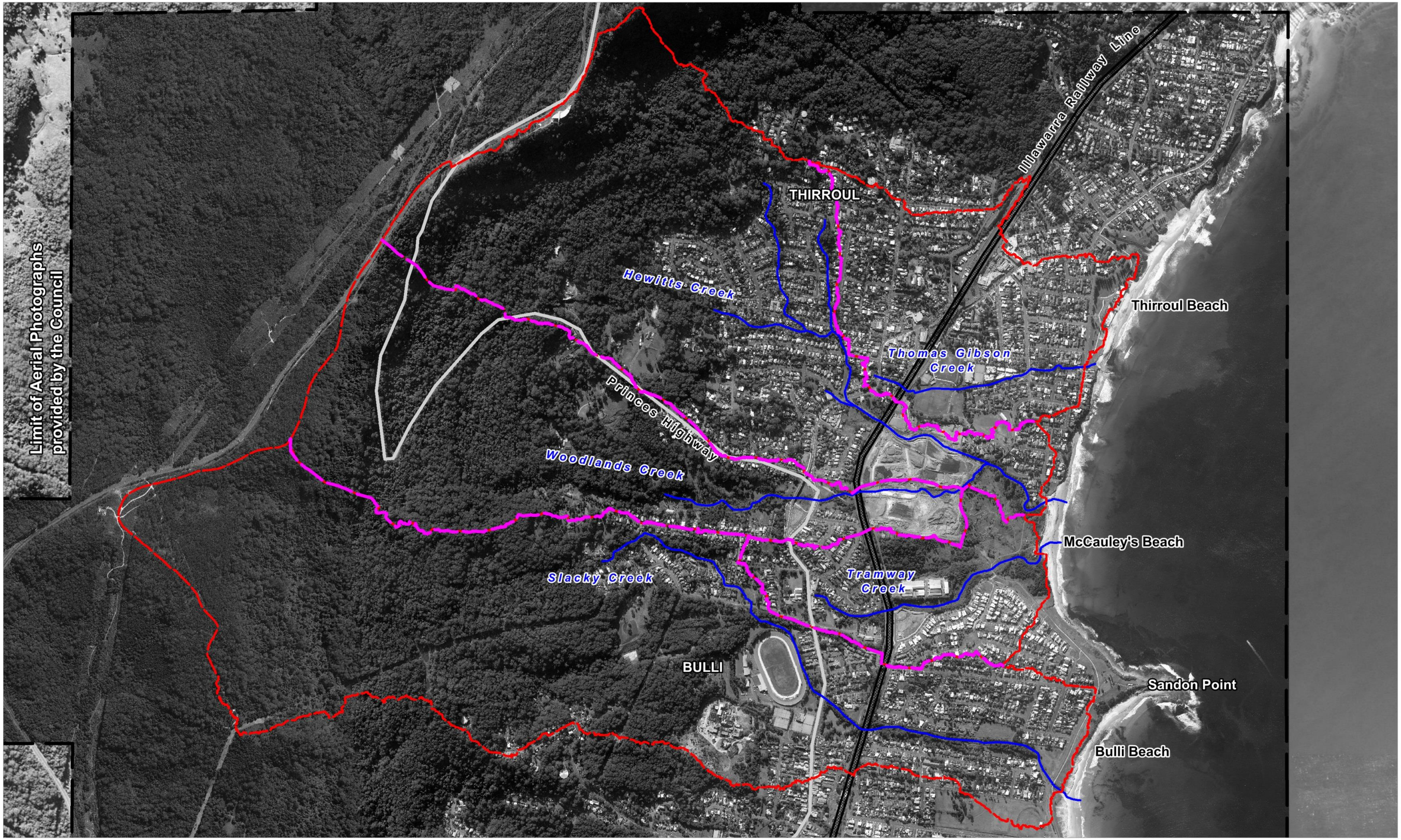
The influence of the Illawarra Escarpment on orographic rainfall increases the propensity for flooding in the study area with rapid catchment response to intense rainfall. The study area is traversed by the major transport corridors of the Princes Highway and Illawarra Railway (Figure 2-2) which are often elevated on embankments above the natural floodplain levels, with flood flows restricted to bridges and culverts at various cross drainage locations. Flooding within the study area is exacerbated by blockages to these structures and by the deposition of sediment and presence of vegetation within the watercourses.

2.2 Known Flooding Problems

Information available from historic flood events and results from the Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a) indicate that the presence of structures has the most significant influence on the flooding behaviour in the study area. Some of the known flooding issues associated with these structures (and their potential blockage) are described below:

- The coal haulage embankment of the now disused railway line within the Slacky Creek catchment is known to divert flows eastwards along Hobart Street to the Tramway Creek catchment during flood events due to the capacity of the culverts being exceeded. Blockage of the culverts at this embankment will increase upstream flood risk and diversion of flow to Tramway Creek.
- The culvert beneath Lachlan Street, Thirroul (Hewitts Creek) does not convey all flood waters during high flows and results in a diversion of flow eastwards along Lachlan Street and into Thomas Gibson Creek. This flow diversion increases in the event of a blockage to the Lachlan Street culvert.
- The culverts beneath Cliff Parade, Thirroul (Thomas Gibson Creek) do not convey all flood waters during high flows and results in a flow diversion in larger flood events. The diversion flows northwards along Cliff Parade and joins overland flow from Bath Street, with diverted flows continuing northwards to Flanagans Creek at the Esplanade. Flooding along Cliff Parade and surrounding streets is affected when the capacity of the drainage system is exceeded resulting in the accumulation and diversion of flood waters in the area.
- In the event that flood waters exceed the capacity of the culvert beneath the Illawarra Railway on Tramway Creek, upstream properties, particularly at Allenby Parade, Bulli, are subject to flooding. This flood risk is increased in the event of the culvert becoming blocked.

All of the watercourses drain to the Tasman Sea, therefore, the downstream portion of the catchments is influenced by oceanic conditions. Flooding of properties along Corbett Avenue, Thirroul, for example, is known to be influenced by the oceanic conditions in Hewitts Creek.



LEGEND

Watercourses

Sub Catchment Boundary

Catchment Boundary

Title:
Study Area

Figure: **2-1**

Rev: **1**

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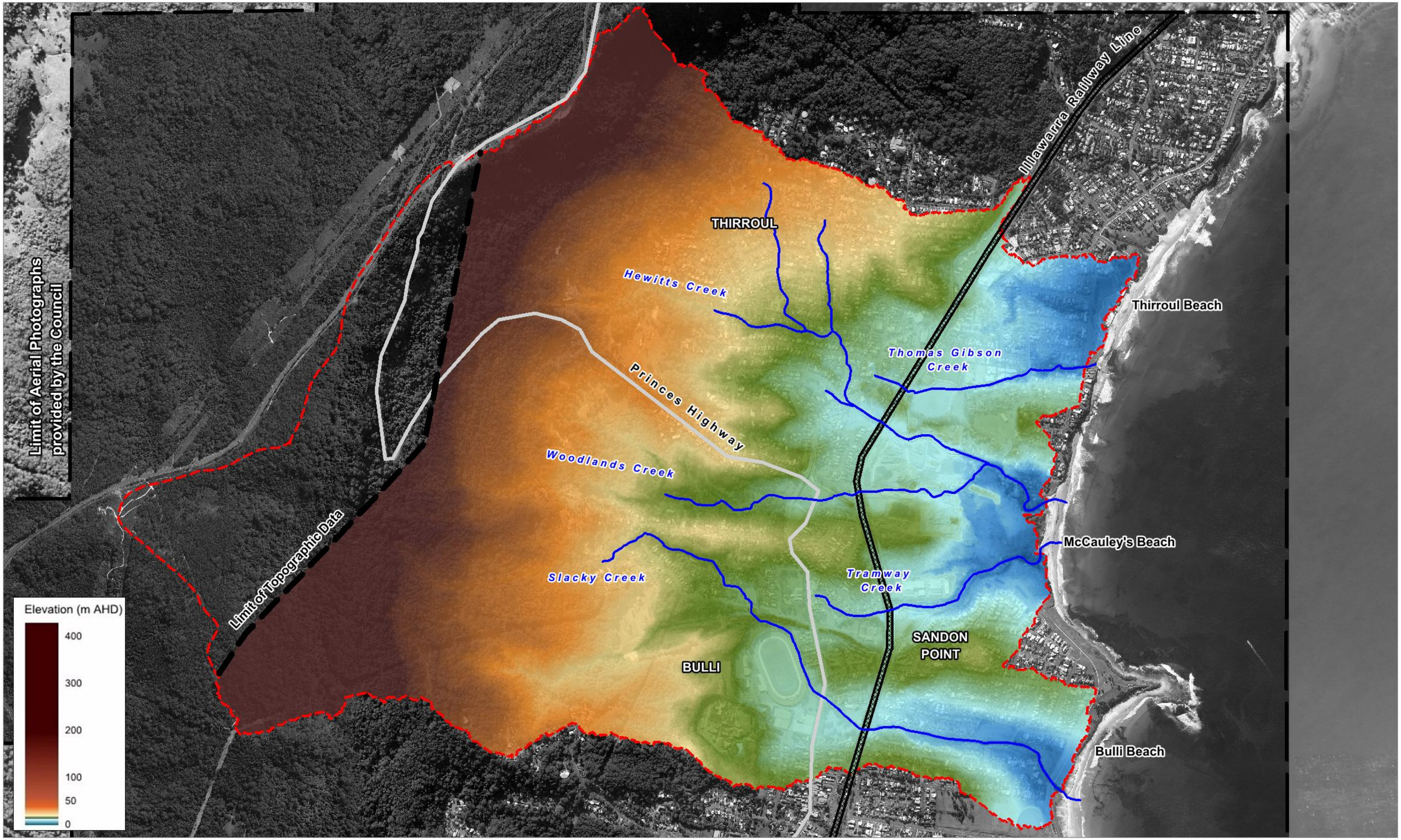

LEGEND

Watercourses

Catchment Boundary

Title:

Topography of the Hewitts Creek Study Area

Figure:

2-2

Rev:

1

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3 COMPILATION AND REVIEW OF AVAILABLE DATA

3.1 Previous Investigations

A Flood Study of the Hewitts Creek catchments has previously been completed in 2002. This Flood Study was subsequently followed by a Floodplain Risk Management Study and Plan which was also prepared in 2002. Relevant information from these previous reports (and other relevant documents) is presented in the following sections.

Numerous smaller flood studies have also been undertaken as part of flood mitigation works and residential developments as listed in Table 1-1. Information from these studies has been used to inform the development of the hydraulic model.

3.1.1 1998 Storm Data Report (Wollongong City Council, 2002)

This report documents the extensive data related to the storm event in Wollongong, which occurred on 17 August 1998. The report provides details on available data from the 1998 flood event and the extent of damage caused by the flood.

The information in this report has been used to inform the calibration of the TUFLOW hydraulic model for the August 1998 flood event for this current study.

3.1.2 Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a)

This study investigates and quantifies the existing flood behaviour in the Hewitts, Slacky, Tramway, Woodlands and Thomas Gibson Creeks in accordance with the NSW State Government Flood-Prone Land Policy. The study involved data collection, topographical surveys, preparation of hydrological and hydraulic models, calibration and validation of the models (1988, 1991 and 1998 flood events) and determination of flood levels and velocities in nominated reaches of each creek for the 5% AEP, 2% AEP, 1% AEP and Probable Maximum Flood (PMF) events.

The information provided in this report has been used to inform the review of existing data, and the development of hydrological and hydraulic models for this current study.

3.1.3 Hewitts Creek Floodplain Risk Management Study and Plan (Forbes Rigby Pty Ltd., 2002b)

This report provides details of the various flood risk management strategies to address flooding problems identified in the Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a) which identified flood risk areas. A total of 15 schemes were considered, comprising generally 2 or 3 alternate schemes for each of the five main creeks to reduce flood damages via structural measures. A range of non- structural measures were also considered for adoption on a catchment wide basis. Based on a cost benefit analysis, the preferred scheme for each catchment was identified and recommended in the plan.

Information in the 2002 report has been used in this current study to develop a TUFLOW hydraulic model of the study area which incorporates the flood mitigation measures that have been implemented from the Floodplain Risk Management Plan (Forbes Rigby Pty Ltd., 2002b).

3.1.4 Riparian Corridor Management Study (Department of Infrastructure, Planning and Natural Resources, 2004)

This study has been prepared in response to the 1999 Commission of Inquiry into the "Long Term Planning and Management of the Illawarra Escarpment". Three categories of riparian environmental objectives were developed for the streams in the study area that reflect their relative environmental significance - Environmental Corridor, Terrestrial and Aquatic Habitat, and Bank Stability & Water Quality. All of the streams in the study area were allocated a category and presented on maps. The mapping reflects the natural resources of the streams and the influence of a combination of known flooding and the geomorphology of the streams.

Information in this report has helped inform appropriate channel and riparian zone roughness values for the TUFLOW hydraulic model developed as part of this current study.

3.1.5 Estuary Management Plan for Several Wollongong Creeks and Lagoons Estuary Processes Study, December (GHD, 2007)

This study incorporated investigations into the aquatic and riparian flora, an assessment of fauna habitat values, a fishery and macro-invertebrate study, and an assessment of estuary geomorphology and bank erosion, together with a review of relevant literature and water quality data. The study area comprised the tidal waterways, foreshores, surrounding open space and adjacent lands of a number of creeks in the Wollongong region and includes Slacky Creek which forms part of the study area.

Information from this report has informed the development of the TUFLOW hydraulic model as part of the current study, particularly at the outlet of Slacky Creek which is often affected by the natural build-up of sand at its ocean entrance.

3.1.6 Wollongong Development Control Plan (Wollongong City Council, 2009)

Chapter E13 (Floodplain Management) and Chapter E14 (Stormwater Management) of the Development Control Plan provide respective details on Council's requirements for development upon flood liable land and requirements for stormwater drainage design and onsite stormwater detention for all developments within the Wollongong Local Government Area (LGA).

Information in this document has been used to inform the preliminary residential flood planning level and flood planning area as part of the current study.

3.2 Historical Flood Levels

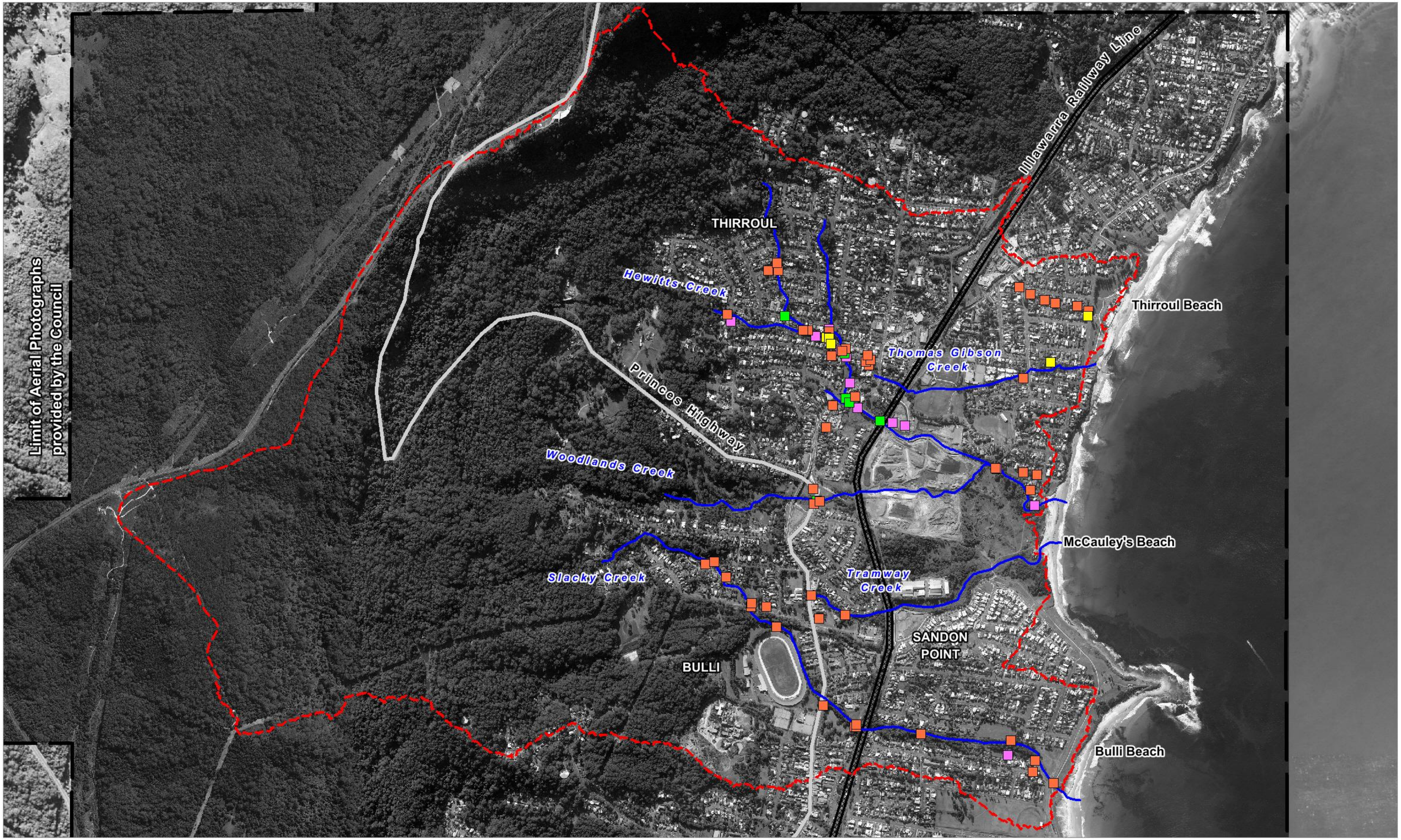
The Hewitts Creek study area has a history of flooding with the most recent significant flood event having occurred on 17 August 1998. Other flood events which occurred in the study area and which flood data is available for include events in July 1991 and April 1988.

