Middle Harbour Southern Catchments Flood Study

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Author	Kieran Smith, Nam Nguyen
Reviewed By	Nathan Cheah, Jacquie Hannan
Project Manager	Nathan Cheah

Amendment Record

The Amendment Record below records the history and issue status of this document.

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Executive Summary

The Middle Harbour Southern Catchments Flood Study has been prepared for Ku-ring-gai Council to define the existing flood behaviour within this portion of the Ku-ring-gai Local Government Area. The study area covers an approximately 9.7 km^2 catchment that drains to the Middle Harbour Estuary, and includes the suburbs (or parts) of Roseville Chase, Roseville, Lindfield, East Lindfield, Killara and East Killara. The study is focused on local overland flooding conditions within the urban environment in response to rainfall.

This flood study forms an initial stage towards the development of a comprehensive Floodplain Risk Management Study and Plan that will ultimately guide the direction of future floodplain risk management activities across the Middle Harbour Southern Catchments. The primary objective of the study is to define the flood behaviour under historical, existing and future conditions (incorporating potential impacts of climate change) for a range of design floods. The definition of flood behaviour will aid in Council's management of flood risk, including flood related land use and development controls, emergency management planning and response within the study area.

Specifically, the study comprised the following components:

- Compilation and review of existing information relevant to the study;
- Additional data collection, including survey;
- Community consultation and participation program to identify local flooding concerns and collect information on historical flood behaviour;
- Development of appropriate hydrologic and hydraulic models and verification for historical events to confirm that simulated results match the observed conditions within the catchment;
- Determination of design flood conditions for a range of design events for local overland flows, including the 20%, 10%, 5%, 2%, 1%, 0.5% and 0.2% Annual Exceedance Probability (AEP) events, and the Probable Maximum Flood (PMF); and
- Assessment of the potential impact of climate change using the latest guidelines.

The principal output from the flood modelling is a comprehensive set of design flood maps to visualise the potential flood inundation and associated flood risks across the study area. This includes peak flood level, depth, velocity, hazard and flood function mapping. The study also includes the following information to assist Council in future floodplain management and land use planning:

- Identification of properties experiencing flooding in each design event;
- Derivation of a Flood Planning Area (FPA) for application of land use development controls;
- Flood Planning Constraint Categories to guide land use planning for future development;
- SES Flood Emergency Response Classification of Communities.

The Flood Study is documented in the following two volumes:

- Volume 1 - Report and Appendices
- Volume 2 – Mapping

Glossary

afflux	The change in water level from existing conditions resulting from a change in the watercourse or floodplain – e.g. construction of a new bridge.
Annual Exceedance Probability (AEP)	The chance of a flood of a given size (or larger) occurring in any one year, usually expressed as a percentage. For example, if a peak flood discharge of 500 m^3/s has an AEP of 5%, it means that there is a 5% chance (i.e. a 1 in 20 chance) of a peak discharge of 500 m^3/s (or larger) occurring in any one year. (see also average recurrence interval)
Australian Height Datum (AHD)	National survey datum corresponding approximately to mean sea level.
astronomical tide	Astronomical tide is the cyclic rising and falling of the Earth's oceans water levels resulting from gravitational forces of the Moon and the Sun acting on the Earth.
attenuation	Weakening in force or intensity
Average Recurrence Interval (ARI)	The long-term average number of years between the occurrence of a flood as big as (or larger than) the selected event. For example, floods with a discharge as great as (or greater than) the 20yr ARI design flood will occur on average once every 20 years. ARI is another way of expressing the likelihood of occurrence of a flood event. (see also annual exceedance probability)
Australian Rainfall and Runoff (AR&R)	Engineers Australia publication pertaining to rainfall and flooding investigations in Australia
calibration	The adjustment of model confuguration and key parameters to best fit an observed data set
catchment	The catchment at a particular point is the area of land that drains to that point.
critical duration	The critical duration is the design storm duration which provides the highest peak water levels for a given design flood (e.g. 1% AEP) at a given location. For example, if the following design durations were modelled - 2-hour, 6-hour, 9-hour and 12-hour – and the 9-hour duration resulted in the highest peak water level at a given location then the critical duration for that location would be 9-hours.
design flood event	A hypothetical flood representing a specific likelihood of occurrence (for example the 100yr ARI or 1% AEP flood).
development	Existing or proposed works that may or may not impact upon flooding. Typical works are filling of land, and the construction of roads, floodways and buildings.

discharge	The rate of flow of water measured in tems of 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).
Extreme Flood	An extreme flood deemed to be the maximum flood likely to occur (for this study the Extreme Flood event was defined as three times the 1% AEP event).
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) or Extreme Flood event.
floodplain management	The co-ordinated management of activities that occur on the floodplain.
floodplain risk management plan	A document outlining a range of actions aimed at improving floodplain management. The plan is the principal means of managing the risks associated with the use of the floodplain. A floodplain risk management plan needs to be developed in accordance with the principles and guidelines contained in the NSW Floodplain Management Manual. The plan usually contains both written and diagrammatic information describing how particular areas of the floodplain are to be used and managed to achieve defined objectives.
Flood Planning Area (FPA)	The area of land below the Flood Planning Level and subject to flood related development controls.

Flood Planning Levels (FPLs)	Flood Planning Levels selected for planning purposes are derived from a combination of the adopted flood level plus freeboard, as determined in floodplain management studies and incorporated in floodplain risk management plans. Selection should be based on an understanding of the full range of flood behaviour and the associated flood risk. It should also take into account the social, economic and ecological consequences associated with floods of different severities. Different FPLs may be appropriate for different categories of landuse and for different flood plans. The concept of FPLs supersedes the “standard flood event”. As FPLs do not necessarily extend to the limits of flood prone land, floodplain risk management plans may apply to flood prone land beyond that defined by the FPLs.
flood prone land	Land susceptible to inundation by the probable maximum flood (PMF) or Extreme Flood 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. In this study, overland flow is the primary source of 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	The term given to the study of water flow in rivers, estuaries and coastal systems.
hydrodynamic	Pertaining to the movement of water
hydrograph	A graph showing how a river or creek’s discharge changes with time.
hydrographic survey	Survey of the bed levels of a waterway.
hydrologic	Pertaining to rainfall-runoff processes in catchments
hydrology	The term given to the study of the rainfall-runoff process in catchments.

hyetograph	A graph showing the depth of rainfall over time.
Intensity Frequency Duration (IFD) Curve	A statistical representation of rainfall showing the relationship between rainfall intensity, storm duration and frequency (probability) of occurrence.
LiDAR	Light Detection and Ranging –a remote sensing method used to generate ground surface elevation. Typically acquired through airborne surveys from which an aeroplane can cover large areas.
overland flow	Overland flow is surface run off before it enters a waterway. It is caused by rainfall which flows downhill along low points concentrating in gullies, channels, surface depressions and stormwater systems.
peak flood level, flow or velocity	The maximum flood level, flow or velocity that occurs during a flood event.
pluviometer	A rainfall gauge capable of continously measuring rainfall intensity
Probable Maximum Flood (PMF)	An extreme flood deemed to be the maximum flood likely to occur.
probability	A statistical measure of the likely frequency or occurrence of flooding.
riparian	The interface between land and waterway. Literally means “along the river margins”.
runoff	The amount of rainfall from a catchment that actually ends up as flowing water in the river or creek.
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.

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1 Introduction

1.1 Background

The Kur-ring-gai Local Government Area (LGA) is located in Sydney's northern suburbs. The Middle Harbour Southern Catchments Flood Study covers an area of approximately 9.7 km^2 draining to the southern tributaries of Middle Harbour within the LGA.

Steep terrain and ridge-top development have historically contributed to flood risk within the Ku-ring-gai LGA, resulting in flash flooding along headwater streams and drainage depressions. Whilst Ku-ring-gai Council ("Council") has previously developed large-scale flood models and undertaken drainage assessments for this catchment, there is currently insufficient information available to provide a detailed understanding of flood behaviour for use in flood risk management and planning. Furthermore, recently completed and future planned developments have highlighted the need for updated flood mapping.

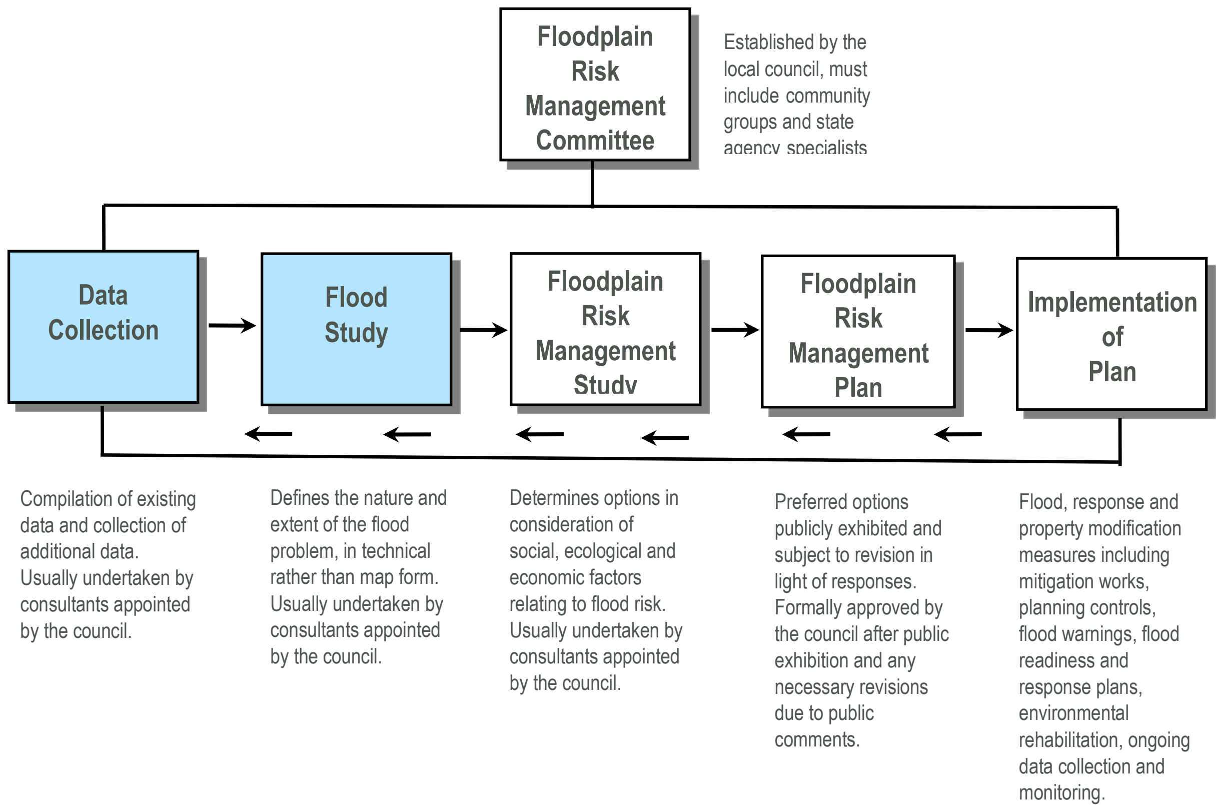
Accordingly, Ku-ring-gai Council engaged BMT Commercial Australia Pty Ltd ("BMT") to undertake the Middle Harbour Southern Catchments Flood Study to define the historic, existing, and potential future flood risk across the southern portion of the LGA. The flood study will form the basis upon which future flood risk management processes and a flood risk management study and plan will be undertaken which will guide future flood risk management actions. The study will also be used in the assessment of development applications and for other future planning decisions.

1.2 Floodplain Risk Management Process

Flooding in NSW is managed in accordance with the NSW Government's Flood Prone Land Policy. The Policy is directed towards providing solutions to existing flooding problems in developed areas, understanding potential future increases in flood risk, and ensuring that new development is compatible with its flood risk exposure and does not create additional flooding problems in other areas.

The NSW Government's *'Floodplain Development Manual'* (2005) supports the Policy by defining the responsibilities, roles and processes for the management of flood liable land in NSW. Under the Policy, the management of flood liable land is the responsibility of the local authority, in this case Ku-ring-gai Council, with technical and financial support from the NSW Government. This includes the development and implementation of local flood studies and floodplain risk management studies and plans to define and manage flood risk. These are prepared through the staged approach defined by the NSW Floodplain Management Process shown in Figure 1.1.

The Middle Harbour Southern Catchments Flood Study represents Stage 1 of the process and aims to compile relevant data and provide an understanding of flood behaviour in the study area. Ku-ring-gai Council has prepared this document with financial assistance from the NSW Government through its Floodplain Management Program. This document does not necessarily represent the opinions of the NSW Government or the Office of Environment and Heritage.



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

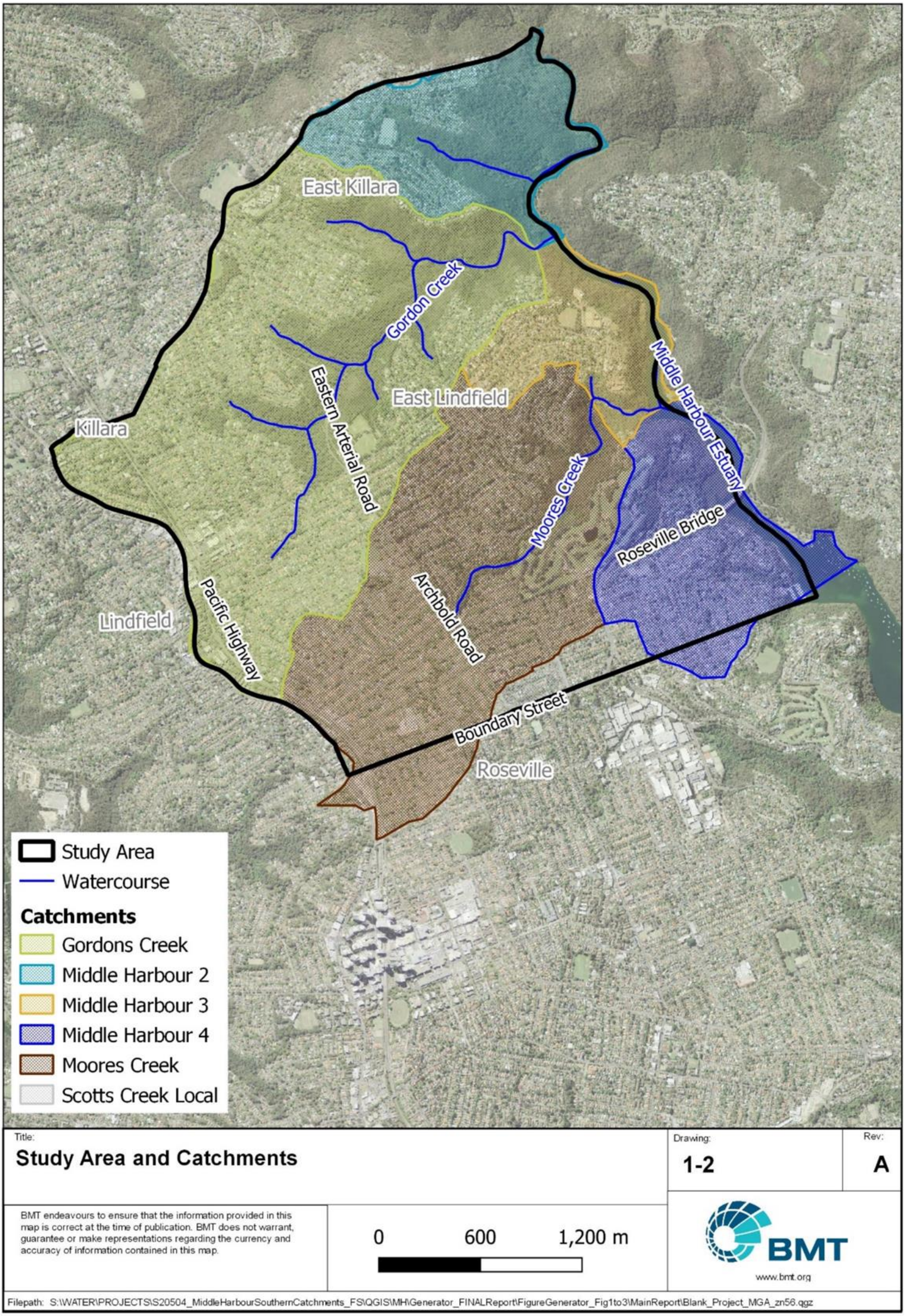
Figure 1.1 Stages of the Floodplain Management Process

1.3 Study Area

The extent of the study area is shown in Figure 1.2 and comprises an area of approximately 9.7 km^2 that drains to the Middle Harbour Estuary, which lies along the eastern boundary of the LGA (and the study area). It covers the southern portion of the Ku-ring-gai LGA, including the suburbs (or parts) of Roseville Chase, Roseville, Lindfield, East Lindfield, Killara and East Killara.

Watercourses within the study include Gordon Creek and Moores Creek. Moores Creek comprises both natural channel sections, as well as a 400 m long concrete channel section that forms a Sydney Water stormwater easement. Gordon Creek is a natural channel, with a small reach located in urban areas upstream of Tryon Road and the remainder located in heavily vegetated areas discharging to Middle Harbour. The study area has been divided up into primarily five catchments draining either into Moores Creek, Gordon Creek or directly into Middle Harbour (split into 3 catchments named Middle Harbour 2, Middle Harbour 3 and Middle Harbour 4), as shown in Figure 1.2. Also shown in the figure is a small catchment north of Boundary Street which discharges into Scotts Creek located within the Willoughby LGA.

The local catchments comprise predominantly residential areas located at the top of ridgelines which drain through steep bushland reserves to undeveloped, vegetated waterway corridors (such as Gordon Creek and Moores Creek) and valleys that ultimately drain to Middle Harbour. Higher density residential and commercial development is centralised along the Pacific Highway and North Shore rail corridor in the west of the catchment and Boundary Street in the south of the catchment. Several large open recreational areas (notably Lindfield Oval, Roseville Park, Swain Gardens and Roseville Golf Course), as well as several schools such as Roseville Public School, Lindfield Public School, Cromehurst School and Lindfield East Public School, are also located within the study area.



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Study Area and Catchments

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Accordingly, the upstream catchment is generally characterised by lower rainfall infiltration losses and more rapid response to runoff due to the higher proportion of impervious surfaces (e.g. roadways, paved surface, buildings, etc). Whilst lower, undeveloped sections of the catchments are typically characterised by higher rainfall infiltration losses and relatively slower runoff response due to the higher proportion of pervious surfaces (e.g. vegetation, grass, etc).

Urban areas of the catchments are typically drained by drainage networks comprising open channels and sub-surface stormwater systems. These stormwater networks either connect into watercourses that drain into the major creeks or discharge directly to the major receiving watercourses. During periods of heavy rainfall, there is potential for the capacity of the stormwater system to be exceeded. In these circumstances, the excess water travels overland and may result in inundation of roadways and adjoining properties. There is also potential for floodwaters to overtop the banks of channels and inundate the adjoining floodplain where open watercourse sections drain through urban areas.

During major flooding, the lower parts of the catchments can also be inundated by backwater from Middle Harbour. Elevated water levels in receiving watercourses may also inhibit drainage of the study area following a major flood event.

1.4 Objectives and Scope of this Study

The primary objective of this flood study is to define overland flood behaviour across the urbanised portions of the study area under historic, existing and future conditions (incorporating potential impacts of climate change). This improved appreciation of flood behaviour will aid in Council's management of flood risk, including informing flood impact assessment, strategic land use, flood-related development control, stormwater management and flood emergency response. It will also enable the identification of flooding "hot spots" and the relative magnitude of flood-related problems to be prioritised to provide Council with a basis upon which to undertake a program of more detailed overland flow flood studies.

The general approach adopted to achieve the study objectives is as follows:

- Compilation and review of relevant data, including site inspections;
- Development of computer based hydrologic and hydraulic models;
- Calibration and validation of the computer models to reproduce historical flood behaviour;
- Simulation of the 20%, 10%, 5%, 2%, 1%, 0.5% and 0.2% Annual Exceedance Probability (AEP) design events and the Probable Maximum Flood (PMF) for existing topographic and development conditions;
- Determination of design flood characteristics, flood risk and flood emergency response considerations within the study area;
- Assessment of potential climate change impacts.

1.5 Report Structure

This report comprises two volumes:

- Volume 1 (this document) contains the report text and appendices including:
  - Section 1 provides background to the study, introduces the flood study, and describes the study area.
  - Section 2 details the data collection and review.
  - Section 3 describes the community consultation process.

  - Section 4 details the development of the hydrologic and hydraulic models.
  - Section 5 details the model verification process and outcomes.
  - Section 6 details the design flood modelling approach.
  - Section 7 details the design flood results.
  - Section 8 details the sensitivity and climate change assessment.
  - Section 9 provides information pertaining to flood planning.
  - Section 10 provides the study conclusions and recommendations.
  - Section 11 provides the list of references used in the study.
- Volume 2 contains all flood mapping relevant to the study.

2 Data Collection and Review

2.1 Overview

The initial stage of this flood study involved the collection and review of relevant data, including:

- Previous studies (Section 2.2);
- Geographical Information System (GIS) data (Section 2.3);
- Hydrologic data (Section 2.4);
- Topographic data (Section 2.5);
- Stormwater network data (Section 2.6);
- Land-use planning information (Section 2.7);
- Building footprints (Section 2.8);
- Site inspections (Section 2.9);
- Additional survey (Section 2.10).

A description of each dataset and its relevance in the context of the current study are presented in the following sections.

2.2 Previous Studies

2.2.1 Moores Creek (SWC 69) Capacity Assessment (Sydney Water Cooperation, 2002)

Sydney Water undertook a quantitative performance review of Sydney Water's Moores Creek (SWC 69) stormwater drainage system which drains to Middle Harbour. The report provides detailed catchment and drainage asset information, including information about the various branches and conduit types that form the Moores Creek system.

The performance of the system, measured in terms of peak hydraulic capacity during specific average recurrence interval events, was determined based on flow rates calculated using the Rational Method and hydraulic capacity of the assets determined based on the Manning's Equation. The report documents the following hydraulic capacity for the Moores Creek system:

- 67% of the drainage network has capacity below the 20% AEP event;
- 78% of the drainage network has capacity below the 10% AEP event;
- 94% of the drainage network has capacity below the 5% AEP event.

2.2.2 Local Catchment Plans, Rocky Creek, Gordon Creek, Moores Creek, Middle Harbour Creeks (Hughes Trueman, 2004)

Hughes Trueman completed a local catchment plan for Council in 2004. This plan covered the areas of Ku-ring-gai LGA that drain via Rocky Creek, Gordon Creek, Moores Creek and four un-named creeks to Middle Harbour. It included the development of combined hydrologic and hydraulic models for each catchment using DRAINS software, and simulation of the models for the 20%, 10%, 5% and 1% AEP events, as well as the Probable Maximum Precipitation (PMP) event.

The DRAINS models developed as part of the '*Local Catchment Plans, Rocky Creek, Gordon Creek, Moores Creek, Middle Harbour Creeks*' (Hughes Trueman, 2004) have been utilised as the hydrologic input for this flood study[1]. Specific details of the DRAINS models and findings from the study for the Moores Creek and Gordon Creek catchments are outlined below.

Review of DRAINS Models

Sub-catchment Delineation and Parameterisation

The DRAINS models utilised pit and pipe data supplied by Council (including 4,042 pits and nodes) as the starting point for which sub-catchments, overland flow paths and design rainfall conditions were derived.

GIS contours were used to determine the contributing catchment draining to each inlet pit, headwall or node (pipe discharging to creeks) as well as the slope. For each contributing catchment (or sub-catchment), the proportion of impervious area was determined from inspection of aerial photography and catchment type (i.e. whether the area was residential, commercial, parkland or bushland). A supplementary area (defined as an impervious area draining through a pervious area) was assigned to each sub-catchment with a pervious percentage greater than 20% (an arbitrarily chosen amount).

For each sub-catchment area draining to a pit, a flow path length was drawn representing the longest path water would be likely to travel to reach the pit outlet. This flow path length was assigned to the impervious portion of the catchment, however depending on the impervious flow path length an additional grass flow path length was added to represent the different travel times across various surfaces in the catchment.

A GIS layer of the delineated sub-catchments for four of the five DRAINS models was supplied to BMT at the beginning of the study. The GIS layer for the Middle Harbour 2 (MH2) sub-catchments could not be sourced. A review of the sub-catchments undertaken by BMT found that the catchment sizes, slopes and flow path lengths generally matched the latest available Digital Elevation Model (DEM) data, although there were a few locations where catchments had to be redefined to ensure all contributing upstream areas were included. The review also determined that for areas in the downstream part of the study area (where inlet nodes were not supplied), no sub-catchments had been delineated by Hughes Trueman (2004).

Design Rainfall Information

Rainfall data used in the DRAINS models was determined from Ku-ring-gai Council's Rainfall Intensity-Frequency-Duration (IFD) data published in Ku-ring-gai Council's '*Water Management Development Control Plan*' (2004). Design storms for the 20%, 10%, 5% and 1% AEP and the PMP storm events were run in DRAINS for each sub-catchment for the 10, 20, 30, 45, 60, 90, 120 and 180 minute storm events.

Rainfall Losses

Values for the initial loss in paved (representing impervious) and grassed (representing pervious) areas were taken as 1 mm and 5 mm respectively as recommended in the DRAINS software manual. A DRAINS soil type "3" was nominated for the study area, indicating an area that has higher runoff potential and a lower infiltration rate.

[1] Seven (7) DRAINS models were developed as part of the Hughes Trueman (2004) Study. Three (3) covered the areas of the major tributaries of Middle Harbour (Rocky Creek, Gordon Creek and Moores Creek) and four (4) covered the area draining to the Middle Harbour tributary itself (Middle Harbour 1, 2, 3 and 4). The Middle Harbour 1 and Rocky Creek DRAINS models form part of the Middle Harbour Northern Catchments Flood Study and are not discussed in this report. The Gordon Creek, Moores Creek and Middle Harbour 2, 3 and 4 DRAINS models have been utilised in this study.

The DRAINS software package allows for the selection of an Antecedent Moisture Condition (AMC) which accounts for the moisture condition of the soil in the leadup to an event. An AMC of 3 (representing a rather wet catchment that has experienced between 12.5 and 25 mm rainfall in the previous 5 days) was chosen for all storm events.

Summary

The DRAINS models developed as part of Hughes Trueman (2004) have been adopted as a preliminary input for use in this study. Alterations to the DRAINS models to match current catchment conditions, updated delineation of sub-catchments within the MH2 catchment and downstream areas, and conversion of the model for use with Australian Rainfall and Runoff 2019 (ARR 2019) methodologies have been undertaken as part of this study (see Section 4.2 for further details).

Results of the Study

The results of the Hughes Trueman (2004) DRAINS modelling were used to assess the performance of the existing drainage systems (at the time the study was completed). Hughes Trueman (2004) found that the pipe system capacity across the Middle Harbour did not comply with modern design standards primarily due to inadequate capacity of stormwater inlet pits. Specifically, the study found that:

- 66% of the pipe drainage system is capable of conveying the flow from a 5% AEP storm;
- 70% of the inlet pits have inadequate capacity to drain flows from a 5% AEP storm.

A summary table of the report's findings in terms of both pit and pipe inlet capacities are shown in Table 2.1.

Table 2.1 Drainage Constraints Identified by Hughes Trueman (2004)

Drainage Constraint	AEP Event							
	20%		10%		5%		1%	
	No.	%	No.	%	No.	%	No.	%
Pits with Inlet Constraints	2,865	71%	2,824	70%	2,811	70%	2,746	68%
Pipes with Flow Constraints	479	12%	565	13%	548	14%	637	16%
No Constraints	698	17%	693	17%	683	17%	659	16%

Table 2.2 Pipe Capacities Identified by Hughes Trueman (2004)

Event	Percentage of total pipe network with capacity at or below nominated event
<1 EY	9%
1 EY	7%
0.5 EY	9%
20% AEP	5%

Event	Percentage of total pipe network with capacity at or below nominated event
10% AEP	4%
5% AEP	5%
2% AEP	3%
1% AEP	27%
PMP	31%

The study found these inadequate capacities led to widespread nuisance flooding throughout the catchment. The report identified the following flooding hotspots within the study area:

- Lindfield Avenue to Woodside Avenue, Lindfield – Overland flow down Lindfield Avenue passes through properties downstream of Woodside Avenue, across the Havilah Road sag through properties on Milray Street and into the open channel.
- Nelson Road, Lindfield – flow draining to the open channel on Milray Street is constrained at the opening and floods properties along Nelson Road and Lightcliff Avenue.
- Bancroft Avenue near Wandella Avenue, Roseville – constrained drainage network in the Bancroft Road area constricts larger overland flows in the area causing backwater effects.

2.2.3 Ku-ring-gai Council Preliminary Flood Mapping Report (Mott MacDonald, 2011)

Ku-ring-gai Council commissioned Mott MacDonald to complete preliminary floodplain mapping for the LGA that would inform flood planning and land use zoning. The DRAINS models from Hughes Trueman (2004) were used for hydrologic estimates and a HEC-RAS 1D (One-Dimensional) hydraulic model was developed. The following parameters were adopted for design flood conditions:

- Impervious (paved) depression storage of 1 mm; and
- Pervious (grassed) depression storage of 5 mm.

DRAINS outputs were verified against Rational Method calculations. The DRAINS model hydrologic data was input into the HEC-RAS model where:

- Flows exceeded the drainage system capacity and were surcharging onto the surface; and
- Flows were discharging into the open channel sections of the network.

A 20% and 50% blockage factor were applied to on-grade and sag pits.

Flood levels obtained from the HEC-RAS hydraulic model were processed to develop a continuous water surface profile between the model cross-sections. The level difference between the water surface profile and the ground elevation provided an indicative 5% AEP and 1% AEP flood extents. The report identified the chief flood mechanism in the catchment is characterised by the occurrence of short intense storms which lead to fast flowing surface runoff through residential areas.

2.3 Geographic Information System (GIS) Data

A number of digital Geographic Information System (GIS) layers were also provided by Council to assist with this flood study, including:

- Study area extent;

- Cadastral lot boundaries;
- Locations of community hall, schools and childcare centres;
- Locations of drainage infrastructure including pits and pipes;
- Drainage catchments;
- Environmental management data including watercourses assessment lines;
- Current flood risk mapping;
- Roadway data (used for roadway labels);
- Land use zoning from Council's Local Environment Plan (LEP) 2015;
- Mapping from Hughes Trueman (2004), including catchment polygons, catchment outlets, stormwater networks details and overland flow paths from the DRAINS model;
- Locations of cycle facilities (i.e. cycle paths);
- Locations and details of water quality devices and catchments.

In general, the GIS layers provide a suitable basis for preparing report figures and informing the development of hydrologic and hydraulic models. Further details on the outcomes of the review of the stormwater layers is provided in Section 4.3.7.

2.4 Hydrologic Data

2.4.1 Rainfall Data

Daily and sub-daily gauge data provides a high-quality rainfall dataset for use in the model calibration and validation process. It is used to define when historical rainfall events occurred, as well as the temporal pattern and rainfall depths for these events.

The Bureau of Meteorology (BoM) operates an extensive network of rainfall gauges across Australia. At present, there are twenty-four (24) operational gauges within a 15 km radius of the Middle Harbour Southern Catchments study area centroid, with another eighty-nine (89) being discontinued sometime previously. Of these twenty-four (24) gauges, twenty (20) are daily read rainfall gauges and the remaining four (4) are sub-daily rainfall gauges.

Sydney Water also operates an extensive network of sub-daily rainfall gauges across Australia. At present, there are thirty-one (31) operational gauges within a 15 km radius of the Middle Harbour Southern Catchments study area centroid, with another three (3) being discontinued sometime previously.

