Mosman LGA Flood Study

Final Report

Report MHL3019
November 2025

Prepared for:

Mosman Council

Department of Climate Change, Energy, the Environment and Water

Cover Photograph: Flooding of Chowder Bay Mosman. Courtesy of Mosman Council

Mosman LGA Flood Study

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Foreword

The NSW government's professional specialist advisor, Manly Hydraulics Laboratory (MHL) was engaged by Mosman Council (Council) to undertake a detailed flood study of Mosman LGA, Sydney. The Mosman LGA Flood Study has been prepared in accordance with the New South Wales Government's Flood Risk Management Manual (2023) which was provided for evaluation of strategies and formulation of plans that achieve effective flood risk management outcomes accounting for technical, social, economic, ecological and cultural factors, together with community aspirations for the use of flood prone land.

The outcomes of the study include a detailed flood model and comprehensive flood mapping which provides the basis for the future preparation of a Flood Risk Management Study and Plan. During the subsequent Flood Risk Management Study and Plan phase of the process, the potential economic, social and environmental impacts of flooding will be quantified and used as a basis to assess various options to manage flood risk.

By following the NSW Flood Risk Management Process, Mosman Council is adopting a best practice, State supported pathway for the methodical identification, assessment and implementation of robust and effective flood risk management measures in order to reduce the impacts of flooding on the community and existing development, and to ensure that future development is compatible with flood risk. Councils following the NSW Flood Risk Management Process demonstrate duty of care with respect to the management of flood liable land and are exempted from liability under Section 733 of the Local Government Act 1993.

The information provided in this flood study report improves knowledge of flood behaviour in the Mosman LGA and will also help inform the NSW State Emergency Service (SES) of risk areas during times of flood.

The report was prepared by Atikul Islam, and Matthieu Glatz.

Executive summary

E.1 Introduction

The Mosman LGA Flood Study aims to provide an up-to-date understanding of flood behaviour and flood risk throughout Mosman. Together with the numerical flood model developed during the study, this information lays the foundation for a future Flood Risk Management Study and Plan (FRMS&P). The FRMS&P will evaluate the potential economic, social, and environmental impacts of flooding and propose measures for effective flood risk management. Additionally, this Flood Study supplies critical flood information to the State Emergency Service (SES) for improved emergency response.

E.2 Data Review

A 1 m resolution LiDAR dataset (2020) was used to represent the study area's topography. Data from local rainfall, flow, water level, and tidal gauges informed the calibration and validation of the flood model. Continuous rainfall records were obtained from Taronga Zoo, Mosman Bowling Club, and Spit Bridge stations, located within a 4.5 km aerial radius of each other. The rain gauge placement allowed the significant spatial variability in rainfall across the Mosman LGA to be captured. Radar weather data was also reviewed to identify representative areas for each rainfall station. Ocean water level data was sourced from Middle Harbour (Sydney Station ID 213470) to be use as the downstream boundary condition.

Stormwater network verification included field surveys at approximately 70 locations to confirm pipe dimensions. Pipes with diameters exceeding 300 mm and associated pits were then integrated into the flood model to ensure an accurate representation of stormwater infrastructure. Pipes smaller than 300 mm were not included in the model, as their contribution to overall flood behaviour is generally minor and their inclusion would significantly increase model complexity and model simulation time.

E.3 Community Consultation

On commencement of the Flood Study, a letter with a link to a Community Flood Questionnaire was distributed to all properties in Mosman and 237 responses were received, with about 55% reporting property flooding—predominantly in yards—between 2018 and 2023. These insights proved invaluable for verifying and enhancing the flood model's accuracy.

During the Public Exhibition period of the Draft Mosman LGA Flood Study between 14 August 2025 and 30 September 2025 there were multiple opportunities for the community to receive information and interact with Council to learn more and comment about the Draft Flood Study. The exhibition of the Draft Flood Study was notified via a dedicated Council webpage, posters, flood study information leaflet distribution to all properties, letters to owners of properties identified as being within the Preliminary Flood Planning Area (FPA) and advertisements in 'Mosman Daily'. During the public exhibition period, there were approximately 2,400 visits to the website, 38 meetings with residents at one-on-one sessions held at the Barry O'Keefe library and 20 interactions with Council's pop-up stand at the September 2025 Mosman Market. A total of 115 written correspondences and submissions were received with all information provided by the community being considered when finalising the Mosman LGA Flood Study.

E.4 Flood Model Development

A coupled one-dimensional–two-dimensional (1D–2D) hydraulic model was developed using TUFLOW software to simulate flood behaviours across the entire Mosman LGA. The 2D model terrain was derived from 2020 LiDAR data, supplemented by 5 m Marine LiDAR (2018) for coastal bed profiles. Approximately 3,000 stormwater pipes and about 1,750 stormwater pits (excluding manholes and junction pits) were integrated into the model, ensuring a detailed representation of the drainage network.

Rainfall was applied directly to the 2D model grid—an approach well-suited for urbanised catchments. This method captures the complexity of urban flood dynamics, including flow around buildings, fences, and potential debris blockages. Fences were modelled as flow-constriction lines, reflecting their potential to alter overland flow.

Surface roughness was delineated based on NSW land use data and satellite aerial imagery, with Manning's 'n' values assigned according to references such as Chow (1959) and AR&R (2019). Middle Harbour tidal data formed the downstream boundary condition.

E.5 Calibration and Validation

The TUFLOW flood model was calibrated using data from the rainfall events on 12 January 2022 and 8 March 2022, and validated using the 9 February 2023 event. The calibrated and validated model results closely matched observed water levels at flow gauging stations, as well as flood depths reported by residents (within approximately 0.1 m), which is considered acceptable for urban flood modelling. The calibrated and validated TUFLOW flood model was subsequently simulated for the 20%, 10%, 2%, 1%, and 1 in 200 Annual Exceedance Probability (AEP) and Probable Maximum Flood (PMF) design events, using selected critical durations and temporal patterns. Rainfall data for the design events was collected in accordance with the new Australian Rainfall and Runoff 2019 (AR&R 2019) Guidelines.