Following the 1998 flood event, a significant amount of data on observed flood levels was captured in the study area from flood marks left by the flood. At the time, Council and State Government agencies undertook land surveys shortly after the 17 August 1998 storm event to capture the level of the flood marks. Council also issued questionnaires to residents in flood affected areas to gain further knowledge on the flood heights and damages to private and commercial property. This information was used to undertake further surveys of historical flood levels. The information related to the survey of historical flood levels has been entered into a Geographical Information System (GIS) database and their locations are shown in Figure 3-1.

In addition to the extensive survey of flood levels for the 1998 flood event, surveyed flood levels are also available for the 1991 and 1988 events. The extent of these levels is significantly less than the data available for the 1998 flood event with their locations shown in Figure 3-1.

Additional historical flood level data has been collected as part of the community consultation process for the current study. A questionnaire was sent to residents located within the PMF extent as defined in the Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a). From a review of the questionnaire responses received, a flood event in February 2013 was identified as the most recent flood event for which information is available on observed flood levels. Further discussion on the flood level information gathered as part of the community consultation is in Section 4, with the locations of observed flood levels for the February 2013 flood event shown in Figure 3-1.

Flood level data is also available from three continuous water level recorders within the study area operated under the NSW Office of Environment and Heritage (OEH) coastal and flood data collection programme. The water level recorders are operated by NSW Public Works Manly Hydraulic Laboratory (MHL), on behalf of OEH. Further details on these water level recorders are provided in Section 3.3.



LEGEND

Watercourses

Catchment Boundary

Historical Flood Levels

- April 1988
- June 1991
- August 1998
- February 2013

Title:

Location of Surveyed Historical Flood Levels in the Study Area

Figure: 3-1

Rev: 1

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3.3 Continuous Water Level Data

Three continuous water level recorders are located within the study area. Further details for each recorder are presented in Table 3-1 and the location of the recorders is shown in Figure 3-2.

Table 3-1 Location of Continuous Water Level Recorders within the study area

Waterway	Location	Period of Data
Hewitts Creek	Entrance of the creek adjacent to the existing footbridge	May 2005 - Current
Hewitts Creek	Upstream of culvert at Lawrence Hargrave Drive, Thirroul	October 2001 – Current
Hewitts Creek	Downstream of culvert at Lawrence Hargrave Drive, Thirroul	October 2001 – Current

3.4 Rainfall Data

The Bureau of Meteorology (BoM) operates the majority of rainfall stations within the Wollongong region. There are four active and twelve inactive/closed daily rainfall stations operated by the BoM located within or in close proximity to the study area. The daily rainfall stations, including closed stations are shown in Table 3-2 with their respective period of record. The distribution of the rainfall stations is shown in Figure 3-3.

Table 3-2 Summary of BoM Daily Rainfall Stations within the Wollongong region

Station No.	Name	Start Year	End Year
68046	Mount Pleasant	1907	1964
68049	O'Briens Gap	1925	1954
68056	Sherbrooke	1892	1970
68057	Sublime Point (Tooma)	1940	1967
68103	Mount Keira Summit	1962	1966
68107	Coledale Railway Station	1943	1984
68108	Woonona (Popes Rd)	1886	Current
68119	Towradgi	1962	1975
68146	Kembla Heights	1956	1973
68148	Cataract Reservoir (Letterbox)	1907	1948
68149	Mount Kembla	1895	1918
68153	Wollongong (Rosemount)	1913	1934
68169	Mount Keira (Yates Ave)	1966	2007
68219	Wollongong (Appin)	1982	Current
68223	Wombarra (Reef Ave)	1971	Current
68228	Bellambi AWS	1988	Current

In addition to the daily rainfall stations, pluviograph (continuous) data is available from eighteen stations within the Wollongong region. Table 3-3 provides details of these pluviograph stations including source and period of record of the available data and any closed stations. Figure 3-3 shows the distribution of the pluviograph stations in the Wollongong region.

Table 3-3 Summary of Pluviograph Stations in the locality of the study area

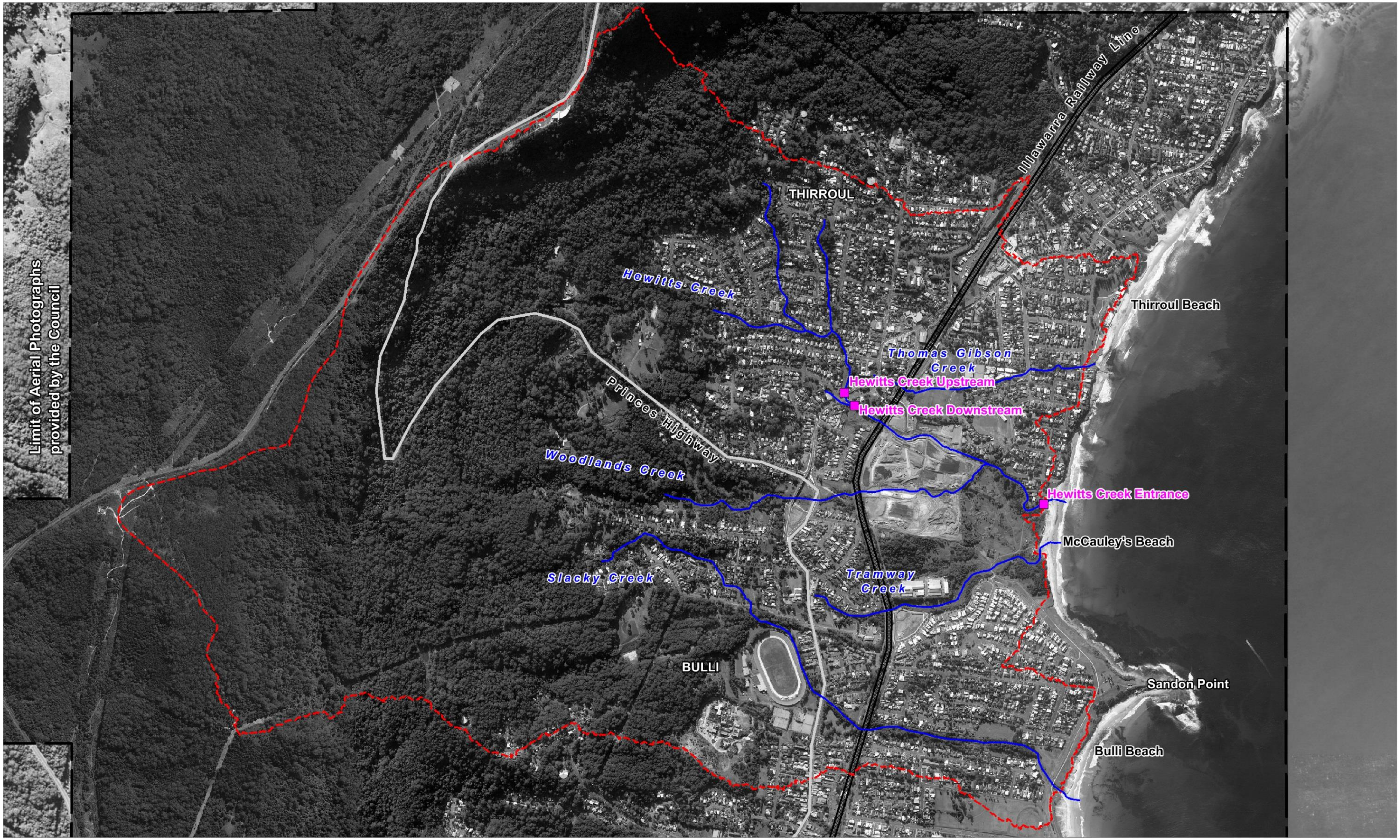
Name	Source	Start Year	End Year
Rixons Pass	OEH	1985	Current
Russel Vale	OEH	1985	Current
Mt Pleasant	OEH	1997	Current
Mount Kembla	OEH	1985	Current
Bulli Pass	OEH	1983	1988
Thirroul Bowling Club	Sydney Water	1990	Current
Balgownie Reservoir	Sydney Water	Not available	Not Available
Bellambi Point	Sydney Water	Not available	Not available
Corrimal	Sydney Water	Not available	Not available
Mount Ousley	RMS	Not available	Not available
Wollongong University	BOM	1970	2008
Mount Keira Scout Camp	BOM	1944	1992
Orange Gve (Cataract C)	BOM	1964	1998
Balgownie (Brokers Road)	BOM	1998	Current
Figtree (O'Briens Road)	BOM	1998	Current
Mount Keira	SCA	1964	Current
Upper Cordeaux	SCA	1973	Current
Cataract Dam	SCA	1904	Current

Further discussion on recorded rainfall data for historical events is presented in Section 7 – Model Calibration and Validation.

3.5 Ocean Tide Data

Ocean tide (water level) data has been used to represent the downstream water level boundary, i.e. the Tasman Sea boundary. The National Tide Centre of the Bureau of Meteorology has been collecting ocean tide data at Port Kembla in Wollongong since 1990. Data from this gauge has been used to derive the downstream water level boundary for the calibration and validation events, and inform the design event boundary conditions.

Wave climate data for the Wollongong region is available from records collected by the Waverider buoy deployed off Port Kembla in 1974 which is operated by MHL on behalf of OEH.



LEGEND

Continuous Water Level Recorder

Watercourses

Catchment Boundary

Title:

Continuous Water Level Recorders in the Study Area

Figure: 3-2

Rev: 1

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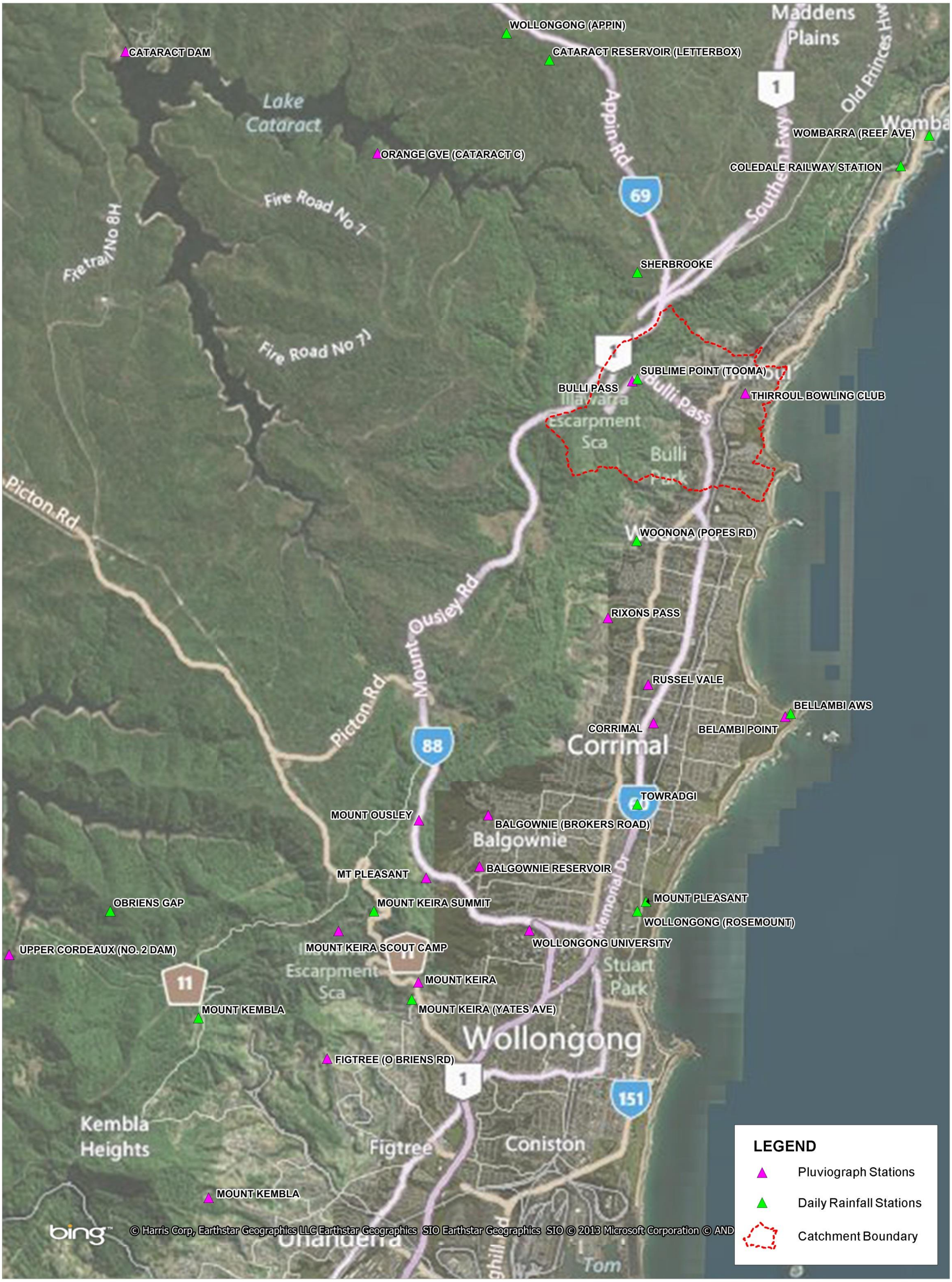

Title:

Rainfall Stations in the Vicinity of the Study Area

Figure: 3-3

Rev: 2

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3.6 Topographic Data

3.6.1 Aerial Survey

Aerial topographic survey in the form of LiDAR data covering the majority of the study area has been provided by the Council as discussed in Section 1.4.2.

3.6.2 Detailed Survey Data

As part of the 2002 Flood Study, detailed ground and hydraulic structure survey data was captured for Hewitts, Woodlands, Slacky, Thomas Gibson and Tramway Creek systems by the NSW Public Works. Additional survey was captured in 2013 as part of the current study as discussed in Section 5.

3.6.3 Design and "Works-as-Executed" Data

A number of design and works-as-executed drawings containing topographic data of various works were provided by the Council and are summarised as follows:

- Works-as-executed drawings for the new residential development at McCauley Beach, Thirroul, which includes contour data of the revised channel layout and floodplain re-profiling works;
- Works-as-executed drawings of modifications to the detention basin at Black Diamond Place, Bulli, which includes contour data of the new and re-profiled detention basin embankment;
- Design drawings of the new bridge and associated road works at Princes Highway, Thirroul and Lawrence Hargrave Drive, Thirroul, which provide details of the elevation and layout of the new roads and containment barrier;
- Design drawings with elevations and layout of the new footbridge at 51 George Street, Thirroul;
- Design drawings with elevations and layout of improvements to the culvert at Lachlan Street;
- Design drawings with contour data of the new overland flow path at The Esplanade, Thirroul; and
- Design drawings of the embankment and creek rehabilitation works as part of the Old Bulli Mine Dam site, Bulli.