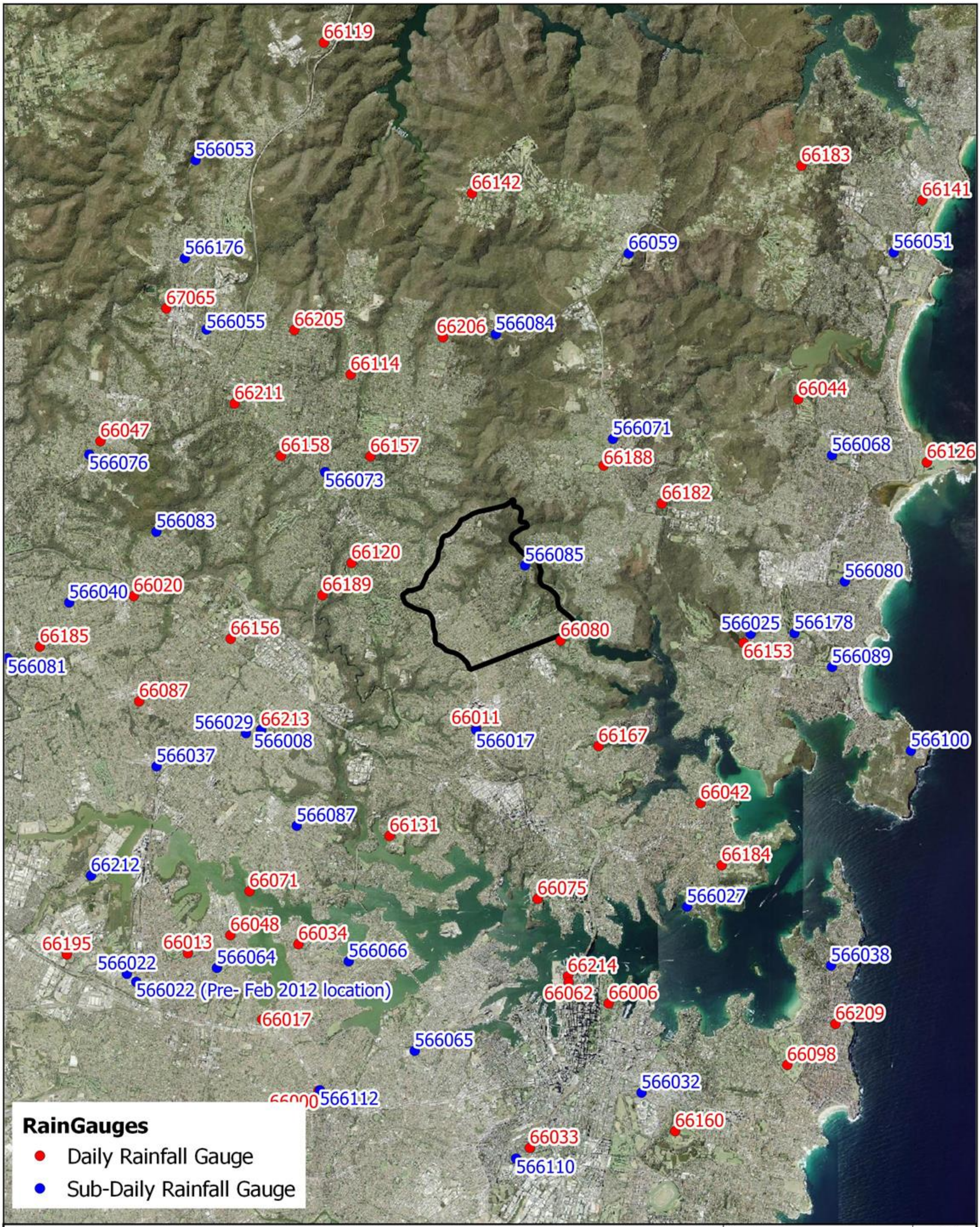
Annex A contains the full list of rainfall stations (including closed stations) and their respective periods of record. The location of gauges with data from 1998 to present (the period within which significant storms were identified as part of the Community Consultation - refer Section 3) is shown in Figure 2.1.

For historical events, the recorded rainfall totals at daily and continuous rainfall gauges provide the observed rainfall depth, whilst the recorded hyetographs at the sub-daily rainfall gauges provide the temporal pattern. The spatial distribution of the gauges throughout the region allowed for the reasonable approximation of the historical temporal patterns across the study area.

The number of sub-daily gauges within 15 km of the study area, along with long operating periods results in at least thirty-hour (34) gauges operating between 1900 and 2020. For the period between 1970 and 2020, at least three (3) gauges operated concurrently. For the period between 1990 and 2020, ten (10) gauges operated concurrently.

2.4.2 Stream Gauge Data

There are no streamflow gauges found within the study area following a review of the data from the Manly Hydraulics Laboratory and WaterNSW.



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Rainfall and Water Level Gauges

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2.5 Topographic Data

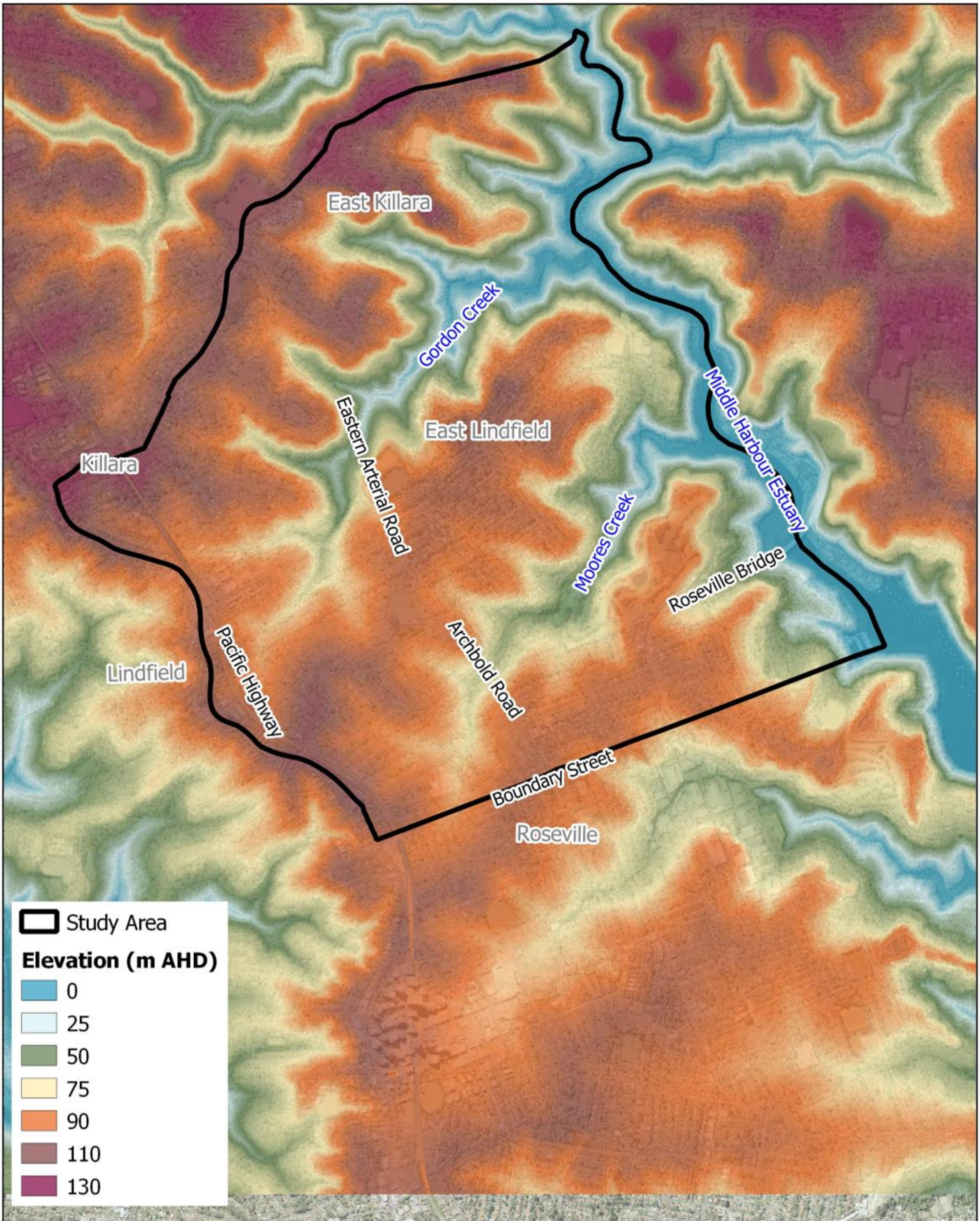
Aerial topographic survey, also known as LiDAR (Light Detection and Ranging) survey, covering the study area has been provided by Council. The survey was captured by the NSW Government's Department of Finance, Services and Innovation in 2013. The LiDAR data was supplied on a 1 m grid resolution, with a stated horizontal accuracy of +/- 0.8m @ 95% confidence and a vertical accuracy of +/- 0.3 m @ 95% confidence. LiDAR generally provides a good representation of the variation in ground surface elevations in the catchment; however, the datasets can provide a less reliable representation of the terrain in areas of high vegetation density or in close proximity to buildings.

As a means to verify the accuracy of the LiDAR, the ground surface elevations from the 2013 LiDAR datasets were compared against spot levels obtained as part of the additional survey collection (see Section 2.10) There were a total of 6,691 surveyed spot levels where data was able to be verified against the collected survey. It was determined that 21% of the surveyed marks lie within +/- 0.05 m of the LiDAR ground elevations with 63% within +/- 0.2 m of the LiDAR ground elevations.

LiDAR data was also captures by the Department of Finance, Services and Innovation in 2020. The 2020 LiDAR data was supplied on a 1 m grid resolution, with a stated horizontal accuracy of +/- 0.8m @ 95% confidence and a vertical accuracy of +/- 0.3 m @ 95% confidence. The 2020 LiDAR dataset was compared against the same 6,691 surveyed spot levels, and it was determined 12% of the surveyed marks lie within +/- 0.05 m of the LiDAR ground elevations with 46% within +/- 0.2 m of the LIDAR ground elevations. The 2013 LiDAR data is therefore considered a better match with the ground survey and has been utilised in this study.

Taking into account the vertical accuracy, confidence limits and resolution of the available topographic data, the simulated flood levels presented in this flood study will be limited to one decimal place so as not to imply a higher level of model accuracy than the adopted topographic data allows.

The topography within the study area is shown in Figure 2.2. The highest point in the catchment is at Koola Avenue in East Killara at approximately 130 m AHD. The catchments steeply descend into Middle Harbour to approximately -0.5 m AHD. Currently there are no available detailed bathymetry datasets for the Middle Harbour Estuary.



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Catchment Topography

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2.6 Stormwater Network Data

The stormwater system can play a significant role in defining flood behaviour across the developed sections of the catchments, particularly during more frequent flood events. Therefore, it is important to include a representation of the stormwater system in the flood models developed for this study.

A GIS database comprising an extensive network of stormwater drainage infrastructure was provided by Council in August 2020. This database primarily consists of a pit and pipe stormwater network and a number of open channels. It provides the location, alignment and attributes of Council owned stormwater pipes and culverts, as well as the locations and attributes of stormwater pits or inlets. A summary of this data is provided in Table 2.3.

Table 2.3 Summary of Council's Pit and Pipe Database

Asset Type	Data Provided	Number of Assets
Pit	Location, Pit ID, Installation Date, Type (sag pit, junction pit, gully pit, grated pit, surface inlet, headwall), Dimensions	2,235
Pipe	Location, Length, Installation Date, Dimensions, Depth to Invert (Upstream and Downstream), Material of structure, Type (pipe, channel, gully)	1,997

A detailed review of these layers was completed to confirm if the available information was sufficient to include a representation of the stormwater system in the flood model. In general, the pit and pipe layers provide sufficient information. However, the following limitations were identified:

- Invert elevations provided were estimated from 2 m contours developed from orthographic maps. Many of the inverts were found not to be a good match with the 2013 LiDAR data and therefore, invert elevations were corrected for use in this study. This is discussed in further detail in Section 4.3.7.
- Several identified pits were the upstream and downstream nodes for major overland flow paths extracted from the Hughes Trueman (2004) DRAINS model. These were removed from the drainage dataset.

2.7 Land Use Planning Information

Land Use Planning Zones were provided by Ku-ring-gai Council. This data includes land use planning information that provides a means to distinguish between land use types across the study area and enable spatial variation of distinct hydrologic (e.g. rainfall losses) and hydraulic properties (e.g. Manning’s ‘n’ roughness values).

2.8 Building Footprints

Building footprints were provided by Council. A visual assessment of the building footprints was undertaken against buildings shown in recent aerial imagery for the study area. In general, this dataset was determined to be representative of the building extents and locations, however it should be noted that there are data gaps in areas of dense vegetation and tree canopy cover.

Overall, this data provides a means to represent the localised blockages associated within buildings across the study area and will be incorporated into the hydraulic model.

2.9 Site Inspections

Site inspections have been undertaken during the study (both physical assessments and virtual desktop assessments via Google Street View) to gain an appreciation of local hydraulic features and their potential influence on the catchment flood behaviour. Some of the key observations accounted for during the site inspections included:

- Presence of local structural hydraulic controls such as bridges, culverts, road embankments and natural topographical controls such as channel constrictions or steep reaches;
- General nature of the catchment landforms, vegetation type and coverage and the presence of significant flow paths;
- Location of existing development and infrastructure in the study area.

This visual assessment was useful for defining hydraulic properties within the hydraulic model and ground-truthing of topographic features identified in the DEM. Physical site inspections will be undertaken to confirm calibration/validation and initial design results.

2.10 Additional Survey

Whilst the 2013 LiDAR data should generally provide a good representation of the variation in ground surface elevations across much of the catchment, the reliability of this data may be reduced in important conveyance areas due to the presence of vegetation and/or water within channels at the time the data was collected. LiDAR data will also not provide any information on features such as bridges and culverts, which can have a significant impact on flood behaviour.

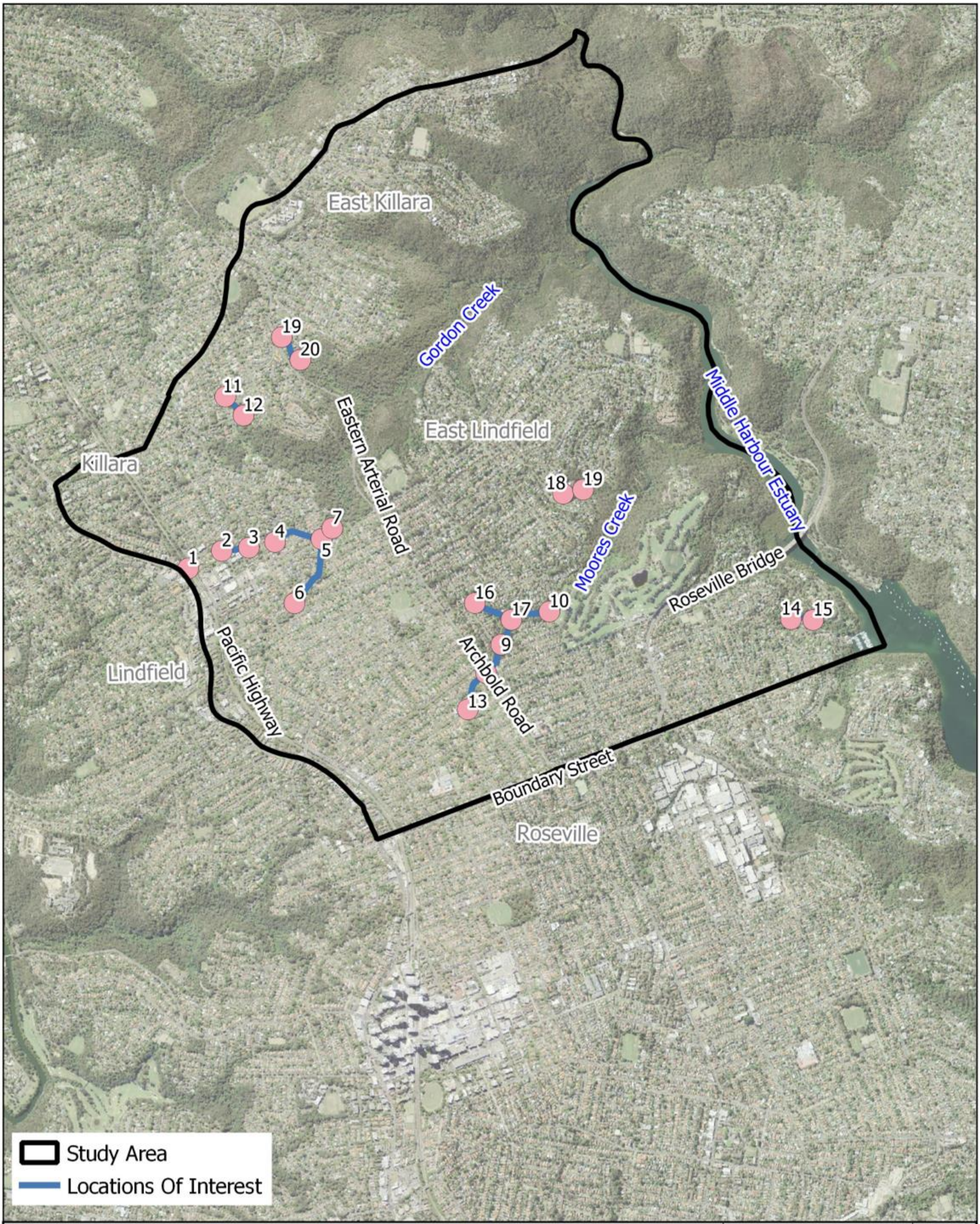
Therefore, review of available topographic data identified the requirement for additional survey to be collected to provide the necessary coverage and detail required to develop the hydraulic model. Accordingly, detailed survey was completed by Project Surveyors during July and August 2020. This included:

- Survey of seventy-six (76) cross-sections to determine the conveyance of key channels and adjacent floodplain; and
- Survey of thirteen (13) hydraulic structures to collect details of several bridges and culverts on major tributaries and cross-drainage across major roadways. Data collected included structure dimensions, waterway areas and invert levels

The locations of surveyed cross-sections and structures are listed in Table 2.4 and shown in Figure 2.3. The survey plans provided by Project Surveyors are enclosed in Annex B.

Table 2.4 Surveyed Hydraulic Structures and Cross-Sections Locations

ID	Location
Location 1	Carcoola Road
Location 2-3	Cassandra Avenue
Location 4-5	Lightcliff Avenue to Slade Avenue
Location 6-7	Gordon Creek Valley Road to Tryon Road
Location 8-9	Moores Creek Archibald Road to Roseville Avenue
Location 9-10	Moores Creek Roseville Avenue to Roseville Golfclub
Location 11-12	Stanhope Road
Location 13-8	Lord Street to Archibald Road
Location 14-15	Allard Avenue
Location 16-17	Carnavon Road to Luxor Parade
Location 18-19	Namoi Place to Carlyle Road
Location 19-20	Rosetta Avenue



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Additional Survey - Location of Hydraulic Structures and Cross-Sections

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3 Community Consultation

3.1 Purpose

Council recognises that community consultation is an important component of the flood study for the Middle Harbour Southern Catchments. Therefore, the community was consulted throughout the preparation of the flood study. The consultation with the community aimed to:

- Inform the community about the study;
- Gather information from the community on their flood experiences within the catchment;
- Collect feedback regarding community concerns and attitudes;
- Develop and maintain community confidence in the study results.

The consultation was completed via a number of different consultation methods at various points within the flood study, as detailed in the following sections.

3.2 Study Webpage

A study webpage was established for the duration of the study and made available via Council's online community engagement portal:

https://www.krg.nsw.gov.au/Environment/Extreme-weather/Flood-management.

The webpage was developed to provide the community with detailed information about the study, as well as to provide an online forum to ask questions and complete the online questionnaire (this questionnaire was identical to the one distributed to the community, as discussed in the following section). 392 responses to the online questionnaire were received via the webpage.

3.3 Media Release, Community Letter and Questionnaire

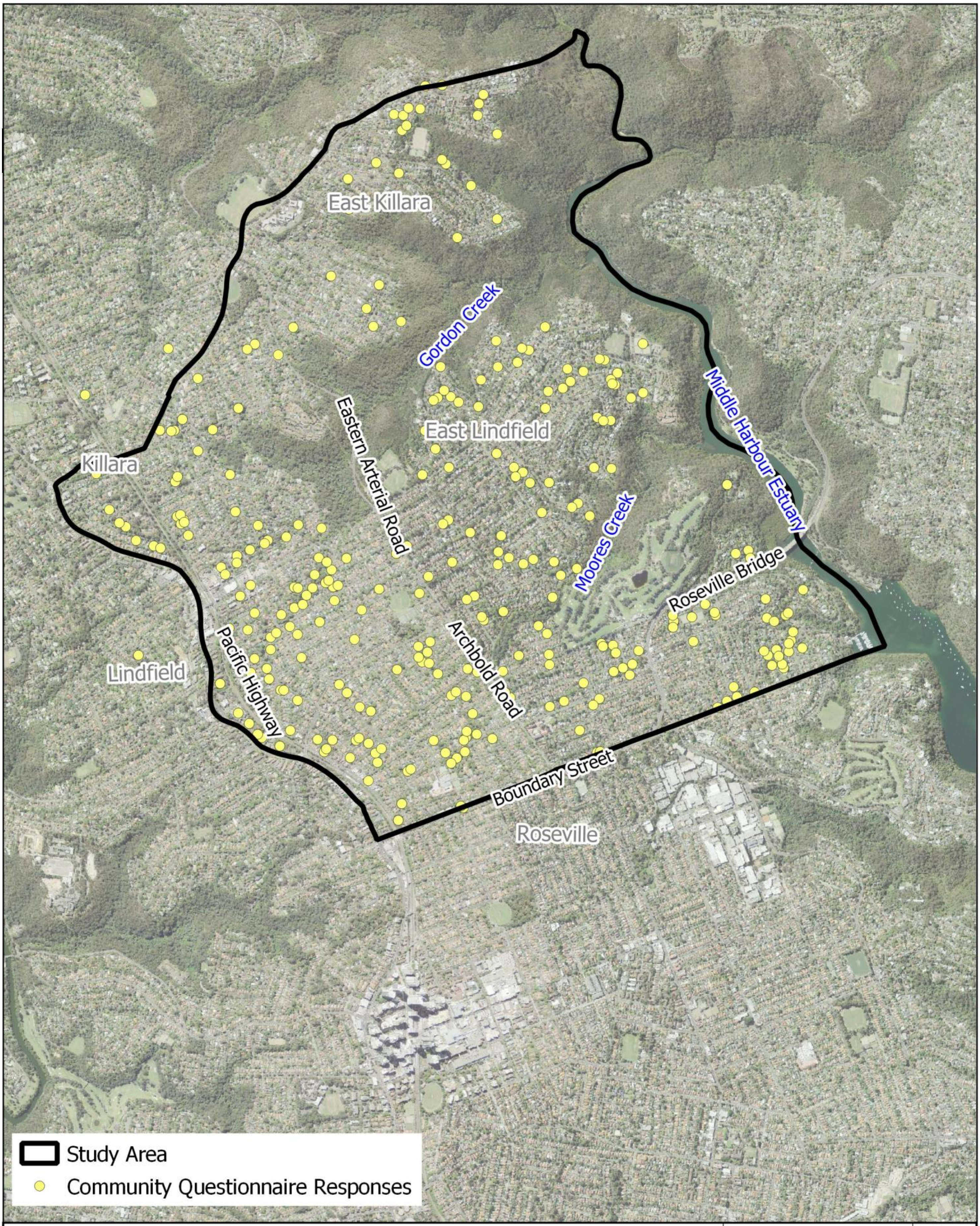
A media release was prepared and distributed to local media outlets during the initial stage of the study. This media release provided a brief overview of the study, informed the community of the commencement, purpose and objectives of the study, and earmarked that a newsletter and questionnaire would be distributed.

A community information letter, Frequently Asked Questions (FAQ) sheet and questionnaire were distributed to all landowners, residents and businesses located within the study area in December 2019 (refer copies enclosed in Annex C).

The information letter provided an overview of the flood study, while the questionnaire sought to collect information on the community's past flood experiences and concerns. More specifically, the focus of the questionnaire was to gather relevant flood information from the community, including photographs, observed flood depths and descriptions of flood behaviour within the catchment. Photographs and comments relating to flood behaviour contained within the responses were extracted to assist with the model calibration process. As discussed, the questionnaire was also accessible through Council's online community engagement portal.

A total of 414 questionnaire responses were received (392 online surveys and 22 returned questionaries). These responses were compiled into a GIS database that has been used to analyse the spatial distribution of responses (refer Figure 3.1), as well as colour coded according to whether flooding issues (and what type of issue) were reported at that location (refer Figure 3.2).

Figure 3.1 indicates a comprehensive coverage of responses across the study area. A number of respondents opted not to provide their name or address and therefore, the locations of these respondents could not be shown.



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Community Questionnaire Responses

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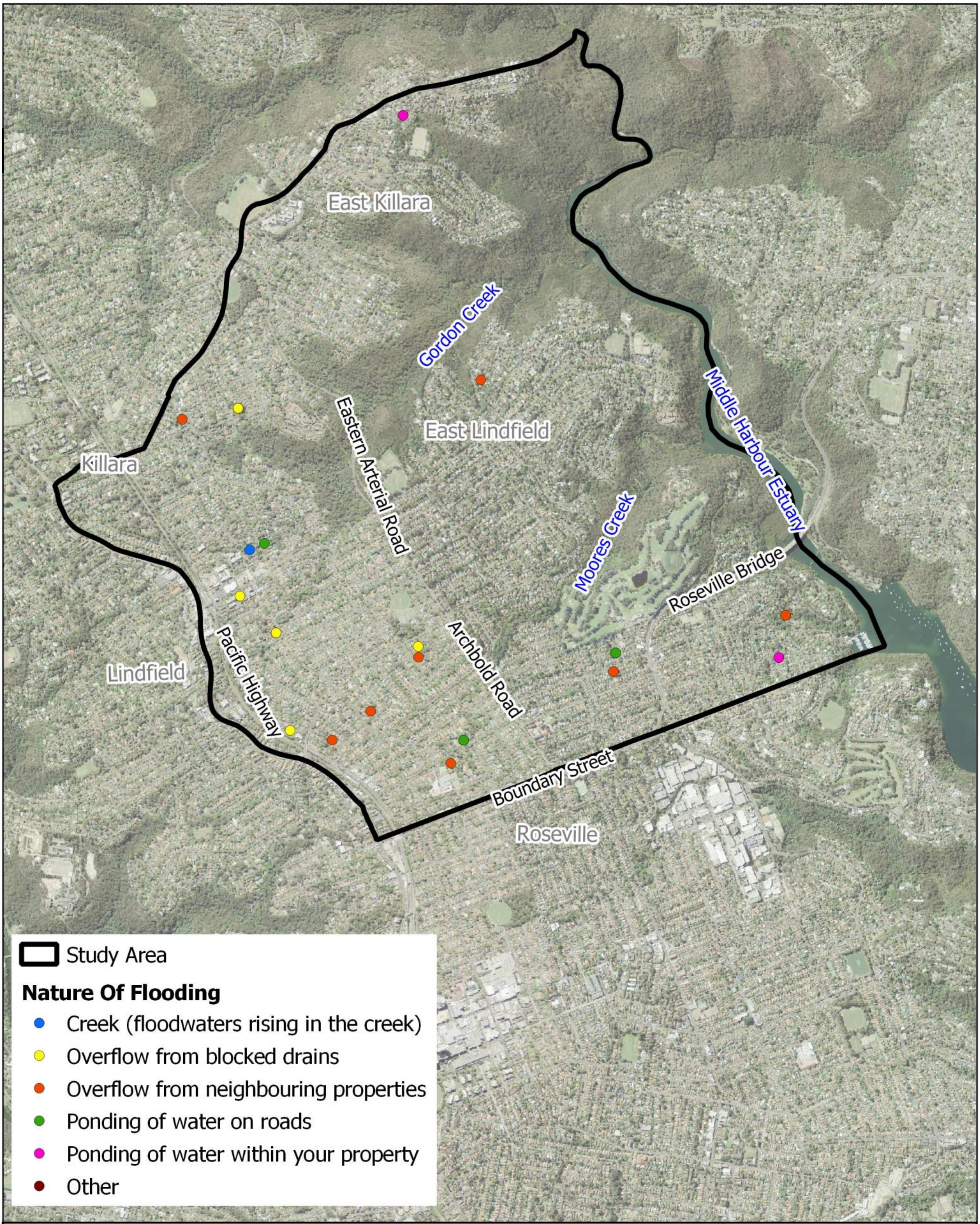

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Community Questionnaire Responses Nature of Flooding

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The responses to the questionnaire indicate that:

- The majority of the respondents have resided at their property for over 20 years, with reported experience provided for a 1986 flood event. A summary of the length of residence the respondents have been at their property is shown in Table 3.1.
- Approximately 50% of respondents had experienced flooding either within or outside of their property. Several historic events were identified from the consultation, with the February 2010 and February 2020 events being identified consistently by respondents as the most significant. The November 2009, October 2015, June 2016, February 2018, November 2019 and January 2020 events were also identified as significant events.
- Multiple respondents referred to frequent flooding due to overflow from neighbouring properties, overflow from blocked drains or overflow from water rising in creeks. Shallow flood depths of less than 30 cm were reported.
- Limited historical flood marks were identified during community consultation. A total of thirty-six (36) respondents reported having a flood mark; however no additional details were provided. Other respondents were unsure when the event occurred. One hundred and twenty-five (125) granted permission to be contacted.
- Two-hundred and five (205) respondents have experienced some degree of flooding. Where flooding was identified as an issue, the community were asked to separately report on the type of flooding observed. The nature of flooding experienced for the 205 respondents is shown spatially in Figure 3.2 and summarised in Figure 3.3. Overall, the number of responses for each category indicates comparatively greater observations of local stormwater overflow and ponding, and fewer observations of rising floodwaters from open watercourses.
- One hundred (100) respondents reported they had observed overflow from blocked drains. Some reports indicated that inlet pits were blocked, with between 10% and 100% blockage reported. In some reports, pipes were noted as blocked or under capacity for the event.
- A number of respondents provided suggestions for alleviating the flood risk in the catchment. These suggestions included:
  - Increased maintenance of the drainage system, e.g. ensuring pits, stormwater drains and waterways are kept clear of debris;
  - Increasing capacity of the drainage system, e.g. upgrading pits and pipes to larger size to accommodate higher flows; and
  - Increasing widths of drainage easements.

A number of respondents provided photos of historic floods. A selection of these photographs is provided in Annex D.

Table 3.1 Length of Residence of Respondents at Property

Length of Residence	No. of Respondents
0-2 years	42
3-5 years	28
6-10 years	70
11-20 years	95
More than 20 years	176
Not stated	3

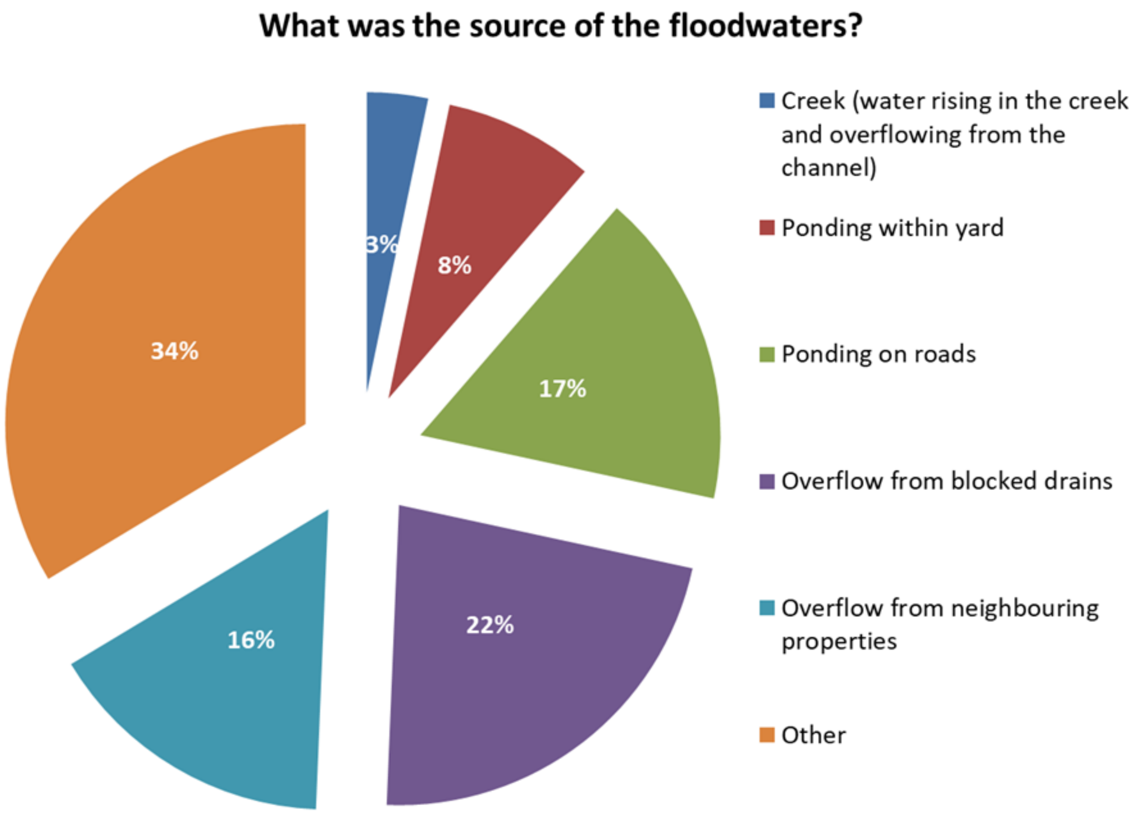


Figure 3.3 Questionnaire Responses – Nature of Flooding Experienced

3.4 Public Exhibition of Draft Flood Study Report

3.4.1 Public Exhibition and Community Session Details

The Draft Flood Study Report was placed on public exhibition during the period 20 April 2022 – 24 May 2022 through which public submissions were invited on the study. Letters informing the public exhibition were also mailed directly to owners with properties impacted by the draft Flood Planning Area (FPA) and Probable Maximum Flood (PMF) mapping.