E.6 Sensitivity

Sensitivity analysis is a crucial aspect of flood modelling, as it assesses how changes in key variables impact model outcomes and helps ensure robust, reliable predictions. This study evaluated the sensitivity of several factors, including stormwater blockage, rainfall losses, roughness coefficients, tide levels, and climate change. Results indicate that uncertainties in rainfall losses, roughness coefficients, and low tide levels have minimal impact on modelled flood behaviour. However, climate change may exacerbate flood depths and extents throughout the LGA. Additionally, the analysis underscores that while the stormwater system may have limited capacity, flood severity is generally mitigated during a frequent flood event under most conditions.

E.7 Results and Discussion

This study generated flood depth, water level, flood velocity, and flood hazard maps for each design event by enveloping results from various critical durations and temporal patterns. Additional map sets were produced to illustrate:

- **Hydraulic categories/flood functions**: Identifying areas crucial for natural flow and storage, including floodway, flood storage, and flood fringe areas.
- **Preliminary Flood Planning Area (FPA)**: Outlining locations where developments may be subject to flood-related controls to minimise flood risks.

- **Flood emergency response classification**: Determining appropriate flood-related emergency management strategies, warning procedures, and evacuation requirements.
- **Flood Planning Constraint Categories (FPCC)**: A tiered system (FPCC1 through FPCC4) of flood-related development constraints.

This study also identified key areas where flooding is more severe than in other parts of the Mosman LGA, particularly around The Esplanade, Kiora Avenue, Pearl Bay Avenue, Bay Street, Killarney Street, Julian Street, Wyong Road, Cowles Road, and Wolger Road. During a PMF event, sections of these roads may be rendered unusable, with surrounding properties severely impacted.

E.8 Conclusion

This study establishes a robust technical foundation for future Flood Risk Management Studies and Plans within the Mosman LGA. The insights gained will inform planning controls, emergency response strategies, and community awareness initiatives, ultimately enhancing Mosman's resilience against both current and future flood risks. Further investigations, including floor-level surveys and flood damage assessment are recommended to refine flood risk management strategies and strengthen community preparedness.

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 Classification: Public

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1 Introduction

1.1 Background

Flooding in New South Wales has significant economic, social, and environmental impacts, with estimated annual damages of approximately $250 million. Flooding within the Mosman LGA has been reported periodically, prompting Mosman Council (Council) to complete the Mosman LGA Flood Study to better understand, and thus manage flood risks.

NSW Government's Manly Hydraulics Laboratory (MHL) was engaged by Council to undertake a flood study with financial and technical support from the NSW State Government Floodplain Management Program, managed by the Department of Climate Change, Energy, the Environment and Water (DCCEEW).

1.2 Objective of the study

The purpose of the Flood Study is to improve understanding of flooding issues in the Mosman LGA including through community participation. The Flood Study provides Mosman Council with a comprehensive, catchment-wide flood model that will support effective floodplain management, infrastructural works, planning, development control, and emergency management across the Mosman LGA. The primary objective is to simulate flood behaviour under existing conditions, assess sensitivity to potential future impacts due to climate change, and identify key areas at risk of flooding. Developing a detailed flood model will guide future development within the catchment and inform strategic decision-making.

Additionally, the Flood Study lays the groundwork for identifying emergency management measures and provides critical flood information needed by the State Emergency Services (SES) to facilitate flood response actions.

The study also serves as a foundation for any future Flood Risk Management Study and developing a Flood Risk Management Plan, with a focus on implementing effective flood mitigation solutions for the most affected areas within the study region. Overall, the Flood Study aligns with Council's commitment to investing in innovative, cost-effective, and sustainable long-term flood mitigation strategies for the LGA.