Additional survey data of residential development works at McCauley Street, Thirroul and Sandon Point, Bulli, was captured as part of the additional survey as discussed in Section 5.

The new residential development adjacent to Thomas Gibson Creek at Wrexham Road, Thirroul and Lawrence Hargrave Drive, Thirroul, has been captured in the LiDAR data set.

3.7 Council Data

Digitally available information such as aerial photography, cadastral boundaries, aerial topography, watercourses and road network were provided by Council in the form of GIS datasets.

3.8 Site Inspections

A number of site inspections have been undertaken to gain an appreciation of local features influencing flooding behaviour and to discuss the local issues on-site with Wollongong City Council. Some of the key observations accounted for during the site inspections include:

- Details of the flood mitigation works implemented from the Hewitts Creek Floodplain Risk Management Study and Plan (Forbes Rigby Pty Ltd., 2002);
- The residential development and associated channel improvement works along Woodlands and Hewitts Creeks at McCauley's Beach, Thirroul;
- Location of existing flooding "hotspots" and the hydraulic controls which have an influence on this flooding, e.g. the coal haulage embankment of the now disused railway line within the Slacky Creek catchment;
- General nature of the creeks and associated floodplain noting channel form, channel bed material and vegetation types/density; and
- General location of development and infrastructure on the floodplain.

This visual assessment has been important for defining inputs to the hydraulic model and when analysing model results.

4 COMMUNITY CONSULTATION

4.1 The Community Consultation Process

Community consultation is an important component of the Flood Study, with the aim of informing the wider community about the development of the Flood Study and its outcomes. Community consultation also provides an opportunity for the community to provide details of their flood experience, their concerns regarding flooding issues and to provide feedback and ideas on potential floodplain management activities (as part of future floodplain risk management study and plan).The success of the flood planning in the Hewitts Creek study area relies on the community's input to the Flood Study.

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

- Notice in the The Advertiser on the 6th of March 2013 to inform the wider community of the study;
- Development and maintenance of a project website providing general information on the study background and objectives, NSW Government's Flood Prone Land Policy, study progress and community consultation.
- Distribution of a notification letter, questionnaire and newsletter in February 2013 to all landowners, residents and businesses located within the PMF extent (approximately 1100 properties) as defined in the Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a); and
- Public exhibition and community information session for the draft Flood Study.

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

4.2 Website

A website has been established to keep the community informed on the study progress. The website has further information on flooding in the Hewitts Creek study area and has been updated throughout the study as new information becomes available. The website also offers community members the opportunity to:

- Complete a community questionnaire online by the 29th of March 2013;
- Send photographs and videos of flooding; and
- Join a mailing list for study updates and future community information sessions.

The website address is: http://hewittscreek.bmtwbm.com.au/

4.3 Community Newsletter and Questionnaire

A combined community newsletter and questionnaire was distributed to all landowners, residents and businesses located within the PMF extent as defined in the Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a). The purpose of the newsletter and questionnaire was to provide an overview of the study and collect information on the community's previous historical flood experience and flooding issues. The questionnaire asked the community about past flooding at their property and on their street. The community were asked to provide relevant historical flood information, including dates of previous flood events, photographs, observed flood depths and descriptions of flood behaviour within the study area. The full list of questions is detailed in the Community Newsletter and Questionnaire in Appendix A.

Both the newsletter and questionnaire were also made available through the project website with the deadline for responses to the questionnaire required by the 29th of March, 2013.

A total of 186 responses were received by post, email and via the online questionnaire. Of the 186 responses received, 82 identified flooding as an issue at their property and/or on their street. More specifically, 15 respondents had experienced flooding only at their property, 25 respondents experienced flooding only on their street and 42 respondents experienced flooding of both their property and street. Figure 4-1 shows a breakdown of the responses to the question regarding each resident's experience of flooding at their property, with the total number of responses to the question shown in brackets.

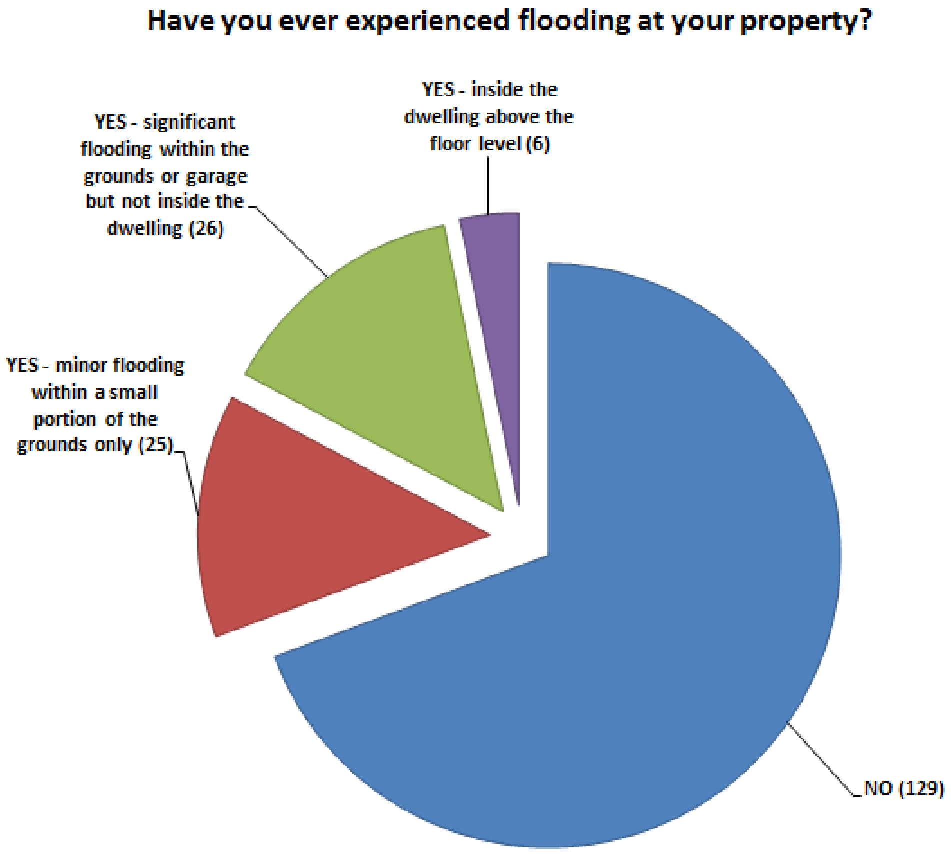


Figure 4-1 Breakdown of the responses to residents experience of flooding at their property

The chart indicates that majority of the responses have not experienced flooding at their property with a total of 57 respondents (i.e. approximately 31% of responses) identifying flooding as an issue at their property.

Figure 4-2 shows a breakdown of the responses to the question regarding each resident's experience of flooding on their street, with the total number of responses to the question shown in brackets. A total of 67 respondents have experienced flooding on their street.

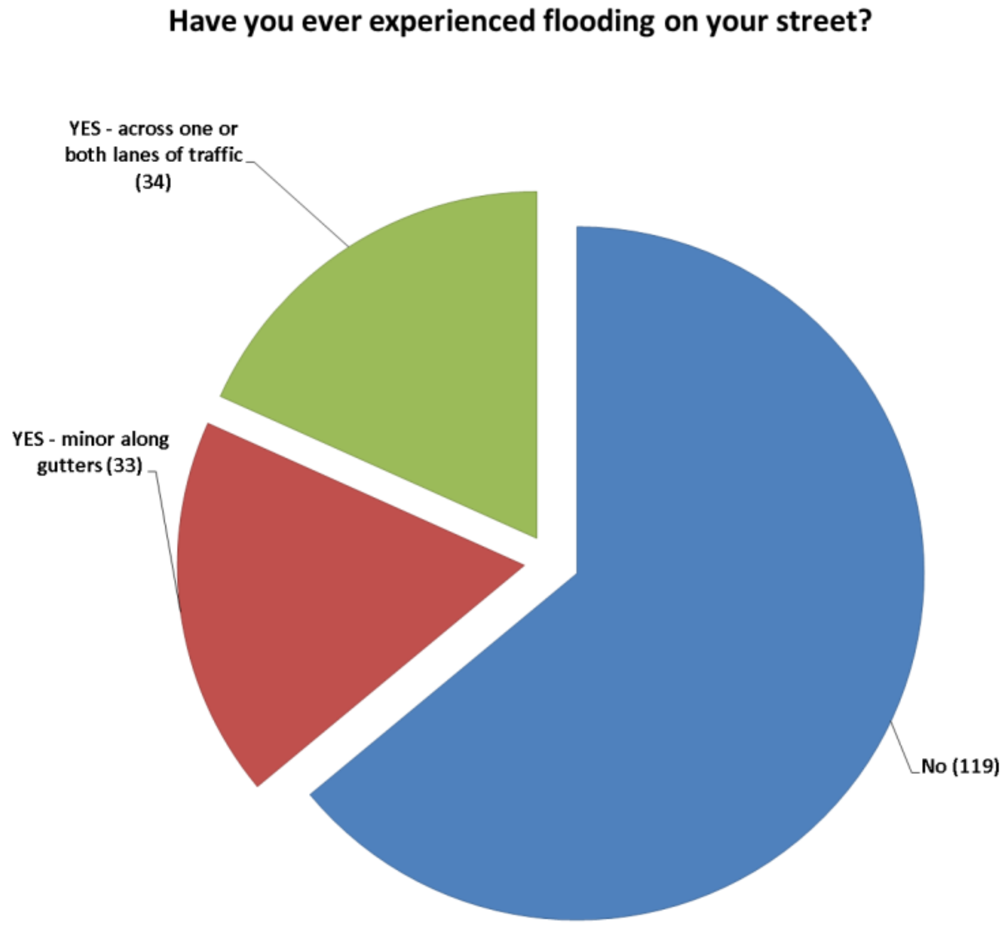
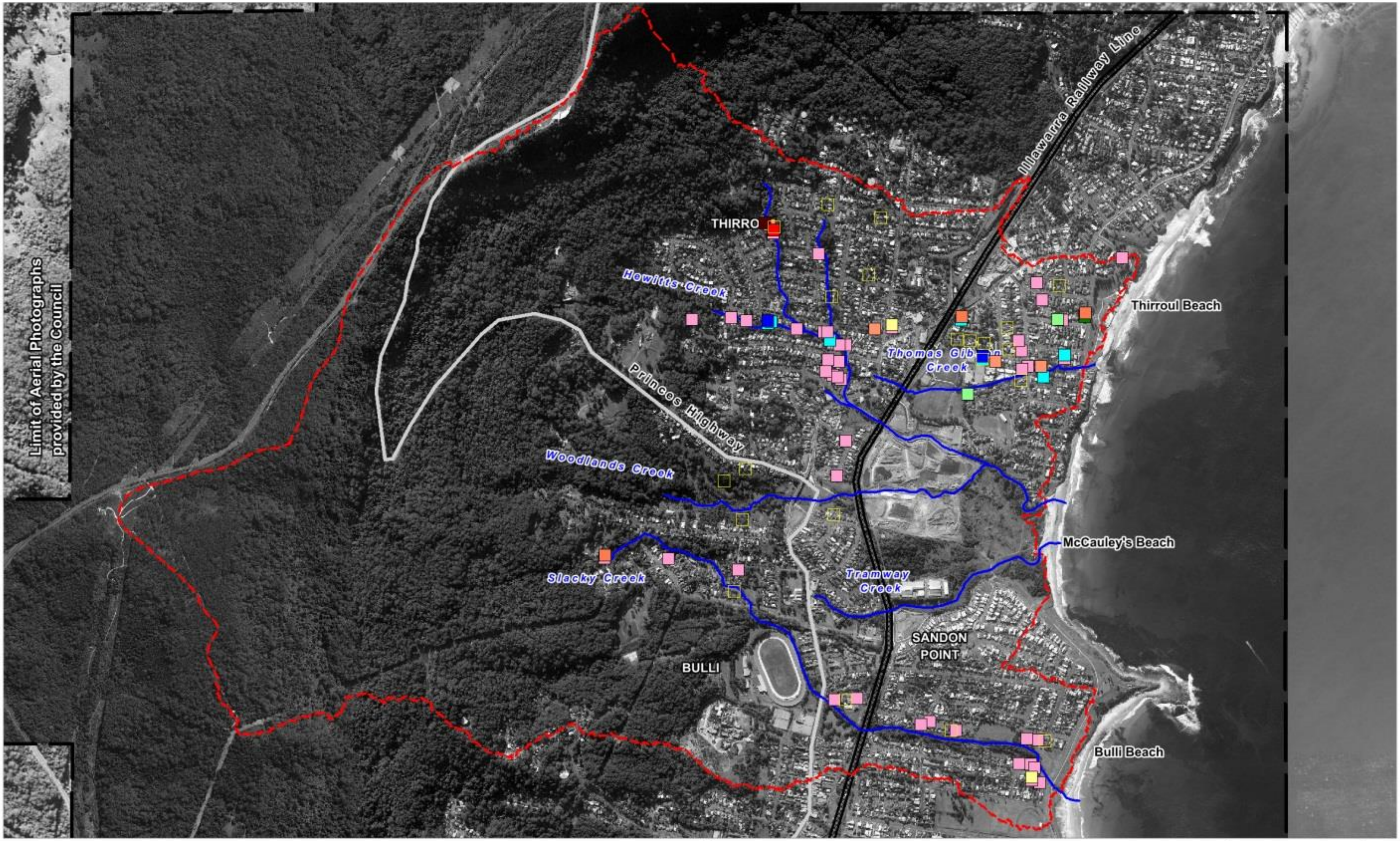


Figure 4-2 Breakdown of the responses to residents experience of flooding on their street

The chart indicates that majority of the responses have not experienced flooding on their street with approximately 36% of responses identifying flooding as an issue on their street.

The flood events years identified by the community include 1975, 1989, 1998, 1999, 2007, 2010, 2011, 2012 and 2013. Figure 4-3 shows the location of the 82 respondents who identified flooding as an issue at their property and/or on their street and the associated flood event years identified.



LEGEND

- February 2013 Survey Responses
- Watercourses
- Catchment Boundary

Survey Responses - flood event year

1975	2010
1989	2011
1998	2012
1999	2013
2007	No date provided

Title:
Community Questionnaire Responses - Location and Flood Event Year where Flooding Identified as an Issue

Figure: 4-3

Rev: 1

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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It can be seen in Figure 4-3 that there is a fairly comprehensive coverage of responses across the study area with the majority of responses (43 out of the 82) identifying the 1998 flood event contributing to flooding at their property and/or on their street.

Flood events for the following specific months are identified in the responses: August 1998, March 2011, February 2012 and February 2013. Comments provided in the responses for these flood events have been reviewed to determine where useful information can be extracted and used for model calibration and validation.

With the exception of August 1998 flood there are a limited number of responses which provide details on specific dates of flood events. A significant amount of observed flood level data has been provided previously by the Council for the August 1998 calibration event (refer to Figure 3-1). Based on a review of the community responses relating to flood level information for this event, we have not identified any responses with observed flood levels which would supplement the observed flood level data provided by Council. The geo-referenced data on the locations affected by flooding for this event (Figure 4-3) has been used to inform the calibration of the model for the 1998 flood event.

February 2013 is the most recent flood event identified, with eight responses identifying flood levels at their property and/or street for a flood event in February 2013. Three questionnaire responses specifically refer to a flood event on the 23 of February and flood levels identified in these responses have been surveyed as part of the Additional Survey (Section 5).

4.4 Public Exhibition of Draft Flood Study Report

4.4.1 Public Exhibition and Community Information Session Details

The Draft Review of Hewitts Creek Flood Study was placed on public exhibition from 13 October 2014 to 10 November 2014. Throughout the exhibition period hard copies of the draft Flood Study report were available for viewing at Wollongong and Thirroul Libraries. An electronic version of the draft Flood Study report was also available for download on the project website and Wollongong City Councils website.