In conjunction with the public exhibition period, three "drop-in" community information sessions were held on the 2nd, 10th and 13th of May 2022 to provide opportunity for the community to talk to Council's engineering staff and BMT to find out more about the study. Some of the general discussions were related to:

- Community experiences during the March 2022 flood event;
- The representation of building structures within the flood model;
- The tagging of properties, particularly within the PMF extent as part of the 2021 NSW Flood Prone Lands Package;
- Identification of areas with inadequate drainage issues.

3.4.2 Community Response

A total of 69 submissions were received during the public exhibition period. The key themes raised in the responses, which are also generally consistent with the feedback during the "drop-in" sessions included (but not limited to):

- Concerns around the tagging of properties, particularly those affected only in the PMF extent (not in the Flood Planning Area) and the potential effect on property values;
- Concerns around inadequate drainage and overdevelopment in parts of the catchment;
- Concerns around how building structures and local topographic features had been represented within the flood model and the potential artificial ponding of water within building footprints as a result;
- Minor amendments to reporting.

The responses received during the public exhibition period raised some concerns over the Draft Flood Study Report, particularly in regard to the representation of buildings within the model and the inclusion of properties within the PMF extent that were affected by minor or isolated water depths.

Following the public exhibition period, several individual site inspections were undertaken by BMT and Council across the catchment as a means of further ground truthing of the modelling results. As a result of the community feedback and in line with the observations from the individual property ground truthing modifications were made to the modelling approach undertaken including:

- The representation of buildings as solid obstructions to flow rather than having a high Manning's 'n' roughness value (see Section 4.3.5 for more detail).
- The filtering of final PMF tagging results to remove areas effected by low depths and isolated areas of ponding in line with the tagging undertaken for the FPA (see Section 9.1 for more detail).

4 Model Development

4.1 Types of Models

The urbanised nature of the study area creates a complex hydrologic and hydraulic flow regime. This is due to its mixture of pervious and impervious surfaces, as well as a combination of open watercourses, overland flow paths, cross-drainage structures and piped stormwater systems.

Computer models are the most common and efficient tools for assessing flood behaviour within a catchment. Separate hydrologic and hydraulic models were developed for this study, whereby:

- The **hydrologic model** transforms rainfall into runoff across the catchment and produces the flows which form the inflow boundaries of the hydraulic model.
- The **hydraulic model** simulates the distribution and movement of the runoff (or flow) across the floodplain, overland flow paths and within the stormwater network, and produces flood levels, depths and velocities.

Information on the topography and characteristics of the catchments and floodplains are built into the hydrologic and hydraulic model. Recorded historical flood data, including rainfall and flood levels, are used to calibrate and validate the models, if possible. Alternatively, models can be verified where there is limited quantity and uncertainty over the accuracy of historical flood information (such as for this study). Once calibrated (or verified), the models can be used to simulate design events and derive design flood conditions (e.g. peak flood extents, flood depths, flood levels, discharges and flow velocities). These predicted flood conditions can be used to produce flood maps and define flood risk.

This section describes the development of the hydrologic and hydraulic models. Specific details of the application of these models as part of the model calibration and design modelling process are provided in Section 5 and Section 6.

4.2 Hydrologic Model

4.2.1 Modelling Approach

The DRAINS models developed for Hughes Trueman (2004) (as discussed in Section 2.2.2) were used as a preliminary input to develop a single DRAINS model that includes all five (5) major sub-catchments (i.e. Gordon Creek, Moores Creek, Middle Harbour 2, Middle Harbour 3 and Middle Harbour 4 catchments) within a single hydrologic model. This hydrologic model includes all catchment areas draining to the outlets of the catchment within the study area.

DRAINS is widely used throughout Australia. DRAINS simulates a catchment and its tributaries as a series of sub-catchment areas linked together to replicate the rainfall and runoff process usually through a drainage network. Input data includes the definition of physical catchment characteristics including:

- Catchment slope, area, vegetation, urbanisation and other characteristics;
- Spatial and temporal variations in the distribution, intensity and amount of rainfall;
- Antecedent moisture conditions (dryness/wetness) of the catchment (i.e. initial and continuing losses).

The output from the hydrologic model is a series of flow hydrographs which form the inflow boundaries of the hydraulic model.

The model development and adopted parameters are discussed in the following sections.

4.2.2 Catchment Delineation and Parameterisation

The study covers five (5) major sub-catchments based on the major watercourse receiving flows from each area. These catchments were previously delineated into sub-catchments as part of Hughes Trueman (2004) based on the topographic divides and the location of key drainage inlets (e.g. culvert crossings).

As outlined in Section 2.2.2, four (4) of these sub-catchment delineations were provided at the start of this study, however sub-catchments for the Middle Harbour 2 catchment were not available. Delineation of sub-catchments for the Middle Harbour 2 catchment and extension of the supplied sub-catchments to areas downstream of the drainage network have been undertaken as part of this study using the CatchmentSIM software. The extent of the TUFLOW hydraulic model has been considered within the sub-catchment delineation to ensure the availability of inflow information at appropriate locations within the model. The number of sub-catchments delineated within each catchment area and average sub-catchment size within urban and non-urban areas of the catchment are listed in Table 4.1.

Table 4.1 Number and Average Size of Sub-catchments

Major Catchment	No. of Sub-catchments	Sub-catchment Size – Urban Areas (ha)	Sub-catchment Size – Non-urban Areas (ha)
Gordon Creek	766	0.4	2.8
Moores Creek	633	0.4	1.2
Middle Harbour 2	81	0.8	3.4
Middle Harbour 3	80	0.5	2.0
Middle Harbour 4	226	0.45	0.84

The model input parameters adopted for each sub-catchment within the DRAINS model are:

- Catchment slope and size (determined as per 4.2.2);
- Percentage of catchment area with a pervious/impervious surface (refer Section 4.2.3);
- Rainfall losses calculated as initial and continuing losses to represent infiltration. Adopted values are discussed in Section 4.2.4.

4.2.3 Impervious/Pervious Areas

Based on ARR 2019 guidelines, rainfall losses within a hydrologic model are differentiated based upon the land surface type. The definitions of each land surface type are provided below:

- Effective Impervious Area (EIA) – incorporates the impervious area of the catchment that generates a rapid runoff response in rainfall events and discharges directly into the drainage system.
- Indirectly Connected Areas (ICA): a contribution of discharges from:
  - Impervious areas which are not directly connected to the drainage network and flow over pervious surfaces before reaching the drainage system (e.g. a roof that discharges onto a lawn) – referred to as Indirectly Connected Impervious Area (ICIA).
  - Pervious areas that interact with Indirectly Connected Impervious Area (e.g. nature strip and lawns next to paved areas) – referred to as Indirectly Connected Pervious Area (ICPA).

- Urban Pervious Area (UPA) – consisting of parkland and bushland that do not interact with impervious areas.

Aerial photography and GIS digitising were used to determine the impervious/pervious area split for several land use categories which were then used to determine the percentage of EIA, ICA and UPA for each sub-catchment within the model.

As part of the digitising activity, it was noted that urban pervious areas are located predominantly in downstream areas of the catchment being made up of generally vegetated creek areas as well as Roseville Golf Club. Outside of these areas, urban pervious areas are limited to singular ovals scattered throughout the catchment. It is also noted that the DRAINS modelling software does not allow for the use of separate loss parameters for EIA, ICA and UPA areas[2]. Therefore, to simplify the loss approach (refer Section 4.2.4), it was decided that each catchment would be split into an EIA percentage (representing the impervious section) and an ICA percentage (representing the pervious section) only, with UPA areas encompassed within the ICA percentage. While this is considered a conservative approach, as most of the UPA area is in the downstream area of the catchment it is not considered to have a significant effect on design flood levels in the developed portion of the catchment.

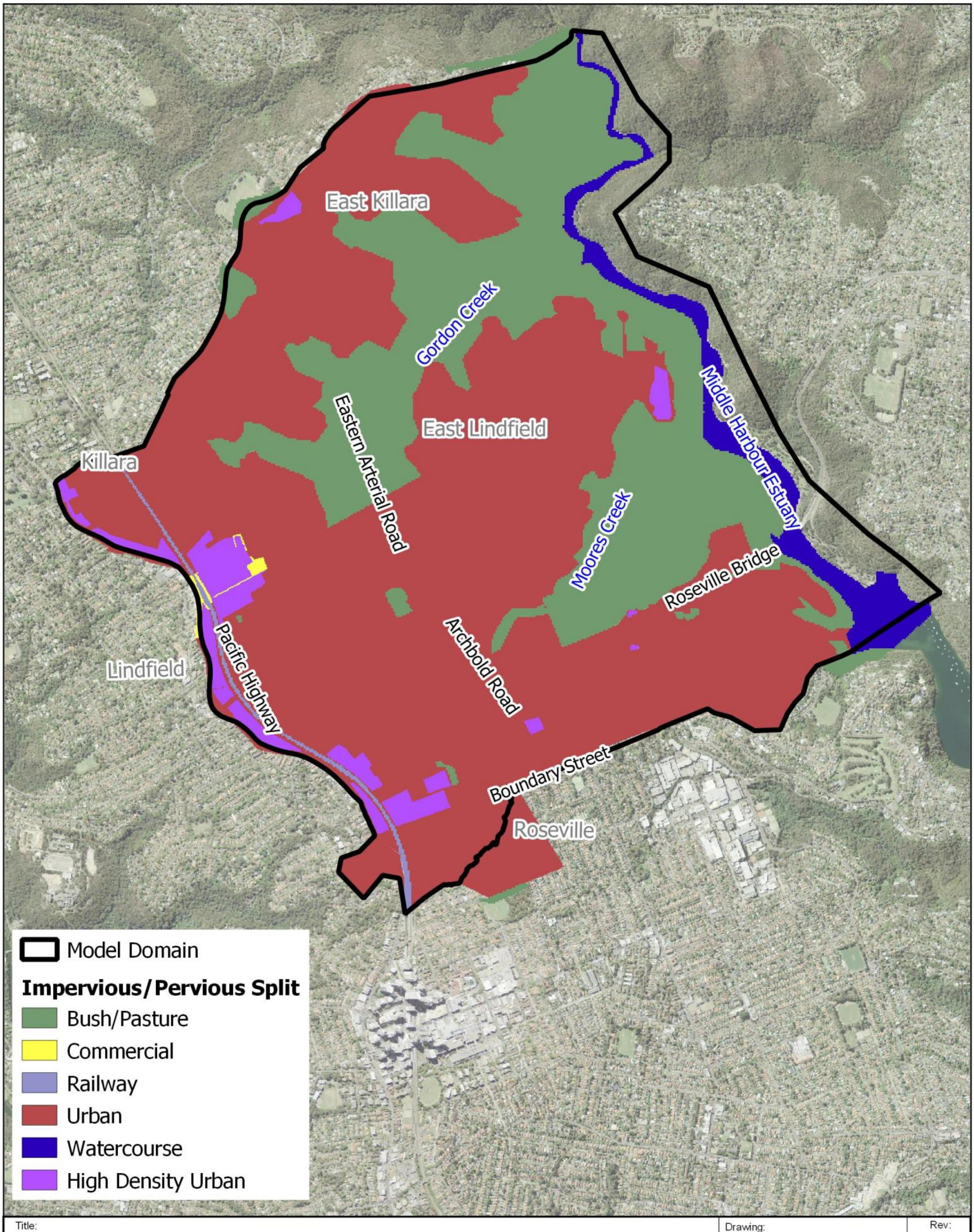
The impervious/pervious area split for the different land use zones is outlined in Table 4.2, with the land use zones shown in Figure 4.1. The initial EIA, ICA, UPA calculation is included along with the final split adopted.

Table 4.2 Land Use Zone with Percentage of Pervious/Impervious Areas

Land Use Zones	GIS Assessment			Adopted Split	
	EIA	ICA	UPA	EIA	ICA
Urban Residential	40%	15%	45%	40%	60%
High Density Urban Residential	80%	10%	10%	80%	20%
Industrial/Commercial	80%	10%	10%	80%	20%
Railway	80%	10%	10%	80%	20%
Bush Pasture	0%	0%	100%	0	100%
Watercourse*	100%	0%	0%	100%	0%

***Note: Watercourse is 100% impervious since rainfall will contribute directly to runoff.**

[2] DRAINS employs a methodology for dealing with losses in urban catchments but it was not considered appropriate for use in this study due to the complex interaction between impervious and pervious areas in low density residential areas.



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Land Use Zones (Impervious and Pervious Area Split)

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4.2.4 Rainfall Losses

The “Initial Loss – Continuing Loss model” approach has been adopted for this study, which is recommended in the ‘*Australian Rainfall and Runoff 2019’* (ARR 2019). This loss model assumes that a specified amount of rainfall is lost during the initial saturation or wetting of the catchment (referred to as the “Initial Loss”). Further losses are applied at a constant rate to simulate infiltration and interception once the catchment is saturated (referred to as the “Continuing Loss Rate”). The initial and continuing losses are effectively deducted from the total rainfall over the catchment, leaving the residual rainfall to be distributed across the catchment as runoff.

The study area includes extensive urban areas that are relatively impervious and areas of “open” space that are pervious. The impervious and pervious sections of the catchment respond differently from a hydrologic perspective, i.e. rapid rainfall response and low rainfall losses across impervious areas and, slower rainfall response and higher rainfall losses across pervious areas. Accordingly, different initial and continuing losses were applied for pervious and impervious areas in the DRAINS model.

In February 2019, the Office of Environment and Heritage (OEH) (now known as the Department of Planning and Environment (DPE)) released the ‘*Review of ARR Design Inputs for NSW’* (2019). This document was prepared to address concerns that the standard ARR 2019 method and parameters may provide an underestimation bias when deriving design event peak flows in NSW. It includes preliminary advice on changes required to address the bias associated with initial and continuing loss rates.

The document also outlines a 5-level hierarchical approach recommended to establish rainfall losses for NSW catchments, as presented Table 4.3. Based on this approach, it was determined that “Approach 5” in Table 4.3 (i.e. adopting ARR Data Hub parameters was suitable for application in this study for the following reasons:

- No observed flood marks were available for reliable calibration of rainfall losses. Therefore, “Approach 1” is considered not suitable.
- Existing studies within the catchment (such as Hughes Trueman (2014)) and in surrounding catchments including the ‘*Blackbutt Creek Flood Study’* (2014) and ‘*Lovers Jump Creek Flood Study*’ (2018) utilised loss values typically in line with the recommendations in AR&R 1987. As this study has been undertaken using ARR 2019 methodologies these loss values were not considered appropriate for use in this study. Therefore, “Approach 2” and “Approach 3” are also considered not suitable.
- NSW FFA (Flood Frequency Analysis) reconciled initial losses are not available for the study area. Therefore, “Approach 4” is considered not suitable.

Table 4.3 Hierarchy of Approaches (listed from most (1) to least preferred (5))

Approach	Data to use	Storm Initial Loss	Pre-burst (transformational)	IL Burst	Continuing Loss
1	Current Study	Average Calibration	Not required or back calculated using $IL_{Storm} - IL_{Burst}$	$L_{Burst\ chosen} = IL_{Storm} * IL_{Burst-ARR} / IL_{Storm-ARR}$	Average Calibration
2	Other Studies within the catchment	Average Calibration	Not required or back calculated using $IL_{Storm} - IL_{Burst}$	$IL_{Burst\ chosen} = IL_{Storm} * IL_{Burst-ARR} / IL_{Storm-ARR}$	Average Calibration
3	Neighbouring Studies	Average Calibration	Not required or back calculated using $IL_{Storm} - IL_{Burst}$	$L_{Burst\ chosen} = IL_{Storm} * IL_{Burst-ARR} / IL_{Storm-ARR}$	Average Calibration
4	FFA	NSW FFA reconciled initial loss	Not required or back calculated using $IL_{Storm} - IL_{Burst}$	Probability Neutral Burst Loss	NSW FFA reconciled continuing losses
5	ARR Data Hub	ARR Data Hub initial loss	Not required or back calculated using $IL_{Storm} - IL_{Burst}$	Probability Neutral Burst Loss	NSW FFA reconciled continuing losses

In accordance with the '*Review of ARR Design Inputs for NSW*' (2019), the following modifications to the ARR Data Hub loss values are recommended for NSW catchments:

- Adoption of the revised Probability Neutral Burst Initial Loss as provided through the ARR Data Hub.
- A multiplication factor of 0.4 should be applied to the ARR Data Hub continuing loss.

The NSW specific Probability Neutral Burst Initial Losses for the Middle Harbour Southern Catchments are provided in Annex E.

In line with current guidance from OEH, a multiplication factor of 0.4 was applied to the ARR Data Hub continuing loss for the catchment, thus, reducing the 1.8 mm/h ARR Data Hub continuing loss to 0.72 mm/h.

As per Book 5 Chapter 3 of ARR 2019, Indirectly Connected Areas should adopt an initial loss equivalent to between 60% and 80% of the recommended rural catchment initial loss. Therefore a 70% scaled initial loss for Indirectly Connected Areas has been adopted for this study, as per Table 4.4.

Table 4.4 Scaled NSW Specific Probability Neutral Burst Initial Loss for ICA Areas (mm)

Duration	50% AEP	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP
60 min	8.6	5.7	6.3	6.1	6	4.6
90 min	8.3	5.7	6.7	6.8	6.7	4.9
120 min	9.4	6.3	7.1	7	7.1	4.2
180 min	9.7	6.5	7.4	7.1	6.2	3
360 min	9.2	6	6.2	5.7	6.4	2.6
720 min	12.3	8.5	8.5	7.4	8.3	2.2

The following loss rates have been adopted in the setup of the DRAINS model:

- Impervious areas:
  - Initial Loss – 1.5 mm;
  - Continuing Loss – 0 mm/h.
- Pervious areas:
  - Initial Loss – As per Table 4 4;
  - Continuing Loss – 0.72 mm/h.

4.3 Hydraulic Model

4.3.1 Modelling Approach

The hydraulic model for this flood study was developed using the TUFLOW modelling software. TUFLOW was developed by BMT and is the most widely used 1D/2D (One/Two-Dimensional) flood modelling software in Australia.

An integrated 1D/2D TUFLOW model was created to model the dynamic interactions between waterways and floodplains, complex overland flow paths, converging and diverging of flows through structures, and the interaction between surface and sub-surface flow (i.e. stormwater drainage system). This has involved the schematisation the study area based on the following key model features:

- Floodplain and overland flow areas represented in the 2D domain;
- Open watercourse channels and bridge crossings are represented within the 2D model;
- Culvert structures represented as 1D elements;
- Stormwater drainage network represented as 1D elements, dynamically linked to the 2D domain;
- Hydrologic inflows derived using the DRAINS model applied as upstream and local inflows;
- Water levels within receiving watercourses applied as tailwater conditions.

The development of the hydraulic model and adopted parameters are discussed in the following sections.

4.3.2 Model Extent and Grid Size

The hydraulic model for the Middle Harbour Southern Catchments was developed using TUFLOW (version 2020-10-AA-ISP). The TUFLOW Heavily Parallelised Compute (HPC) solver was utilised for the study to improve modelling run times.

The area modelled within the TUFLOW 2D domain represents a total area of approximately 9.7 km^2. The model domain was defined by combining catchment areas within the southern parts of the Ku-ring-gai LGA that drain into Middle Harbour from Koola Avenue, East Killara in the north-west to the model boundary along Middle Harbour adjacent to Echo Point in the south-east.

The TUFLOW software uses a grid to define the spatial variation in topography and hydrologic/hydraulic properties (e.g. Manning's 'n' roughness, rainfall losses) across the study area. Accordingly, the choice of grid size can have a significant impact on the performance of the model. In general, a smaller grid size will provide a more detailed and reliable representation of flood behaviour relative to a larger grid size. However, a smaller grid size will take longer to perform all of the necessary hydraulic computations. Therefore, it is typically necessary to select a grid size that makes an appropriate compromise between the level of detail provided by the model and the associated computational time required.

A grid size of 2 metres was adopted for the hydraulic model and is considered to provide a reasonable compromise between reliability and simulation time.

4.3.3 Topography

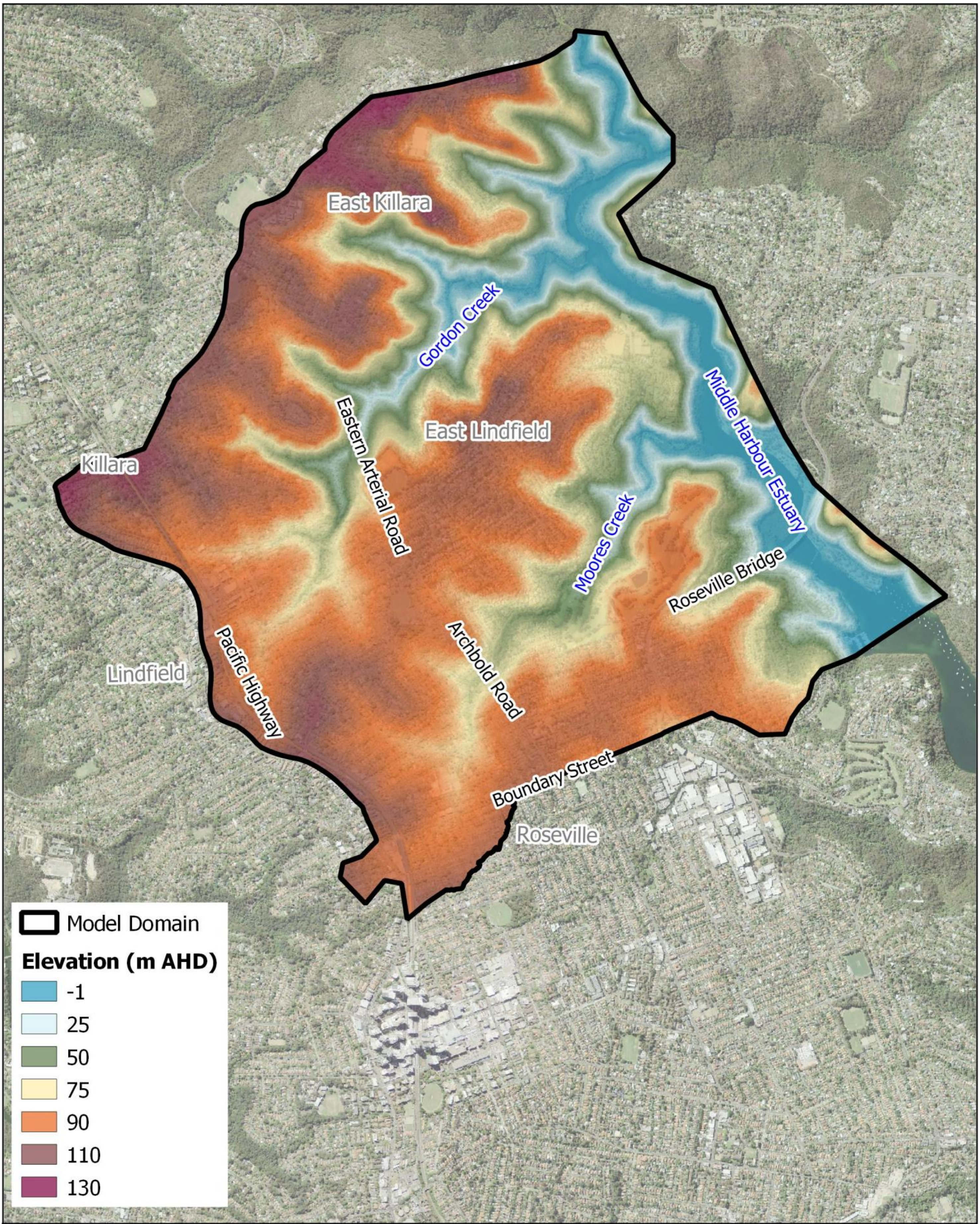
The overland flow regime in urban environments is typically characterised by inundation of urban development with interconnecting and varying flow paths at varying depths. Road networks often convey a considerable proportion of floodwaters due to the hydraulic efficiency of the road surface compared to residential properties. A high-resolution DEM was derived for the study area from 2013 LiDAR survey data (refer Section 2.5) and cross-section survey undertaken as part of this study (refer

Section 2.10). The ground surface elevation for the TUFLOW model grid points are sampled directly from the DEM and the cross-section survey.

A TUFLOW 2D domain model resolution of 2 m was adopted for the study area. It should be noted that TUFLOW samples elevation points at the cell centres, mid-sides and corners, so a 2 m cell size results in DEM elevations being sampled every 1 m. This resolution provides the necessary detail required for accurate representation of floodplain topography and its influence on out-of-bank flows.

No bathymetry data was available for the Middle Harbour Estuary, which is subject to tidal inundation based on the '*Greater Sydney Harbour Estuary Coastal Management Program Scoping Study'* (BMT, 2018). Given the limitations of LiDAR survey data in deep water areas and the significant elevation difference between the Middle Harbour Estuary and the upstream urban areas which is the main focus of the study, an elevation of -1.0 mAHD can be reasonably assumed for the Estuary bed in the DEM.

The resulting topography of the hydraulic model and the extent of the model domain are presented in Figure 4.2.



Title:

Model Topography

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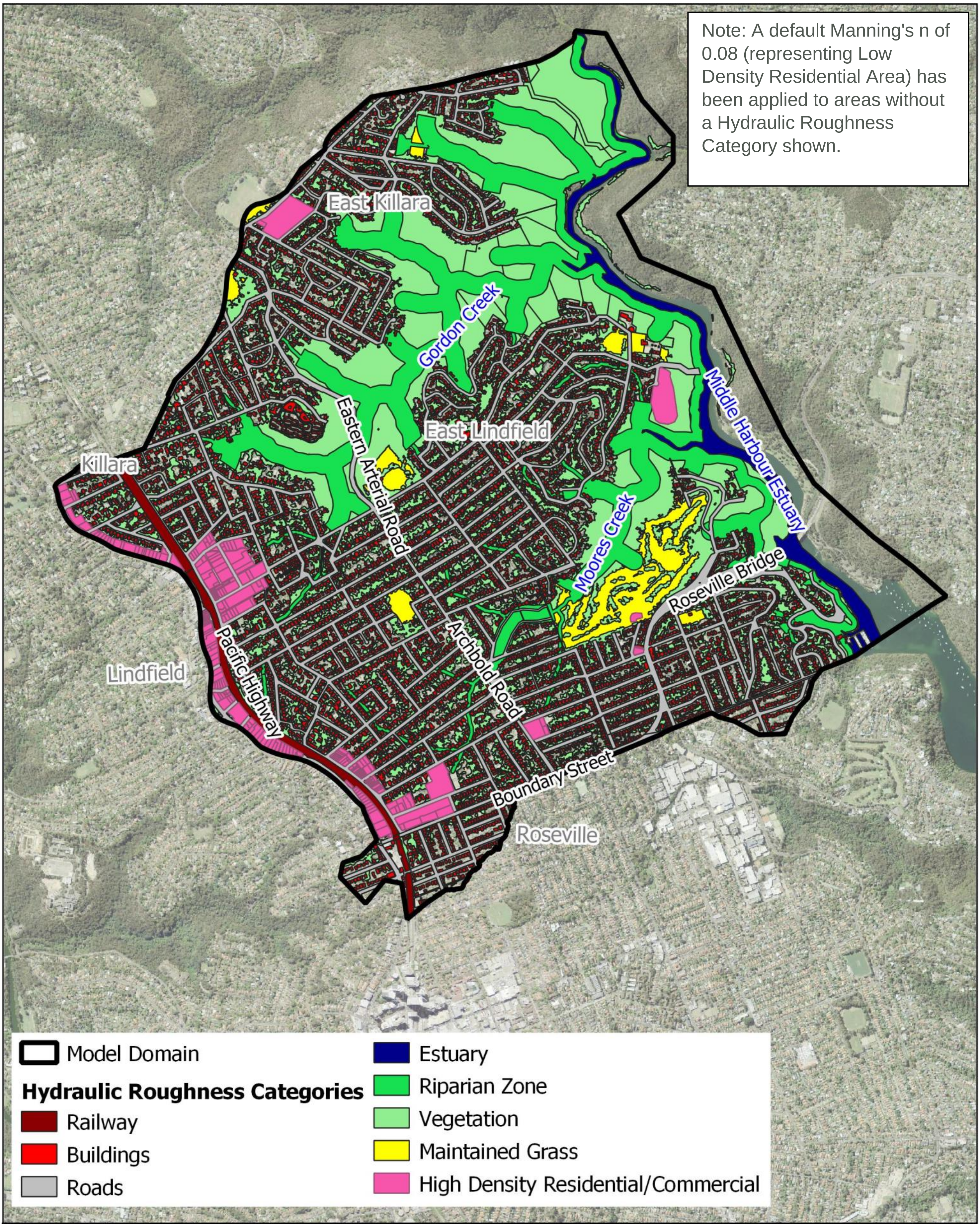
4.3.4 Hydraulic Roughness

Utilising available land use information, the development of the TUFLOW model requires the definition of different hydraulic roughness (Manning's 'n') zones that assign surface materials for each grid cell in the model for simulating the variation in flow resistance afforded by different land-use surfaces within the model extent (e.g. trees, grass, roads, etc). Council's land-use planning data and aerial photography have been used as the basis for defining the different hydraulic roughness zones within the model.

The land-use map used to assign the different hydraulic roughness zones across the model is shown in Figure 4.3 and the adopted Manning's 'n' values are listed in Table 4.5, which are based on industry standard values.

Table 4.5 Adopted Manning's 'n' Values

Land Use Type	Manning's 'n' value
Roads	0.02
Low Density Residential Lots	0.08
High Rise Lots	0.035
Commercial Lots	0.035
Maintained Grass	0.03
Dense Vegetation	0.12
Riparian Zone	0.1
Buildings	1
Railway	0.05
Estuary	0.03



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4.3.5 Representation of Buildings and Localised Obstructions

Building GIS layers were supplied by Council and are shown in Figure 4.3. The representation of buildings is important in areas conveying significant volumes of flow or experiencing significant ponding depth. For this study, buildings are represented in the TUFLOW model as impenetrable obstructions to flow, considering the energy dissipation of water flowing around the building. This approach does not consider or include the potential storage effects of the building being inundated but is considered appropriate for use in this study due to the short-duration, intense flash flooding nature of the catchment and the limitations in the representation of buildings within the adopted LiDAR dataset. Representation of the buildings in this manner has been informed by the community consultation process as discussed in Section 3.4.

Smaller localised obstructions within or bordering private property, such as urban fences (for example Colorbond or wood paling fences), were not explicitly represented within the hydraulic model. Rather, these obstructions have been incorporated into the adopted Manning's 'n' roughness value for urban development land use across the study area (i.e. residential and commercial lots), due to their propensity to fail during large flood events.