1.3 Overview of study area

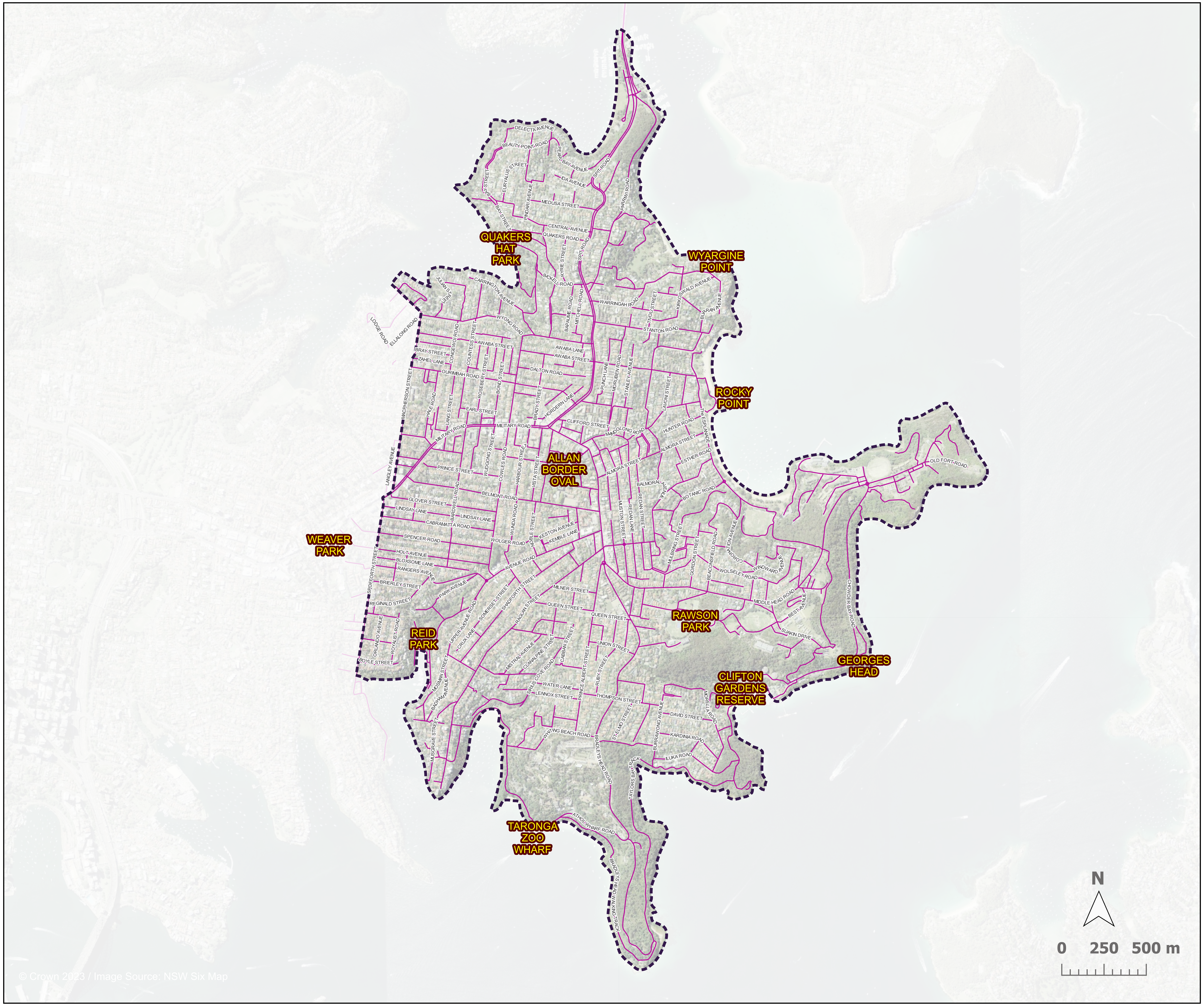
The Mosman LGA Flood Study area comprises the entire Mosman Local Government Area (LGA), located approximately 6 kilometres north of Sydney CBD. The LGA encompasses an area of approximately 8.7 km^2 and is surrounded by the waters of Sydney harbours except its western boundary, as illustrated in **Figure 1.1**. The western boundary generally lies along a ridgeline, limiting runoff from the adjoining suburb of Cremorne entering the Mosman LGA.

Land use within the highly urbanised study area is primarily residential, with some commercial, recreation and park areas. The density of development is generally greatest in the corridor adjoining Military Road. Park areas within the catchment are administered by the Council, National Parks, Taronga Zoo, Sydney Harbour Federation Trust and the Department of Defence, and vary from mown grass to dense forest. Major attractions include Sydney

Harbour, National Park and Taronga Zoo, located on Middle Head and Bradleys Head, both of which feature predominantly bushland cover.

The heavily developed nature of the catchment has meant that the original natural water courses have largely been developed over and replaced by a substantial and complex system of stormwater infrastructure.

Figure 1.1 Study area



Legend

Mosman LGA

Roads

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1.4 History of flooding and rainfall

In recent years, flooding in the Mosman LGA has primarily been triggered by short-duration, high-intensity rainfall events that overwhelm local stormwater infrastructure. The area's steep terrain and local gullies contribute to fast runoff, leading to flash flooding in low-lying streets, driveways, and basements. When rain is exceptionally heavy, the drainage systems can be overwhelmed, causing water to back up onto roads, parks and private properties.

These floods disrupt traffic, damage residential and commercial properties, and temporarily displace community activities. Notably, the Mosman LGA experienced heavy rainfall leading to flooding in recent years in 2012, 2018, 2022, 2023, and 2024, underscoring the recurring nature of these events. **Figure 1.2** illustrates a few locations where flooding has disrupted daily life and community activities.