Two community information sessions were conducted during the public exhibition period on Friday 24 October and Friday 31 October 2014. The community information sessions were hosted by Council, OEH and BMT WBM representatives and attended by the local community. The sessions presented an overview and outcomes of the Flood Study via display posters with Council, OEH and BMT WBM representatives available for both group and individual consultations. Community members were encouraged to discuss their concerns and suggestions with the representatives. Feedback forms were also provided to the attendees.

The community was notified of the public exhibition and community information sessions via advertisements in the Advertiser on the 8 October and 15 October 2014 and notifications on both Council's website and the project website. Council also directly mailed a letter and combined newsletter & feedback form providing information on the Flood Study and notifications of the public exhibition and community information sessions. The mail-out was distributed to approximately 1500 property owners and residents whose property fell within the PMF flood extent as defined by the Draft

Review of the Hewitts Creek Flood Study (BMT WBM, 2014). It should be noted that the PMF is an extremely rare event and significantly greater in magnitude than the 1 in 100 year ARI flood and the August 1998 flood. Therefore, the extent of flooding associated with the PMF event could include properties that may not have experienced flooding in the past. Copies of relevant consultation material are included in Appendix A.

Key project stakeholders were also notified through a Floodplain Risk Management Committee Meeting held on the 17 September 2014. The Draft Review of Hewitts Creek Flood Study was distributed to the committee meeting members for their comments.

4.4.2 Community and Stakeholder Response

A total of 59 written responses were received from the community providing feedback on the draft Flood Study report. A summary of the comments provided in these responses is listed below:

- ***Flood risk***. The majority of responses focussed on property owners opinion as to whether their property should be identified as “flood affected” or similar. Most responses on this matter indicated displeasure that their property was identified as being at risk of flooding having previously never experienced flooding at their property.
- ***Hydraulic model schematisation***. A number of residents within the area of Hewitts Avenue, Thirroul, queried the hydraulic model schematisation and flood levels. The following issues were raised:
    - The extent of the modelled safety barriers at Princes Highway and Lawrence Hargrave Drive;
    - Approach to modelling boundary fences; and
    - Council’s Conduit Blockage Policy (Wollongong City Council, 2009),
- ***Insurance premiums***. A number of responses indicated a fear of rising insurance premiums relating to flood cover as a result of the Flood Study;
- ***Flood mitigation works.*** A number of responses queried why flood mitigation works identified in the in the Hewitts Creek Floodplain Risk Management Study and Plan (Forbes Rigby Pty Ltd, 2002) have not been implemented.
- ***Development Approvals.*** A number of residents were concerned about the flood impact of new developments on surrounding areas; and
- ***Channel maintenance.*** A number of residents expressed concern that a lack of channel maintenance is a factor exacerbating localised flood risk.

In addition to the community feedback, one project stakeholder provided a response on the draft Flood Study report.

4.4.3 Addressing Community Responses

Council sent out a letter to each community member who provided feedback on the draft Flood Study report. The letter acknowledged residents concerns regarding flood affectation of a property noting that Council is required, as per the NSW Government's Flood Prone Lands Policy and Floodplain Development Manual (2005), to identify all properties affected by the PMF.

As noted in Section 4.4.2, a number of residents within the area of Hewitts Avenue, Thirroul, queried the hydraulic model schematisation. To address these concerns, a detailed investigation into the model schematisation within the Hewitts Avenue area has been undertaken. The following amendments have been included in the hydraulic model and reporting to address both the outcomes of the detailed investigation and the community responses:

- The extent of the safety barrier at Princes Highway and Lawrence Hargrave Drive has been updated. The as-constructed barriers are more extensive than the barriers which were originally included in the TUFLOW model. The model results have been updated throughout the report to reflect this change.

- An issue was identified with the schematisation of the culvert blockage at the Illawarra Railway culvert on Hewitts Creek which resulted in a 0% blockage being applied for design model runs. The schematisation of this culvert has been updated to apply a 25% bottom up blockage in line with Council Conduit Blockage Policy (Wollongong City Council, 2009). The model results have been updated throughout the report to reflect this change.

- As noted in Section 6.5.2, fences have not been explicitly incorporated into the model. Additional information has been provided in Section 6.5.4 to explain the approach to modelling fences through increased roughness.

5 ADDITIONAL SURVEY

The following sections outline the additional survey data required to supplement the existing survey data and enable the establishment of a suitable two-dimensional model representation of the channels and floodplain in the study area.

LiDAR survey provides coverage of the majority of the study area, producing a detailed topographic model of the existing ground levels. However, due to limitations in the aerial survey method, the detail of watercourses is often obscured (e.g. by standing water, vegetation, etc.), with ground survey required to provide the required detail of the watercourses to integrate with the LiDAR data.

Existing ground survey data of the channels and structures was undertaken as part of the 2002 Flood Study. Since the completion of the 2002 Flood Study, a number of changes have taken place along the watercourses and in the floodplain through natural geomorphological processes and the implementation of flood mitigation works and developments. In addition, a number of locations were identified where additional survey data was required to supplement the existing survey data for model development.

A survey contractor was appointed to undertake the survey works which commenced on the 8 April 2013.

5.1 Channel Cross Sections

During the August '98 flood, the upper reaches of the mainstream of Hewitts Creek above Kelton Lane and upper Slacky Creek above Rex Avenue were heavily scoured and the reaches downstream filled in with large boulders gravel and silt. This caused significant changes to the capacity of the channel in these areas of erosion and deposition and surveys were undertaken following the '98 flood to capture these changes. Given that there have been smaller flood events since the August '98 flood, a number of cross sections are being surveyed to determine the extent of changes in cross section profiles as a result of natural geomorphological processes since the last surveys were undertaken.

The effectiveness of aerial data capture (LiDAR) to capture these changes in the vicinity of the main creek alignment is limited due to the presence of water and in particular, dense vegetation.

A total of 8 additional cross sections were required to be surveyed on Hewitts and Slacky Creeks with the distribution and average spacing of cross sections defined to provide an appropriate check on existing model sections. The locations of these additional cross sections are shown in Figure 5-1.

5.2 Structures

There are numerous hydraulic structures on the main channels within the study area, with thirteen additional structures specified to be surveyed as part of the additional survey. This would provide the structure details required to build the hydraulic model, such as dimensions, waterway areas, and invert levels. The locations of these structures are shown in Figure 5-1, with further details of these structures presented in Section 6.

5.3 Ground surface profiles

Ground surface profile data is required to determine the change in ground elevation as a result of recent housing development works at Sandon Point and McCauley Street. This information has been used to determine if changes are required to the floodplain topography at these locations. The locations of these ground surface profiles are shown in Figure 5-1.

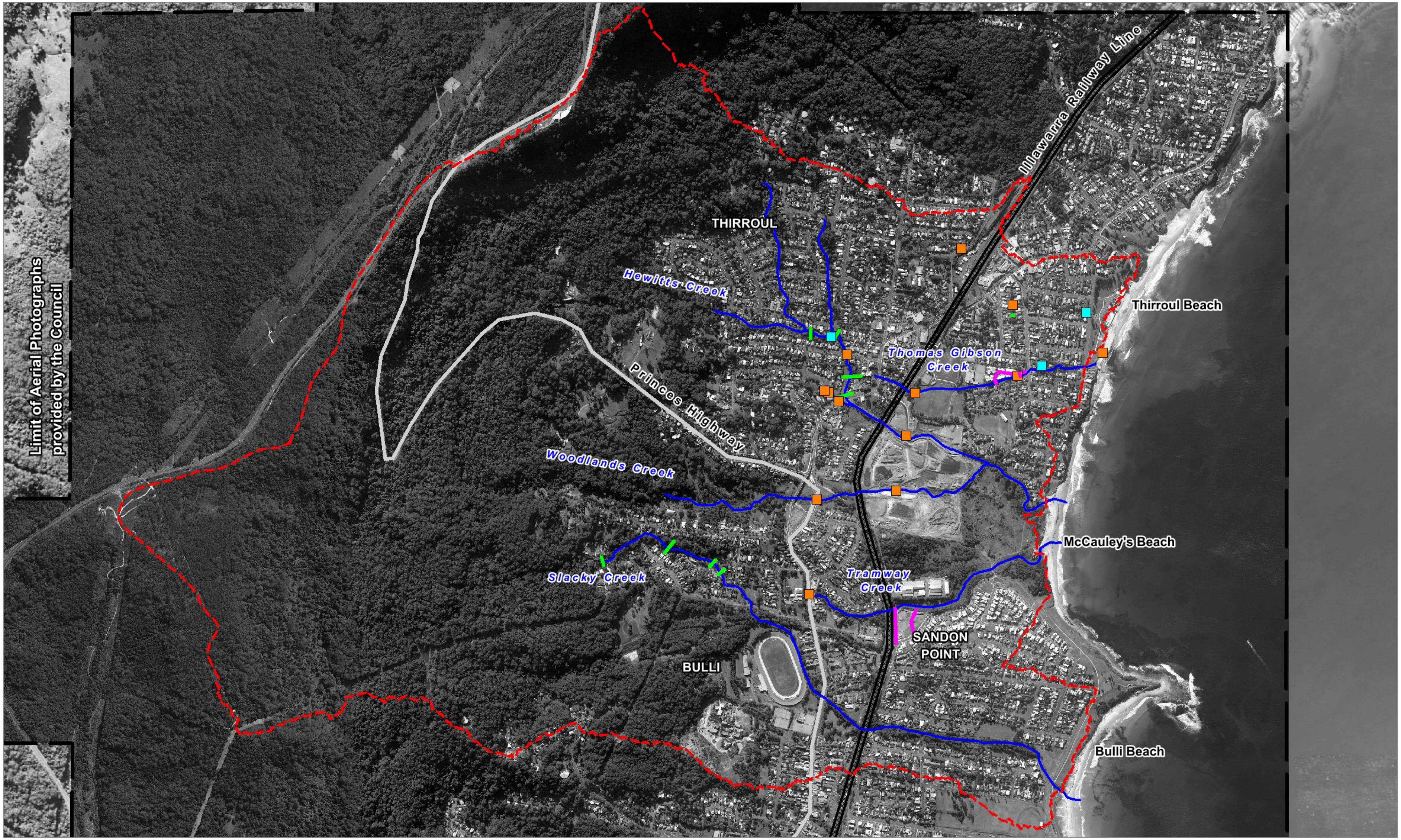
5.4 2013 Flood Level Survey

Details of flood levels for the February 2013 event were collated through community consultation (refer to Section 4). These historical levels generally comprise recorded marks (flood debris marks, lines drawn with marker on a wall, or points reconstructed from the memory of community members) with their elevations captured during the additional detailed survey.

Three locations of historical flood levels were identified through the community consultation for the flood event of 23 February 2013. The respondents' comments are provided in Table 5-1 and the locations shown in Figure 5-1.

Table 5-1 Details of Flood Levels for the February 2013 Flood Event

Address	Response to Question ***"Are you able to indicate the depth that flood waters reached on your property or elsewhere such as roads?"***
Lachlan Street, Thirroul	Across property and into Lachlan Street. Sheds flooded.
Ocean Street, Thirroul	The stormwater drain flooded and rose to 0.5 metre at the gutter, inundating the front garden of unit 3 and coming about 2 metres up the common driveway.
McCauley Street, Thirroul	If the tide is in, the creek running through our property breaks its banks and can turn our house into an island, with water depths up to 50cm.



LEGEND

- Watercourses
- Catchment Boundary

Survey Details

- Structures
- Historical Flood Levels (February 2013)
- Cross Sections
- Long Section Profiles

Title:
Location of Additional Survey Data

Figure: 5-1

Rev: 1

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6 MODEL DEVELOPMENT

Hydrology concerns the occurrence and movement of water in the environment. For assessing fluvial flood risk, the effects of surface water hydrology, which looks at the relationship between rainfall on the land surface and runoff into water bodies (creeks, rivers and lakes) is of particular interest. This relationship is controlled by a wide range of catchment characteristics including urbanisation, vegetation, soils, geology and topography. A hydrological model is used to represent these characteristics and simulate the catchment rainfall-runoff processes, producing stormwater flows for a range of catchment conditions and rainfall events.

A hydraulic model is used to simulate the mechanics of the flow of water over the land surface. For Flood Studies, hydraulic models are used to simulate the flow behaviour of the drainage network and overland flow paths, producing flood levels, flow discharges and flow velocities. The outputs from the hydrological model, together with information on the ocean levels, form the inputs to the hydraulic model. The flow behaviour is influenced by a number of factors including the catchment topography, land use and structures.

6.1 Modelling Tools Discussion

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 hydrologic model and a hydraulic model are developed.

Information on the topography and characteristics of the catchment, drainage network and floodplain are built into the models. Recorded historical flood data, including rainfall and flood levels, are used to simulate and validate (calibrate and validate) the models.

The development of a hydrological model generally involves the following steps:

- Subdivision of the catchment into a network of sub-catchments inter-connected by channel reaches representing the creeks. The sub-catchments are delineated, where practical, so that they each have a general uniformity in their slope, land use, vegetation density, etc.;
- Estimation of the pervious and impervious fractions within each sub-catchment;
- Review and analysis of historical rainfall data to identify suitable calibration and verification events;
- Calibration to one or more historic floods;
- Appropriate use of Australian Rainfall and Runoff (ARR) to enable determination of both the calibration and design hydrological inputs; and
- Integration of hydrology with hydraulic modelling.

The output from the hydrological model is a series of flow hydrographs at selected locations describing the quantity, rate and timing of stream flows that result from rainfall events. These hydrographs are input to the hydraulic model to simulate the passage of a flood through a catchment.

The development of a hydraulic model follows a relatively standard procedure:

- Discretisation of the catchment, creek network, floodplain, etc.;
- Incorporation of physical characteristics (creek channels, floodplain levels, structures, etc.);
- Establishment of hydrographic databases (rainfall, flood flows, flood levels) for historic events;
- Calibration to one or more historic floods (calibration is the adjustment of parameters within acceptable limits to reach agreement between modelled and measured values);
- Verification to one or more other historic floods (verification is a check on the model's performance without further adjustment of parameters); and
- Sensitivity analysis of parameters to measure dependence of the results upon model assumptions.

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

- Establishing design flood conditions;
- Determining levels for planning control; and
- Modelling development or management options to assess the hydraulic impacts (as part of the Floodplain Risk Management Study).

6.2 Modelling for the 2002 Studies

The Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a) and Floodplain Risk Management Study (Forbes Rigby Pty Ltd., 2002b) adopted and applied the WBNM hydrological model, a runoff-routing model used to represent catchment rainfall-runoff relationships. HEC RAS, a 1D river modelling program, was used to simulate a range of flood events and determine the design flood flows and levels across the study area.

6.2.1 WBNM Hydrological Model

The 2002 Flood Study adopted and applied WBNM for undertaking the hydrological analysis. WBNM models are developed on the basis of a catchment divided into a number of sub-areas based on the stream network. This allows hydrographs to be calculated at various points within the catchment, and the spatial variability of rainfall and rainfall losses to be modelled. WBNM separates overland flow routing from channel routing, allowing changes to either or both of these processes, for example in urbanising catchments.

Each sub-area is represented by a unit in the model which has the lag properties of the corresponding sub-area, and which takes as input the rain falling on the sub-area. WBNM calculates hydrographs at the outlets of all sub-areas based on the principle of the Conservation of Mass.

WBNM uses a Lag Parameter (also referred to as the C value) to calculate the catchment response time for runoff. The Lag Parameter is important in determining the timing of runoff from a catchment, and therefore the shape of the hydrograph. The general relationship is that a decrease in lag time results in an increase in flood peak discharges (Boyd et al., 2007).

The WBNM hydrological model developed as part of the Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a) was delineated into 120 roughly equal sub-areas recognising key structures or boundaries at which discharge characteristics were sought in the modelling process, i.e. at structures or creek confluences. Key model parameters were selected on the basis of values derived for other catchments in the region. The model was calibrated to the April 1988 flood event and validated against the June 1991 event and August 1998 event. This calibration and validation process was used to refine the values of key model parameters and confirmed that the model was capable of adequately simulating real flood events.