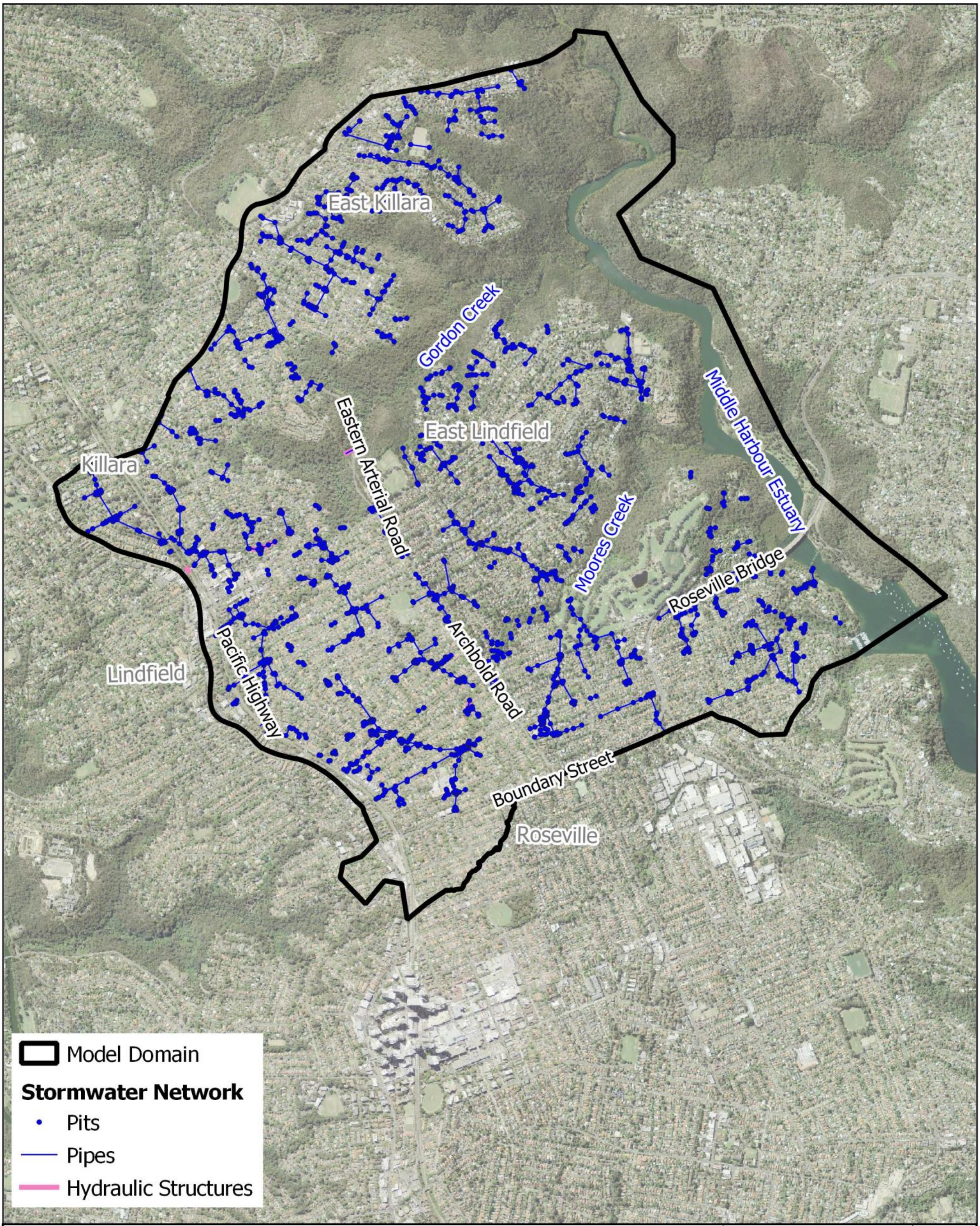
4.3.6 Hydraulic Structures

There are numerous culvert and bridge structures located throughout the study area that enable cross-drainage under major roads. These structures vary in terms of size and configuration, with differing degrees of influence on local hydraulic behaviour. Incorporation of these structures in the model provides for simulation of the hydraulic losses associated with these structures and their influence on flood behaviour within the study area.

The culvert and bridge structures were modelled as either layered flow constriction structures in the 2D domain, or 1D structures embedded within the 2D domain. The adopted structure details (that is invert levels, geometric properties, hand rails/road barriers) were derived from the following sources:

- Cross section and cross-drainage structure survey completed by Project Surveyors (refer Section 2.10). 13 structures were surveyed. Refer to Annex B for the compiled survey drawings and mapping showing the location and details for each structure and cross-section.
- GIS data supplied by Ku-ring-gai Council.
- Site visit completed by BMT.

Hydraulic structure locations are shown in Figure 4.4.



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Modelled Stormwater Network

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4.3.7 Stormwater System

The stormwater system has the potential to convey a significant proportion of runoff across the study area during frequent rainfall events in particular. Thus, it is important to incorporate the stormwater system in the TUFLOW model to ensure the interaction between the underground piped system and overland flows are reliably represented. Figure 4.4 shows the 1D stormwater network developed for the hydraulic model.

The full stormwater system contained within the catchment was included within the TUFLOW model as a dynamically linked 1D network. This allowed representation of the conveyance of flows by the stormwater system below ground as well as simulation of overland flows in the 2D domain once the capacity of the stormwater system is exceeded.

The properties of the stormwater system (e.g., pits types/sizes, pipe lengths/diameters) were defined from a number of different data sources. Data comprising pit/pipe locations, pit inlet type/dimensions and pipe sizes was received in GIS layers as discussed in Section 2.6. The data was used to build the details of the stormwater pipe network into the TUFLOW model as a 1D drainage network, dynamically linked to the 2D domain. Pipe invert levels nominated in the GIS layers were found to be not a good match for the 2013 LiDAR data, hence pipe inverts were re-estimated as the LiDAR elevation level minus the pipe diameter and a 0.4 m pipe cover and corrected where required to ensure positive and realistic pipe grades. Pit inlet capacities are based on the Hughes Trueman (2014) study DRAINS model and determined using lintel opening lengths and grate sizes.

A summary of the modelled stormwater drainage network is presented in Table 4.6 with the spatial distribution of the drainage network shown in Figure 4.4.

For the magnitude of the events under consideration in the study, the pipe drainage system capacity is anticipated to be exceeded, with the major proportion of flow conveyed in overland flow paths. Therefore, any limitations in the available pipe data or model representation of the drainage system is expected to have minimal effect on the design flood results.

Table 4.6 Summary of Modelled Stormwater Infrastructure Elements in Hydraulic Model

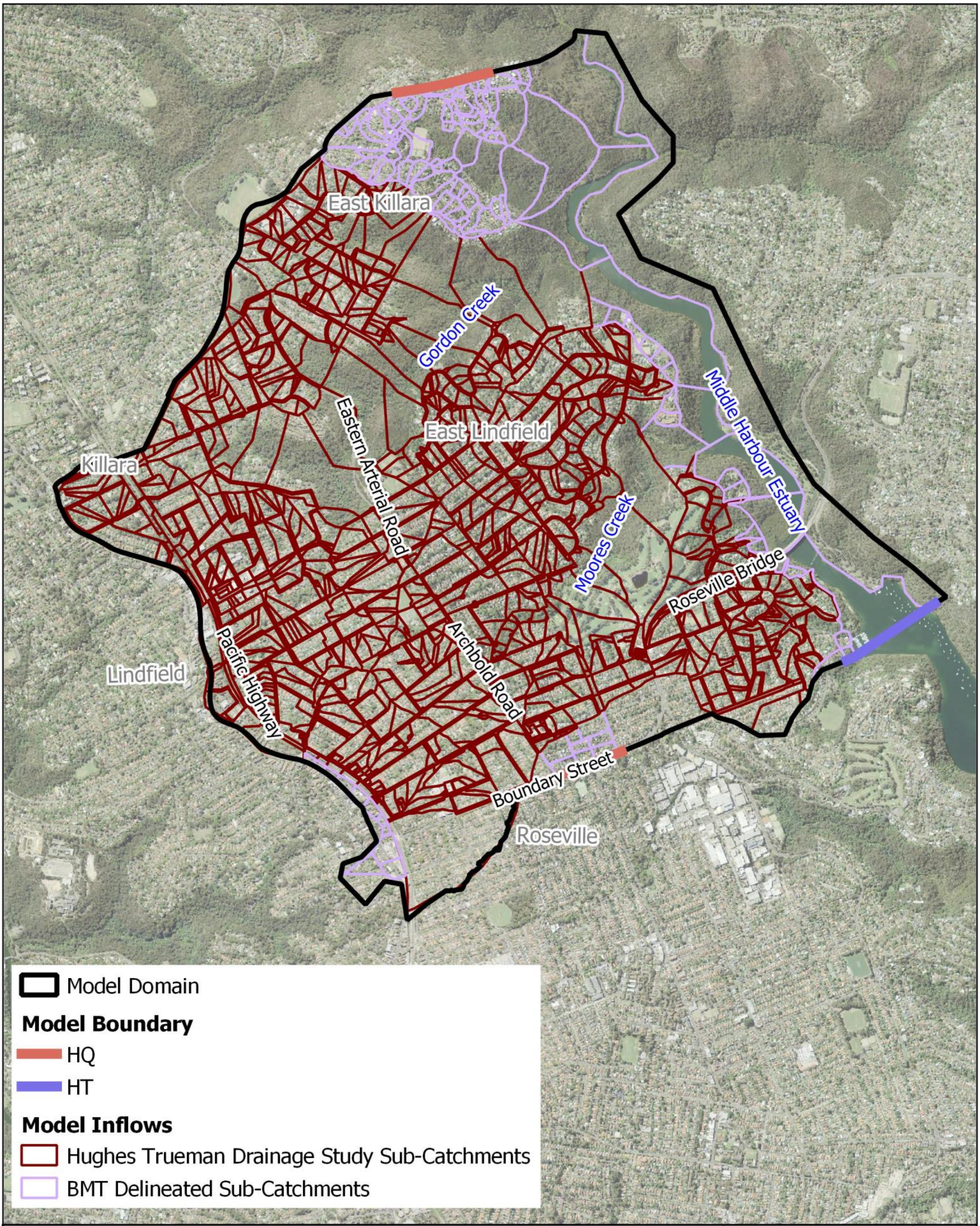
Stormwater Infrastructure Type	Number of Elements
Circular	1865
Rectangular	141
TOTAL PIPES/CULVERTS	**2006**
Pits	1858
Nodes	100
Outlets/Headwalls	217
TOTAL NODES/PITS	**2175**

4.3.8 Model Boundary Conditions

The specification of suitable boundary conditions that account for design flows into the system and tailwater conditions at the outlet of the system is a critical component of flood simulations. Model boundary locations are shown in Figure 4.5. The boundary conditions used in the TUFLOW model include:

- Local inflow conditions: Local catchment runoff hydrographs derived by the DRAINS model are applied directly to the hydraulic model as inflow hydrographs. For sub-catchments with modelled stormwater drainage, the inflows are applied directly to the 2D domain where the cells are connected to the 1D stormwater network (i.e. inflows are directly applied to the top of the pit inlet). The advantage of this method is that any blockage assigned to a pit will be appropriately modelled. For sub-catchment areas containing no stormwater drainage network, the catchment runoff is applied directly to the 2D domain at the outlet of the catchment. The hydrographs for historical and design events were derived from the results of the DRAINS hydrologic model developed for the study (discussed further in Section 2.2.2 and Section 4.2).
- Downstream boundary conditions: The study area is primarily affected by local overland flows and flooding from local creeks across the study area (i.e. Gordon Creek and Moores Creek). However the lower parts of the catchment may be impacted by tidal conditions within the Middle Harbour Estuary. Accordingly, tailwater conditions have been determined using the '*Modelling the Interaction of Catchment Flooding and Oceanic Inundation in Coastal Waterways'* (OEH, 2015). See Section 6.2.7 for further detail. These tailwater conditions have been applied as a 'Head vs Time' or 'HT' boundary, downstream of Echo Point. A 'Stage-Discharge' or 'HQ' boundary has been applied to areas north of East Killara to prevent flows ponding against the model boundary.

Figure 4.5 shows the DRAINS sub-catchments used in this study, including the original catchments developed as part of Hughes Trueman (2004) and the MH2 sub-catchment and downstream areas delineated as part of this study (as discussed in Section 4.2.2).



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TUFLOW Model Configuration

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5 Model Verification

5.1 Overview

The selection of suitable historical events for calibration of the computer model is largely dependent on available historical flood information. Ideally, the calibration and validation process should cover a range of flood magnitudes, to demonstrate the suitability of the model for the range of design event magnitudes considered.

As there were no existing historical records of overland flood levels within the catchment, data received from the community consultation process was relied upon for the verification process. Limited observed flood level information was available from the community and the information provided was mostly limited to anecdotal flood behaviour information. As such, a model verification process was undertaken in place of a proper model calibration and validation to verify the predicted model results against observed anecdotal flood behaviour. The June 2016 and February 2020 events were both identified by the community to be major events within the study area and have been utilised for the model verification herein.

5.2 June 2016 Model Verification Event

5.2.1 Verification Data

Rainfall Data
The East Lindfield Bowling Club rainfall gauge is located within the catchment area and there are four additional rainfall gauges situated within 10.8 km of the study area. These rain gauges have been analysed to estimate the likely range of rainfall intensities experienced within the study area (see locations in Figure 2.1).

The recorded daily totals (for the 24 hours to 9 am) from the 4 June the 6 June 2016 for active gauges is shown in Table 5.1.

Table 5.1 Recorded Daily Rainfall Totals for June 2016 Events

Gauge Name	Gauge ID	To 9AM 04/06/2016	To 9AM 05/06/2016	To 9AM 06/06/2016
East Lindfield Bowling Club	566085	34.5	133	127.5
Chatswood Bowling Club	566017	29	120.5	122
Pymble Bowling Club	566073	13	139	150.5
Castle Cove (Rosebridge Avenue)	66080	38	119	148
Belrose (Evelyn Place)	66188	39.2	120.4	134

As shown in Table 5.1, rainfall across the region occurred over a 3-day period from the 4 June to the 6 June 2016, with the largest amount of rainfall occurring in the 24 hours to 9am on the 5 June and 6 June. There was a spatial similarity observed across the region, with the largest rainfall recorded at the Castle Cove (Rosebridge Avenue) gauge north-west of the study area.

The available sub-daily rainfall data for the East Lindfield Bowling Club was available in 6-minute increments. The records indicate that the event was characterised by a distinct burst between 10pm on the 4 June and 2pm on the 5 June, with 190.5 mm of rainfall recorded across the period.

To gain an appreciation of the relative intensity and magnitude of the June 2016 event, the rainfall depth for various durations within the storm is compared against design IFD (Intensity-Frequency-Duration) rainfall curves, as presented in Figure 5.1. The design IFD rainfall curves were obtained from BoM. As shown in Figure 5.1, the rainfall input is estimated to be in the order of a 5% AEP event for an event duration between 9 and 48 hours.

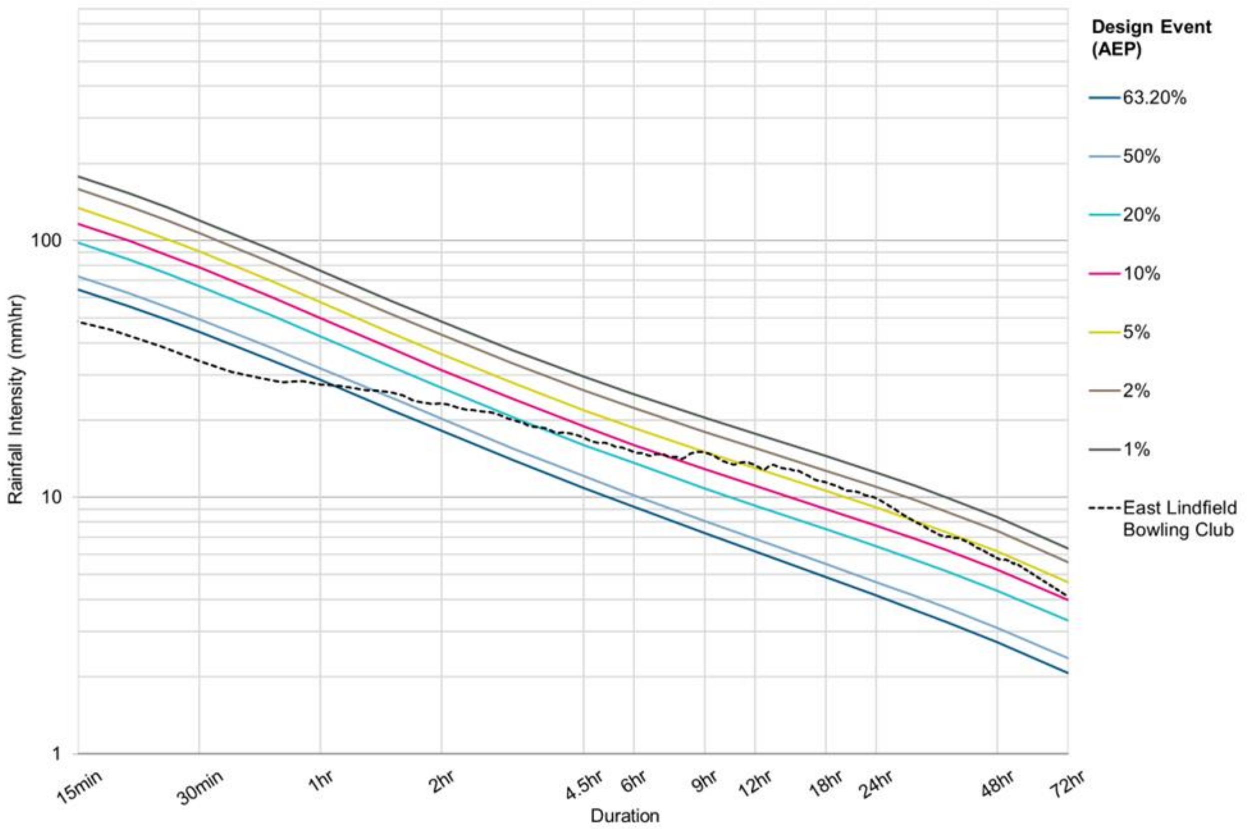


Figure 5.1 Comparison of Recorded June 2016 Rainfall with IFD Relationships

Downstream Boundary Condition

Coincident flooding of the Middle Harbour Southern Catchments with tidal conditions in the Middle Harbour Estuary have been conservatively assumed to define the downstream model boundary for this study (see Section 6.2.7). A High High Water Spring (HHWS) tailwater level has been adopted for the June 2016 event.

5.2.2 Flood Level Data

There is no available data within the catchment area to provide recorded water levels for the June 2016 event. Anecdotal flood data for the event was obtained through the community questionnaire responses. This data does not provide definitive flood levels, but rather is indicative of depths of flooding, observations of flow paths and extent of inundation.

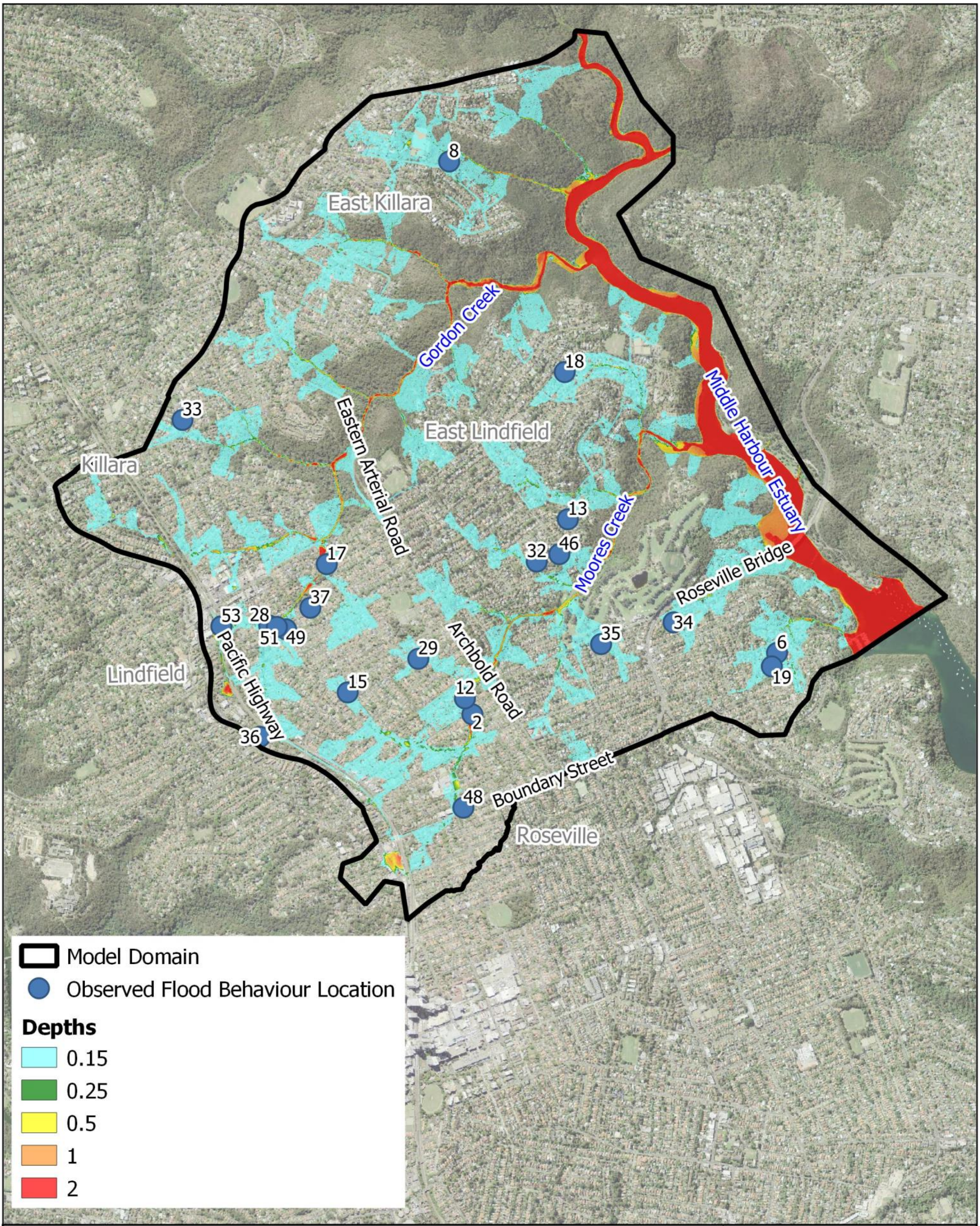
The observations are useful to provide some confidence in the model representation of the observed flood behaviour, as discussed further below. It should be noted that instances where members of the community indicated flooding occurred “years ago” or “whenever it rains heavily” have been included in the comparison.

5.2.3 Observed and Predicted Flood Behaviour

The modelled peak flood depths based on the historical rainfall data for the East Lindfield Bowling Club rainfall gauge are presented in Figure 5.2. The community consultation process indicated that the June 2016 event led to significant affectation on private properties, which is reflected in the TUFLOW model results. Overland flows travelling through urban areas discharged through private property in several locations before reaching the downstream watercourses within the catchment area.

Anecdotal flood behaviour information was acquired from limited photographs provided by residents and from the responses provided as part of the community questionnaire. A comparison of the flood behaviour observed by the community members against the flood behaviour predicted by the modelling results is included in Table 5.2.

It is noted that there is generally good correlation between observed flood behaviour and historical flood behaviour predicted by the flood model. However, in several locations there was only partial correlation (or in some cases poor correlation) between observed and predicted flood behaviour. Review of the model in these areas indicates that this is due to the delineation of catchments and the placement of inflows, which encourages inflows to discharge directly into stormwater assets where possible and often at the lowest point within a catchment. The benefit to such a strategy is that nuisance stormwater flow (which is often found upstream within individual catchments) is not represented in the flood model results. This may help reduce overly conservative flood tagging of properties in subsequent stage which are affected only by minor stormwater flows in rare events, and which development may not cause a significant change to flood conditions elsewhere in the catchment. The disadvantage of this approach is that flooding of any property that is located upstream of the inflow location will not be represented in the modelled results. The direct inflow to drainage pits approach has been adopted in this study, with the acknowledgement that this will result in minor nuisance flooding not being identified for certain properties in both the verification mapping and final design modelling.



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June 2016 Verification Event - Peak Flood Depth and Observed Flood Data Distribution

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Table 5.2 Comparison of Observed and Predicted Flood Behaviour – June 2016 Event

ID	Location	Observed Flood Behaviour	Predicted Flood Behaviour
2	Lord Street, Roseville	Ponding along low point, some shallow flow in buildings	Satisfactory correlation
6	Calga Street, Roseville Chase	Shallow flow along road, some flow in rear of blocks along street	Satisfactory correlation. Some major flow paths not represented due to placement of inflows.
8	Saiala Road, East Killara	Shallow flow in reserve behind Saiala Road	Good correlation
12	Lord Street, Roseville	Flooding in Moore Creek adjacent to Lord Street	Good correlation
13	Canberra Crescent, East Lindfield	Flow cascading into Canberra Crescent from Crana Avenue	Good correlation
15	Intersection of Trafalgar Avenue and Clanville Road, Roseville	Shallow flow across rear of properties	Good correlation
17	Howard Street, Lindfield	Rising floodwaters in creek behind properties	Good correlation
18	Wellington Road, East Lindfield	Water ponding on road and running overland through granny flats and garages and into yards	Good correlation
19	Calga Street, Roseville Chase	Floodwaters overflowing from creek and cascading through property	Good correlation
28	Middle Harbour Road, Lindfield	Ponding along Middle Harbour Road	Good correlation
29	Gregory Street, Roseville	Flooding under houses in this location	Good correlation
32	Mycumbene Avenue, East Lindfield	Knee depth flooding due to a blocked easement	Observed behaviour not replicated, most likely due to placement of inflows.
33	Garnet Street, Killara	Flooding underneath buildings	Observed behaviour not replicated due to placement of inflows.
34	Warrane Road, Roseville Chase	Flooding in backyard	Observed behaviour not replicated due to placement of inflows.
35	Haig Street, Roseville	Flooding along golf course fairway	Good correlation
36	Pacific Highway, Lindfield	Ponding on road and overflowing into properties	Observed behaviour not replicated due to placement of inflows.

ID	Location	Observed Flood Behaviour	Predicted Flood Behaviour
37	Middle Harbour Road, Lindfield	Mild flooding midway along Middle Harbour Road	Good correlation
46	Melbourne Road, East Lindfield	Water cascading from Melbourne Road and Canberra Crescent into Carnarvon Road	Good correlation
48	Boundary Street, Roseville	Overland runoff through properties	Observed behaviour not replicated due to placement of inflows.
49	Middle Harbour Road, Lindfield	Ponding along Middle Harbour Road	Satisfactory correlation
51	Intersection of Trafalgar Avenue and Middle Harbour Road, Roseville	Ponding at roundabout	Good correlation
53	Intersection of Lindfield Avenue and Russell Avenue, Lindfield	Ponding on road	Good correlation

5.3 February 2020 Model Verification Event

5.3.1 Verification Data

Rainfall Data
The recorded rainfall daily totals (for the 24 hours to 9 am) from the 7 February to 11 February 2020 for active rainfall gauges within or nearest to the catchment are provided in Table 5.3.

Table 5.3 Recorded Daily Rainfall Totals for February 2020 Event

Gauge Name	Gauge ID	To 9AM 07/02/2020	To 9AM 08/02/2020	To 9AM 09/02/2020	To 9AM 10/02/2020	To 9AM 11/02/2020
East Lindfield Bowling Club	566085	63	61.5	106.5	201	0.5
Chatswood Bowling Club	566017	68.5	74	115	207	0
Pymble Bowling Club	566073	58.5	58.5	117.5	196	0
Castle Cove (Rosebridge Avenue)	66080	60	64	92	240	0
Gordon Golf Club	66120	40.6	74	42	240	0

As shown in Table 5.3, rainfall was recorded across the region primarily for a 4-day period from the 7 to 10 February 2020, with the largest depth of rainfall occurring in the 24 hours to 9am on 10 February. There was a spatial similarity observed across the region, with the largest rainfall recorded at the Castle Cove (Rosebridge Avenue) gauge within the study area.

The sub-daily rainfall data for the East Lindfield Bowling Club was available in 6-minute increments. The records indicate that the event was generally characterised by extended rainfall on the 7 February to the 9 February.

To gain an appreciation of the relative intensity and magnitude of the February 2020 event, the rainfall depths for various durations within the storm was compared against design IFD rainfall curves, as presented in Figure 5.3. The design IFD rainfall curves were obtained from BoM. As shown in Figure 5.3, the scaled rainfall input is estimated to be in the order of a 50% to a 20% AEP for event durations between 15 minutes and 1 hour, and approaching 1% AEP for event durations between 9 and 18 hours.

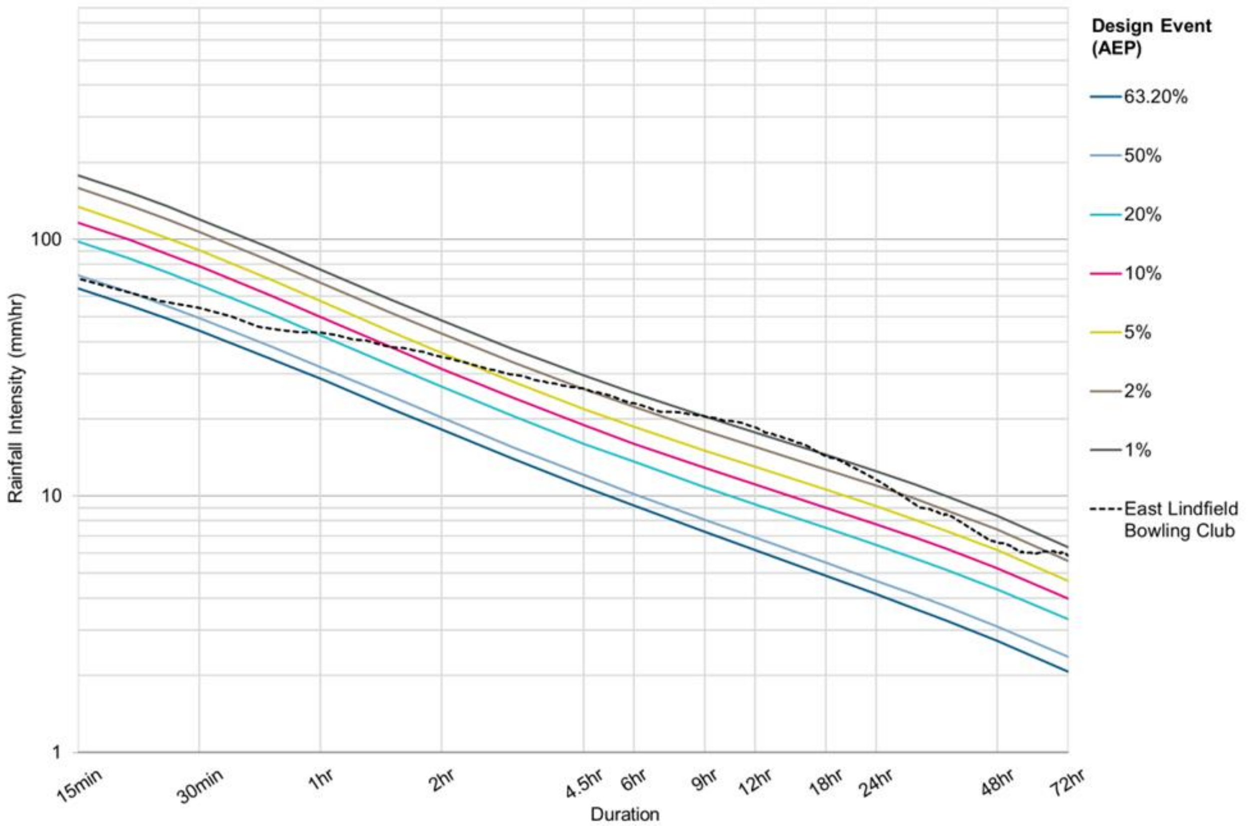


Figure 5.3 Comparison of Recorded February 2020 Rainfall with IFD Relationships

Downstream Boundary Condition

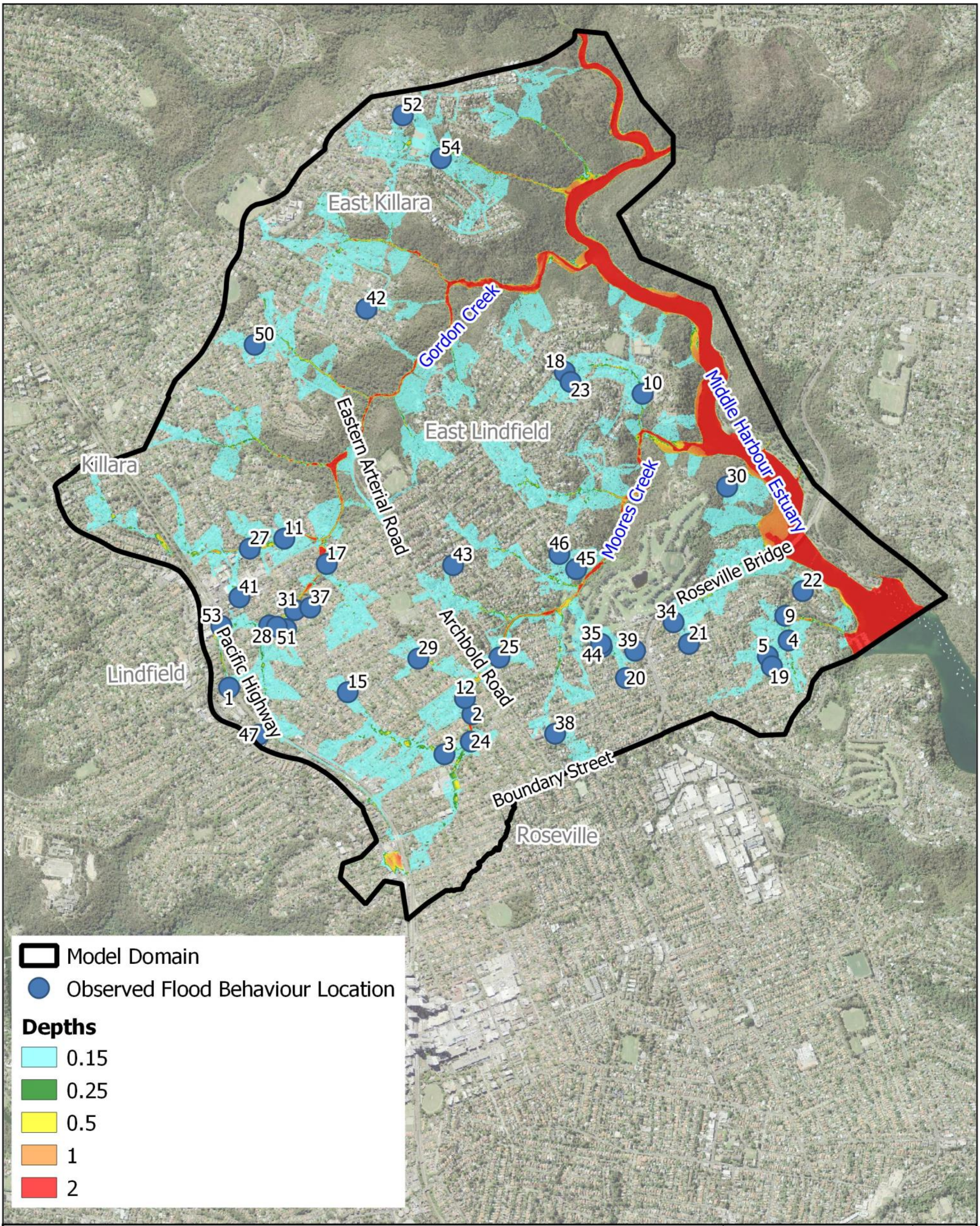
Coincident flooding of the Middle Harbour Southern Catchments with tidal conditions in the Middle Harbour Estuary have been conservatively assumed to define the downstream model boundary for this study (see Section 6.2.7). A High High Water Spring (HHWS) tailwater level has been adopted for the February 2020 event.