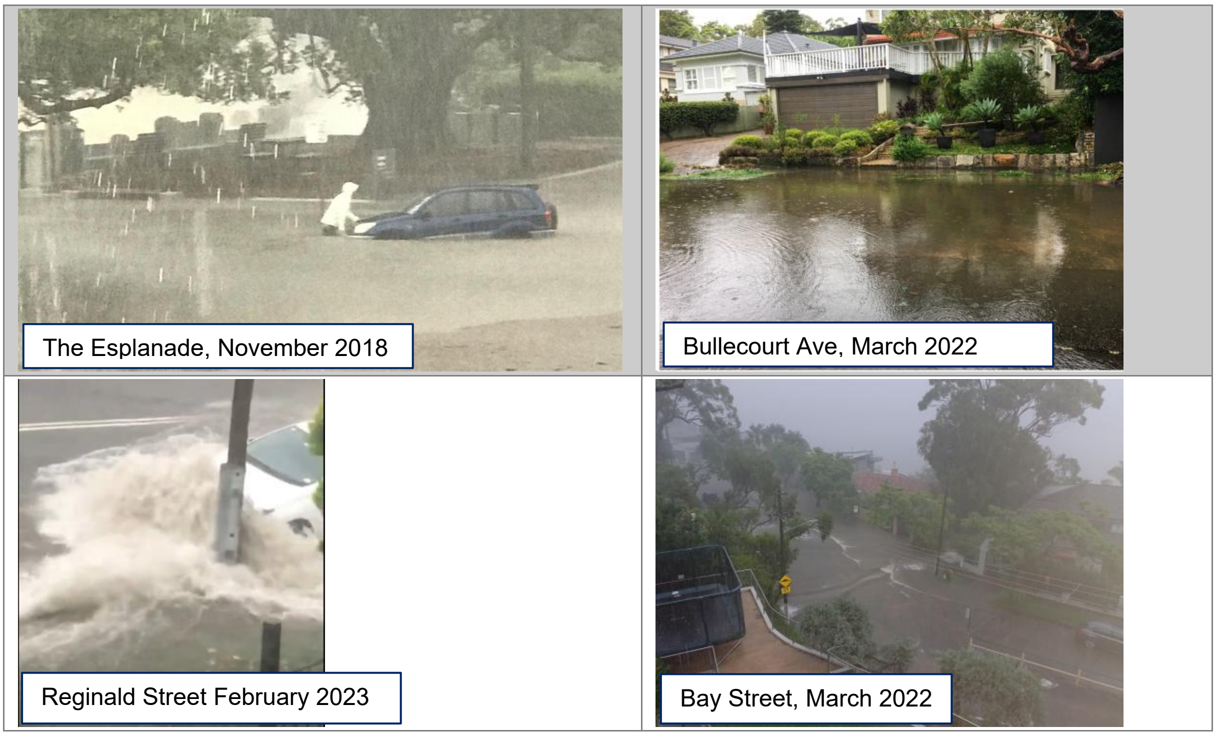


Figure 1.2 Photos showing flooding in Mosman LGA
Source: Community Consultation

1.5 Demographic overview

Understanding the social characteristics of the study area can help ensure appropriate risk management practices are adopted and shape the methods used for community engagement. House tenure and age distribution information obtained from census data can indicate the community experience with recent flood events, and hence an indication of community flood awareness. As per The Bureau of Meteorology Flood Preparedness Manual, using the population census data and other information held by councils and state agencies can help to identify the potential number and location of people in an area with special needs or requiring additional support during floods (Australian Government (Attorney – General's Department), 2009). The relevant information has been extracted from the 2021 Census for Mosman and tabulated in **Table 1.1**. According to the data, the total population of Mosman in 2021 was 28,329, with 11% of residents aged over 75.

Table 1.1 Mosman demographic overview based on the 2021 census.

Source: https://www.abs.gov.au/census/find-census-data/quickstats/2021/LGA15350

Population	28,329
Property tenure	Owned: 7,402 (64.1%, either outright or with a mortgage) Rented: 3,822 (33.1%) Other: 319 (2.8%)
Number of persons over the age of 75	3,126 (11%)
Number of single-parent families	862 (11.2%)
Language	English only is spoken at home: 22,671 (80%) A non-English language spoken at home: 2,308 (20%)
Average number of children per families with children	1.8
Average number of children per all households	0.6
Employed (including worked full-time, part-time and away from work)	14,676 (61.9%)

1.6 Relevant Policies, legislation and guidance

The NSW Flood Risk Management Process

The Mosman LGA Flood Study has been prepared in accordance with the New South Wales Government's Flood *Risk Management Manual* (NSW Government, 2023). The primary objective of which is to:

> *"reduce the impact of flooding and flood liability on communities and individual owners and occupiers of flood prone property, and to reduce private and public losses resulting from floods, utilising ecologically positive methods wherever possible."*

Under the NSW flood risk management framework, as outlined in the Flood Risk Management Manual (2023), primary responsibility for flood risk management rests with local government. Financial and technical assistance is provided to councils by the NSW Government.

The *Flood Risk Management Manual* defines the following steps in the Flood Risk Management Process:

- Formation of Flood Risk Management Committee and optionally a Project Technical Working Group
- Data Collection
- Flood Study Preparation
- Flood Risk Management Study Preparation
- Flood Risk Management Plan Preparation
- Flood Risk Management Plan Implementation

By following the NSW Flood Risk Management Process, Mosman Council is and has been adopting a best practice, State supported pathway for the methodical identification, assessment and implementation of robust and effective flood risk management measures in order to reduce the impacts of flooding on the community and existing development, and to ensure that future development is compatible with flood risk. Councils following the NSW Flood Risk Management Process demonstrate duty of care with respect to the management of flood liable land and are exempted from liability under Section 733 of the Local Government Act 1993.

Environmental Planning and Assessment Act 1979

The NSW Environmental Planning and Assessment Act 1979 (EP&A Act) creates the mechanism for development assessment and determination by providing a legislative framework for the development and protection of the environment from adverse impacts arising from development. The EP&A Act outlines the level of assessment required under State, regional and local planning legislation and identifies the responsible assessing authority.

Mosman Local Environmental Plan 2012

The EP&A Act is the governing legislation for planning and controlling land uses and development within NSW. Mosman Council's planning provisions as enabled by this Act include the Mosman Local Environmental Plan (LEP) 2012. This Plan aims to make local environmental planning provisions for land in Mosman in accordance with the relevant standard environmental planning instrument under section 3.20 of the Act.

SEPP (Resilience and Hazards) 2021 – Chapter 2 Coastal Management

SEPP (Resilience and Hazards) 2021 Ch. 2 Coastal Management aims to promote an integrated and coordinated approach to land use planning in the coastal zone. Mapping of the coastal zone under the SEPP is shown in **Figure 1.3**. For areas mapped as 'coastal wetland and littoral rainforest's – development consent is required for the clearing of native vegetation, and for earthworks, construction of a levee, draining the land and environmental protection works, and for any other development. For areas mapped as 'coastal environment areas' – covering much of the study area along the coastline – development consent must not be granted unless the consent authority has considered whether the proposed development is likely to cause an adverse impact on "the integrity and resilience of the biophysical, hydrological (surface and groundwater) and ecological environment" amongst other factors. The development must be designed, sited and managed to either avoid, minimise or mitigate adverse impacts.

Figure 1.3 SEPP (Resilience and Hazards) 2021 – Coastal Mapping

Source: NSW Planning Portal, https://www.planningportal.nsw.gov.au/

Other State legislative and policy requirements

- *Protection of the Environment Operations Act 1997* (POEO Act): Activities should be carried out in a manner which does not result in the pollution of waters.

- *National Parks and Wildlife Act 1974* (NPW Act) and *Amendment* 2010: Provides protection of Aboriginal cultural heritage in NSW. DCCEEW administers the NPW Act and requires Aboriginal consultation to be undertaken in accordance with statutory requirements.