A kinematic wave based model, PSxRM-V8 developed by Aron (1980) and Rigby (1992), was used in a backup role to confirm the reasonableness of results obtained from the WBNM model in Hewitts and Woodlands Creeks. Both RORB and XP-RAFTS hydrological models of Hewitts, Woodlands and Slacky Creeks, developed as part of previous studies in the catchment, were also used in the calibration and validation of this WBNM model.

The adopted critical design storm duration for the study area was two hours. For the design events, the inflow hydrographs were based on an initial loss of 0mm and continuing loss of 2.5mm/h for pervious areas, and an initial loss of 0mm and continuing loss of 0mm/h for impervious areas. Design flood hydrographs were generated for the 5% Annual Exceedence Probability (AEP), 2% AEP, 1% AEP and the Probable Maximum Flood (PMF). Please refer to Section 7 for further discussion on Annual Exceedence Probability and design flood terminology. The generated design hydrographs were imported into the HEC RAS hydraulic model to determine the flows and flood levels along the modelled watercourses.

6.2.2 HEC RAS Hydraulic Model

HEC RAS is a one-dimensional (1D) river modelling program developed by the U.S. Army Corps of Engineers. The defining assumption for 1D modelling is that only the forces, velocities, and variations in the stream direction (upstream and downstream) are significant, and that those in the transverse or lateral direction are negligible. A 1D model is typically arranged with branches or channels representing the flow paths and cross-sections defining the conveyance characteristics of the branch. Storage may be defined separately or interpolated from adjacent cross sections.

Four separate hydraulic models were constructed for the 2002 Flood Study using data from previous NSW Public Works surveys:

- Slacky Creek;
- Tramway Creek;
- Hewitts & Woodlands Creeks; and
- Thomas Gibson Creek

The model was calibrated to the April 1988 flood event and validated against the June 1991 and August 1998 flood events. The model geometry developed for the 1998 validation event formed the initial basis for the design flood modelling.

For the design flood modelling, the following key parameters were adopted in the HEC RAS model:

- The model was run with a critical storm duration of 2 hours for all parts of the study area. Storm hydrographs were developed in the WBNM model and then imported into the HEC RAS model

- Two downstream boundary scenarios were run within the model:

  i) a 100 year storm event over the catchment and a coincident ocean level of RL1.0m AHD: and

  ii) 100 year ocean level of RL 2.7m AHD (based on no coincident catchment flow)

- Culvert and handrail blockages were included in the model in accordance with Council's Conduit Blockage Policy. Three blockage scenarios were modelled:

  i) Fully clear (all structures clear);

  ii) Blocked (all structures blocked as per Councils Conduit Blockage Policy – refer to Section 6.5.5.4); and

  iii) Critical blockage pattern (flow maximised with all structures blocked as per Councils Conduit Blockage Policy except those required to be clear to maximise flow) in the various study reaches.

  - Slacky Creek - For lower Slacky Creek (downstream of Hobart Street, Bulli), peak flow is maximised when the culverts at Hobart St., Bulli and through the coal haulage embankment of the now disused railway line are clear, resulting in minimum diversion to Tramway Creek.

  - Tramway Creek - For Tramway Creek, peak flow is maximised when the culverts at Hobart St., Bulli and through the coal haulage embankment of the now disused railway line are blocked, at the same time as the Woodlands Creek railway culvert is clear. This results in a maximum diversion into Tramway Creek from both Slacky and Woodlands Creeks.

  - Woodlands Creek - For lower Woodlands Creek (downstream of Lawrence Hargrave Drive, Thirroul), peak flow is maximised when the disused heavy vehicle safety ramp and railway culverts are all clear, resulting in minimum diversion to Hewitts Creek.

  - Hewitts Creek - For lower Hewitts Creek (downstream of Lachlan St., Thirroul), peak flow is maximised when the Lachlan Street culvert is clear (thereby reducing diversion out of Hewitts Creek), at the same time as the Woodlands Creek railway culvert is blocked.

  - Thomas Gibson Creek

    - South Arm (upstream of Cliff Parade, Thirroul), peak flow is maximized when the Lachlan St., Thirroul culvert is blocked and the informal basin at Thomas Gibson Park, Thirroul is also blocked.

- South Arm (downstream of Cliff Parade, Thirroul), peak flow is maximized when the Lachlan St., Thirroul culvert is blocked, the informal basin at Thomas Gibson Park, Thirroul is blocked and the culverts at Cliff Parade, Thirroul are clear.

- North Arm (downstream of Cliff Parade, Thirroul), peak flow is maximized when the Cliff Parade, Thirroul culvert on Thomas Gibson Creek -South Arm is blocked.

The WBNM model outputs were input to the HEC RAS hydraulic model and flood profiles simulated for the 5% AEP, 2 AEP%, 1% AEP and PMP events. Design flood envelopes have been defined throughout the system for by the upper envelope of the flood profiles produced by the downstream boundary scenarios and the three culvert blockage scenarios, i.e. ‘fully clear’, ‘blocked’ and ‘critical blockage pattern’.

Sensitivity testing of key model parameters on design flood conditions was also undertaken.

6.2.3 Summary of Modelling from the 2002 Studies

A comparison of results between the WBNM model and various other hydrological models that have been applied in the study area indicates that the hydrological model discharge predictions by the various models are generally in good agreement providing confidence in the WBNM model outputs.

Results from the model calibration and validation indicate that the HEC RAS model generally correlates well with observed flood levels and mechanisms for these calibration and validation events.

The design model results identified a number of overland flow paths between adjacent sub-catchments (refer to Section 2.2 for details). The 2002 Flood Study report concludes that whilst flows are generally contained within the creek banks in the upper reaches of most streams for floods up to the 1% AEP event, the depth of flow, high velocities and rapid rise of flood waters in these upper reaches presents a potential hazard. With streams being founded for the most part in talus, these high velocities also lead to major scour problems with banks undermined and properties threatened.

The report also concludes that the level and frequency of flooding of land upstream of the Illawarra Railway is adversely impacted by the many culverts and bridges on streams and intrusions of development onto the floodplains of streams. Frequent partial blockage of these structures and poor control of overtopping flows has and will continue to exacerbate these problems.

6.3 Modelling Tool Selection

The WBNM (Watershed Bounded Network Model) hydrologic model has been selected for this study to simulate the catchment rainfall-runoff relationships. WBNM has considerable functionality and flexibility permitting simulation of complex flood studies. The WBNM model has also been verified against substantial empirical data, including data from the Wollongong region and therefore provides a good indication of expected runoff hydrograph results for the study area. WBNM has been used for the majority of flood studies undertaken in the Wollongong region for Council, including the Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a), Mullet and Brooks Creek Flood Study (Bewsher, 2010), Duck Creek Flood Study (BMT WBM, 2012) and Wollongong City Flood Study (WMA Water, 2012).

TUFLOW, a fully 2D hydraulic modelling software package, has been selected to simulate the mechanics of the flow of water over the land surface. 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 Hewitts Creek catchment.

WBNM outputs a flow hydrograph at the sub-area outlets which are then used as inputs into the 2D hydraulic model (TUFLOW). The TUFLOW model simulates the behaviour of the runoff by routing the flow hydrographs through a two dimensional grid of the study area representing the topography of the creeks and floodplain. A combination of WBNM total flow hydrographs and local flow hydrographs have been used within the TUFLOW model. Total flow hydrographs are summed from all of the contributing sub-areas to an outlet and have been applied at the upstream hydraulic model limit (i.e. at the base of the escarpment). Local flow hydrographs have been used throughout the remainder of the 2D model domain (refer to Figure 6-1).

In recent years the advancement in computer technology has enabled the use of the direct rainfall approach as a viable alternative over the use of "traditional" hydrological models such as XP –RAFTS and WBNM. With the direct rainfall method the rainfall depths are applied directly to the individual cells of the 2D hydraulic model where it is routed as sheet flow until the runoff contribution is substantial enough to generate an overland flow path. This is particularly useful for overland flow studies where model results are desired in areas with very small contributing catchments. This approach removes the need for a separate hydrologic model.

A verification of the selected approach has involved comparing the results from the WBNM flows routed through the TUFLOW model against results from the Direct Rainfall approach for the August 1998 Calibration event.

The Direct Rainfall approach applies this method over the lower reaches of the study area, whilst for the upper reaches of the study area the WBNM model has been used to provide the total flows from the sub-areas representing the Illawarra Escarpment (Refer to Section 6.4 and Figure 6-1).

A comparison of results between the WBNM model outputs and the Direct Rainfall approach indicates that the average difference in water levels between the two modelling approaches is less than 0.2m across the majority of the study area. The results indicate that there is more extensive flooding in the study area when applying the direct rainfall approach which can be attributed to overland flooding being represented in the Direct Rainfall approach in addition to mainstream flooding.

Given the nature of the fluvial flood risk in the study area, i.e. rapid runoff from the Illawarra Escarpment discharging to a defined creek network downstream of the escarpment, the adopted approach of applying total flow hydrographs from the Illawarra Escarpment and local flow hydrographs at the sub-catchment outlet as inputs into the 2D hydraulic model is considered a valid and most proficient approach for this study area.

6.4 Hydrological Model Development

A review of the 2002 hydrological model has been undertaken to ensure that the level of detail is sufficient for modelling the required flooding mechanisms within the 2D model of the study area.

6.4.1 WBNM Model Updates

The following model schematisation and parameters were reviewed and updated where necessary as part of a review of the WBNM model:

- Catchment and sub-area delineation;
- Proportion of impervious area (also referred to as Fraction Impervious); and
- Weightings for spatial distribution of rainfall.

Table 6-1 summarises the key sub-area parameters adopted for the updated WBNM model, including the area and percentage impervious. Figure 6-1 provides details of the WBNM model schematisation.

Table 6-1 WBNM Sub-Area Properties

Sub-Area ID (Refer to Figure 6-1)	Area (hectares)	Fraction Impervious (%)	Sub-Area ID (Refer to Figure 6-1)	Area (hectares)	Fraction Impervious (%)
TGC_1	1.9	45	HC_43	8.5	14
TGC_2	3.7	47	HC_44	7.3	36
TGC_3	4.6	29	HC_45	4.3	40
TGC_4	2.9	46	HC_46	3.5	32
TGC_5	3.0	54	HC_47	4.3	37
TGC_6	1.3	68	HC_48	1.5	54
TGC_7	3.8	61	HC_49	5.7	38
TGC_8	3.4	49	HC_50	6.3	42
TGC_9	4.6	51	HC_51	5.7	35
TGC_10	1.7	30	HC_52	9.0	28
TGC_11	1.9	41	WC_1	20.2	4
TGC_12	1.8	45	WC_2	8.2	2
TGC_13	3.1	48	WC_3	6.0	2
TGC_14	2.0	48	WC_4	9.6	6
TGC_15	1.1	46	WC_5	4.7	26
TGC_16	2.2	50	WC_6	12.4	3
TGC_17	3.9	52	WC_7	11.9	3
TGC_18	2.6	52	WC_8	8.2	2
TGC_19	1.7	61	WC_9	11.1	3
TGC_20	3.9	51	WC_10	16.6	1
TGC_21	4.6	37	WC_11	6.8	2
TGC_22	2.8	49	WC_12	7.6	4
TGC_23	0.5	58	WC_13	17.6	18
TGC_24	1.9	53	WC_14	4.8	35

Sub-Area ID (Refer to Figure 6-1)	Area (hectares)	Fraction Impervious (%)	Sub-Area ID (Refer to Figure 6-1)	Area (hectares)	Fraction Impervious (%)
TGC_25	4.5	7	WC_15	9.5	38
TGC_26	7.8	35	TC_1	4.7	43
TGC_27	2.5	41	TC_2	3.2	41
TGC_28	2.0	50	TC_3	2.1	48
TGC_29	3.7	46	TC_4	6.6	47
HC_1	10.4	0	TC_5	12.5	40
HC_2	8.3	2	TC_6	1.7	45
HC_3	2.0	24	TC_7	8.8	18
HC_4	5.2	0	TC_8	6.7	2
HC_5	6.2	1	TC_9	9.2	31
HC_6	2.8	13	SC_1	23.9	0
HC_7	2.1	50	SC_2	16.1	0
HC_8	1.1	44	SC_3	11.7	0
HC_9	1.6	44	SC_4	21.4	0
HC_10	1.9	44	SC_5	11.3	0
HC_11	2.7	25	SC_6	5.8	11
HC_12	2.6	47	SC_7	4.7	16
HC_13	4.0	38	SC_8	2.6	26
HC_14	2.0	48	SC_9	6.8	34
HC_15	2.4	43	SC_10	2.5	46
HC_16	4.3	6	SC_11	2.8	28
HC_17	7.3	6	SC_12	1.3	18
HC_18	3.1	32	SC_13	6.8	0
HC_19	8.0	7	SC_14	21.2	0
HC_20	3.5	0	SC_15	12.0	0
HC_21	9.0	1	SC_16	12.9	7
HC_22	5.0	0	SC_17	8.8	2
HC_23	4.1	4	SC_18	10.2	1
HC_24	7.4	2	SC_19	7.3	5
HC_25	5.7	3	SC_20	2.2	23
HC_26	10.7	11	SC_21	9.1	10
HC_27	5.7	9	SC_22	9.4	28
HC_28	8.2	7	SC_23	6.1	36
HC_29	5.7	16	SC_24	2.9	29
HC_30	3.4	46	SC_25	4.0	7
HC_31	2.5	48	SC_26	7.0	39
HC_32	0.8	47	SC_27	3.1	8
HC_33	1.4	16	SC_28	5.0	43
HC_34	1.2	25	SC_29	2.3	47
HC_35	1.7	39	SC_30	5.4	28
HC_36	0.3	48	SC_31	4.8	39

Sub-Area ID (Refer to Figure 6-1)	Area (hectares)	Fraction Impervious (%)	Sub-Area ID (Refer to Figure 6-1)	Area (hectares)	Fraction Impervious (%)
HC_37	0.9	37	SC_32	9.9	46
HC_38	0.9	42	SC_33	4.5	38
HC_39	0.5	51	SC_34	6.4	38
HC_40	2.8	42	SC_35	2.7	50
HC_41	1.7	20	SC_36	5.9	39
HC_42	4.9	9	SC_37	6.9	36
			SC_38	4.8	28

6.4.1.1 Catchment and Sub-Area Delineation

The catchment and sub-area delineation has been updated based on a high resolution (1m grid) Digital Elevation Model (DEM) developed from the LiDAR data (2005). GIS catchment delineation tools within Discover for MapInfo have been used to delineate the catchment and sub-area boundaries based on sub-area outlet points. The location of these sub-area outlet points have been derived based on:

- The upstream hydraulic model limit;
- The location of hydraulic structures;
- A review of the Direct Rainfall overland flow routes; and
- The observed flood mechanisms identified during the August 1998 flood event.

The updated sub-area delineation as part of the current Flood Study has resulted in an increase in the total number of sub-areas from 120 (2002 Flood Study) to 143. This increase in sub-areas is necessary to more accurately route the flow hydrographs through the two dimensional grid of the study area.

As noted in the 2002 Flood Study, the overall catchment boundary is generally well defined with limited opportunity for flood flows to transfer to adjoining catchments. The main sub-catchment boundaries of Slacky, Tramway, Woodlands, Hewitts and Thomas Gibson Creeks are not so well defined. Based on historical flood information and data from previous hydraulic modelling, the following known flood flow transfers occur between these sub-catchments:

- Slacky Creek to Tramway Creek at Hobart Street, Bulli:
- Woodlands Creek to Hewitts Creek immediately west (upstream) of the Illawarra Railway, Bulli/Thirroul;
- Woodlands Creek to Tramway Creek east (downstream) of the Illawarra Railway, Bulli;
- Hewitts Creek to Thomas Gibson Creek at George Street, Thirroul; and
- Hewitts Creek to Thomas Gibson Creek at Lachlan Street, Thirroul.

To the north of the study area, flood waters transfer to the adjoining catchment of Flanagans Creek at the Esplanade, Thirroul.