5.3.2 Flood Level Data

As per the June 2016 event, there is no available data within the catchment area to provide recorded water levels for the February 2020 event. Anecdotal flood data for the event was again obtained through the community questionnaire, with a higher number of responses provided for the event.

5.3.3 Observed and Predicted Flood Behaviour

The modelled peak flood depths based on the historical rainfall data for the East Lindfield Bowling Club rainfall gauge are presented in Figure 5.4. The community consultation process indicated that the February 2020 event led to significant affectation on private properties, which is reflected in the TUFLOW model results. Overland flows travelling through urban areas discharged through private property in several locations before reaching the downstream watercourses within the catchment area.



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February 2020 Verification Event - Peak Flood Depth and Observed Flood Data Distribution

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A summary of the flood behaviour observed by the community members against the predicted flood behaviour is provided in Table 5.4. Overall, there is generally good agreement between observed flood behaviour and historical flood behaviour predicted by the flood model at most locations for this event.

Table 5.4 Comparison of Observed and Predicted Flood Behaviour – February 2020 Event

ID	Location	Observed Flood Behaviour	Predicted Flood Behaviour
1	Llewellyn Street, Lindfield	Ponding at bottom of street	Good correlation
2	Lord Street, Roseville	Ponding along low point, some shallow flow in buildings	Satisfactory correlation
3	Bancroft Avenue, Roseville	Flooding in backyards and inside garages	Good correlation
4	Allard Avenue, Roseville Chase	Heavy flow in yards, shallow ponding in buildings	Good correlation
5	Calga Street, Roseville Chase	Strong flow of water through yards, ankle deep flooding on road	Satisfactory correlation. Widespread flooding present in area. Some major flow paths not represented due to placement of inflows.
9	Allard Avenue, Roseville Chase	Flow in yard	Good correlation
10	Mayfair Place, East Lindfield	Flow running under buildings	Good correlation
11	Lightcliff Avenue, Lindfield	Fast moving flow through yards and under buildings, shallow overfloor flooding	Good correlation
12	Lord Street, Roseville	Flooding in Moore Creek adjacent to Lord Street	Good correlation
15	Intersection of Trafalgar Avenue and Clanville Road, Roseville	Shallow flow across rear of properties	Good correlation
17	Howard Street, Lindfield	Rising floodwaters in creek behind properties	Good correlation
18	Wellington Road, East Lindfield	Water ponding on road and running overland through granny flats and garages and into yards	Good correlation
19	Calga Street, Roseville Chase	Floodwaters overflowing from creek and cascading through property	Good correlation
20	Addison Avenue, Roseville	Overflow from street drainage floods garages/sheds	Good correlation
21	Warrane Road, Roseville Chase	Water runs downhill into properties/garages	Good correlation
22	Babbage Road, Roseville Chase	Fast moving flow runs downhill through yards and into garages/sheds	Good correlation

ID	Location	Observed Flood Behaviour	Predicted Flood Behaviour
23	Pleasant Avenue, East Lindfield	Flooding in yards and along carports	Good correlation
24	Bancroft and Wandella Ave	Overflow from street into yards and garages	Good correlation
25	Moores Creek	Water overtopped banks between Luxor Parade and Amarna Parade	Good correlation
27	Intersection of Nelson Road and Tryon Road, Lindfield	Rising water in creek caused widespread flooding in yards	Good correlation
28	Middle Harbour Road, Lindfield	Ponding along Middle Harbour Road	Good correlation
29	Gregory Street, Roseville	Flooding under houses in this location	Good correlation
30	Ormonde Road, Roseville Chase	Fast moving flow through yards	Good correlation
31	Middle Harbour Road, Lindfield	Gordon creek overflowed, shallow flooding in yards	Good correlation
34	Warrane Road, Roseville Chase	Flooding in backyard	Observed behaviour not replicated due to placement of inflows.
35	Haig Street, Roseville	Flooding along golf course fairway	Good correlation
37	Middle Harbour Road, Lindfield	Mild flooding midway along Middle Harbour Road	Good correlation
38	Duntroon Avenue, Roseville	Ponding on road	Satisfactory correlation. Some water present on road, but major ponding not present. May be due to placement of inflows.
39	Links Avenue, Roseville	Overflow into garages and sheds	Observed behaviour not replicated due to placement of inflows.
41	Tryon Road, Lindfield	Overflowing leading to shallow flooding inside buildings	Observed behaviour not replicated due to placement of inflows.
42	Eastgate Avenue, East Killara	Water cascading into rear yards before flowing onto road	Observed behaviour not replicated due to placement of inflows.
43	Chelmsford Avenue, Lindfield	Knee deep flooding in rear yards leading to flooding of garages	Observed behaviour not replicated due to placement of inflows.
44	Haig Street, Roseville	Flow through yards leading to flooding of buildings	Observed behaviour not replicated due to placement of inflows.

ID	Location	Observed Flood Behaviour	Predicted Flood Behaviour
45	Carnarvon Road, Roseville	Overflow from Canberra Crescent into Carnarvon Road	Good correlation
46	Melbourne Road, East Lindfield	Water cascading from Melbourne Road and Canberra Crescent into Carnarvon Road	Good correlation
47	Pacific Highway, Lindfield	Ankle level water on driveways	Observed behaviour not replicated due to placement of inflows.
49	Middle Harbour Road, Lindfield	Ponding along Middle Harbour Road	Satisfactory correlation
50	Rosetta Avenue, East Killara	Ankle level flooding in backyards, cascading to lower properties	Satisfactory correlation. Higher depths present in modelling than those observed by community. May be due to placement of inflows or due to timing of observation.
51	Intersection of Trafalgar Avenue and Middle Harbour Road, Roseville	Ponding at roundabout	Good correlation
52	Redfield Road, East Killara	Water cascading to lower lying properties, ankle depth flooding in yards	Observed behaviour not replicated due to placement of inflows.
53	Intersection of Lindfield Avenue and Russell Avenue, Lindfield	Ponding on road	Good correlation
54	Saiala Road, East Killara	Heavy flow in creek with shallow flooding of yards and garages/sheds	Good correlation

5.4 March 2022 Storm Event

A significant rainfall event occurred within the Middle Harbour Southern Catchments in March 2022. While this event occurred following the completion of design flood modelling and model verification, the event was raised a number of times during the community consultation period as discussed in Section 3.4. Given the significance of the event and the community interest a summary of the recorded rainfall totals and IFD relationship are included below.

Table 5.5 Recorded Daily Rainfall Totals for March 2022 Event

Gauge Name	Gauge ID	To 9AM 05/03/2022	To 9AM 06/03/2022	To 9AM 07/03/2022	To 9AM 08/03/2022	To 9AM 09/03/2022
East Lindfield Bowling Club	566085	12	49	45.5	82	179
Pymble Bowling Club	566073	9.5	38	54.5	68	152.5
Castle Cove (Rosebridge Avenue)	66080	16	38	52	82	181
Gordon Golf Club	66120	0	100	36	187	2.5

As shown in Table 5.5, rainfall was recorded across the region primarily for a 4-day period from the 6 to 9 March 2022, with the largest depth of rainfall occurring in the 24 hours to 9am on 9 March 2022. There was some spatial variability observed across the catchment, with the Gordon Golf Club gauge recording the largest amount of rainfall in the 24 hours prior to 8 March in contrast to the other 3 gauges which recorded their peak rainfall in the 24 hours prior to 9 March. This is most likely explained by the timing of rainfall occurring either before or after 9AM at the various gauges.

The sub-daily rainfall data for the East Lindfield Bowling Club was available in 6-minute increments. The records indicate that the event was generally characterised by extended rainfall on the 6 to 9 March 2022.

To gain an appreciation of the relative intensity and magnitude of the March 2022 event, the rainfall depths for various durations within the storm was compared against design IFD rainfall curves, as presented in Figure 5.5. The design IFD rainfall curves were obtained from BoM. As shown in Figure 5.5, the scaled rainfall input is estimated to be in the order of a 20% to a 5% AEP for event durations between 15 minutes and 45 minutes and in the order of a 2% AEP to a 1% AEP for event durations between 1 hour and 12 hours, with intensities exceeding a 1% AEP event for the 2 hour duration.

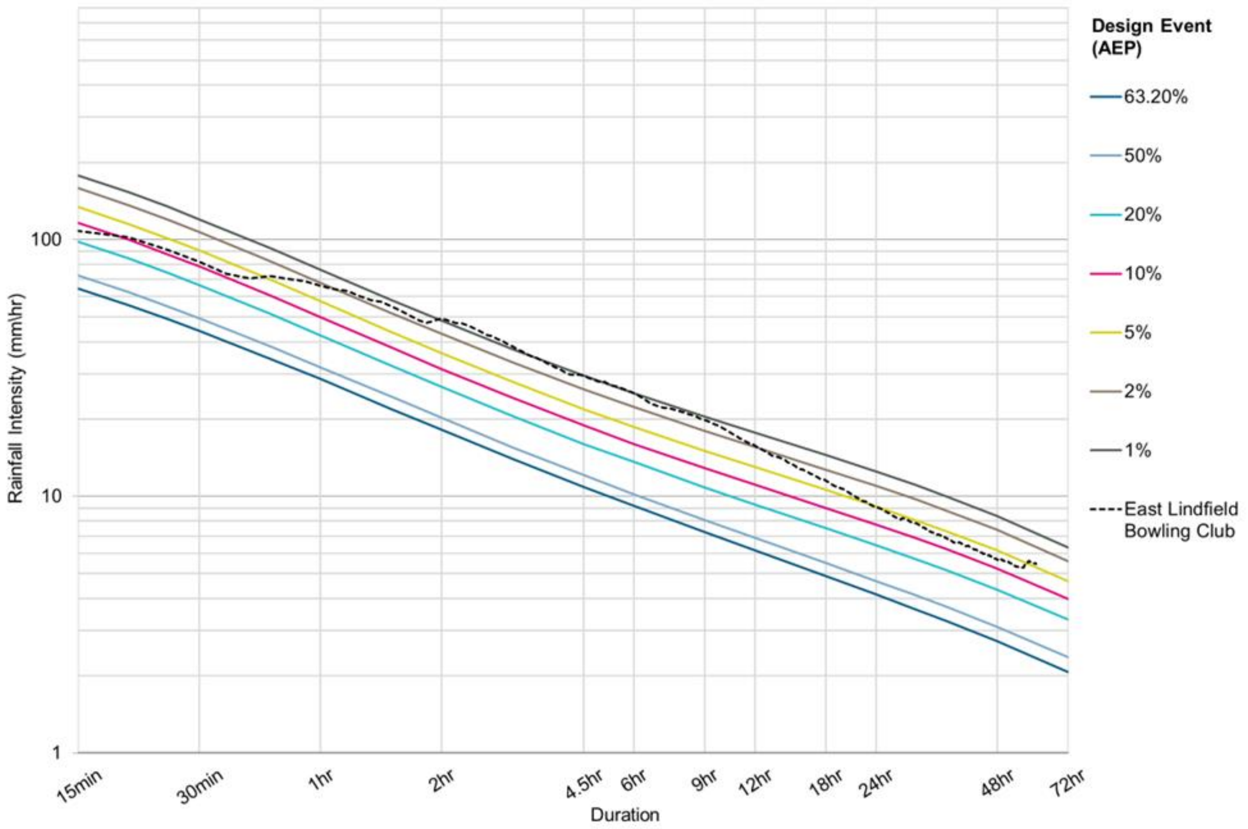


Figure 5.5 Comparison of Recorded March 2022 Rainfall with IFD Relationships

5.5 Summary of Model Verification

The model verification process has involved the development of an appropriate hydraulic model to best represent the flooding conditions within the study area utilising the available data. Rainfall inputs were developed for the models utilising available rainfall gauge data for two historical verification events: June 2016 and February 2020, respectively. Whilst there is no recorded peak flood level data upon which to base a quantitative model calibration, the flood behaviour predicted by the TUFLOW model results generally agreed with the anecdotal observed flood behaviour provided as part of the community consultation process.

In the absence of quantitative calibration data, a sensitivity analysis has been undertaken to assess the influence of the adopted model parameters on predicted flood conditions (see Section 8). This analysis provided a basis for determining the relative accuracy of modelling results, and an initial focus for future floodplain management planning.

6 Design Flood Modelling

6.1 Design Floods

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

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

This report uses the AEP terminology as per ARR 2019 recommendations. Refer to Table 6.1 for a definition of AEP and the ARI equivalent.

Table 6.1 Design Flood Terminology

AEP[1]	ARI[2]	Comments
Extreme Flood / PMF		A probabilistic or statistical estimate of flood or combination of floods, which represent an extreme scenario.
0.2% AEP	500 years	A probabilistic or statistical estimate of flood or combination of floods likely to occur on average once every 500 years or with a 0.2% probability of occurring in any given year
0.5% AEP	200 years	As for the 0.2% AEP flood but with a 0.5% probability or 200-year return period.
1% AEP	100 years	As for the 0.2% AEP flood but with a 1% probability or 100-year return period.
2% AEP	50 years	As for the 0.2% AEP flood but with a 2% probability or 50-year return period.
5% AEP	20 years	As for the 0.2% AEP flood but with a 5% probability or 20-year return period.
10% AEP	10 years	As for the 0.2% AEP flood but with a 10% probability or 10-year return period.
20% AEP	Approximately 5 years	As for the 0.2% AEP flood but with a 20% probability or approximately 5-year return period.

Note:

1 Annual Exceedance Probability (%)

2 Average Recurrence Interval (years)

6.2 ARR 2019 Approach

6.2.1 Overview

The ARR 2019 guidelines comprise significant changes to the previous AR&R 1987 guideline. Some of the key changes in ARR 2019 include:

- Intensity-Frequency-Duration (IFD) 2016 design rainfalls – revised IFD rainfall estimates underpin the ARR 2019 guidelines. The updated IFD, developed by BoM, includes an additional 30 years of rainfall data as well as in increase in the number of available pluviograph and daily rainfall gauges (600 to 2280 pluvio gauges and 7500 to 8074 daily gauges).

- Areal reduction factors (ARFs) – revised equations have been developed as part of ARR 2019 with regionalised parameters to define ARFs for catchments based on catchment area and storm duration.
- Design rainfall losses – estimation of initial and continuing loss rates (as applied in the hydrologic model) are provided in ARR 2019 as gridded spatial data. Representative losses for catchments are extracted from the database. This is a significant change from the previous approach (AR&R 1987) in which basic ranges were recommended for broad areas that is eastern or western NSW.
- Pre-burst rainfall – ARR 2019 provides procedures for the consideration of pre-burst rainfalls for consideration along with design initial losses. The procedures provide for generation of tabular outputs of pre-burst rainfall for the catchment of interest based on a combination of storm duration and return period.
- Temporal patterns – the change in temporal patterns represents one of the most significant differences from the ARR 2019 guidelines. Each design duration now has an ensemble of 10 temporal patterns as opposed to a single temporal pattern for each duration for AR&R 1987.

The ARR 2019 parameters are sourced via the ARR Data Hub (https://data.arr-software.org/). The ARR 2019 Data Hub report for the study area is included in Annex E.

6.2.2 IFD Design Rainfall

Design rainfall grids (based on the 2016 IFDs) were obtained from the BoM website for a range of AEP/duration combinations. The IFD grids have a grid cell spacing of 0.025 decimal spacing (an area of approx. 2.8 km^2). Spatial variability in design rainfall depth is present between the eastern and western portions of the catchment. IFD rainfall depths are highest in the north-east portion of the catchment (over the upstream Middle Harbour Estuary), and the central and western parts of the catchment have similar rainfall across all events. However, an assessment of at-site rainfall data (as outlined in Section 6.2.3) has determined that the 2016 IFDs underestimate expected rainfall behaviour within the study area based on historical record.

6.2.3 At-Site IFD Analysis

As part of this study, “at-site” gauge data has been compared against the 2016 IFD design rainfalls supplied by BoM to establish if:

- There is a significant bias between the two datasets; and
- 2016 IFD design rainfall potentially overestimates or underestimates likely catchment rainfall conditions.

Historical rainfall data was supplied by Sydney Water for the three pluviographs closest to the catchment. A summary of each pluviograph and its period of record is shown in Table 6.2. Only the East Lindfield Bowling Club pluviograph is within the Middle Harbour Southern Catchment area.

Table 6.2 Rainfall Gauges Used For At-Site Rainfall Analysis

Gauge Name	Gauge Number	Period of Record	Length of Record (years)
Chatswood Bowling Club	566017	1962-2021	~59
Pymble Bowling Club	566073	1987-2021	~34
East Lindfield Bowling Club	566085	1990-2021	~31

The annual maximum rainfall depth for all design durations at the 3 gauges was used to produce an annual maximum series (AMS) for each gauge. The TUFLOW FLIKE software was then used to fit a probability distribution through the AMS depths (using a GEV probability model with an LH moments inference method). The probability distribution for each gauge was then compared against the 2016 IFDs as shown in Figure 6.1 to Figure 6.3.

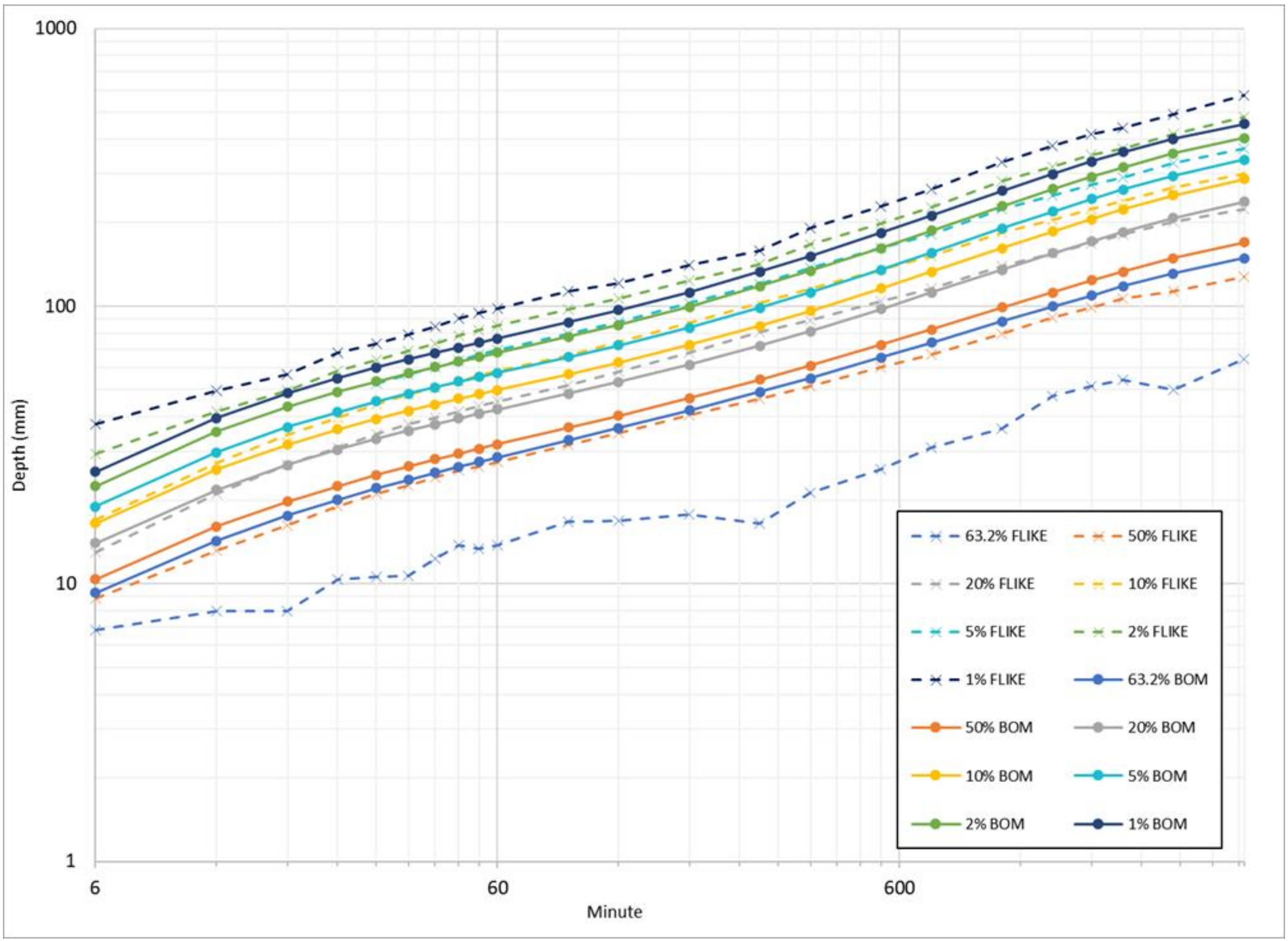
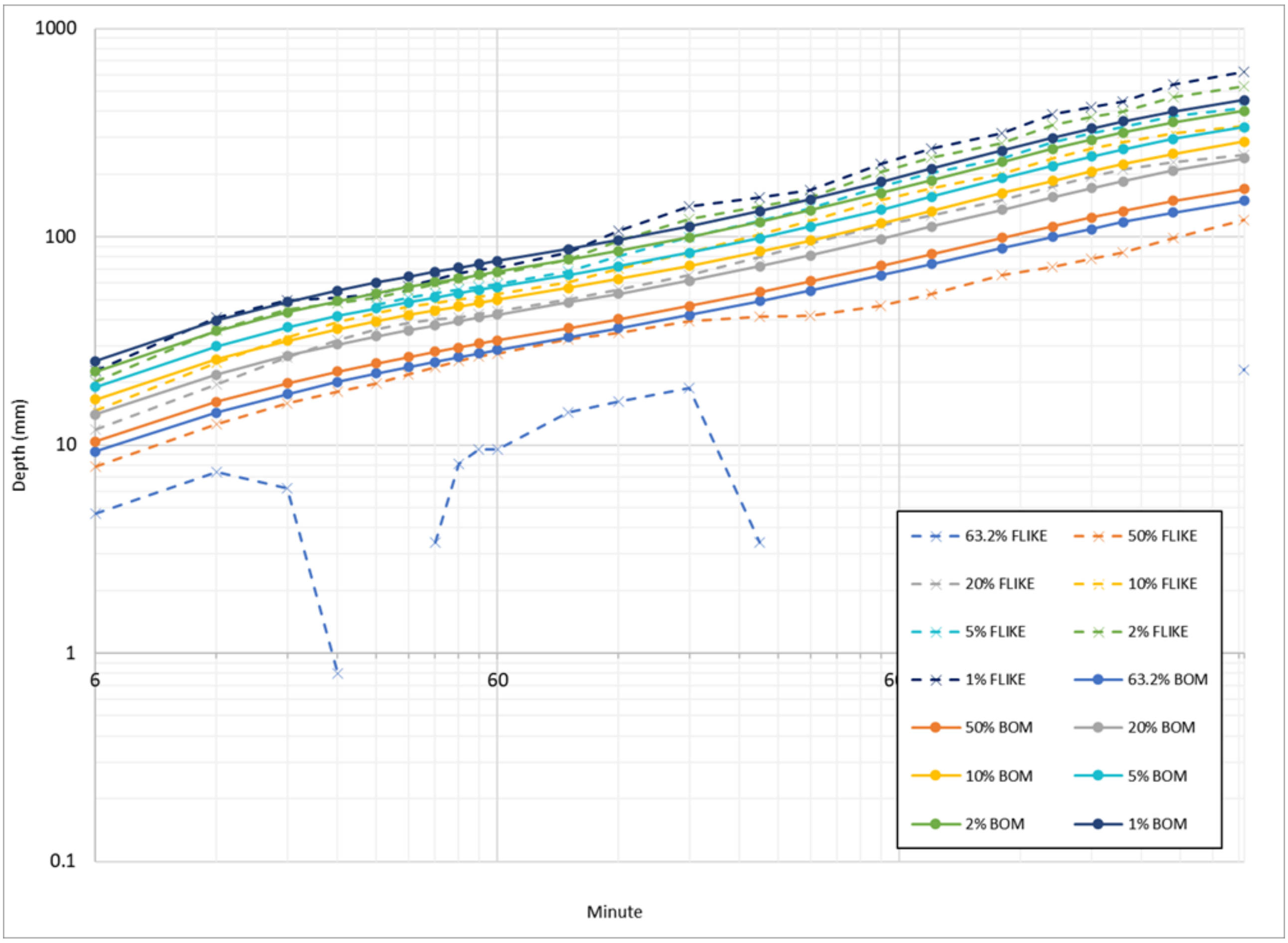


Figure 6.1 At-site Rainfall vs 2016 IFD Comparison for Chatswood Bowling Club Gauge



Note, negative values are not displayed on chart.

Figure 6.2 At-site Rainfall vs 2016 IFD Comparison for Pymble Bowling Club Gauge

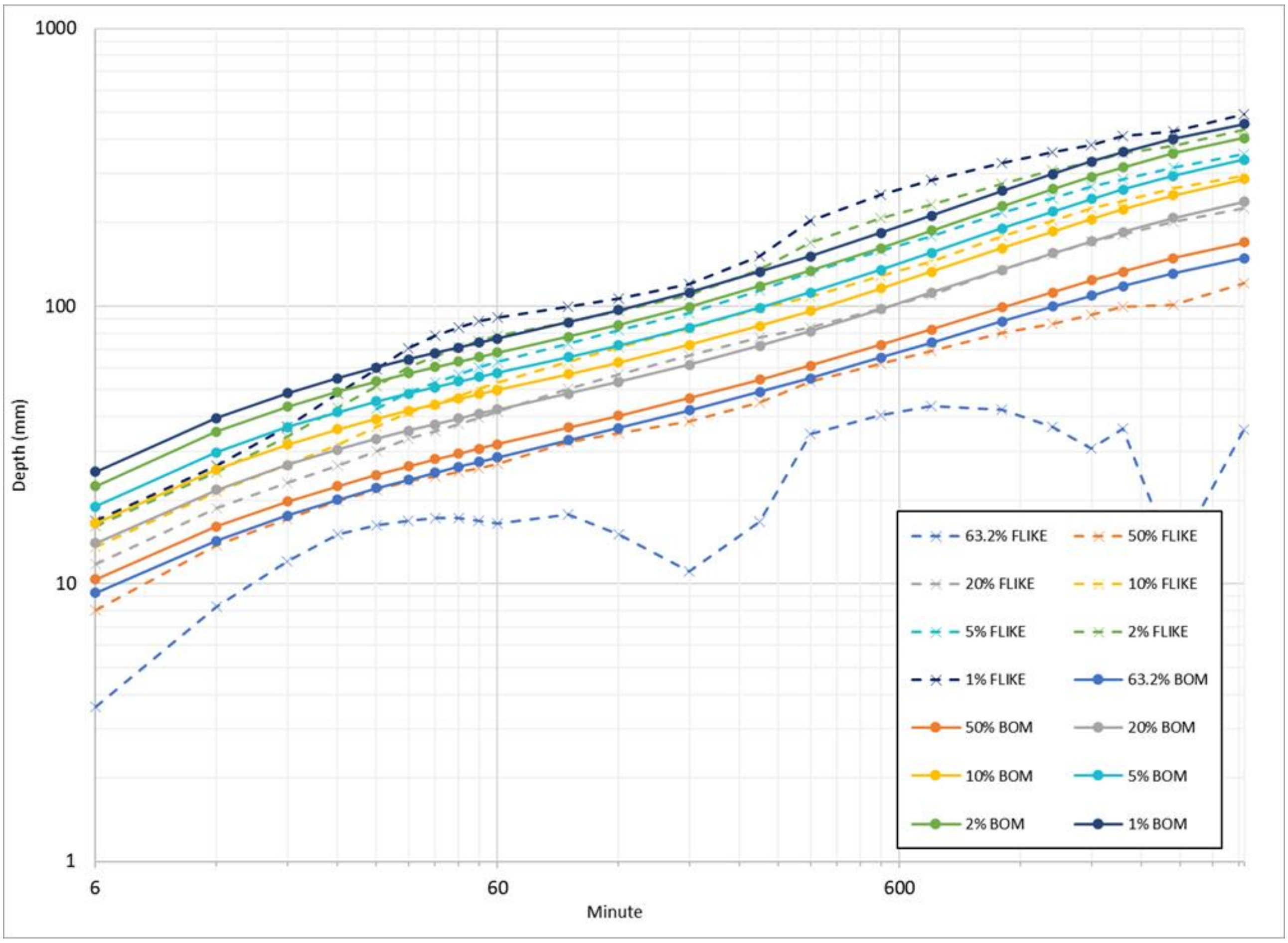


Figure 6.3 At-site Rainfall vs 2016 IFD Comparison for East Lindfield Bowling Club Gauge

Of the three gauged datasets, only the Chatswood Bowling Club gauge is considered appropriate for use in this assessment as it is the only gauge with a long enough period of record (59 years) from which a conclusive pattern can be drawn.

As shown in Figure 6.1, the results of the at-site rainfall analysis for the Chatswood Bowling Club gauge indicate that the 2016 IFDs underestimate expected rainfall depths within the study area based on historical records. This was found to be particularly true for shorter duration storms likely to be critical in urban areas, with IFD rainfall depths being on average 17% lower than historical rainfall data for durations of less than 3 hours. It was therefore decided to scale the 2016 IFD rainfall depths to match the at-site rainfall analysis of the Chatswood Bowling Club gauge and to use these scaled rainfall depths for modelling design rainfall events in this study. The adopted rainfall depths are outlined in Table 6.3.