- *Crown Lands Management Act 2016*: The purpose of this Act is to consolidate statutory provisions dealing with the ownership, use and management of Crown land into one Act. The objects of the Act include facilitating Aboriginal people's use of Crown land, with emphasis on the co-management of Crown land where appropriate.

- *Biodiversity Conservation Act 2017*: Provides legislative requirements for environmental assessment for potential impact on threatened species, or ecological communities listed in the *NSW Fisheries Management Act* or *NSW Biodiversity Conservation Act*, or their habitats.

- *Fisheries Management Act 1994 (FM Act)*: The FM Act 1994 contains provisions that allow for the preparation of threat abatement plans, threatened species recovery plans and habitat protection plans. These tools are enacted by legislation, and they outline actions to protect and rehabilitate aquatic habitats and threatened species, populations and communities.

- *Marine Estate Management Act 2014* and *Marine Estate Management Regulation 1999*: The Act declares and manages NSW marine parks. The Regulation outlines requirements for protection of various zones within marine parks.

- *Water Management Act 2000*: The objects of the Water Management Act 2000 are to provide for the sustainable and integrated management of the water sources of the state for the benefit of both present and future generations and, in particular: Ecologically sustainable development. Protect, enhance and restore water recourses.

- *Coastal Management Act 2016* - The Coastal Management Act 2016 replaced the Coastal Protection Act 1979 and establishes a new strategic framework and objectives for managing coastal issues in NSW. The Act defines the coastal zone as comprising four coastal management areas. SEPP (Resilience and Hazards) 2021 Ch. 2 Coastal Management gives effect to the objectives of the Act from a land use planning perspective, by specifying how development proposals are to be assessed if they fall within the coastal zone. The four coastal management areas are:

1. Coastal wetlands and littoral rainforests area — areas which display the characteristics of coastal wetlands or littoral rainforests that were previously protected by SEPP 14 and SEPP 26
2. Coastal vulnerability area — areas subject to coastal hazards such as coastal erosion and tidal inundation
3. Coastal environment area — areas that are characterised by natural coastal features such as beaches, rock platforms, coastal lakes and lagoons and undeveloped headlands. Marine and estuarine waters are also included
4. Coastal use area — land adjacent to coastal waters, estuaries and coastal lakes and lagoons.

Commonwealth Legislation

Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act): the EPBC Act identifies the following matters of national environmental significance:

- World heritage;
- National heritage;
- Wetlands of international importance;
- Listed threatened species and communities;
- Listed migratory species;
- Protection of the environment from nuclear actions; and Marine environment.

A preliminary matters of national environmental significance search has identified the following for the Mosman LGA area:

- Listed Threatened Ecological Communities: 6

- Listed Threatened Species: 101
- Listed Migratory Species: 55

1.7 Flooding behaviour

The Mosman LGA catchment can be impacted by three primary flooding mechanisms:

- Local overland flooding,
- Mainstream flooding, and
- Coastal inundation.

1.7.1 Local overland flooding

Local overland flooding is caused by heavy rainfall flowing across the ground or overflowing pipes, pits, and gutters. It is inundation resulting from local runoff rather than from overbank flows discharging from a watercourse, lake or dam. Overland flooding is often characterised by a rapid rise in water levels, particularly where the local catchment is relatively steep and small. Local overland flooding is the main flooding mechanism in Mosman LGA.

1.7.2 Mainstream flooding

Mainstream flooding occurs when a river or creek overtops its banks or when the capacity of a large trunk drainage system is exceeded. While Mosman LGA does not have defined creeks or rivers, it features a large trunk drainage system in Reid Park, approximately 3.4 m wide and 1.5 m deep, as well as natural flow paths in Balmoral Beach and Quakers Hat Bay. When these systems exceed their capacity, flooding occurs in the surrounding low-lying areas.

1.7.3 Coastal inundation

Coastal inundation occurs when elevated ocean levels combine with increased wave activity, spring tidal cycles, and ocean anomalies (storm surge, coastal trapped waves, etc.). Low-lying land around the edge of Mosman LGA is likely to be affected by coastal inundation during such event.

2 Previous studies

Mosman LGA Flood Study (2017)

Mosman Council initiated a flood study in 2017 but could not complete the study due to debates of the ‘Sea Lavel Rise’ indicators to be used for the flood studies and then the uncertainty of Council amalgamation. Once those key matter were resolved, Council engaged a specialist consultant to refine the flood study in all aspects considering the latest guidelines including the NSW Government’s Flood Risk Management Manual (2023), Australian Rainfall and Runoff 2019, the latest most accurate digital survey data, and advancement in technology in flood modelling, hardware, and software.

Hydraulic Study and On-Site Detention Modelling for Mosman Bay West Catchment (Sinclair Knight Merz 1998)

Mosman Council commissioned Sinclair Knight Merz (SKM) to undertake a hydrologic and hydraulic study of the stormwater infrastructure at the time of the study in the Mosman Bay West catchment. There were three stated objectives of this study:

- to examine the capacity of the Council’s stormwater system at the time
- identify areas that may require upgrading
- develop a policy for on-site stormwater detention (OSD) for implementing in Mosman.

To undertake this study a site survey and stormwater data collection exercise was undertaken. A pluviograph was installed in Reid Park, and water levels and velocities were gauged at the upstream end of the box culvert that runs through Reid Park. These data collection sites were monitored for four months between February 1998 and May 1998.

Using this data, an ILSAX model was set up to simulate the drainage network and determine the capacities of the system. Blockages were applied to the on-grade and sag pits of 20% and 50% respectively in order to make the network response more realistic. The creek draining into Reid Park was not surveyed and was instead modelled as a box culvert.