6.4.1.2 Fraction Impervious

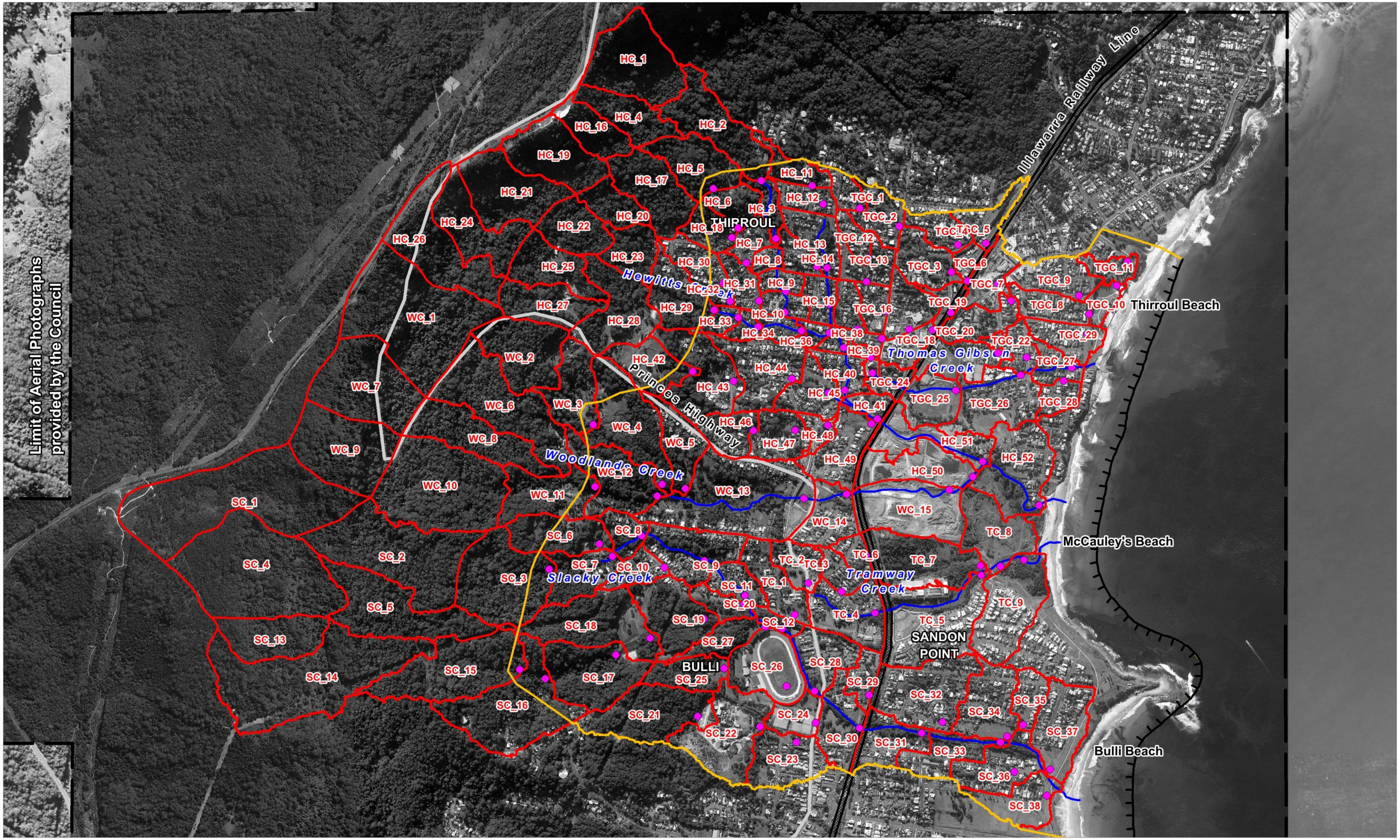
The urbanisation of a catchment increases both flood volumes and flood peaks through the replacement of naturally vegetated surfaces by impervious surfaces such as roofs and pavements. For modelling the effects of urbanisation within WBNM, each sub-area is split into a directly connected impervious part and the remaining pervious and semi-pervious part.

The percentages of pervious and impervious areas have been estimated based on the land use surface types within the study area. Detailed land use surface types have been identified for determining the hydraulic roughness zones within the study area (refer to Section 6.5.4). Aerial photography, cadastral data and site visit notes have been used to identify different land use surface types (e.g. forest, cleared land, roads, urban areas, etc.) across the study area. These land use surfaces have been grouped into pervious areas (i.e. roads and roofs) and impervious areas (i.e. vegetated surfaces) and used to estimate the fraction impervious for each sub-area within the WBNM model. The catchment-wide fraction impervious has increased from an average of 17% (2002 Flood Study) to 28% as part of the current Flood Study.

6.4.1.3 Spatial Rainfall Distribution

The orographic influence of the Illawarra Escarpment rainfall generally results in higher rainfall depths in the upper reaches of the catchment near the escarpment. This effect is supported by historic rainfall data for the study area.

For modelling historic flood events, the spatial variability in the depth of rainfall across the study area has been updated based on rainfall isohyets for each of the calibration and validation events. For the design flood events, the spatial variability in the depth of rainfall within the WBNM model is based on Australian Rainfall and Runoff (AR&R) intensity frequency- duration (IFD) data.



LEGEND

- Model Inflow Location
- Watercourses
- Downstream Model Boundary
- WBNM Sub-Area Boundaries
- SC_8 WBNM Sub-Area Label
- TUFLOW Model Boundary

Title:
WBNM Model Sub-Area Layout

Figure: **6-1**

Rev: **2**

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6.4.2 Rainfall Data

Rainfall information is the primary input and driver of the hydrological model which simulates the catchment's response in generating surface runoff. 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. 240mm in 24 hours or average intensity 10.0mm/h); 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 stations provide the observed rainfall depth and temporal pattern (refer to Section 3.4 for details of the rainfall station locations). The daily rainfall totals from both the continuous and daily rainfall stations have been used to inform the development of rainfall isohyets.

For design events, rainfall depths are most commonly determined by the estimation of IFD design rainfall curves for the catchment. Standard procedures for derivation of these curves are defined in AR&R (Pilgrim, 2001). Zone 1 temporal patterns from AR&R (Pilgrim, 2001) are built into the WBNM model and have been used for this Study.

New AR&R IFD data was released in 2013 as part of revision of Engineers Australia design handbook - *Australian Rainfall and Runoff: A Guide to Flood Estimation*. The other outputs from the revision project will include revised temporal patterns, areal reduction factors, losses and base flow. The revised AR&R aims to achieve AEP neutrality (where the technique results in a design flood estimate with the same probability of exceedance as the IFD design rainfall estimate). Therefore updates to the other design flood inputs are needed to ensure new design flood estimates are produced with the same AEP as the new 2013 IFD design rainfalls. Until these updates are available, it is advised to use the 1987 edition of Australian Rainfall and Runoff (AR&R87) design flood estimation techniques as adopted for this study (BOM, 2013).

The rainfall inputs for the historical calibration/validation events are discussed in further detail in Section 7 with further details on the deign rainfall event data in Section 8.

6.4.3 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. An initial loss- continuing loss model has been adopted for 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/h) for the duration of the runoff event.

Typical design loss rates applicable for eastern NSW catchments are initial loss of 10 to 35 mm and continuing loss of 2.5mm/h (Pilgrim, 2001). Table 6-2 shows initial and continuing loss values adopted in other studies undertaken within the Wollongong region (derived from BMT WBM (2012)).

Table 6-2 Loss Values Adopted in Other Wollongong LGA Studies

Rainfall Loss Type	Surface Type	Typical Values
Initial Loss	Pervious	0 - 50mm
Initial Loss	Impervious	0 - 2mm
Continuing Loss	Pervious	2 - 2.5mm/h
Continuing Loss	Impervious	0mm/h

The rainfall loss parameters for the historical calibration/validation events and design events are discussed in further detail in Section 7 and Section 8 respectively.

6.4.4 WBNM Lag Parameter and Flow Routing

The routing of flows for this study is primarily carried out in the hydraulic model. For the upper reaches of the study area, the WBNM model has been used to provide the total flows from the sub-areas representing the Illawarra Escarpment. Downstream of the Illawarra Escarpment, the WBNM model has been used to provide local flow inputs into the TUFLOW hydraulic model at the various sub-area outlets. Therefore, the routing of flow along the major flow paths downstream of the Illawarra Escarpment is carried out in the TUFLOW model and not in the WBNM hydrological model. Figure 6-2 shows the location of the WBNM inflows to the TUFLOW model.

WBNM recommends a Lag Parameter of 1.7 .Experimental derivation of the Lag Parameter for 129 storms on 10 catchments in eastern NSW found that a value of 1.68 gave a good fit to all the data. Similar data has been obtained for Queensland, Victoria, and South Australia, with estimated values of 1.47, 1.74, and 1.64 respectively. A Lag Parameter Value of 1.7 is a good 'average' value particularly for catchments where calibration data are not available to verify this parameter. However the Hewitts Creek catchment is quite unique and far from idealised, in particular the steepness of the upper catchment at the Illawarra Escarpment.

The WBNM model has been calibrated against recorded flood data in order to ensure that the adopted Lag Parameter is representative. Further discussion on calibration of the WBNM model is in Section 6.4.5 and Section 7.2.4.1. Sensitivity testing has also been undertaken to assess the value of the WBNM lag parameter as discussed in Section 10.1.

6.4.5 WBNM Model Calibration

It is beneficial to calibrate the WBNM model against recorded flood data to ensure that the adopted parameters are representative of the Hewitts Creek catchment. As there were no historic data on storm flows discharging to the Tasman Sea, the procedure adopted for calibration of the WBNM model involved the generation of flow hydrographs for the 17 August 1998 flood event using a selected set of WBNM model parameters adopted as part of the 2002 Flood Study. The flow hydrographs were input to the TUFLOW hydraulic model and the resulting flood levels compared with recorded flood marks.

As the starting point for the calibration of the WBNM model was the parameters adopted as part of the 2002 Flood Study, it was found that these parameters generated flow hydrographs, which when applied to the calibrated TUFLOW hydraulic model, gave a reasonable fit to historic flood data in the study area. Further discussion on the calibration of the WBNM model is discussed in Section 7.2.4.1.

6.5 Hydraulic Model Development

Hydraulic modelling for the Hewitts Creek study area has utilised 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 flow paths using a linked 2D / 1D flood modelling approach.

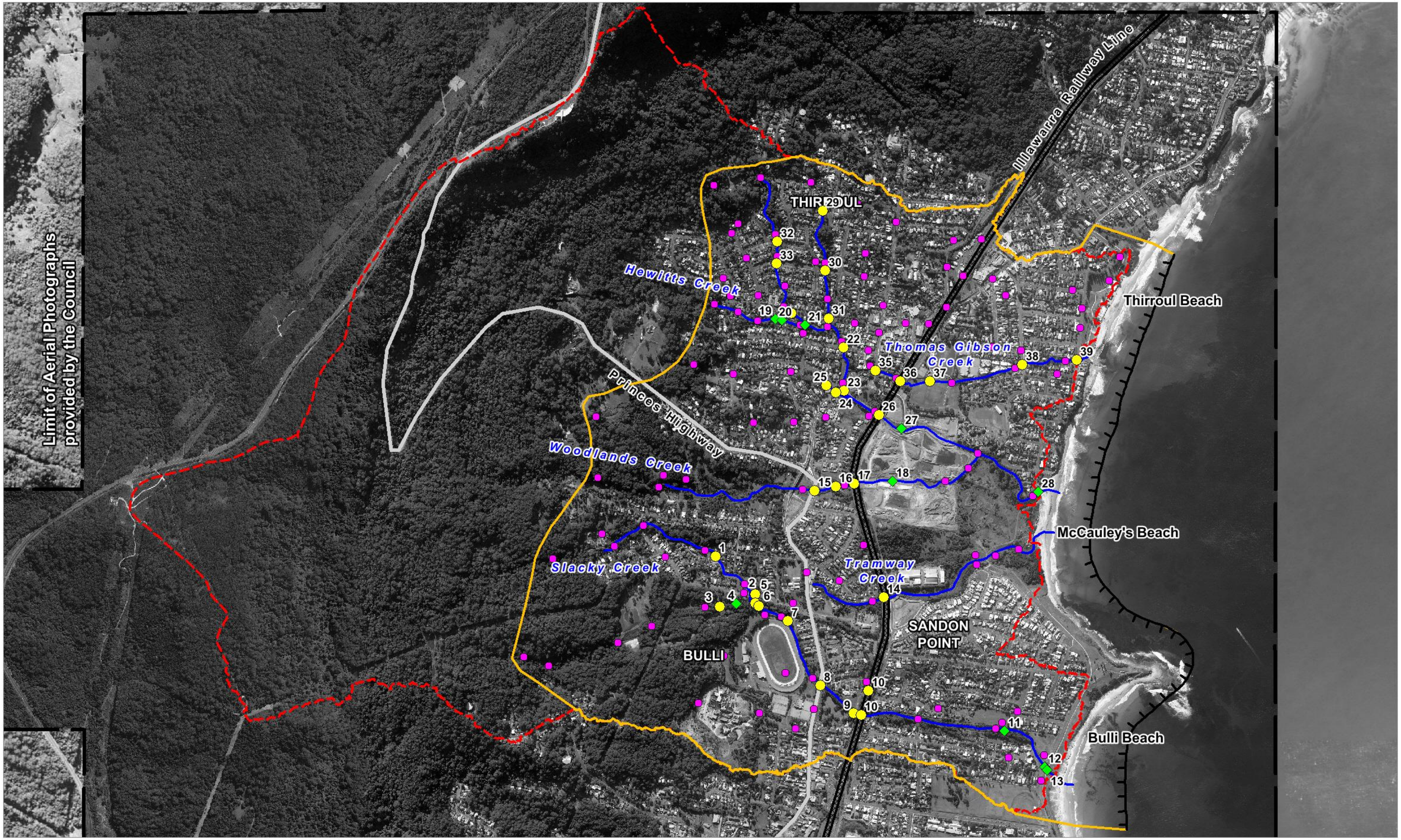
6.5.1 Model Configuration

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

- Topographical data coverage and resolution (e.g. LiDAR);
- Location of recorded data (e.g. levels/flows for calibration);
- Location of controlling features (e.g. embankments, culverts, bridges);
- Catchment specific factors (e.g. creek entrances at the Tasman Sea);
- Desired accuracy to meet the study's objectives; and
- Computational limitations.

With consideration to the available survey information and local topographical and hydraulic controls, a fully 2D model has been developed for the study area extending from the foothills of the Illawarra Escarpment to the Tasman Sea. The upstream limit of the 2D model generally corresponds with the western extent of the residential and commercial development within the study area. The total floodplain area modelled within the 2D domain comprises an area of approximately 5.3km^2. The adopted TUFLOW model layout is shown in Figure 6-2.

A TUFLOW 2D model grid resolution of 2m has been adopted for the Hewitts Creek study area. It should be noted that TUFLOW samples elevation points at the cell centres, mid-sides and corners, so a 2m cell size results in DEM elevations being sampled every 1m. This resolution has been selected to give the necessary detail required for accurate representation of the floodplain, creek channels and key floodplain obstructions (such as buildings and road/structure embankments) and to keep simulation times within acceptable limits considering the size of the model domain.



LEGEND

- Model Inflow Location
- 1D Structure Location (15) Structure Label
- 2D Structure Location (18) Structure Label
- Watercourses
- Downstream Model Boundary
- TUFLOW Model Boundary
- Catchment Boundary

Title:
TUFLOW Hydraulic Model Layout Representing Current Day Conditions (2013)

Figure: **6-2**

Rev: **2**

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6.5.2 Topography

The ability of the model to provide an accurate representation of the both the creek flows and overland flow distribution on the floodplain ultimately depends upon the quality of the underlying topographic data. For the Hewitts Creek model, the ground surface elevation grid (2m resolution) has been derived from a combination of the following data sets:

- 1m DEM developed from LiDAR survey data;
- Additional topographical ground survey data; and
- Design and “works-as-executed” construction drawings.

The ground surface elevation for the TUFLOW model grid points are sampled directly from the DEM. It is a representation of the ground surface and does not include features such as buildings or vegetation. A high resolution DEM is important to suitably represent both in-bank and overland flow paths, such as roadway/gutter flows that are expected to provide significant flood conveyance within the study area.