Table 6.3 Adopted Rainfall Depths

Duration	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	1 in 200 AEP	1 in 500 AEP
15 min	23.9	30.8	36.8	45.6	53.1	57.3	64.8
20 min	28.1	36.1	42.8	52.5	60.4	65.2	73.8
25 min	31.5	40.4	48.2	59.4	68.8	74.3	84.1
30 min	34.7	44.4	52.5	63.9	73.2	79.2	89.6
45 min	40.8	52.2	61.9	75.8	87.3	94.6	107.1
1 hour	45.3	58.4	69.4	85.2	98.2	106.5	120.7
1.5 hour	51.9	66.7	79.4	97.6	112.9	122.4	138.1
2 hours	58.0	74.1	87.5	106.2	121.4	131.8	148.1
3 hours	68.2	87.2	102.7	123.9	140.7	152.0	172.1
4.5 hours	80.6	102.6	119.7	142.0	159.0	171.0	192.5
6 hours	89.2	115.4	137.0	166.9	190.9	204.8	231.4
9 hours	104.3	135.6	161.6	198.3	228.2	244.3	275.3
12 hours	115.3	151.1	182.0	226.9	264.5	283.2	319.4

6.2.4 Areal Reduction Factors

An Areal Reduction Factor (ARF) considers how the rainfall depth varies across a catchment under the assumption that larger catchments will not experience the same rainfall depth over the entire area. Equations have been developed as part of ARR 2019 with regionalised parameters to define event specific ARFs for catchments, based on catchment area and storm duration. ARFs are only applied to catchments larger than 1 km^2.

Whilst the study area in its entirety is approximately 9.7 km^2, it is made up of the 5 sub-catchments represented within the DRAINS hydrologic model (Gordon Creek, Moores Creek, Middle Harbour 2, Middle Harbour 3 and Middle Harbour 4). ARF estimates have been determined based on the catchment areas of the smaller catchment systems rather than the whole study area.

The details for each catchment system and their contributing catchment area are presented in Table 6.4. The locations of these catchments are shown in Figure 1.2. The Middle Harbour 3 catchment has an area of less than 1 km^2 hence the ARF has not been applied for this catchment.

Table 6.4 ARFs – Contributing Catchment Areas

Catchment System	Catchment Area (km^2)
Gordon Creek	4.5
Moores Creek	3.1
Middle Harbour 2	1.2
Middle Harbour 3	0.8
Middle Harbour 4	1.3

The short duration (12 hours or less) equations were used with applicable regional parameters to derive ARFs for the nominated catchment areas. The equations are based on regionalised parameters and were obtained from the ARR Data Hub (refer to Annex E). Table 6.5 provides an overview of the ARF estimates for Moores Creek (the southern-most tributary). ARF Estimates for the remaining 3 catchments are included in Annex F.

Table 6.5 ARF Estimates for the Moores Creek Catchment

Duration	20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	1 in 200 AEP	1 in 500 AEP
15 min	0.944	0.942	0.941	0.938	0.937	0.935	0.933
20 min	0.951	0.949	0.948	0.945	0.944	0.942	0.94
25 min	0.956	0.954	0.952	0.95	0.948	0.946	0.944
30 min	0.96	0.958	0.956	0.953	0.952	0.95	0.947
45 min	0.967	0.965	0.962	0.96	0.958	0.955	0.953
1 hour	0.971	0.968	0.966	0.963	0.961	0.958	0.955
1.5 hour	0.975	0.973	0.97	0.966	0.964	0.961	0.957
2 hours	0.978	0.975	0.972	0.968	0.965	0.962	0.958
3 hours	0.981	0.978	0.974	0.97	0.967	0.963	0.959
4.5 hours	0.985	0.982	0.979	0.976	0.973	0.97	0.966
6 hours	0.988	0.987	0.985	0.982	0.981	0.979	0.977
9 hours	0.992	0.991	0.99	0.988	0.987	0.986	0.985
12 hours	0.993	0.992	0.991	0.99	0.989	0.988	0.986

6.2.5 Rainfall Losses

A detailed discussion regarding the derivation of rainfall losses was previously provided in Section 4.2.4. The rainfall losses used for design event modelling are as follows:

- Pervious surfaces - Initial loss as per Table 4.4 and 0.72 mm/h continuing loss.
- Impervious surfaces – 1.5 mm initial loss and 0 mm/h continuing loss.

6.2.6 Temporal Patterns

The ARR 2019 temporal patterns provide one of the most significant changes in the approach to design flow estimation from AR&R 1987, with an ensemble of ten temporals patterns used instead of a single temporal pattern for each AEP and duration combination. The ARR 2019 method has three temporal pattern bins that are used for various design events as shown in Figure 6.4. These include:

- Frequent – more frequent than a 14.4% AEP event;
- Intermediate – between a 3.2% AEP and 14.4% AEP event;
- Rare – rarer than a 3.2% AEP event;
- Very Rare – currently in development and not available at the time of this study. The Rare patterns are adopted for all events rarer than a 3.2% AEP event (except for the PMF event).

The ten temporal patterns for each AEP and duration combination vary in terms of their distribution and variability. As a result, a wide range of flooding behaviour can be simulated across the catchment. The ARR 2019 temporal patterns for the study area were downloaded from the ARR Data Hub.

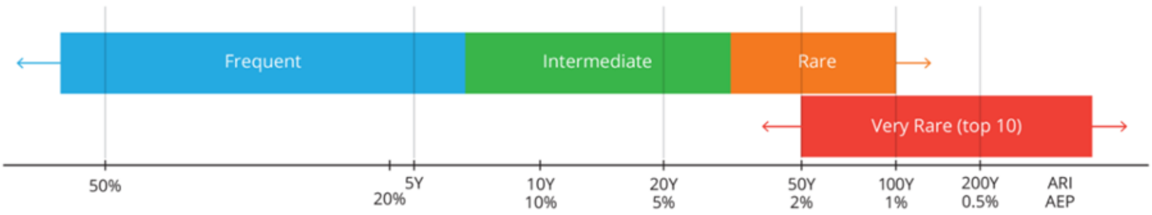


Figure 6.4 Temporal Pattern Bins (ARR 2019)

6.2.7 Downstream Boundary Conditions

The study area discharges into Middle Harbour either via a series of channel confluences and pipe inlets or overland via the steep forested areas in the east of the catchment.

Coincident flooding of the Middle Harbour Southern Catchments with tidal conditions in the Middle Harbour Estuary have been conservatively assumed to define the downstream model boundary for this study. The adopted downstream boundary conditions for this study are presented in Table 6 6 and are consistent with the approach recommended in the *'Modelling the Interaction of Catchment Flooding and Oceanic Inundation in Coastal Waterways'* (OEH, 2015).

Table 6.6 Adopted Downstream Boundary Conditions

Design Event	Local Catchment Rainfall Event	Middle Harbour Tidal Event	Downstream Boundary Level (mAHD)
20% AEP	20% AEP	HHWSS	1.25
10% AEP	10% AEP	HHWSS	1.25
5% AEP	5% AEP	HHWSS	1.25
2% AEP	2% AEP	5% AEP	1.4
1% AEP	1% AEP	5% AEP	1.4
1 in 200 AEP	1 in 200 AEP	1% AEP	1.45
1 in 500 AEP	1 in 500 AEP	1% AEP	1.45
PMF	PMF	1% AEP	1.45

6.3 Blockage Assumptions

6.3.1 Blockage of Hydraulic Structures

ARR 2019 includes guidance regarding the procedure to estimate blockage levels of structure inlets for design flood modelling (refer Book 6: Flood Hydraulics – Chapter 6 Blockage of Hydraulic Structures). The ARR 2019 assessment procedure includes classification of the following mechanisms:

- Debris type and dimensions (including identification of the average length of the longest 10% of the debris that could arrive at the site (termed as L^{10}). In line with the value suggested in ARR 2019 an L^{10} of 1.5m has been adopted for this study.
- Debris availability in the study area.
- Debris mobility.
- Debris transportability.

A classification is applied to each of the above components and the combination of these classifications provides a debris potential classification of either Low, Medium or High.

This assessment has also adopted an AEP adjusted scaling of the 'most-likely' inlet blockage based upon the magnitude of a design event. That is, more frequent flood events are likely to have lower blockages than a rarer event. The ARR 2019 blockage assessment sheet is included as Annex G.

In addition to the structure blockage condition, industry standard pipe and culvert losses have been applied at all relevant conduits in the TUFLOW hydraulic model, specifically:

- An entry and exit loss of 0.5 and 1.0 respectively;
- Height and width contraction coefficients of 0.6 and 0.9 for culverts and 0 and 1.0 for pipes.

6.3.2 Pit Inlet Blockages

Pit Inlet Blockages were adopted in accordance with Ku-ring-gai Council's *Development Control Plan Part 24: Water Management* (2015) and following discussions with Council. The blockage percentages for the inlet condition and inlet type are provided in Table 6.7.

Table 6.7 Adopted Pit Inlet Blockages

Inlet Type	Blockage Percentage
Side Entry	20%
Grated	50%
Combination	Side inlet capacity only, Grate completely blocked
Letterbox	50%

6.4 Critical Duration and Temporal Pattern Assessment

The critical duration (and its associated mean temporal pattern) was selected through assessment of the peak flood levels across the catchment predicted by the modelling. This analysis was completed for each of the temporal pattern bins associated with the selected design events (i.e. frequent, intermediate and rare storm events).

The following method was adopted to undertake the critical duration assessment:

1. Using DRAINS to run an ensemble of temporal patterns from the 15-minute duration to the 720-minute duration. This included 13 durations; 15, 20, 25, 30, 45, 60, 90, 120, 180, 270, 360, 540 and 720-minute.
2. Applying the hydrographs from the DRAINS models to the TUFLOW model. In total, 130 TUFLOW runs were completed for each temporal pattern bin.

3. For each duration and AEP combination, determine the temporal pattern that provided the level that was one above the mean of the ensemble of ten temporal patterns.

4. Once a representative mean temporal pattern was identified for each duration, the duration or combination of durations providing the peak flood level was identified to be the critical duration(s) for the study area.

The critical duration or combination of durations identified for each design event is presented in Table 6.8. It can be seen in Table 6.8 that shorter durations are typically critical across the catchment due to the urbanised nature of the upstream catchment, lack of major storage and steep terrain.

Table 6.8 Design Critical Durations and Mean Temporal Patterns

Design Event (AEP)	Temporal Pattern Bin	Critical Duration and Associated Mean Temporal Pattern
20%	Frequent	45 min (TP5)
10%	Intermediate	30 min (TP9)
5%	Intermediate	20 min (TP9)
2%	Rare	25 min (TP10)
1%		
0.5%	Rare	30 min (TP7)
0.2%		
PMF	See Section 6.5	

6.5 Probable Maximum Precipitation

The Probable Maximum Precipitation (PMP) is used to derive the Probable Maximum Flood (PMF) event. The definition of the PMP is *"the theoretical maximum precipitation for a given duration under modern meteorological conditions*" (WMO, 2009). The ARI of a PMP/PMF event ranges between 10^4 and 10^7 years and is beyond the "credible limit of extrapolation" (Pilgrim, 1987). That is, it is not possible to use rainfall depths determined for the more frequent events (1% AEP and less) to extrapolate the PMP. For this study, the PMP has been estimated using the Generalised Short Duration Method (GSDM) derived by the BoM (2003), which is appropriate for durations up to 360 minute (6 hours) and considered suitable for small catchments (less than 1,000 km^2).

An ensemble of storm durations were simulated using the DRAINS and TUFLOW model to determine the critical duration(s) for the PMF event. The storm durations that were assessed included the 15, 30, 45, 60, 90, 120, 150, 180, 270, 300 and 360 minute durations. The rainfall for each duration was estimated following the GSDM methodology. There is one temporal pattern used as shown in Figure 6.5. This pattern is scaled to the appropriate duration and rainfall total for each storm duration.

The critical durations were identified to be the 15 and 30 minute durations for the Middle Harbour Southern Catchments, with the 30 minute duration generally critical for the major overland flow paths. The spatial distribution of the PMF critical durations is shown in Figure 6.6 (note: flood extents shown are raw unfiltered results).

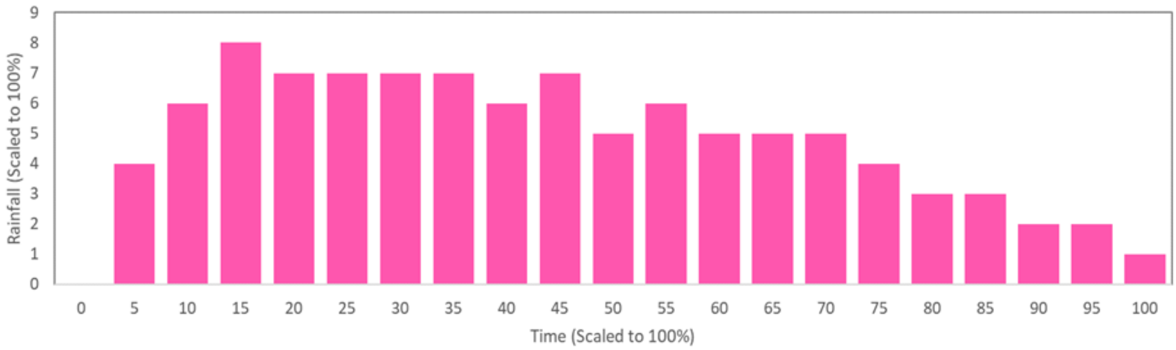
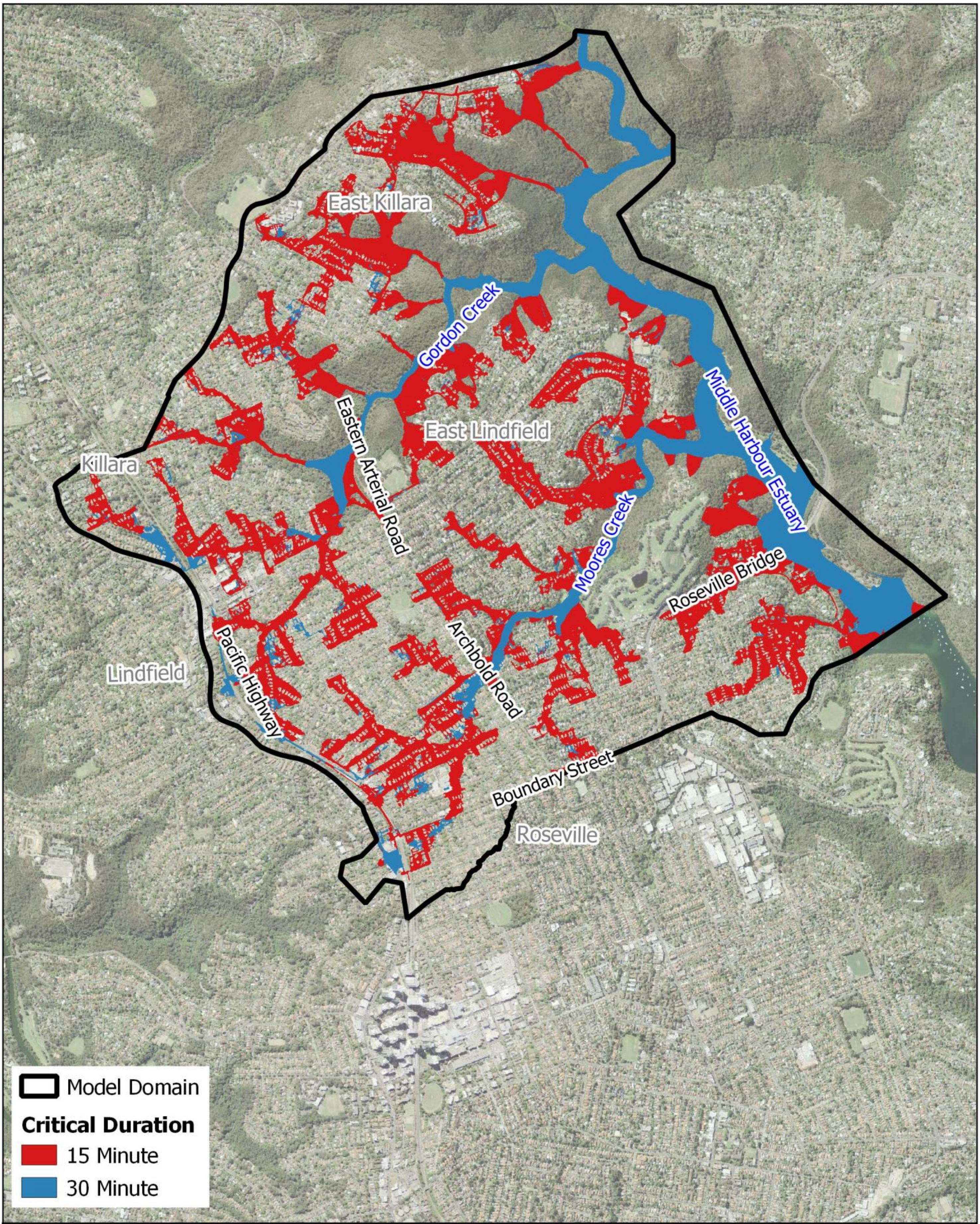


Figure 6.5 PMP Temporal Pattern



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Spatial Distribution of Critical Duration PMF Event

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7 Design Flood Conditions

7.1 Overview

The simulated design floods include the 20%, 10%, 5%, 2%, 1%, 0.5%, 0.2% AEP and PMF events. A series of design flood maps for selected events are provided in Annex H. The following results are provided:

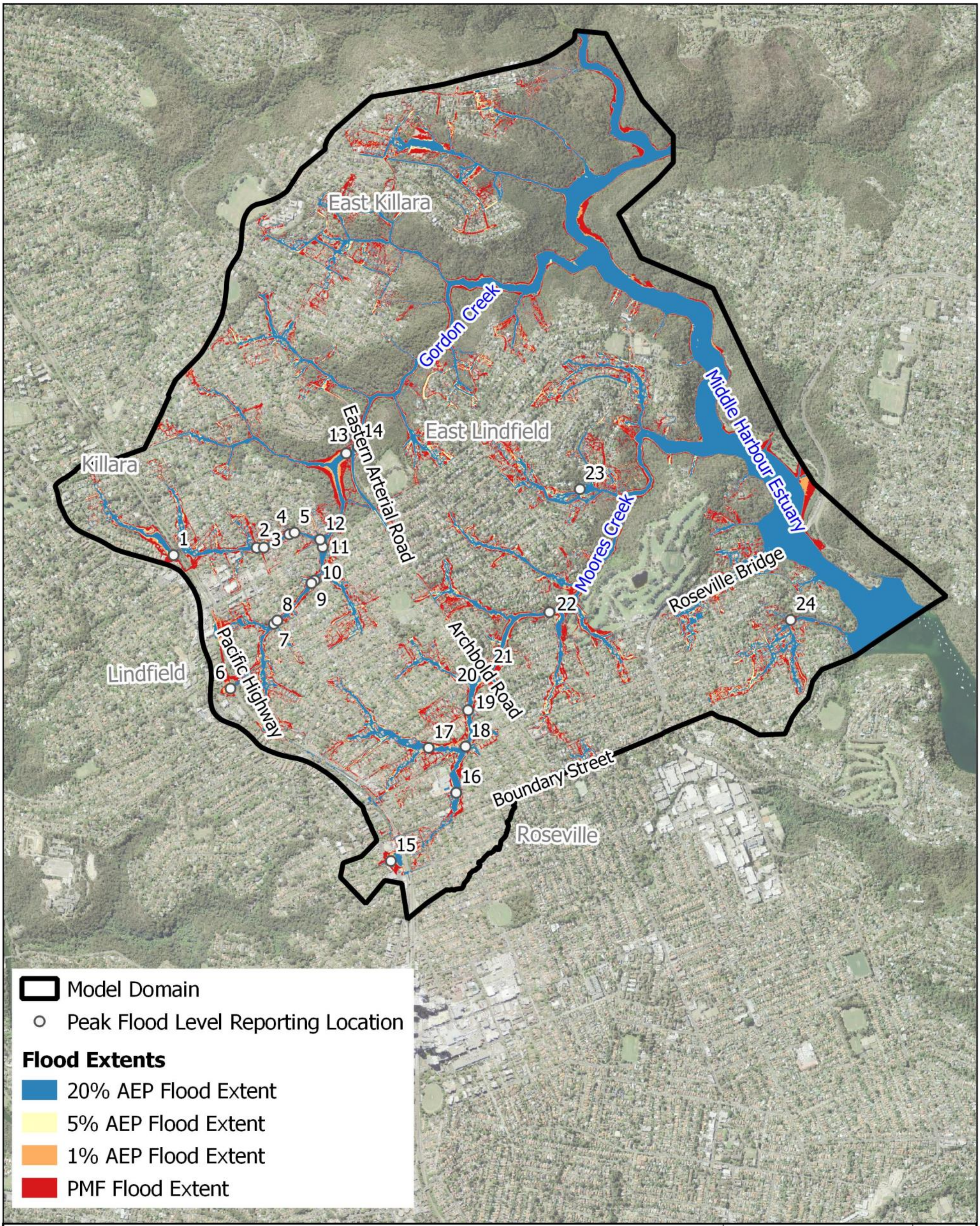
- Peak Flood Depths – Figure H1 to Figure H8;
- Peak Flood Levels – Figure H9 to Figure H16;
- Peak Flood Velocities – Figure H17 to Figure H24;
- Provisional Hazard Categorisation – Figure H25 to Figure H27;
- Provisional Hydraulic Classification (Flood Function) – Figure H28 to H30.

7.2 Peak Flood Conditions

For each design flood, a map of peak flood level, depth and velocity covering the study area is included in Annex H. The following filtering approach was applied to the results to identify areas of critical flow:

- Inclusion of areas with peak flood depths greater than or equal to 0.3 m;
- Inclusion of areas with peak flood depths greater than or equal to 0.1 m AND peak flood velocity-depth product greater than 0.1 m^2/s; and
- Inclusion of areas with peak flood depths greater than or equal to 0.05 m AND peak flood velocity-depth product greater than 0.025 m^2/s.

The design flood inundation extents for the 20%, 5% and 1% AEP and PMF events are presented in Figure 7.1. Modelled peak flood levels at selected locations (as shown in Figure 7.1) are presented in Table 7.1 for the full range of design floods considered.



Title: **Peak Flood Extents**		Drawing: 7-1	Rev: A
BMT endeavours to ensure that the information provided in this map is correct at the time of publication. BMT does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.	0 600 1,200 m	BMT www.bmt.org	

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Table 7.1 Modelled Peak Flood Levels

ID	Location	Modelled Peak Flood Level (m AHD)							
		20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP	PMF
H01	Upstream Railway at Wolseley Road, Lindfield	93.9	94.1	94.1	94.6	94.9	95	95.2	97.1
H02	Upstream Nelson Road, Lindfield	79.3	79.3	79.4	79.5	79.5	79.5	79.6	79.9
H03	Downstream Nelson Road, Lindfield	78.1	78.3	78.5	78.7	78.9	78.9	79.1	79.8
H04	Upstream Lightcliff Avenue, Lindfield	72.1	72.1	72.2	72.3	72.3	72.3	72.4	72.8
H05	Downstream Lightcliff Avenue, Lindfield	68.8	68.9	69	69.1	69.2	69.2	69.3	69.8
H06	Upstream Railway at Llewellyn Street, Lindfield	97.5	97.7	98	98.3	98.5	98.6	98.7	99.2
H07	Upstream Trafalgar Avenue, Roseville	80.1	80.2	80.2	80.3	80.3	80.3	80.4	80.8
H08	Downstream Trafalgar Avenue, Roseville	78.2	78.4	78.4	78.5	78.6	78.6	78.7	79.4
H09	Upstream Howard Street, Lindfield	72.9	72.9	72.9	73	73.1	73.1	73.2	73.7
H10	Downstream Howard Street, Lindfield	69.5	69.6	69.6	69.8	69.8	69.9	69.9	70.7
H11	Upstream Tryon Road, Lindfield	66.9	67	67	67.2	67.2	67.3	67.3	67.8
H12	Downstream Tryon Road, Lindfield	62.5	62.8	62.8	63.2	63.4	63.5	63.7	64.8
H13	Upstream Eastern Arterial Road, Lindfield	37.9	38.7	38.6	40.7	41.9	42.4	43.2	47.5
H14	Downstream Eastern Arterial Road, Lindfield	33	33	32.9	33.1	33.2	33.3	33.3	35.5
H15	Upstream Railway at Pacific Highway, Roseville	96.1	96.1	96.1	96.1	96.1	96.1	96.2	96.7
H16	Victoria Street, Roseville	82.8	82.9	82.9	82.9	83	83	83	83.3
H17	Glencroft Avenue, Roseville	81.8	81.9	81.9	82	82.1	82.1	82.2	83.2
H18	Bancroft Avenue, Roseville	76.4	76.4	76.5	76.6	76.7	76.7	76.8	77.9
H19	Lord Street, Roseville	72.4	72.5	72.6	72.8	72.9	73	73.1	74.1

ID	Location	Modelled Peak Flood Level (m AHD)							
		20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP	PMF
H20	Upstream Archbold Road, Roseville	67.7	68.3	68.7	69.5	69.6	69.7	69.8	70.5
H21	Downstream Archbold Road, Roseville	66.1	66.3	66.3	66.7	66.9	66.9	67	67.8
H22	Moores Creek at Roseville Golf Course	51.2	51.3	51.3	51.6	51.8	51.9	52.1	53.2
H23	Corner Namoi Place and Carlyle Road, East Lindfield	55.3	55.4	55.4	55.4	55.5	55.5	55.5	55.7
H24	Allard Avenue, Roseville Chase	29.8	29.9	30	30.1	30.1	30.2	30.2	30.6

Table 7.2 Modelled Peak Flood Depths

ID	Location	Modelled Peak Flood Depth (m)							
		20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP	PMF
H01	Upstream Railway at Wolseley Road, Lindfield	1.4	1.6	1.7	2.1	2.5	2.6	2.8	4.6
H02	Upstream Nelson Road, Lindfield	0.6	0.7	0.7	0.8	0.9	0.9	0.9	1.3
H03	Downstream Nelson Road, Lindfield	1.4	1.6	1.8	2.0	2.2	2.2	2.4	3.1
H04	Upstream Lightcliff Avenue, Lindfield	2.6	2.7	2.7	2.8	2.8	2.9	2.9	3.3
H05	Downstream Lightcliff Avenue, Lindfield	1.8	2.0	2.0	2.2	2.2	2.3	2.3	2.9
H06	Upstream Railway at Llewellyn Street, Lindfield	2.4	2.6	2.9	3.2	3.4	3.5	3.6	4.1
H07	Upstream Trafalgar Avenue, Roseville	0.8	0.9	0.9	0.9	1.0	1.0	1.1	1.5
H08	Downstream Trafalgar Avenue, Roseville	0.6	0.7	0.7	0.9	0.9	1.0	1.0	1.7
H09	Upstream Howard Street, Lindfield	4.0	4.1	4.1	4.2	4.3	4.3	4.4	4.9
H10	Downstream Howard Street, Lindfield	2.4	2.5	2.5	2.7	2.8	2.8	2.9	3.6
H11	Upstream Tryon Road, Lindfield	4.0	4.1	4.1	4.3	4.3	4.4	4.4	4.9
H12	Downstream Tryon Road, Lindfield	1.2	1.5	1.5	1.9	2.1	2.2	2.3	3.5
H13	Upstream Eastern Arterial Road, Lindfield	4.8	5.5	5.5	7.5	8.8	9.3	10.0	14.4
H14	Downstream Eastern Arterial Road, Lindfield	1.5	1.6	1.5	1.7	1.8	1.8	1.9	4.0
H15	Upstream Railway at Pacific Highway, Roseville	0.3	0.3	0.3	0.3	0.3	0.4	0.4	1.0
H16	Victoria Street, Roseville	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.9
H17	Glencroft Avenue, Roseville	0.2	0.3	0.3	0.4	0.5	0.6	0.7	1.7
H18	Bancroft Avenue, Roseville	0.4	0.5	0.5	0.7	0.8	0.8	0.9	1.9
H19	Lord Street, Roseville	0.5	0.6	0.7	0.9	1.0	1.1	1.2	2.2

ID	Location	Modelled Peak Flood Depth (m)							
		20% AEP	10% AEP	5% AEP	2% AEP	1% AEP	0.5% AEP	0.2% AEP	PMF
H20	Upstream Archbold Road, Roseville	2.7	3.3	3.6	4.4	4.6	4.7	4.8	5.5
H21	Downstream Archbold Road, Roseville	2.6	2.8	2.8	3.2	3.4	3.5	3.6	4.4
H22	Moores Creek at Roseville Golf Course	2.2	2.3	2.3	2.7	2.9	3.0	3.1	4.3
H23	Corner Namoi Place and Carlyle Road, East Lindfield	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.7
H24	Allard Avenue, Roseville Chase	0.7	0.7	0.8	0.9	0.9	1.0	1.0	1.4

7.3 Predicted Flood Behaviour

7.3.1 Description of Flood Behaviour

Floodwaters within the Middle Harbour Southern Catchment originate in the steep urbanised portions of the upstream area, generally flowing along urbanised flow paths into Gordon Creek and Moores Creek and then down into Middle Harbour itself. Within the upper catchment, nuisance stormwater affectation is generally widespread, with greater concentrations of flow along areas of lower elevations which form part of major trunk lines and/or discharge into Gordon Creek, Moores Creek and their tributaries. Due to the highly urbanised nature of the upper catchment, many of these overland flow paths form part of property backyards in the upper reaches before they reach the vegetated areas in the lower catchment. Flooding to property and infrastructure occurs primarily at these locations, where the capacity of backyards or roadways is exceeded and high depths of ponding occur as a result. This occurs notably in the area between Boundary Street and Archbold Road, with the severity of flooding scaling with magnitude up to the PMF event.

The overland flow paths drain to the major watercourses and their tributaries, which contain most of the catchment flooding for events up to and including the PMF event. This owes in part to both the steep nature of the catchment and the sizeable riparian zone. Significant depths of water occur along the watercourses, notably at both the culverts underneath Eastern Arterial Road and Roseville Golf Course.

In the lower/western portion of the catchment the steep terrain and heavy vegetation result in flooding being localised within the Middle Harbour Estuary itself.

7.3.2 Key Flood Locations

Major overland flooding occurs in several locations within the upper reach. Notable flooding occurs in the following areas:

- The area upstream of the railway line – floodwaters pond along the upstream (western side) of the railway line at low points at Boundary Street, Llewellyn Street and Wolseley Road. Due to the elevated railway, floodwaters build on the western side partially blocking roads and affecting several properties.
- Treats Road to Slade Avenue – a significant major overland flow path stretches from Treats Road south towards Woodside Avenue before continuing east towards Slade Avenue. In the upstream portion of the flow path (Treats Road to Woodside Avenue with contributions from the areas ponding behind the railway line at Wolseley Road), floodwaters flow into low lying areas between roads inundating properties. Once floodwaters reach Havilah Road, they flow down a vegetated overland flow path (with inundation of properties only occurring at the outer fringe of the flow path in rarer events) before discharging into a tributary of Gordon Creek.
- The area downstream of the railway line and Majorie Street to Tryon Road – a significant major overland flow path forms between Middle Harbour Road and Tryon Road with upstream contributions from areas downstream of the railway line and Majorie Street. Floodwaters from the railway line (at Russell Avenue and Strickland Avenue) flow into low lying areas between roads partially inundating properties. Similar behaviour is observed between Majorie Street and Middle Harbour Road. Floodwaters downstream of Middle Harbour Road flow down a vegetated overland flow path (with inundation of properties only occurring at the outer fringe of the flow path in rarer events) before discharging into a tributary of Gordon Creek.
- Bancroft Avenue to Archbold Road – High depth, high velocity floodwaters flow from Bancroft Avenue to Archbold Road with upstream contributions discharging from Boundary Street, Bancroft Lane and Clanville Road. In the upstream areas, floodwaters pond along low lying areas between roads significantly inundating properties. Once floodwaters reach Archbold Road they flow down a

narrow vegetated overland flow path, significantly inundating properties at the outer fringes, particularly upstream of Archbold Road. Floodwaters discharge from Archbold Road to a tributary of Moores Creek.