From the data that was collected, two storm events were identified to calibrate the ILSAX model. The largest event was recorded on 10 April 1998, and a smaller storm event was recorded on 9 April 1998. For the event on 10 April a peak flow of 2.397 m^3/s was recorded at the upstream end of the box culvert in Reid Park, while a peak level of 1.510 m was recorded at the same location where the flow exceeded the capacity of the Reid Park culvert. For the event on 9 April, a peak flow of 1.910 m^3/s was recorded, with a peak level of 1.164 m.

The SKM 1998 study provides critical insights into historical stormwater system performance and calibration data, which inform the assumptions and validation processes in the current flood study’s hydraulic modelling.

Mosman Drainage Investigation (Sinclair Knight Merz 1983)

As a result of heavy rain events in March 1983, Mosman Council requested that SKM conduct an investigation into the flooding and drainage problems that were experienced by residents. More than 150 residents were affected by overflow from the streets or drainage system. The study aimed to identify problems with the performance of the Council’s infrastructure, as well as identify measures that could be undertaken by residents to minimise property damage. Detailed notes on the flooding that occurred at the time were made.

The SKM 1983 investigation highlights historical drainage issues and community impacts, which are essential for understanding flood behaviour and assessing the adequacy of drainage system in Mosman.

3 Data collection and assessment

This section summarises the collation of available and relevant data in the study area.

3.1 Topographic data

Light Detection and Ranging (LiDAR) survey data of the study area and its immediate surroundings were obtained from ELVIS (https://elevation.fsdf.org.au/). Two LiDAR datasets were available: 1 m 2013 LiDAR and 1 m 2020 LiDAR data (**Table 3.1**). The accuracy of the ground information from the LiDAR survey can be adversely affected by several factors including the nature and density of vegetation, terrain variability, the proximity of buildings, and the presence of water bodies. The horizontal accuracy of both datasets is 0.8 m at a 95% confidence interval, while the vertical accuracy is 0.3 m at the same confidence interval. Given that 1 m 2020 LiDAR dataset represents the most recent topography of the study area, it has been adopted for the present study. The terrain of the study area is illustrated in **Figure 3.1**.

The 2020 LiDAR dataset shows that the topography of the Mosman LGA is mostly hilly. The land elevation within the study area varies from 0 m to 100 m AHD. The highest elevations are primarily located around Rawson Park and Spit Road. Military Road runs along the ridge line, roughly dividing the study area into two parts with the land sloping towards the shoreline. The average slope of the study area ranges from steep to very steep, between 2.5% and 27%. The steepest slopes are found around the outer edges of the study area, near the shoreline.

The latest available bathymetry data, 5 m 2018 Marine LiDAR, was utilised to define the bed profile of the coastline. Acquired by the NSW Office of Environment and Heritage, the 2018 Marine LiDAR data provide detailed bed profiles, extending seaward to water depths of 20–40 m.

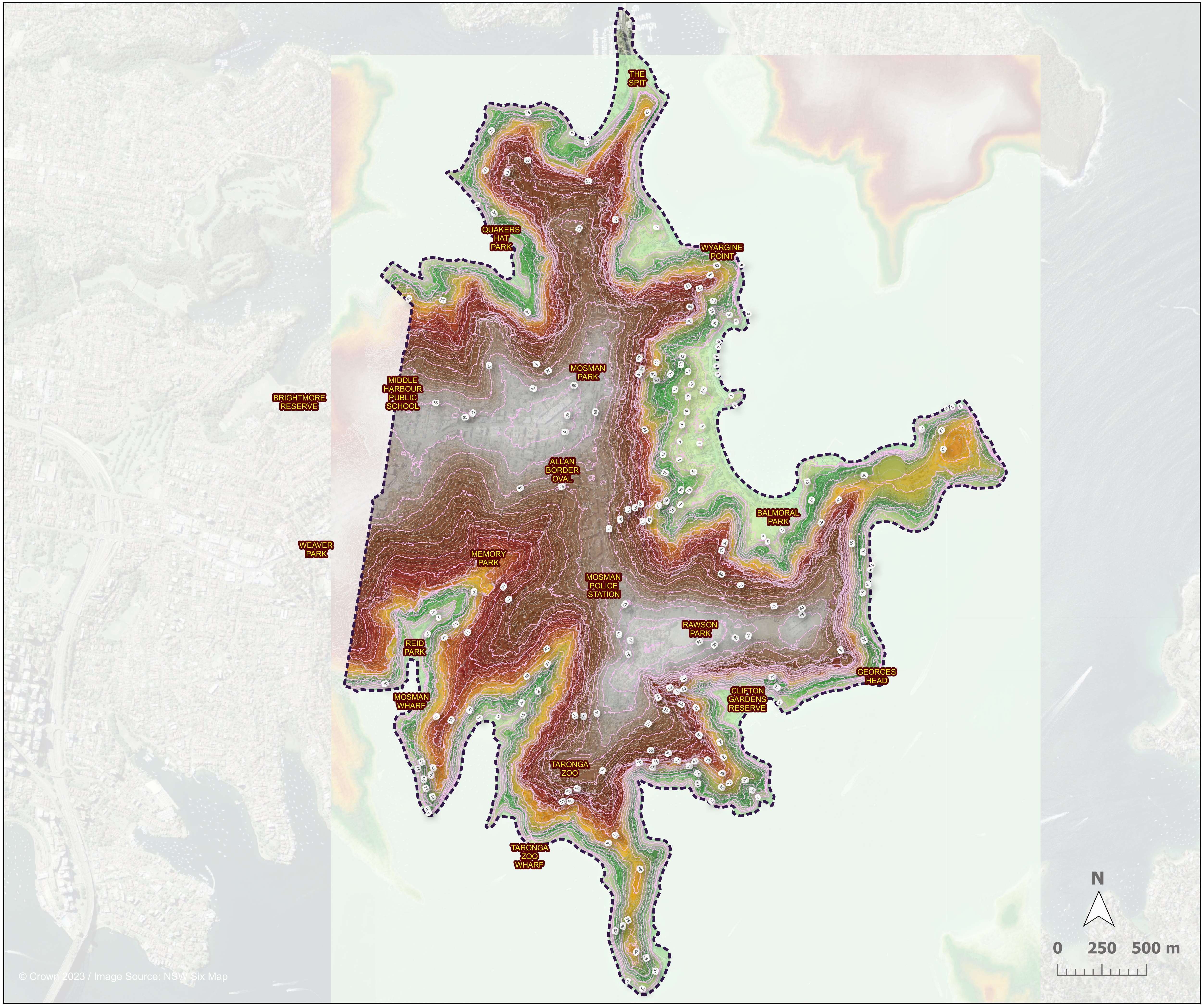
Table 3.1 List of available topographic survey data