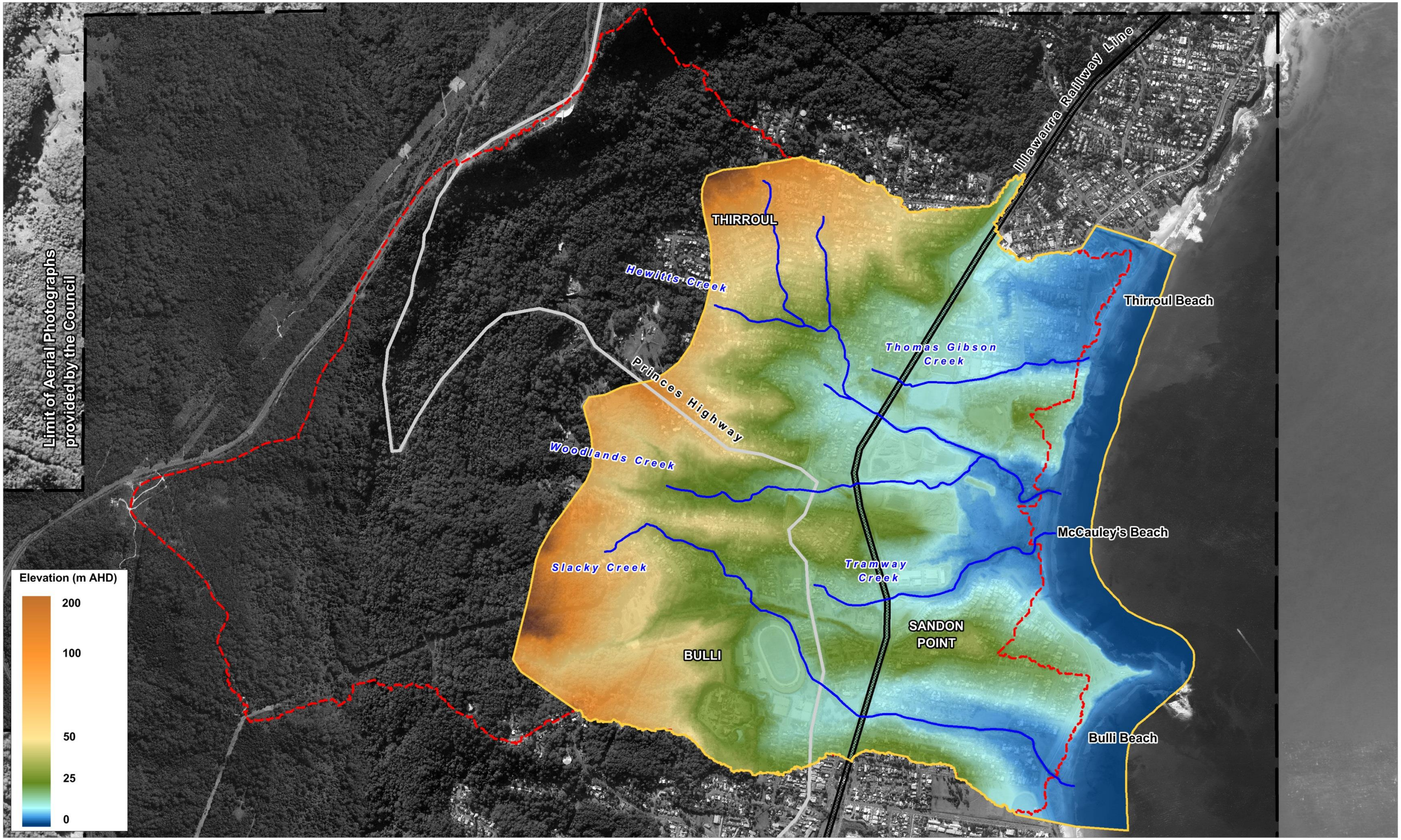
Local modifications to modelled ground surface levels have been made where appropriate to represent the creek channels and key floodplain features, i.e. embankments. These modifications have been based on topographical ground survey data and design and “works-as-executed” drawings.

It is noted that although brick walls and fences could also significantly affect local overland flood flow paths, these have not been explicitly incorporated into the model in urban areas except where:

- Significant lengths of continuous walls could impact on floodplain flows (i.e. the noise wall on the right bank of Tramway Creek alongside the Illawarra Railway at Sandon Drive, Bulli); and
- Historical flood information indicates that walls have had a localised impact on flood mechanisms and levels.

The influence of brick walls and fences on flood flows has been modelled using Manning’s ‘n’ roughness values, with appropriate Manning’s ‘n’ values based on industry standards (e.g. Chow, 1959) and verified as part of model calibration (refer to Section 7.2.4.5).

Details of the modifications to the modelled ground surface are outlined in the following sections. The resulting topography of the hydraulic model representing current day conditions (2013) is illustrated in Figure 6-3.



LEGEND

- Watercourses
- TUFLOW Model Boundary
- Catchment Boundary

Title:

Topography of the Hydraulic Model Representing Current Day Conditions (2013)

Figure: **6-3**

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6.5.2.1 Buildings

In general, a DEM developed from LiDAR data does not adequately represent building footprints, particularly for larger buildings.

For this Flood Study, ground elevations defining building footprints were processed on an individual basis using elevations sourced from the LiDAR-based DEM. The footprints of these buildings within the study area have been digitised from the available aerial photography.

Buildings have been modelled with a high Manning's 'n' value to represent the energy dissipation of water flowing through and around building (refer to Section 6.5.4).

6.5.2.2 Open Channels

LiDAR surveys are generally considered insufficient to define open channel geometry with an appropriate level of detail. In addition, LiDAR surveys cannot provide information on hydraulic structures, such as culverts and bridges. The LiDAR data was therefore supplemented with topographical survey data of the creeks to provide the necessary detail on channel shape and dimensions for representation in the hydraulic model.

Topographic survey data of the creeks was captured as part of the Hewitts Creek Flood Study (Forbes Rigby Pty Ltd., 2002a) by NSW Public Works (see Section 3.6). This survey data includes the post August 1998 geometry of Hewitts Creek and Slacky Creek which were surveyed to capture the erosion and deposition along these watercourses.

This data was supplemented with additional survey data captured in 2013 as part of the current Flood Study. This additional survey data was used to infill gaps in the survey data and undertake checks on the 2002 Flood Study data, particularly where natural geomorphological processes may have affected the shape and dimension of the creeks since the NSW Public Works survey data was captured.

For example, Figure 6-4 shows a comparison of the creek cross sections on Hewitts Creek upstream of Lachlan Street between survey data used to develop the hydraulic model as part of the 2002 Flood Study and the 2013 survey data.

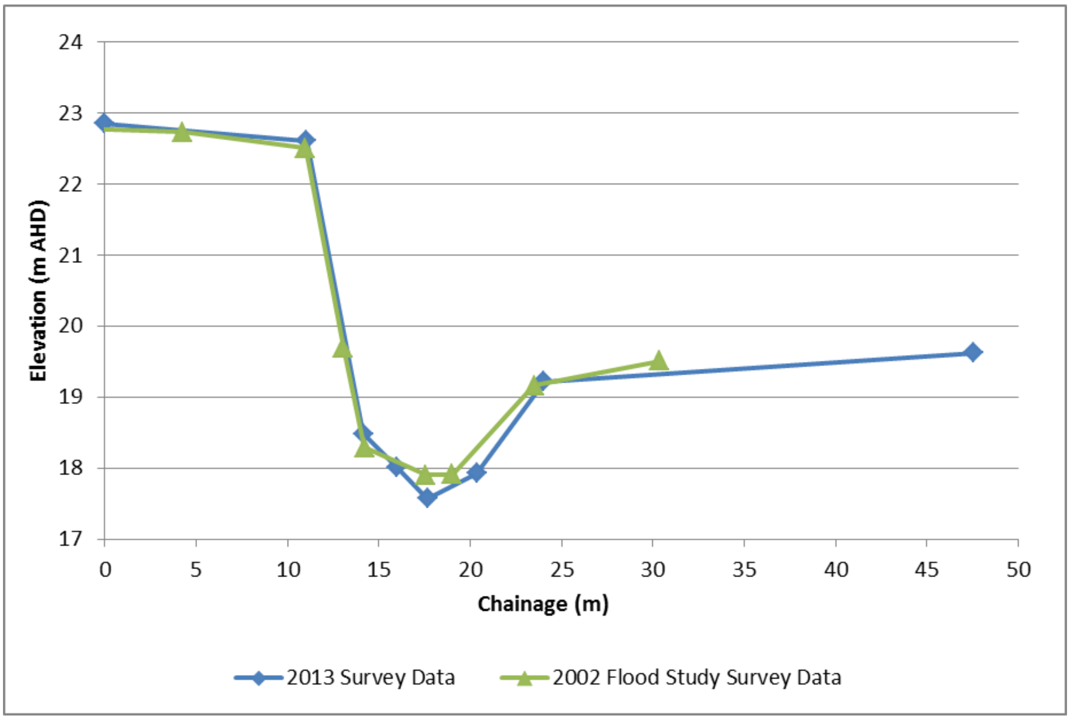


Figure 6-4 Comparison of Creek Cross Sections

The figure shows that there are minor differences between the two cross section profiles. This comparison has been undertaken at a total of eight locations along the creeks in the study area. The results for the majority of cross sections indicate minimal changes in both the in-bank and out of bank cross section profile. Based on this comparison, it its assumed that limited changes have occurred to the in-bank creek profiles surveyed as part of the 2002 Flood Study and that this survey data is sufficiently accurate for defining the geometry of the creeks throughout the study area as part of the current study. Therefore, the creek profiles surveyed as part of the 2002 Flood Study have been used to define the channels as part of the current study.

6.5.2.3 Topographical Features of the Calibration and Validation Models

The following topographical features have been included or removed from the TUFLOW model as part of model calibration and validation (refer to Section 7 for further details on selection of model calibration and validation events). Details of these features were gathered as part of the additional survey works and through data supplied by Council (refer to Section 3.6.3). These changes to the ground elevation of the hydraulic model have been required to represent features not captured within the DEM of the study area:

1998 Calibration Model

- The embankment of the detention basin adjacent to Slacky Creek at Black Diamond Place, Bulli, have been lowered at the railway underpass to Beacon Avenue to reflect the ground levels at this location prior to the embankment works undertaken in 2005;

<u>2013 Validation Event</u>

- Ground re-profiling works have been included in the model to represent the overland flow path constructed at the Esplanade, Thirroul, adjacent to Flanagans Creek;
- Revised channel representation has been included in the model upstream of Lachlan Street, Thirroul, to model improvements to culvert inlet on Hewitts Creek;
- Revised channel layout and floodplain re-profiling works as part of the new McCauleys Beach residential development in Thirroul, adjacent to Hewitts and Woodland Creeks, have been included in the model;
- Modifications to the floodplain of Woodlands Creek to include embankments and retaining wall as part of the construction of a bridge and associated road works at Princes Highway and Lawrence Hargrave Drive, Thirroul, have been included in the model;
- Noise wall on the right bank of Tramway Creek alongside the Illawarra Railway at Sandon Drive, Bulli has been included in the model;
- Ground re-profiling works as part of the residential development at Sandon Point, Bulli have been included in the model; and
- Embankment upgrade works and creek rehabilitation on a tributary of Slacky Creek at the site of the Old Bulli Mine Dam, Bulli have been included in the model.

<u>1988 Validation Model</u>

- Revised channel layout on Hewitts Creek to represent channel meanders adjacent to Corbett Avenue, Thirroul has been included in the model;
- Modifications to the channel at William Street, Bulli, to represent the overland flow path prior to the construction of the bridge has been included in the model; and
- The detention basin adjacent to Slacky Creek at Black Diamond Place, Bulli has been removed from the model.

6.5.3 Creek Entrances

The entrances to these creeks naturally open and close to the ocean predominantly as a result of sediment transport, tidal, wave, wind and fluvial process. The entrances will naturally close as waves and wind deposit sand in the entrances forming a berm. Runoff from the catchment and/or saline water from waves then builds up on the catchment side until the ponding level is higher than the berm. Naturally when the water level gets higher than the berm, the sand is scoured and the creek is connected to the ocean. This can also occur at lower levels if citizens illegally dig a channel through the berm. The entrance will then close over time.

Flanagans Creek, Slacky Creek and Hewitts Creek are defined as Intermittently Closed or Open Lakes or Lagoons (ICOLLs). ICOLLs are shallow coastal water bodies that are connected intermittently to the ocean. Under natural conditions, the berm is breached when either the ponding level reaches the berm level or catchment storm flows force a breach in the berm. Once the berm is breached, the lagoons tend to remain open to the ocean for only a few days.

Further discussion on the approach to modelling these ICOLLs and creek entrances for the calibration events is in Section 7, with discussion on the design event modelling approach in Section 8.

6.5.4 Hydraulic Roughness

The development of the TUFLOW model requires the assignment of different hydraulic roughness (Manning's 'n') zones. Values of the roughness coefficients have been based on industry standards (e.g. Chow, 1959) and adopted values of previous TUFLOW models developed by BMT WBM. Hydraulic roughness values have been applied based on the land use surface types present. Aerial photography, cadastral data and site visit notes have been used to identify different land use surface types (e.g. forest, cleared land, roads, urban areas, etc.) across the extent of the hydraulic model and apply appropriate Manning's n values to these surfaces.

Buildings have been modelled with a high Manning's 'n' value. This approach has been favoured over blocking out buildings as it includes the storage effects of the building being inundated. Figure 6-5 shows the hydraulic roughness zones adopted for the study area.

Fences can cause significant blockages to floodwaters and they have the added complication of tending to collapse during a flood. They may also be partially open (e.g. a picket fence), and may also become blocked with debris. These complex conditions are difficult to model on an individual fence by fence basis. As noted in Section 6.5.2, fences have not been explicitly incorporated into the model and the approach has been to apply an average impact (through increased roughness) to all urban blocks to allow for all fences within the Hewitt Creek Study Area.

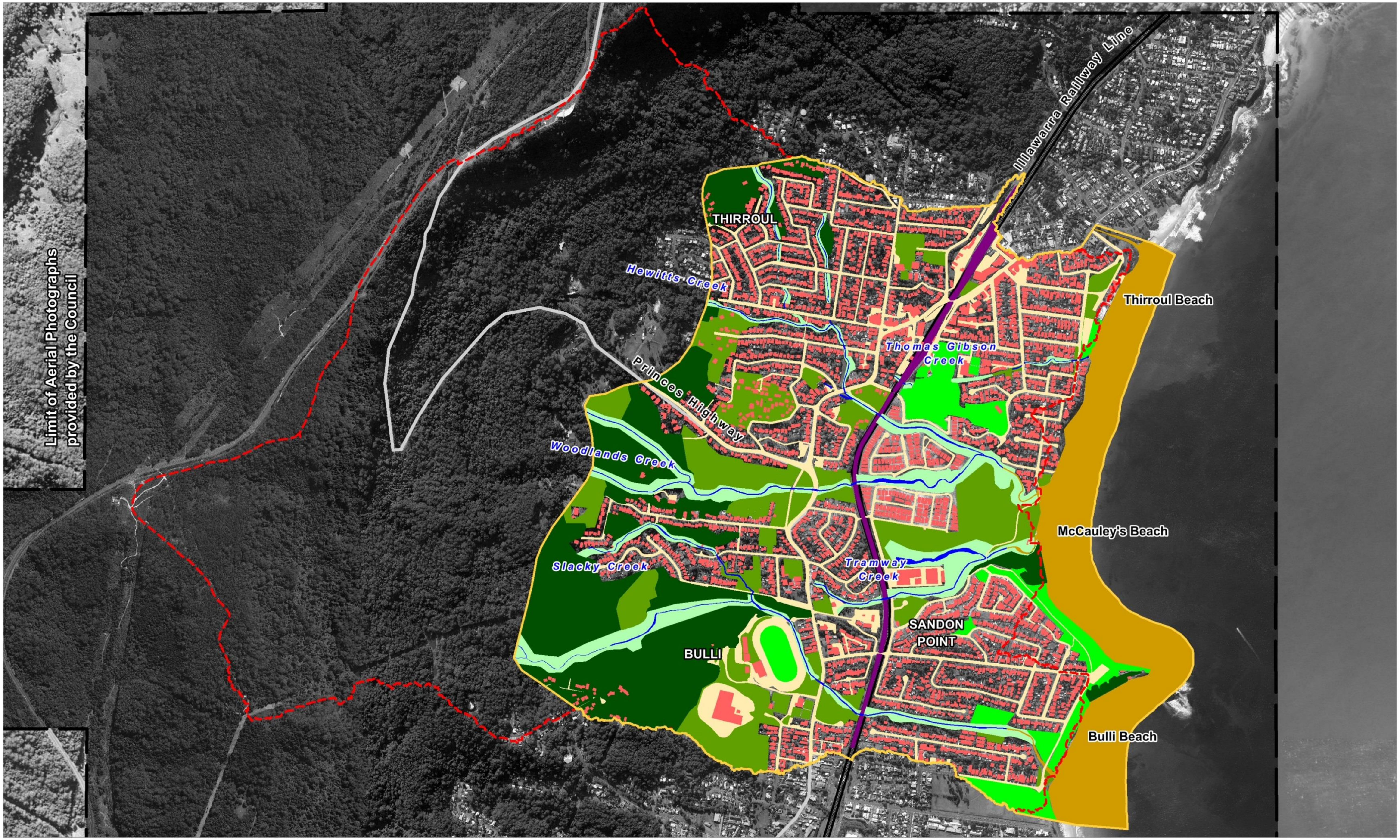
Hydraulic roughness is one of the principal calibration parameters within the hydraulic model and has a major influence on flow routing and flood levels. During the model calibration process the Manning's 'n' surface roughness values are adjusted locally (within reasonable bounds) to provide best fit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

Typical values of Manning's 'n' roughness coefficients for various land uses are shown in Table 6-3.