- Woodlands Road to Moores Creek – Two flow paths discharge areas upstream of Woodlands Road to Moores Creek downstream of Luxor Parade. In the upstream portion of the flow path, several properties are inundated by ponding floodwaters prior to their discharge through vegetated areas downstream.
- Wellington Road to Moores Creek – Two flow paths discharges areas upstream of Wellington Road to Moores Creek downstream of Carlyle Road and Mayfair Place. Floodwaters run both perpendicular to Wellington Road along Melbourne Road (south-west) and parallel to Wellington Road towards Carlyle Road (north-east) before discharging through vegetated areas into Moores Creek. Significant affectation occurs at properties on the corner of Carlyle Road and Wellington Road in particular.

In addition to the above location, there are several other localised sag points and minor overland flow paths that form throughout the study area resulting in relatively minor inundation of roadways and private properties. These include but are not limited to:

- The area upstream of Allan Small Oval;
- The area downstream of Killara High School;
- Springdale Road and Eastern Arterial Road;
- The area upstream of Swain Gardens;
- The area to the south-west of Roseville Golf Club;
- Warrane Road to Roseville Bridge; and
- Loorana Street to Echo Point.

7.4 Provisional Flood Hazard

Flood hazard defines the potential impact that flooding will have on vehicles, people and structures across different areas of the floodplain. For this study, the variation in flood hazard was defined based on the composite six-tiered hazard classification defined in '*Australian Disaster Resilience Handbook 7 Managing the Floodplain: A Guide to Best Practice in Flood Risk Management in Australia'* (AIDR, 2017) and reproduced in Figure 7.2. The six hazard classifications are summarised in Table 7.2.

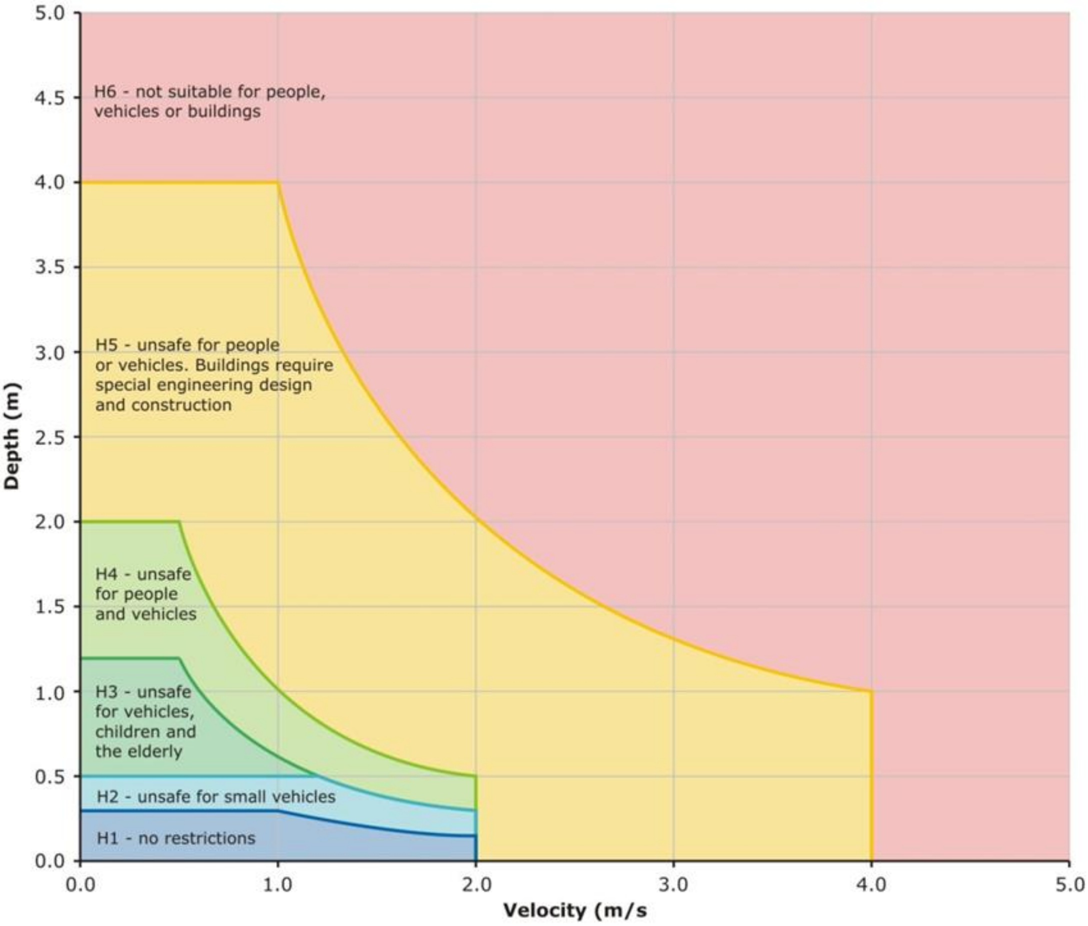


Figure 7.2 Combined Flood Hazard Curves

Table 7.3 Best Practice Provisional Flood Hazards (AIDR, 2017)

Hazard Classification	Description
H1	Relatively benign flow conditions. No vulnerability constraints.
H2	Unsafe for small vehicles.
H3	Unsafe for all vehicles, children and the elderly.
H4	Unsafe for all people and vehicles.
H5	Unsafe for all people and vehicles. Buildings require engineering design and construction.
H6	Unconditionally dangerous. Not suitable for any type of development or evacuation access. All building types considered vulnerable to failure.

As shown in Figure 7.2, the hazard curves define the potential vulnerability of people, cars and structures based upon the depth and velocity of floodwaters. Peak depth, velocity and velocity-depth product outputs generated by the TUFLOW model were used to map the variation in flood hazard across the catchments. Provisional hazard mapping for the study area is included in Annex H for the

1% and 0.2% AEP floods and PMF (note: the filtering approach outlined in Section 7.2 has been applied to the mapping).

The hazard mapping indicates that for the 1% AEP and 0.2% AEP events, urban areas are typically classified as “H1”, with up to “H4” classifications in areas of ponding. Hazards within major overland flow paths and tributaries are generally between the “H4” and “H6” classifications, which are considered unsafe for people and vehicles.

A larger portion of the urban area is classified as high hazard during the PMF, with classification of up to “H5” in ponded areas. Major overland flow paths and tributaries are typically subject to “H6” high hazard flow conditions. In “H6” hazard conditions, cars and people would be exposed to a significant flood risk and there is potential for structural damage to buildings.

7.5 Flood Function

The flood function categories (also referred to as hydraulic categories) defined in the ‘*Floodplain Development Manual*’ (NSW Government, 2005) are:

- Floodway - Areas that convey a significant portion of the flow. These are areas that, even if partially blocked, would cause a significant increase in flood levels or a significant redistribution of flood flows, which may adversely affect other areas.
- Flood Storage - Areas that are important in the temporary storage of the floodwater during the passage of the flood. If the area is substantially removed by levees or fill it will result in elevated water levels and/or elevated discharges. Flood Storage areas, if completely blocked would cause peak flood levels to increase by 0.1m and/or would cause the peak discharge to increase by more than 10%.
- Flood Fringe - Remaining area of flood prone land, after Floodway and Flood Storage areas have been defined. Blockage or filling of this area will not have any significant effect on the flood pattern or flood levels.

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

The criteria listed in Table 7.3 has been applied to the mapping of hydraulic categories in this study. Hydraulic category mapping is included in Annex H for the 1% and 0.2% AEP floods and PMF (note: the filtering approach outlined in Section 7.2 has been applied to the mapping).

Table 7.4 Flood Function Categories

Classification	Criteria	Definition
Floodway	Area within the flood extent where: • Velocity x Depth > 0.3 m^2/s AND • Velocity > 0.5 m/s AND • Depth > 0.15 m	Areas and flow paths where a significant proportion of floodwaters are conveyed (including all bank-to-bank creek sections).
Flood Storage	Remaining area within the flood extent where Depth > 0.15 m	Areas where floodwaters accumulate before being conveyed downstream. These areas are important for detention and attenuation of flood peaks.
Flood Fringe	Remaining area in the floodplain (i.e. area within the flood extent) outside the Floodway and Flood Storage areas.	Areas that are low-velocity backwaters within the floodplain. Filling of these areas generally has little consequence to overall flood behaviour.

During the 1% AEP flood, floodways and flood storage areas are largely contained within the downstream watercourses and along the trunk drainage lines discharging to the watercourses in the upstream of the catchment. Some roads adjacent to major overland flow path crossings, including Middle Harbour Road and Bancroft Avenue, act partially as floodways adjacent to the discharge point into the watercourse. Notable flood storage areas are located at Wolseley Road upstream of the railway line, in the areas upstream of Roseville Avenue, upstream of Eastern Arterial Road and within Middle Harbour.

The extent of both the floodway and flood storage areas increase with event rarity, with generally similar flow behaviour is predicted in the 0.2% AEP flood and PMF event. However during the PMF, the Eastern Arterial Road and Archbold Road roadways, the area upstream of Woodside Avenue and a larger portion of the Middle Harbour tributary are predicted to form floodways.

8 Sensitivity and Climate Change Assessment

8.1 Summary

Computer flood models required the adoption of several modelling parameters that may not be known with a high degree of certainty or are subject to natural variation (e.g. summer vs. winter vegetation). Calibration is completed, where possible, in an attempt to ensure the adopted model parameters generate reliable estimates of flood conditions. However, as discussed in Section 5.1, model calibration and validation could not be undertaken for the models in this study due to the lack of available historical data; and it was only possible to complete model verification based on anecdotal flood information in some locations.

As inputs can impact on the results generated by the models, it is important to understand how any uncertainties in key model input parameters or changes to parameters (e.g. due to climate change) may impact on the results predicted by the models. Accordingly, a sensitivity and climate change assessment has been undertaken for the 1% AEP design event in order to observe changes to predicted design flood behaviour when varying the model parameters listed in Table 8 1. In defining sensitivity tests, consideration has been given to the most appropriate parameters considering catchment properties and simulated design flood behaviour.

Table 8.1 Sensitivity and Climate Change Assessment Criteria

Sensitivity Assessment	Details
Rainfall Losses	+ 50% Probability Neutral Burst Loss - 50% Probability Neutral Burst Loss
Hydraulic Roughness	+ 20% Manning's 'n' values - 20% Manning's 'n' values
Hydraulic Structure Blockage	0% Blockage 100% Blockage
Climate Change	Increased rainfall as per ARR 2019 guidelines 2100 Sea Level Rise (+0.9 m)

The rationalisation for each of these sensitivity tests along with adopted model parameters and results are summarised in the following sections.

Predicted peak 1% AEP flood levels at the key reporting locations shown in Figure 7.1 are provided in Table 8.2 for each sensitivity and climate change scenario.

In general, flood levels were most sensitive to changes in hydraulic structure blockage and reflected the likely impacts of climate change on the catchment in the future. Overall, results were shown to be relatively insensitive to the test variables, with an average change in peak levels of ±0.02 m across the wider study area for the non-blockage-based sensitivity parameters. The average change in peak flood levels as a result of changes to blockage was ±0.2 m, however this can generally be accommodated within the 0.5 m freeboard applied to 1% AEP flood levels to determine the Flood Planning Level (see Section 9.1).

Table 8.2 Sensitivity Assessment: 1% AEP Peak Flood Level Comparison

ID	Peak Flood Level (m AHD)									
	1% AEP	1% AEP plus 50% rainfall loss	1% AEP minus 50% rainfall loss	1% AEP plus 20% Manning's 'n' Roughness	1% AEP minus 20% Manning's 'n' Roughness	1% AEP with 0% Blockage	1% AEP with 100% blockage	1% AEP plus rainfall increase (2090 RCP 4.5 Scenario)	1% AEP plus rainfall increase (2090 RCP 8.5 Scenario)	1% AEP plus rainfall increase (2090 RCP 8.5 Scenario) and 0.9 m sea level rise
H01	94.9	94.9	94.9	94.9	94.9	94.8	95.5	95.1	95.2	95.2
H02	79.5	79.5	79.5	79.5	79.5	79.5	79.5	79.5	79.6	79.6
H03	78.9	78.9	78.9	78.9	78.8	78.7	78.7	79	79	79
H04	72.3	72.3	72.3	72.3	72.3	72.3	72.3	72.4	72.4	72.4
H05	69.2	69.2	69.2	69.3	69.1	69.2	69.1	69.2	69.3	69.3
H06	98.5	98.5	98.5	98.5	98.5	97.8	98.5	98.6	98.7	98.7
H07	80.3	80.3	80.3	80.3	80.3	80.4	80.4	80.3	80.4	80.4
H08	78.6	78.6	78.6	78.6	78.5	78.6	78.6	78.6	78.7	78.7
H09	73.1	73.1	73.1	73.1	73.1	73.1	73.2	73.1	73.2	73.2
H10	69.8	69.8	69.8	69.9	69.8	69.9	69.8	69.9	69.9	69.9
H11	67.2	67.2	67.2	67.2	67.2	67.2	67.3	67.3	67.3	67.3
H12	63.4	63.4	63.4	63.4	63.5	63.5	63.3	63.5	63.6	63.6
H13	41.9	41.8	42	41.8	42	41.6	44.2	42.5	43.1	43.1
H14	33.2	33.2	33.2	33.3	33.1	33.4	32.3	33.3	33.3	33.3
H15	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.1	96.2	96.2

ID	Peak Flood Level (m AHD)									
	1% AEP	1% AEP plus 50% rainfall loss	1% AEP minus 50% rainfall loss	1% AEP plus 20% Manning's 'n' Roughness	1% AEP minus 20% Manning's 'n' Roughness	1% AEP with 0% Blockage	1% AEP with 100% blockage	1% AEP plus rainfall increase (2090 RCP 4.5 Scenario)	1% AEP plus rainfall increase (2090 RCP 8.5 Scenario)	1% AEP plus rainfall increase (2090 RCP 8.5 Scenario) and 0.9 m sea level rise
H16	83	83	83	83	83	83	83	83	83	83
H17	82.1	82.1	82.1	82.1	82	82.1	82.2	82.1	82.2	82.2
H18	76.7	76.7	76.7	76.8	76.6	76.7	76.7	76.8	76.8	76.8
H19	72.9	72.9	72.9	73	72.8	72.9	73	73	73.1	73.1
H20	69.6	69.6	69.6	69.6	69.7	69.6	69.9	69.7	69.8	69.8
H21	66.9	66.8	66.9	66.9	66.8	66.9	66.6	66.9	67	67
H22	51.8	51.8	51.9	51.9	51.8	51.8	51.9	52	52.1	52.1
H23	55.5	55.5	55.5	55.5	55.5	55.4	55.5	55.5	55.5	55.5
H24	30.1	30.1	30.1	30.1	30.1	30.1	30.1	30.2	30.2	30.2

8.2 Rainfall Losses

A sensitivity analysis for rainfall losses was completed to assess the relative impact on flood behaviour across the catchment. A 50% increase and 50% decrease to the scaled NSW Specific Probability Neutral Burst Initial Loss for ICA Areas was considered. The values adopted for the 1% AEP critical storm duration are listed below:

Table 8.3 Rainfall Loss Values for the Sensitivity Assessment

Adopted Design Initial Loss	50% Initial Loss Increase	50% Initial Loss Decrease
4.6	6.9	2.3

It is evident that the change in rainfall losses has a relatively minor effect on the peak flood levels across the study area. Increased losses result in flood level reductions upstream of the Eastern Arterial roadway (where a significant portion of flow is conveyed in the catchment) of up to 0.1 m, as well as minor flood level reductions within storage areas upstream of the railway at Wolseley Road and in the downstream section of the Gordon Creek watercourse. Conversely, decreased losses lead to an increase in flood levels upstream of the Eastern Arterial roadway (up to 0.1 m), upstream of the railway at Wolseley Road and in the downstream section of the Gordon Creek watercourse.

8.3 Hydraulic Roughness

Whilst the adopted hydraulic roughness values are within typical recommended ranges, the inherent variability and uncertainty in hydraulic roughness warrants consideration of the relative impact on adopted design flood conditions. Sensitivity tests on the TUFLOW model results to modified hydraulic roughness (Manning's 'n') were undertaken by applying a 20% increase and a 20% decrease in the adopted values for the design 1% AEP flood conditions, with adopted values listed in Table 8.4.

Table 8.4 Hydraulic Roughness Values for Sensitivity Assessment

Land Use Type	Adopted Manning's 'n'	20% Increase in Manning's 'n'	20% Decrease in Manning's 'n'
Roads	0.02	0.024	0.016
Low Density Residential Lots	0.08	0.096	0.064
High Rise Lots	0.035	0.042	0.028
Commercial Lots	0.035	0.042	0.028
Maintained Grass	0.03	0.036	0.024
Dense Vegetation	0.12	0.144	0.096
Riparian Zone	0.1	0.12	0.08
Buildings	1	1.2	0.8
Railway	0.05	0.06	0.04
Estuary	0.03	0.036	0.024

Peak flood levels (at the locations shown in Figure 7.1) based on adjusted Manning's 'n' values are listed in Table 8.2.

The results of the sensitivity assessment simulations indicate that a 20% decrease in Manning's 'n' value results in the reduction of peak flood levels along watercourses (greater than - 0.2 m) but an increase in flood levels of up to 0.09 m at the Eastern Arterial roadway and 0.03 m at the Wolseley Road storage area. Peak flood level increases in these flood storage areas (particularly the Eastern Arterial roadway) reflect that the existing drainage assets in these locations are unable to cope with the increase conveyance of the watercourse associated with the Manning's 'n' decrease.

Conversely, a 20% increase in Manning's 'n' value is predicted to result in an increase in peak flood level (up to 0.2 m) along watercourses but a decrease in peak flood levels of up to 0.09 m at the Eastern Arterial roadway and 0.03 m at the Wolseley Road storage area. Peak flood level decreases at these locations reflect that the slower moving, deeper floodwaters in the watercourses upstream of these points (behaviour associated with the Manning's 'n' increase) reduce the conveyance discharging to the storage areas.

Whilst the modified hydraulic roughness values do result in some changes to the predicted peak water levels along watercourses, there is minimal impact on inundation extents in urban areas where shallow, higher velocity flows are present and in the Middle Harbour watercourse where deeper, slower moving water is present.

8.4 Hydraulic Structure Blockage

As discussed in Section 6.3, structure and pit inlet blockage are an important consideration in the modelling of design floods. Blockage sensitivities were assessed based on two blockage scenarios, as follows:

- Completely unblocked, i.e. 0% blockage for all structures across the study area. This includes all cross-drainage structures, pit inlets and headwalls across the study area.
- Full blockage, i.e. 100% blockage for all structures across the study area.

Peak flood levels (at the locations shown in Figure 7.1) based on adjusted blockage factors are listed in Table 8.2.

The unblocked scenario generally resulted in localised decreases in peak flood levels immediately upstream of cross-drainage structures and corresponding localised increases downstream of the structures. Conversely, the full blockage scenario generally resulted in peak flood level increases immediately upstream of cross-drainage structures and corresponding localised decreases downstream of the structures. The key areas experiencing the greater impacts from the change in structure blockage as part of the sensitivity assessment include the area upstream and downstream of the Eastern Arterial roadway and the Wolseley Road storage area. Other areas of notable change are generally restricted to waterway alignments.

8.5 Climate Change

8.5.1 Overview

As outlined in Book 1, Chapter 6 of ARR 2019 there are multiple aspects of design flood estimation that are likely to be impacted by climate change, including:

- rainfall IFD relationships;
- temporal patterns;
- continuous rainfall sequences;
- antecedent conditions;

- coincident flooding extremes.

However, individual impact of any single aspect has not been subject to comprehensive study. As such, ARR 2019 recommends a focus on potential changes in rainfall intensity and sea level rise for the assessment of the likely impacts of climate change.

Book 1, Chapter 6 of ARR 2019 outlines a six-step approach to be used to incorporate climate change risks into the estimation of design flood conditions. The six steps and their application in this study are outlined below:

- *Step 1: Set the Effective Service Life or Planning Horizon* – A 2090 planning horizon has been assumed.
- *Step 2: Set the Design Flood Standard* – The 1% AEP flood has been adopted as the design standard.
- *Step 3: Consider the Purpose and Nature of the Asset or Activity and Consequences of its Failure* – The consequences of increased frequency of exposure and damage are considered to be high in this case.
- *Step 4: Carry out a Climate Change Risk Screening Analysis* – Marginal increase in peak flood levels are expected in events rarer than the 1% AEP (i.e. the 0.5% AEP and 0.2% AEP) across the majority of the catchment. However, larger peak flood level increase are expected in certain locations.
- *Step 5: Consider Climate Change Projections and their Consequences* – ARR 2019 recommends assessment of RCP 4.5[3] and RCP 8.5 scenarios.
- *Step 6: Consider Statutory Requirements* – Impacts of climate change are discussed in this chapter.

The ARR Data Hub provides a series of Interim Climate Change Factors for locations across Australia, these are presented in Table 8.5.

Table 8.5 Climate Change Sensitivity Scenarios (Rainfall Increase in %)

Year	RCP 4.5	RCP 6	RCP 8.5
2030	0.869 (4.3%)	0.783 (3.9%)	0.983 (4.9%)
2040	1.057 (5.3%)	1.014 (5.1%)	1.349 (6.8%)
2050	1.272 (6.4%)	1.236 (6.2%)	1.773 (9.0%)
2060	1.488 (7.5%)	1.458 (7.4%)	2.237 (11.5%)
2070	1.676 (8.5%)	1.691 (8.6%)	2.722 (14.2%)
2080	1.810 (9.2%)	1.944 (9.9%)	3.209 (16.9%)
2090	1.862 (9.5%)	2.227 (11.5%)	3.679 (19.7%)

With consideration of the above table and the six-step process, climate change simulations have been completed for the 1% AEP flood for the following scenarios:

- 9.5% increase in rainfall intensity based on the 2090 RCP 4.5 scenario;
- 19.7% increase in rainfall intensity based on the 2090 RCP 8.5 scenario;

[3] RCP = Representative Concentration Pathway

- 19.7% increase in rainfall intensity based on the 2090 RCP 8.5 scenario combined with a 0.9 m sea level rise.

8.5.2 Rainfall Increase

The change in peak flood levels associated with the adopted increases in rainfall intensities are presented in Figure 8.1 and Figure 8.2 for the 9.5% and 19.7% rainfall increases, respectively. Peak flood levels (at the locations shown in Figure 7.1) based on rainfall increases associated with climate change are listed in Table 8.2.

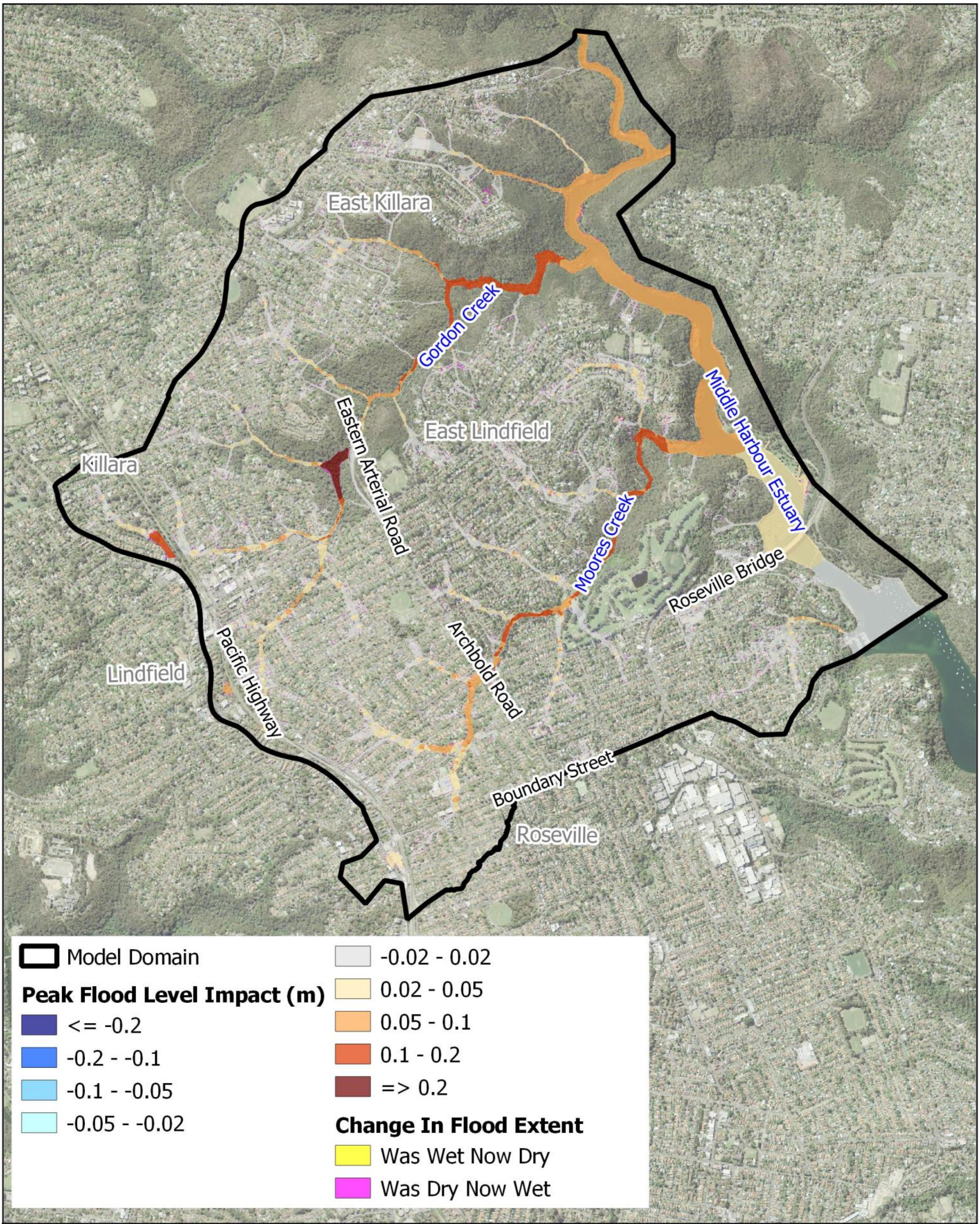
A 9.5% rainfall increase generally results in widespread peak 1% AEP flood levels increases (up to 0.1 m) within the upper reaches of the watercourses, with larger increases (up to 0.2 m) in the watercourses immediately upstream of Middle Harbour. Peak flood level increases are largest in locations immediately upstream of major cross-drainage structures, with notable increases at the Eastern Arterial roadway (0.56 m increase) and Wolseley Road flood storage area.

A 19.7% rainfall increase also results in widespread peak 1% AEP flood level increases (up to 0.25 m) across watercourses in the upstream of the catchment, with larger increases (up to 0.4 m) in the watercourses immediately upstream of Middle Harbour. Peak flood level increases are largest at the Eastern Arterial roadway (1.16 m increase) and Wolseley Road flood storage area (0.31 m). Minor impacts on flood behaviour occur in upstream urban areas.

8.5.3 Combined Rainfall Increase and Sea Level Rise (SLR)

The change in peak flood levels associated with this scenario are presented in Figure 8.3. Peak flood levels (at the locations shown in Figure 7.1) are listed in Table 8.2.

Peak flood level increases associated with the combined 19.7% rainfall increase and 2100 sea level rise scenario are similar to those observed in the 19.7% rainfall increase scenario without sea level rise. This reflects the elevation of the upper portion of the Middle Harbour Southern Catchments above the water levels within the estuary.



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Peak 1% AEP Flood Level Impact - RCP 4.5 2090 Scenario (9.5% Rainfall Increase)

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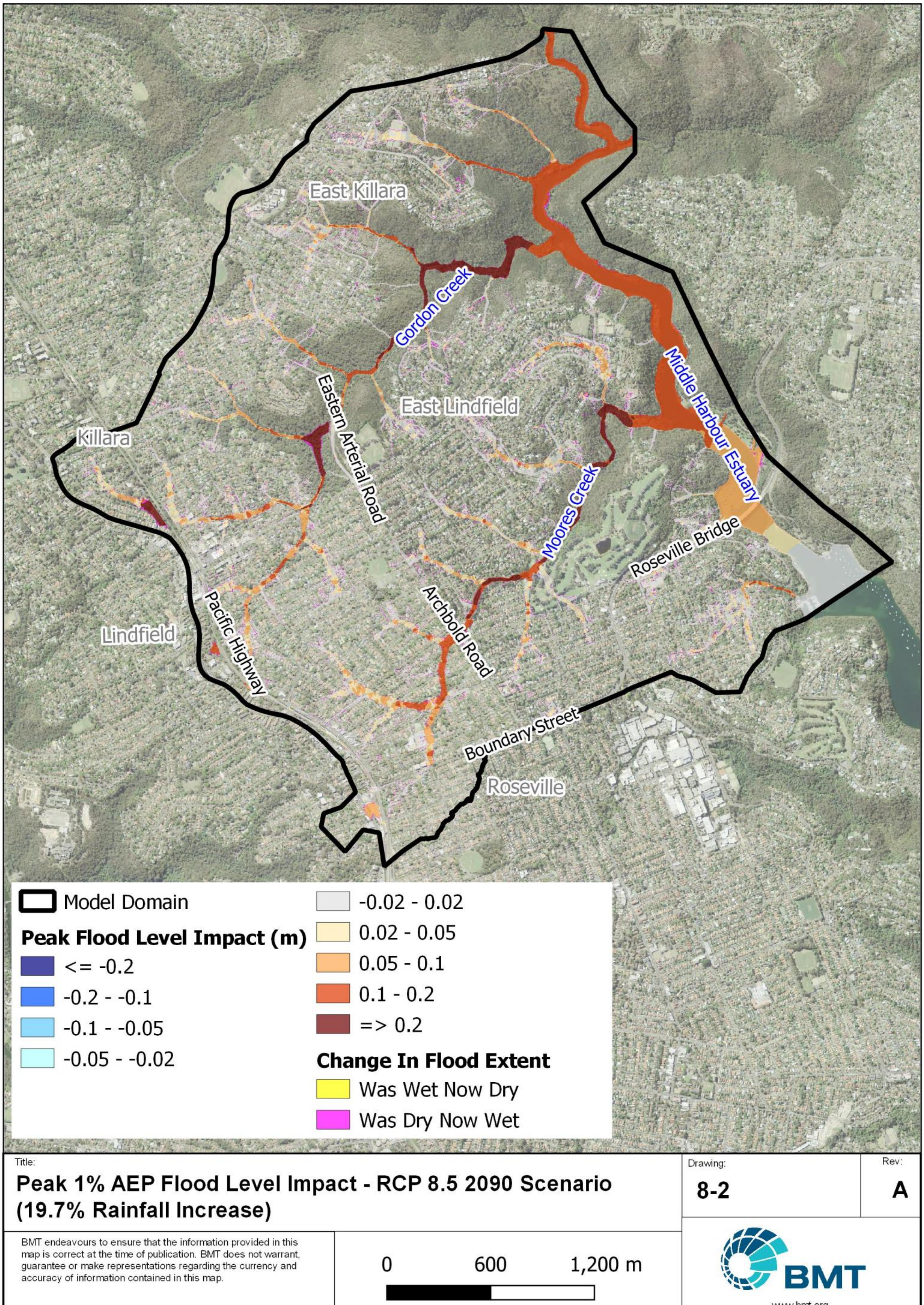

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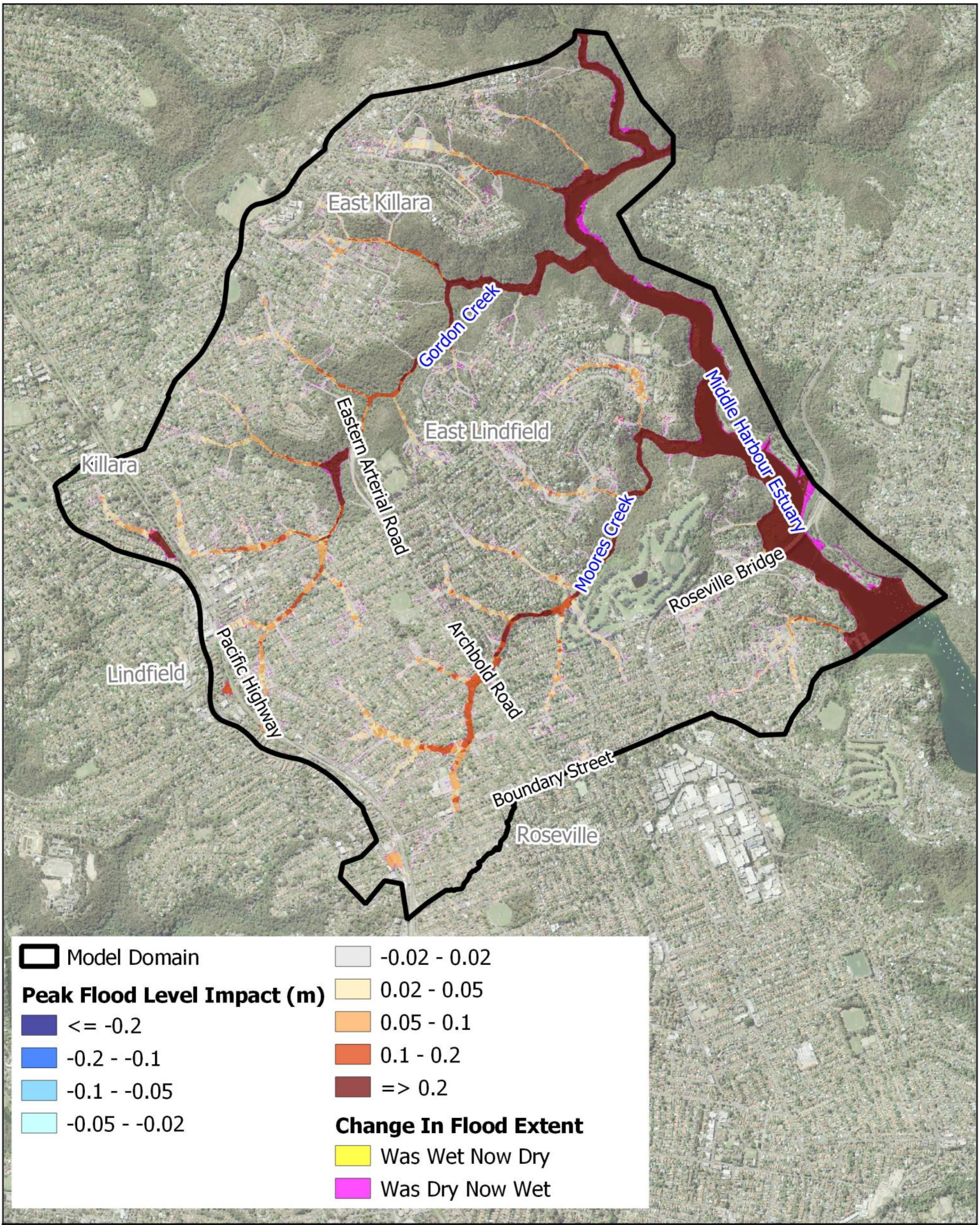

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Peak 1% AEP Flood Level Impact - RCP 8.5 2090 Scenario (19.7% Rainfall Increase) with 0.9 m SLR

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9 Flood Planning Information

9.1 Preliminary Flood Planning Area

Land use planning and development controls are key mechanisms by which Council can reduce flood risk, manage areas impacted by flooding and protect increasing numbers of people located within the floodplain. Such mechanisms will influence future development (and redevelopment) and therefore the benefits will accrue gradually over time.