Type of Data	Source	Date of Collection	Resolution	Accuracy (Horizontal and Vertical)	Comments
LiDAR	NSW LPI	May 2020	1 m	0.8 m and 0.3 m	Adopted for present study
LiDAR	NSW LPI	April 2013	1 m	0.8 m and 0.3 m	
Bathymetry	NSW Marine LiDAR Project	July 2018	5 m	~	This is the latest bathymetric data and was adopted for present study

3.2 Aerial and satellite imagery

Recent satellite imageries including Google Earth (www.googleearth.com), SIX Maps (https://maps.six.nsw.gov.au/) and Nearmap (https://apps.nearmap.com/maps/) were utilised to observe current features within the study area. The imageries were accessed in September 2024.

Figure 3.1 Topographic data of Mosman LGA



Legend

Mosman LGA

Elevation (m AHD)

110

0

Elevation contour (mAHD)

Major - 5m interval

Minor - 1m interval

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3.3 Gauge data for calibration and validation

Weather monitoring stations in the vicinity of the study area include rainfall gauges, flow and water level measurement stations, and tidal water level gauge. These are documented in **Table 3.2** and mapped in **Figure 3.2**. Descriptions of these stations are provided in the following sections and in **Appendix A** :

Table 3.2 Available monitoring stations in the vicinity of Mosman LGA

Station Number	Station Name	Data Type	Data Availability	Utilised for Mosman Flood Study?
566027	Taronga Zoo	Rainfall	1990-present	Yes
566091	Spit Bridge	Rainfall	2013-present	Yes
066062	Sydney (Observatory Hill)	Rainfall	1913-present	No (unlikely to be representative climate of Mosman, refer to **Section 3.3.1** for further information)
566100	North Head STP	Rainfall	1995-present	
566038	Vaucluse Bowling Club	Rainfall	1979-present	
5MOS03	Mosman Bowling Club (BC)	Rainfall	2022-present	Yes
213470	Sydney	Water level	1987-present	Yes
8Mosman06	Reid Park	Water level and Discharge	2022-present	Yes
		Water level and Discharge	2013-2014	No (data is outdated, not suitable for current analysis)
8Mosman08	Balmoral Beach	Water level and Discharge	2022-present	Yes
8Mosman07	Quakers Hat Bay	Water level and Discharge	2013-2014	No (only limited data from 2013–2014; considered outdated for current flood assessment needs)