Table 6-3 Typical Manning's 'n' Roughness Coefficients for Various Land Uses

Land Use	Manning's 'n'
Grass (maintained)	0.025 - 0.035
Parkland	0.030 - 0.050
Dense vegetation	0.070 – 0.160
Creek channel	0.025 – 0.150
Roads, car parks, open concrete	0.014 - 0.020

Further discussion on the adopted Manning's 'n' values for each land use is discussed in Section 7.2.4.5. The roughness values have been subjected to sensitivity testing as discussed in Section 10.3.



LEGEND

TUFLOW Model Boundary	Grass (Maintained)	Creek Channels
Catchment Boundary	Parklands	Railway
	Dense Vegetation	Roads/Concrete
	Riparian Corridor	Buildings
	Estuary/Coast	

Title:
Hydraulic Roughness Zones in the TUFLOW Hydraulic Model Representing Current Day Conditions (2013)

Figure: 6-5

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6.5.5 Structures

There are a number of culverts and bridge crossings over the creek network within the Hewitts Creek study area as illustrated in Figure 6-2. These structures vary in terms of construction type and configuration, with varying degrees of influence on local hydraulic behaviour. Incorporating these major hydraulic structures into the hydraulic model accounts for hydraulic losses associated with these structures and their influence on flood behaviour within the study area.

The structures have been represented in the hydraulic model as either 1D or 2D structures. Table 6-4 details the suitability of modelling approach for the various structures within the study area.

Table 6-4 Hydraulic Structure Modelling Approaches

Structure	1D approach	2D approach
Box culvert (For culverts with a steep slope, use a 1D element)	OK	OK
Circular culvert	OK	N/A
Bridge	OK	OK
Weirs	OK	OK

The 1D approach is preferred where the total structure width is less than one or two 2D cell widths (i.e. 2m or 4m). As most of the structure widths are less than two 2D cell widths, the 1D approach has been used to model the majority of the structures. A 2D approach has been used to model large open structures, for example the new access bridges constructed as part of the McCauley's Beach development. The 2D cells are modified in their height (invert and obvert) and width and the energy losses and blockage caused by the piers and deck are applied directly to the 2D grid cells. Figure 6-2 shows the locations of structures modelled as 1D and 2D in the hydraulic model representing current day conditions (2013).

There are a number of structures where handrails are present. As survey data was not always available on the dimensions of the handrails, Google Street View was used to estimate the dimensions and extents of the handrails. For 2D structures, handrails and handrail blockages are modelled within the TUFLOW structure. For 1D structures, blockages at hand rails have been modelled raising the elevation of the ground levels within the model to represent the blockage.

6.5.5.1 Footbridges

From a review of aerial photos and site visit observations, the following locations were identified where footbridges cross Hewitts Creek:

- George Street, Thirroul, at properties numbered 77, 73, 69, 67, 51, 47, 45 and 37-39; and
- 27 Jennifer Crescent, Thirroul, (two footbridges).

This may not be a comprehensive list of all footbridges in the study area as footbridges are not always visible from aerial photos and access to the rear of properties backing onto the creeks (where the majority of footbridges are located) was difficult during site visits.

From site visit notes and aerial photos, the majority of the footbridges on Hewitts Creek appear to be relatively light structures and would likely be washed away in a significant flood event. Figure 6-6 shows examples of two of the footbridges on Hewitts Creek. These "lighter construction" footbridges are not included in the hydraulic model. Table 6-5 lists the footbridges which have been included in the hydraulic model.

Footbridge at George Street, Thirroul

Footbridge at Jennifer Crescent, Thirroul

Figure 6-6 Examples of two Footbridges on Hewitts Creek

6.5.5.2 Model Structures for Current Day Conditions (2013)

Table 6-5 lists the structures which have been included in the hydraulic model for current day conditions (2013).

Table 6-5 Structures Included within the Hydraulic Model for Current Day Conditions (2013)

Structure ID (Refer to Figure 6-2)	Watercourse	Street or Landmark	Structure Type	Structure Details	Structure Dimensions (m)
1	Slacky Creek	William Street, Bulli	Culvert	3 Rectangular Culverts	2 x 2.4m x 1.5m openings and 1 x 2.4m x 1.67m opening
2	Slacky Creek	Hobart Street, Bulli	Culvert	3 Circular Pipes	3 x 1.12m diameter
3	Slacky Creek, (western tributary)	Hobart Street, Bulli	Culvert	2 Rectangular Culverts	2 x 3.5m x 1.2m openings
4	Slacky Creek, (western tributary)	Hobart Street, Bulli	Culvert	1 Rectangular Culvert	1 x 2.7m x 3.0m opening
5	Slacky Creek	Hobart Street, Bulli	Culvert	2 Circular Culverts	2 x 1.82m diameter
6	Slacky Creek	Hobart Street (Coal haulage embankment), Bulli	Culvert	3 Rectangular Culverts	3 x 2.75m x 1.7m openings

Structure ID (Refer to Figure 6-2)	Watercourse	Street or Landmark	Structure Type	Structure Details	Structure Dimensions (m)
7	Slacky Creek	Adjacent to Bulli Showground and Racing Complex, Bulli	Culvert	4 Circular Culverts	4 x 0.45m diameter
8	Slacky Creek	Princes Highway, Bulli	Culvert	4 Rectangular Culverts	4 x 2.44m x 1.68m openings
9	Slacky Creek	Park at Black Diamond Place, upstream of the Illawarra Railway, Bulli	Culvert	2 Rectangular Culverts	2 x 2.85m x 3m openings
10	Slacky Creek	Illawarra Railway and Beacon Avenue underpass, Bulli	Culvert	2 Rectangular Culverts	1 x 4.8m x 5.9m opening and 1 x 4.8m x 4.05m opening
11	Slacky Creek	South of Beach Street, Bulli	Foot Bridge	Single Span Opening	9.4m wide opening at bridge soffit
12	Slacky Creek	Blackall Street, Bulli	Bridge	Single Span Opening	14.8m wide opening at the bridge soffit
13	Slacky Creek	Blackall Street, Bulli	Foot Bridge	Single Span Opening	14.8m wide opening at bridge soffit
14	Tramway Creek	Illawarra Railway, Bulli	Culvert	1 Circular Culvert	2.4m diameter
15	Woodlands Creek	Princes Highway, Bulli	Culvert	3 Rectangular Culverts	3 x 2.42m x 1.2m openings
16	Woodlands Creek	Disused heavy vehicle safety ramp at Princes Highway, Bulli	Culvert	4 Circular Culvers	4 x 1.52m diameter
17	Woodlands Creek	Illawarra Railway, Bulli	Culvert	1 Circular Culvert	2.57m diameter
18	Woodlands Creek	Air Avenue, Bulli	Bridge	2 Span Bridge	2 x 13.6m wide openings at the bridge soffit
19	Hewitts Creek	George Street, Thirroul	Foot Bridge	Single Span Bridge	5.9m wide opening at the bridge soffit
20	Hewitts Creek	George Street, Thirroul	Foot Bridge	Two Span Bridge	2 x 5.7m wide opening at the bridge soffit
21	Hewitts Creek	Kelton Lane, Thirroul	Bridge	Single Span Bridge	11.4m wide opening at the bridge soffit

Structure ID (Refer to Figure 6-2)	Watercourse	Street or Landmark	Structure Type	Structure Details	Structure Dimensions (m)
22	Hewitts Creek	Lachlan Street, Thirroul	Culvert	2 Rectangular Culverts	2 x 2.7m openings
23	Hewitts Creek	Lawrence Hargrave Drive , Thirroul	Culvert	3 Rectangular Culverts	3 x 2.75m x 2.45m openings
24	Hewitts Creek	Lawrence Hargrave Drive , Thirroul	Culvert	2 Circular Culverts	2 x 1.2m diameter
25	Hewitts Creek	High Street, Thirroul	Bridge	Single Span Bridge	3.2m wide opening at the bridge soffit
26	Hewitts Creek	Illawarra Railway, Thirroul	Bridge	Single Span Bridge	7.38m wide opening at the bridge soffit
27	Hewitts Creek	Brickworks Avenue, Thirroul	Bridge	3 Span Bridge	2 x 12.4m wide openings and 1 x 14.8m wide opening at the bridge soffit
28	Hewitts Creek	Hamilton Road, Thirroul	Foot Bridge	Twin Span Bridge	1 x 23.5m wide opening and 1 x 22m wide opening at the bridge soffit
29	Hewitts Creek (eastern tributary)	Palm Grove , Thirroul	Culvert	1 Circular Culvert	0.9m diameter
30	Hewitts Creek (eastern tributary)	Virginia Terrace, Thirroul	Culvert	1 Circular Culvert	1.2m diameter
31	Hewitts Creek (eastern tributary)	George Street Thirroul	Culvert	1 Circular Culvert	1.0m diameter
32	Hewitts Creek (western tributary)	Deborah Avenue, Thirroul	Culvert	1 Circular Culvert	1.5m diameter
33	Hewitts Creek (western tributary)	Virginia Terrace, Thirroul	Culvert	1 Circular Culvert	1.5m diameter
34	Hewitts Creek (western tributary)	George Street (West), Thirroul	Culvert	1 Rectangular Culvert	2.15m x 1.5m opening
35	Thomas Gibson Creek	Lawrence Hargrave Drive, Thirroul	Culvert	1 Circular Culvert	0.45m diameter
36	Thomas Gibson Creek	Illawarra Railway, Thirroul	Culvert	1 Circular Culvert	1.53m diameter
37	Thomas Gibson Creek	Thomas Gibson Park, Thirroul	Culvert	1 Circular Culvert	0.75m diameter
38	Thomas Gibson Creek	McCauley Street , Thirroul	Culvert	Single Circular Pipe	0.95m diameter

Structure ID (Refer to Figure 6-2)	Watercourse	Street or Landmark	Structure Type	Structure Details	Structure Dimensions (m)
39	Thomas Gibson Creek	Cliff Parade, Thirroul	Culvert	Single Circular Pipe	0.95m diameter

6.5.5.3 Calibration and Validation Model Structures

The hydraulic model representing the current day conditions (2013) was used to simulate the 2013 validation event, which includes the structures described in Section 6.5.5.2. For the 1998 and 1988 calibration and validation events, the following changes were implemented in the hydraulic models to reflect the structures in place at the time of these flood events.

<u>1998 Calibration Model</u>

For the 1998 flood event, the structures listed in Table 6-6 were not included in the hydraulic model as these were constructed after this flood event:

Table 6-6 Structures Not Included in the 1998 Calibration Model

Structure ID (refer to Figure 6-2)	Watercourse	Street	Structure Type	Structure Details
13	Slacky Creek	Blackall Street, Bulli	Foot Bridge	Single Span opening
18	Woodlands Creek	Air Avenue, Bulli	Bridge	3 Span Bridge
27	Hewitts Creek	Brickworks Avenue, Thirroul	Bridge	3 Span Bridge

Table 6-7 lists additional structures which have been included in the 1998 calibration model and which have since been replaced or removed.

Table 6-7 Additional Structures Included in the 1998 Calibration Model

Watercourse	Street	Structure Type	Structure Details	Structure Dimensions (m)
Slacky Creek	Blackall Street, Bulli*	Bridge	3 rectangular culverts	3 x 3.2m x 1.8m openings
Woodlands Creek	McCauley Beach Estate, Bulli	Culvert	2 rectangular culverts	2 x 1.58m x 1.74m openings
Hewitts Creek	Downstream of Illawarra Railway near Lawrence Hargrave Drive, Thirroul	Bridge	Single Span Bridge	5.76m wide opening
Hewitts Creek	Downstream of Illawarra Railway near Lawrence Hargrave Drive, Thirroul	Bridge	Single Span Foot Bridge	5.76m wide opening

*Structure has been replaced by a single span bridge for the design model runs. Refer to structure ID 12 in Table 6-8 .

1988 Validation Model

In addition to the changes listed in Table 6-6 and Table 6-7, the structures listed in Table 6-9 were not included in the model for the 1988 validation event, as these structures were not in place at the time of this event.

Table 6-9 Structures Not Included in the 1988 Validation Model

Structure ID (Refer to Figure 6-2)	Watercourse	Street	Structure Type	Structure Details
1	Slacky Creek	William Street, Bulli	Culvert	3 Rectangular Culverts
9	Slacky Creek	Park at Black Diamond Place u/s of Illawarra Railway, Bulli	Culvert	2 x 2.85m x 3m openings

The dimensions and elevations of the old triple cell culvert at Blackall Street, Bulli, were used to replace the single span culvert at this location.

6.5.5.4 Structure Blockages

The potential for culverts or other hydraulic structures to become blocked by debris during floods was identified as a major contributor to the devastation caused throughout the Wollongong region during the August 1998 floods. In many cases, the hydraulic capacity of culverts, bridges and underground pipe systems was completely eliminated or severely restricted as a result of the blockages.

Referring to the modelled hydraulic structures in Table 6-5, it can be seen that the structure dimensions vary in both size and configuration. Based on Council's Conduit Blockage Policy (Wollongong City Council, 2009), the following blockage factors have been applied to structures across all watercourses for the design flood events:

- 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.

Several model simulations have been undertaken to identify the combination of blocked and unblocked culverts and bridges which produces the worst flooding scenario for the estimation of design flood levels using an enveloped approach. This analysis is described in Section 8.

The degree of blockages applied to culverts and bridges as part of the model calibration and validation is discussed in Section 7.

6.5.6 Boundary Conditions

The model boundary conditions are derived as follows:

- Inflow. The catchment runoff has been determined through the hydrological model and is applied to the TUFLOW model as flow versus time inputs. These are applied to the hydraulic model at the sub-area outlets as either a total or local flow input; and
- Downstream Water Level. The downstream model limit corresponds to the tidal water level in the Tasman Sea. A water level time series has been applied at this location for the duration of the modelled calibration and design events.

Figure 6-2 shows the location of the point inflows and the downstream boundary. The adopted water level boundary for the calibration and design events is discussed further in Sections 7 and 8 with details of the tide gauges used to inform these events in Section 3.5. The model inflows have been subject to sensitivity testing as discussed in Section 10.2. Based on the Councils adopted sea level rise projections, design ocean boundary conditions were raised by 0.4 m and 0.9 m in additional scenarios to assess the potential impact of sea level rise on future flood behaviour as discussed in Section 9.