Flood Planning Levels (FPLs) are an important tool in development and land use planning for the management of flood risk. The flood levels and inundation extents determined through the design flood modelling for this study provide the basis for establishing the Flood Planning Level (FPL) for the Middle Harbour Southern Catchments. When combined with topographic information, FPLs directly determine the extent of the Flood Planning Area (FPA); where the FPA is defined as the area of land subject to flood-related development controls.

The FPL is defined by an established design flood level of selected magnitude combined with a specified freeboard. The purpose of the freeboard is to account for the risk associated with uncertainties in the predicted flood level. These risks may include variation between flood modelling results and actual flood events, the effect of localised factors on flood levels and potential wave action. Following community feedback on the flood planning areas determined as part of the Blackbutt Creek and Lovers Jump Creek Flood Studies, Ku-ring-gai Council adopted the following criteria for definition of the FPL:

- 1% AEP flood level plus 500 mm freeboard for mainstream flooding.
- 1% AEP flood level plus 300 mm freeboard for overland flow flooding.

In order to avoid classification of areas subject only to minor or insignificant flood impacts within the flood planning area, the following approach was applied to filter the design 1% AEP flood results to produce the extent of the FPA:

1. Areas with depths below 150 mm were removed.
2. Isolated areas smaller than 100 m^2 were removed.
3. Isolated small ponds (larger than 100 m^2) were connected to form active flow paths, where possible.
4. For mainstream flooding, a 500 mm freeboard was applied and the grid was stretched laterally until it intersected with the local catchment topography. This defined the mainstream FPA.
5. The area determined in Steps 1-3 that was located outside of the mainstream FPA defined the overland FPA.

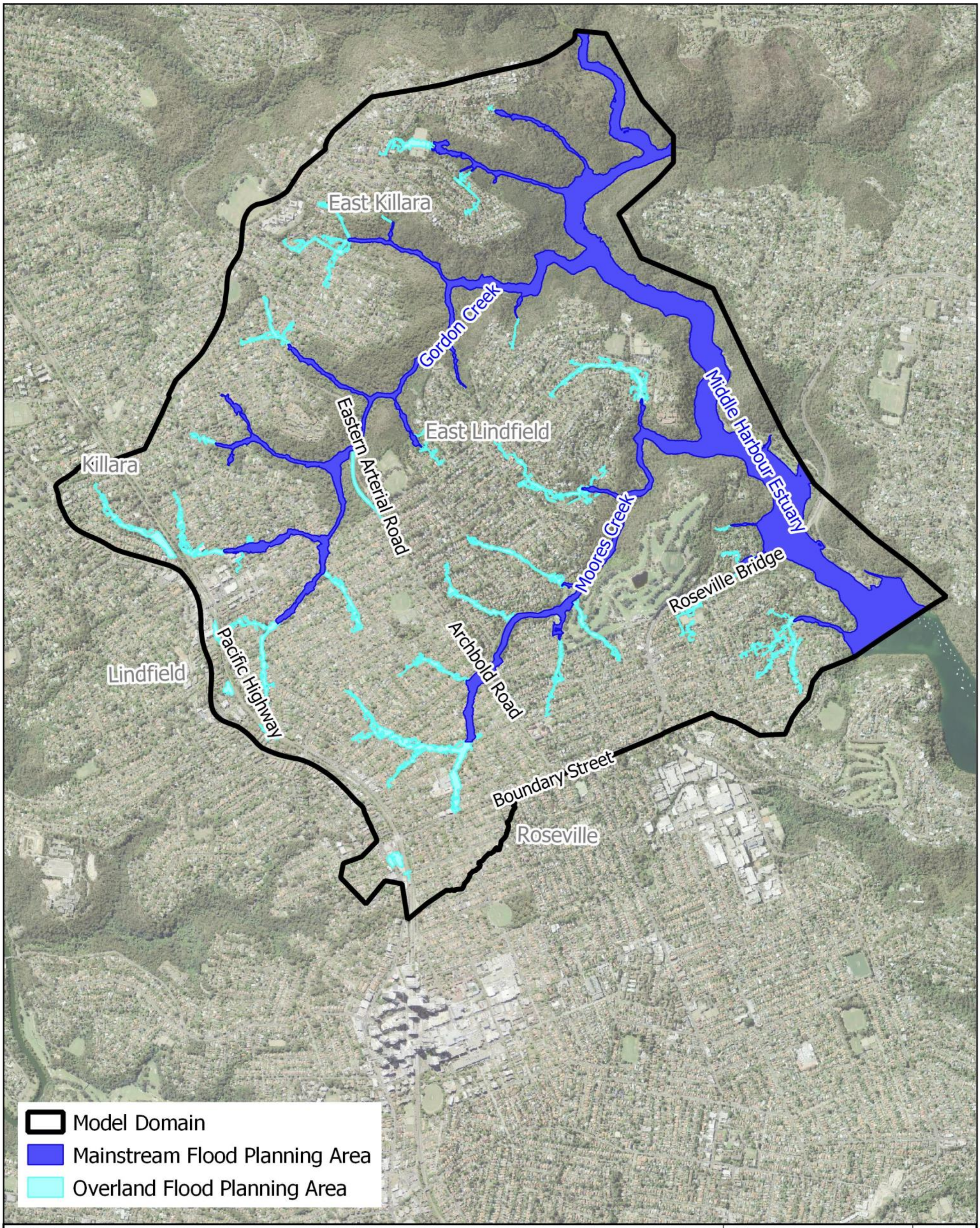
The resulting preliminary FPA is shown in Figure 9.1.

In 2021 the updated NSW Flood Prone Land Package came into effect. The package recommended a modification to the notation of flood affected lots to include both those below the FPL (as identified above) and additionally land above the FPL but below the PMF level. Under the Flood Prone Land Package, flood affected lots are now to be notated on Section 10.7 certificates as either affected in the FPL (Part 7.1) or the PMF (Part 7.2).

Preliminary tagging of properties above the FPL but below the PMF level was undertaken on the basis of the filtering criteria outlined herein. Following community feedback during the consultation period, it has been decided to adopt a similar filtering criterion to the one utilised in the Flood Planning Area designation in the selection of properties to avoid potentially over conservative selection of properties. A modified approach was applied to filter the PMF design flood result to produce the PMF tagging extent, as outlined below:

1. Areas with depths below 300 mm were removed.
2. Isolated areas smaller than 300 m^2 were removed.

The resulting PMF tagging extent is shown in Figure 9.2.



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Flood Planning Area

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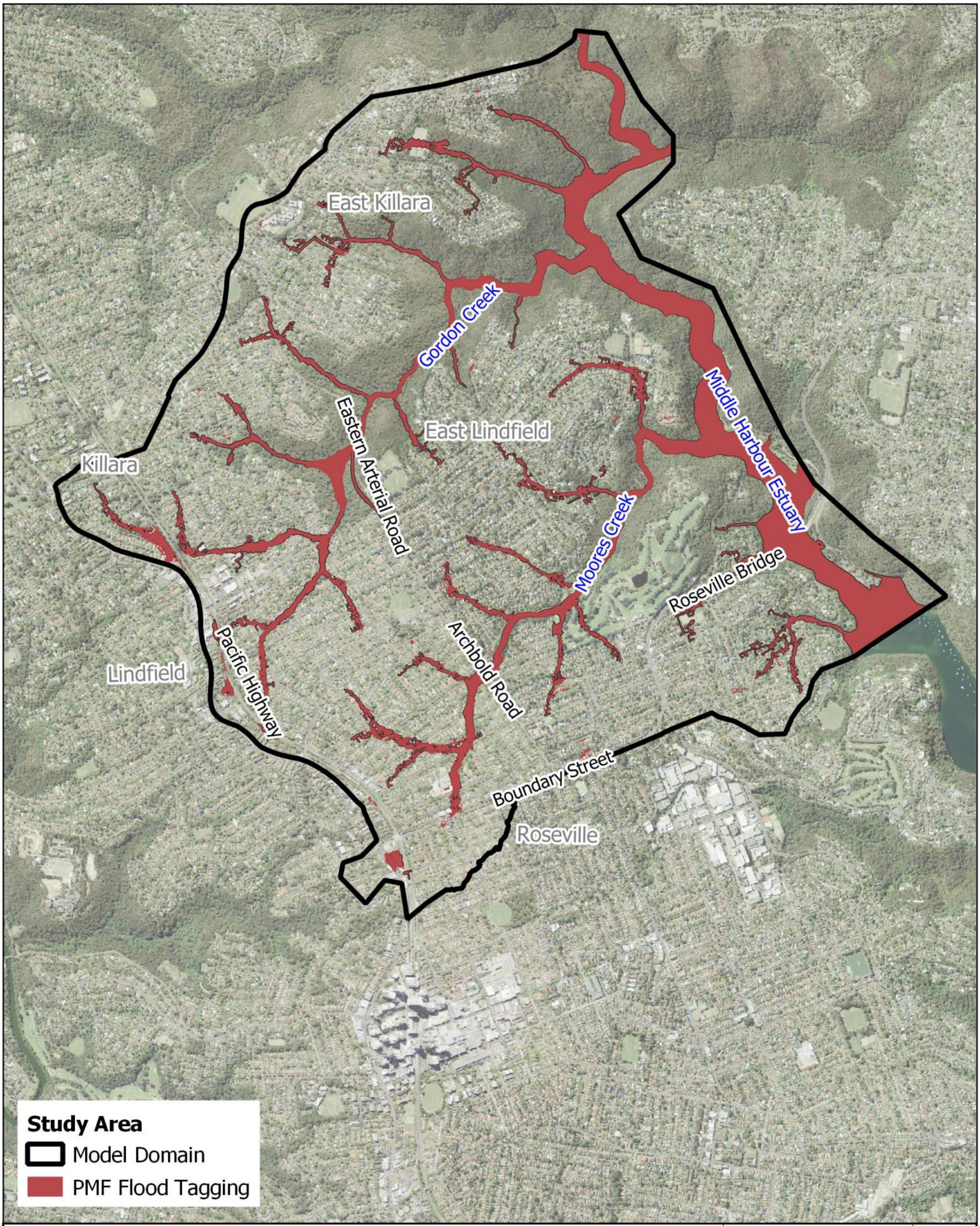

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PMF Flood Tagging Extent

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9.2 Information to Support Decision Making

9.2.1 Flood Emergency Response Classifications

The State Emergency Service (SES) has formal responsibility for emergency management operations in response to flooding. Other organisations generally provide assistance, including BoM, Council, police, fire brigade, ambulance and community groups.

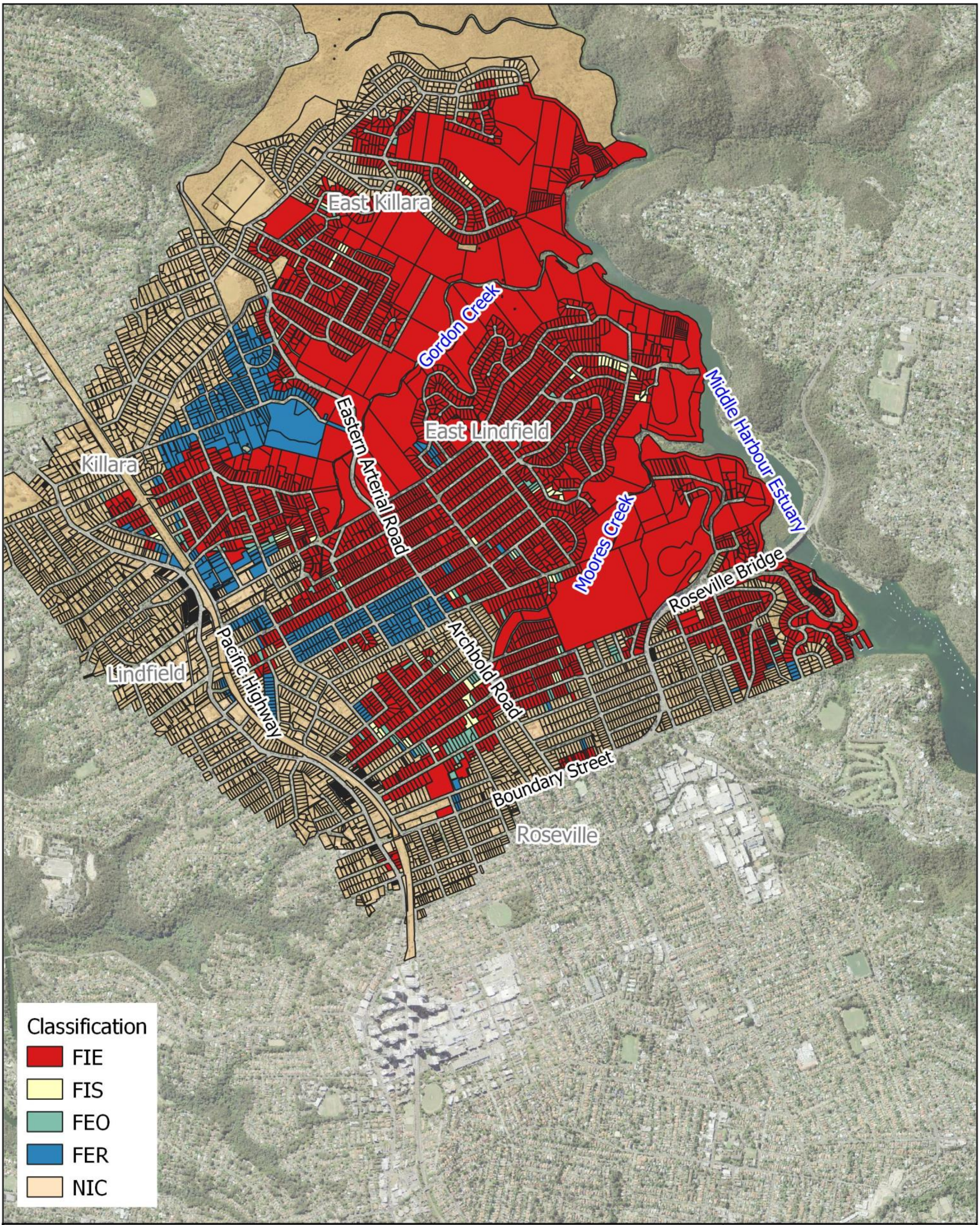
The SES classifies communities according to the impact that flooding has on them. The primary purpose for doing this is to assist SES in the planning and implementation of response strategies. Flood impacts relate to where the normal functioning of services is altered due to a flood, either directly or indirectly, and relates specifically to the operational issues of evacuation, resupply and rescue. Flood emergency response classifications are listed below, with definitions extracted from the AIDR *'Flood Emergency Response Classification of the Floodplain'* (AIDR, 2017).

- Flooded Isolated Elevated (FIE) – Areas flooded in the PMF and isolated from community evacuation facilities by floodwaters or impossible terrain where there is a substantial amount of land elevated above the PMF
- Flooded Isolated Submerged (FIS) — Areas flooded in the PMF and isolated from community evacuation facilities by floodwaters or impossible terrain where all land will be fully submerged in the PMF after becoming isolated
- Overland Escape Route (FEO) – Areas that are flooded in the PMF but not isolated from community evacuation facilities, where evacuation relies upon overland escape routes that rise out of the floodplain
- Rising Road (FER) – Areas that are flooded in the PMF but not isolated from community evacuation facilities, where evacuation routes from the area follow roads that rise out of the floodplain
- Indirect Consequence (NIC) – Areas outside the limit of flooding which are not inundated and do not lose road access but which may be indirectly affected as a result of flooding

The classification of communities is designed for use on broad or precinct basis. The study area was delineated into a series of precincts related to local flood behaviour. The flood classification process was then undertaken to identify the flood classification for each precinct as presented in Figure 9.2 for the PMF event. This mapping indicates that:

- The majority of flood impacted areas within the catchments are best defined as FIE, where access roads will be cut in a PMF but the properties will not be heavily inundated.
- There are also smaller areas classified as having rising road access (FER) or an overland escape route (FEO). Properties in these areas would be subject to heavy inundation, but egress from the site via the road network or in some cases a local path would be possible.
- Some properties located immediately adjacent to watercourses or major drainage assets would likely become FIS in rare and extreme events, with out of bank flooding cutting off road access and causing heavy inundation.
- Due to the steep terrain present across the catchment, large portions of the western and southern portions of the study area would be classified as NIC.

The nature of the overland flooding regime in the local catchments is characterised by relatively short critical duration events, such that limited warning time would be available to respond and effectively evacuate during a rare flood event but the total inundation/isolation time would be only a few hours. The extent and degree of flooding of existing property under PMF conditions indicates that there is minimal requirement for flood evacuation up to and including the PMF event, with a shelter in place strategy the most appropriate emergency management solution in rare and extreme events. Evacuation may be required in localised sections of the study area adjacent to major overland flow paths and waterways where deeper/faster moving floodwaters are present; however, due to steep nature of the catchment and the high urbanisation present, rising road or overland escape routes would be the most appropriate egress in most situations.



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Flood Emergency Response Classification

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9.2.2 Flood Planning Constraint Categories

Guideline 7-5 of the '*Australian Disaster Relief Resilience Handbook'* (AIDR, 2017) highlights the need for appropriate land use planning activities to effectively manage and limit the growth of flood risk within a floodplain. It recommends adoption of four flood planning constraint categories (FPCC), as reproduced in Table 9.1. The purpose of the FPCCs is to separate areas of the floodplain based on their suitability for more concentrated development or intensified land use.

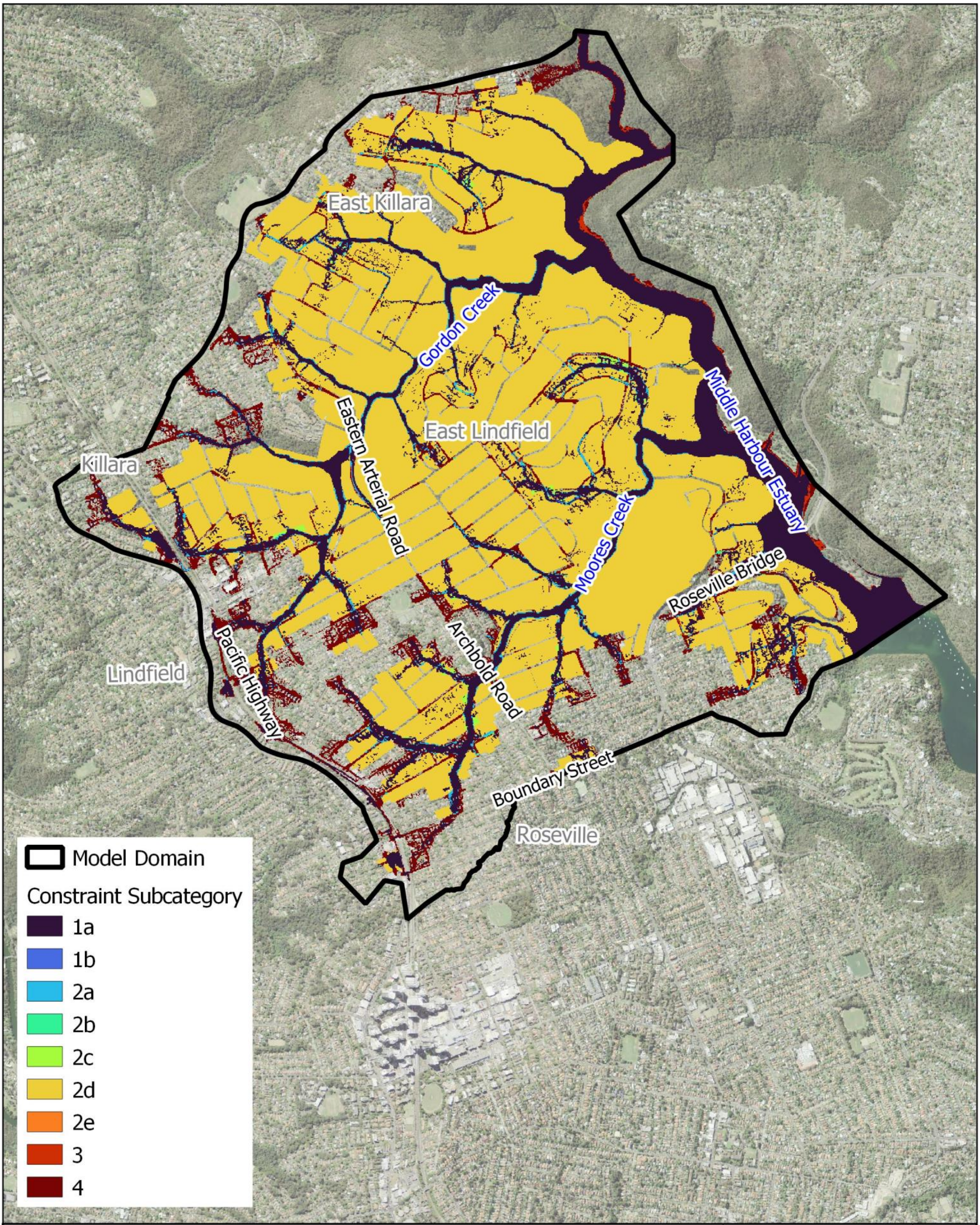
Table 9.1 Flood Planning Constraint Categories (FPCC) (AIDR, 2017)

FPCC	Constraint Subcategory
1	a) Floodway or flood storage area in the DFE*, b) Flood hazard H6 in the DFE*.
2	a) Floodway in events larger than the DFE*, b) Flood hazard H5 in the DFE*, c) Emergency response (isolated and submerged areas), d) Emergency response (isolated but elevated areas), e) Flood hazard H6 in floods large than the DFE*.
3	Remaining area below the DFE* plus freeboard.
4	Remaining area below the PMF or Extreme Flood.

*** DFE = defined flood event – adopted as the 1% AEP event.**

The Flood Planning Constraint Categories were produced using enveloped results for 1% AEP flood and rarer events (i.e. 0.2% AEP and the PMF). The results are presented in Figure 9.3.

The implications and key considerations for development extracted from AIDR (2017), as well as potential flood planning options are outlined in Table 9.2. Due to the steep urbanised nature of the catchment and short critical duration observed across all events, temporary isolation of properties (category 2c and in particular 2d) is likely to occur. This information can be further refined and potentially used to inform land use planning and provision of development controls as part of the subsequent Floodplain Risk Management Study and Plan.



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Flood Planning Constraint Categories

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Table 9.2 Flood Planning Constraint Categories (FPCC): Implications, Key Considerations (AIDR, 2017) and Potential Planning Options

Category	Sub-category	Implications	Key Considerations	Recommended Mitigations
FPCC1	A (Flow conveyance and storage areas in the 1% AEP)	Development or changes to topography within flow conveyance areas and flood storages areas affect flood behaviour, which will alter flow depth or velocity in other areas of the floodplain. Changes can negatively affect the existing community and other property	The majority of developments and uses have adverse impacts on flood behaviour. Consider limiting uses and development to those compatible with maintaining flood function	• Limiting or precluding development in these areas • Proposed developments should demonstrate compatibility with the flood risk. • Flood impact assessment required as part of the development assessment process. • Preparation of a flood emergency response plan for occupation of these areas.
	B (H6 hazard in the 1% AEP)	Hazardous conditions considered unsafe for vehicles and people. All building types are considered vulnerable to structural failure	The majority of developments and uses are vulnerable to failure in this flood hazard category. Consider limiting developments and uses to those that are compatible with flood hazard H6	• Limiting or precluding development in these areas • Proposed developments should demonstrate compatibility with the flood risk. • Preparation of a flood emergency response plan for occupation of these areas.
FPCC2	A (Flow conveyance in events larger than the 1% AEP)	Flow conveyance areas may develop during an event larger than the 1% AEP (for example, 0.2% AEP). People and buildings in these areas may be affected by flowing and dangerous floodwaters	Consider compatibility of developments and users with rare flood flows in this area	• Limiting the scale of development or infilling in these areas • Proposed developments should demonstrate compatibility with the flood risk. • A flood impact assessment should be recommended as part of the development assessment process. • Preparation of a flood emergency response plan for occupation of these areas.

Category	Sub-category	Implications	Key Considerations	Recommended Mitigations
	B (Flood hazard H5 in the 1% AEP)	Hazardous conditions are considered unsafe for vehicles and people, and all buildings are vulnerable to structural damage	Many uses and developments will be vulnerable to flood hazard. Consider limiting new uses to those compatible with flood hazard H5. Consider treatments such as filling (where this will not affect flood behaviour) to reduce the hazard to a level that allows standard development conditions to be applied. Alternatively, consider a requirement for special development conditions	• Limiting or precluding development in these areas • Proposed developments should demonstrate compatibility with the flood risk. • Preparation of a flood emergency response plan for occupation of these areas.
	C (Emergency response—isolated and submerged areas)	Area becomes isolated by floodwater or impassable terrain, with loss of evacuation route to the community evacuation location. The area will become fully submerged with no flood-free land in an extreme event, with ramifications for those who have not evacuated and are unable to be rescued	Consequences of isolation and inundation can be severe. Consider the consequences of: • evacuation difficulty or inundation of the area on the development and its users, which may include limitations on land use, or on land use that has occupants who are more vulnerable to disruption and loss • the development on emergency management planning for the existing community, including the need for additional treatments • the development on community flood recovery • disruption or loss of the development on the users and wider community	• Limiting or precluding development in these areas • Proposed developments should demonstrate compatibility with the flood risk. • Preparation of a flood emergency response plan for occupation of these areas.

Category	Sub-category	Implications	Key Considerations	Recommended Mitigations
	D (Emergency response—isolated but elevated areas)	Area becomes isolated by floodwater or impassable terrain, with loss of an evacuation route to a community evacuation location. The area has some land elevated above the extreme flood level. Those not evacuated may be isolated with limited or no services, and will need rescue or resupply until floods recede and roads are passable	Some developments and their users may be vulnerable to disruption or loss. Consider: • the consequences of disruption or loss of the development on the users and the wider community • limiting land use, or land use that has occupants who are more vulnerable to disruption and loss • additional emergency management treatment requirements • issues associated with the level of support required during a flood, particularly for long-duration flood events	• Preparation of a flood emergency response plan for occupation of these areas should be considered for critical or vulnerable land uses.
	E (Flood hazard H6 in floods larger than the 1% AEP)	Hazardous conditions may develop in an event rarer than the 1% AEP, which may have implications for the development and its occupants	Consider the need for additional development conditions to reduce the effect of flooding on the development and its occupants	• Limiting or precluding development in these areas • Proposed developments should demonstrate compatibility with the flood risk. • Preparation of a flood emergency response plan for occupation of these areas.
FPCC3	Outside FPCC2—generally below the DFE (1% AEP Event) and the freeboard	Hazardous conditions may exist creating issues for vehicles and people. Structural damage to buildings that meet building standards unlikely because of flooding	Standard land-use and development controls aimed at reducing damage and the exposure of the development to flooding in the DFE (1% AEP Event) are likely to be suitable. Consider the need for additional conditions for emergency response facilities, key	• Limit or exclude land use involving vulnerable users. • Developments should demonstrate compatibility with the flood risk.

Category	Sub-category	Implications	Key Considerations	Recommended Mitigations
			community infrastructure and vulnerable users	
FPCC4	Outside FPCC3, but within the probable maximum flood (or similar extreme event)	Emergency response may rely on key community facilities such as emergency hospitals, emergency management headquarters and evacuation centres operating during an event. Recovery may rely on key utility services being able to be readily re-established after an event	Consider the need for conditions for emergency response facilities, key community infrastructure and land uses with vulnerable users	Limit or exclude land use involving vulnerable users.

10 Conclusions

The Middle Harbour Southern Catchments Flood Study was completed to define flood behaviour across the urbanised portions of the southern catchments of the Ku-ring-gai LGA draining to Middle Harbour under historical, existing and future conditions (incorporating the potential impacts of climate change).

Flood behaviour was predicted for a range of design events based on DRAINS hydrologic models updated or developed for the study catchments, as well as a TUFLOW hydraulic model that was developed specifically for this flood study. These models were verified qualitatively using anecdotal flood information for historical events that was collected through the community consultation process.

The DRAINS and TUFLOW models were used to simulate a range of design events including the 20%, 10%, 5%, 2%, 1%, 0.5% and 0.2% AEP and PMF events. The potential impacts of climate change, including increased rainfall intensity and sea level rise, were also assessed. The modelling results were used to prepare design flood mapping, incorporating peak flood depth, flood velocity, flood hazard and flood function.

Flood planning and emergency response information, including definition of the Flood Planning Area (FPA), Flood Emergency Response Classifications (FERCs) and Flood Planning Constraint Categories (FPCC), has also be developed based on the predicted flood characteristics.

Key findings of the study include:

- Due to the steep and highly urbanised nature of the upstream catchment, critical flooding in the Middle Harbour Southern Catchments would occur due to intense, short duration rainfall which would provide very little flood warning time.
- During flood events, the greatest concentration of flow would occur along areas of lower elevation (including local creeks, property backyard and roadways) which run parallel to the major trunk drainage discharging into Gordon Creek, Moores Creek and their tributaries. During rare and extreme events these areas would be subject to high hazard floodwaters conveying a significant amount of flow, which would likely exceed the capacity of the low-lying creeks, backyards and roadways in these locations leading to high depth flooding.
- Due to the short flood warning time available and the high hazard flow present within urban areas a large portion of the catchment would likely be isolated during major flood events, although it is unlikely that this isolation would extend beyond a few hours. However, consideration should be given to this potential isolation when considering future placement of vulnerable communities or critical infrastructure in the catchment.

Overall, the outputs of this study provide an improved understanding of flood behaviour that will aid in Council’s management of flood risk and establish the basis for subsequent floodplain management activities.

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