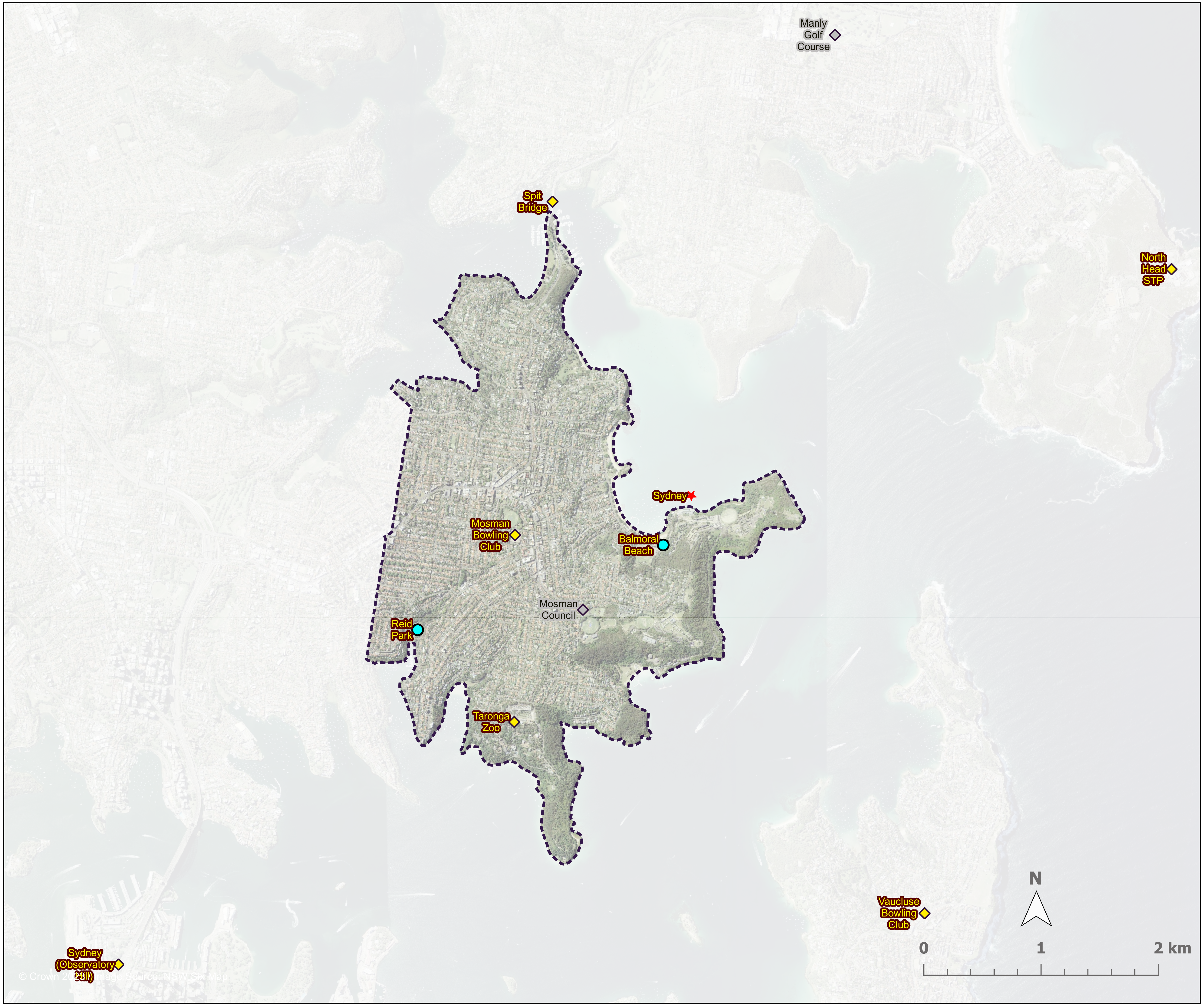

Figure 3.2 Monitoring stations within the vicinity of Mosman LGA

Legend

- Mosman LGA
- Monitoring stations
  - Discharge/water level
  - Ocean tide
  - Rainfall - active
  - Rainfall - inactive

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3.3.1 Rain gauges

There are six active rainfall stations located within approximately a 6 km radius of the study area: Taronga Zoo, Mosman Bowling Club (Mosman BC), Spit Bridge, North Head STP, Vaucluse Bowling Club, and Sydney Observatory Hill (see (**Figure 3.2**). Among these stations, Sydney Observatory Hill, North Head STP, and Vaucluse Bowling Club are situated outside of the study area and are therefore unlikely to represent rainfall patterns of the study area. Consequently, they were excluded from this study. The continuous rainfall data collected from the Taronga Zoo, Mosman BC, and Spit Bridge stations were used for flood model calibration and validation. The Mosman BC rainfall station is located at the centre of the Mosman LGA and is therefore considered most representative of the rainfall across the majority of the catchment area. Taronga Zoo is most representative of the rainfall falling on the southern end and Spit Bridge is most representative of the rainfall falling on the northern end of the Mosman LGA catchment area.

The aerial distance between Taronga Zoo and Mosman BC is 1.5 km, while the distance between Taronga Zoo and Spit Bridge is approximately 4.5 km. Despite their proximity, significant variations in historical rainfall data recorded at these stations suggest that the rainfall pattern in Mosman LGA can vary considerably over short distances and timeframes, as illustrated in **Table 3.3**. Due to this preliminary analysis, a further investigation into rainfall gauging stations and recorded rainfall data was undertaken, including a review of radar weather data for specific rainfall events to identify representative areas for each rainfall station. Details are provided in **Appendix A** .

Table 3.3 Recorded 30-minute rainfall depth at Mosman BC, Taronga Zoo and Spit Bridge

Event Date	Mosman BC		Taronga Zoo		Spit Bridge	
	Rainfall depth (mm)	Corresponding estimated AEP	Rainfall depth (mm)	Corresponding estimated AEP	Rainfall depth (mm)	Corresponding estimated AEP
12 January 2022	32	30%*	39	Between 20% and 10%**	11	> 63.2% AEP**
08 March 2022	36	20% AEP*	19	> 63.2% AEP**	46	Between 10% and 5%**
09 February 2023	64	1% AEP*	42	Between 10% and 5%**	47	Between 10% and 5%**
06 April 2024	29	40% AEP*	30	Between 50% and 20%**	28	Between 50% and 20%**

*Note: Based on IFD analysis at Mosman BC.

**Note: Adopted from Design Rainfall Data System (2016), BOM.

3.3.2 Stormwater flow gauge data

There are two stormwater flow gauge stations in Mosman LGA. MHL has been monitoring water level and flows at these two gauges for Council since December 2021. The gauges were installed within the existing drainage system: one at Reid Park within an open channel, and the other inside a box culvert at Balmoral Beach near Balmoral Sailing Club. The data from these two flow gauges was utilised for model calibration and validation.

At the Reid Park gauge, the channel invert level (gauge zero) is 0.52 m AHD. The maximum channel depth is approximately 1.5 m, which corresponds to a water level of around 2.0 m AHD at the edge of the channel—indicating that overflow occurs when water levels exceed this height.

At the Balmoral Beach gauge, the culvert invert level is 1.075 m AHD. The maximum culvert height is about 0.91 m, also corresponding to approximately 2.0 m AHD at the top of the culvert.

Further details on stormwater flow gauging stations are provided in **Appendix A** .

3.3.3 Tidal Data

Manly Hydraulics Laboratory operates a continuous tidal water level gauge (Sydney, ID 213470) at Cobblers Head in Middle Harbour (refer to **Figure 3.2** for the gauge location and **Table 3.2** for metadata). Water levels in Middle Harbour can directly impact water levels and flooding in low-lying areas of the Mosman LGA. However, most of the Mosman LGA is situated on higher ground, making it unlikely to be affected by water levels in Middle Harbour under normal conditions. Water levels observed during 2022 and 2023 in Sydney Station are presented in **Figure 3.3**.

The peak water level recorded during 2022 and 2023 was approximately 1.4 m AHD on 8 May 2023. This would likely create a 0.9 m depth of water at the Reid Park gauge and a 0.3 m depth at the Balmoral Beach gauge, both of which are at least 0.5 m below the top of bank of their respective culverts or channels.

However, to ensure the TUFLOW hydraulic model accurately simulates flood behaviour, the observed water levels of Middle Harbour were used as the downstream boundary condition to calibration and validation the TUFLOW model against historical rainfall events.

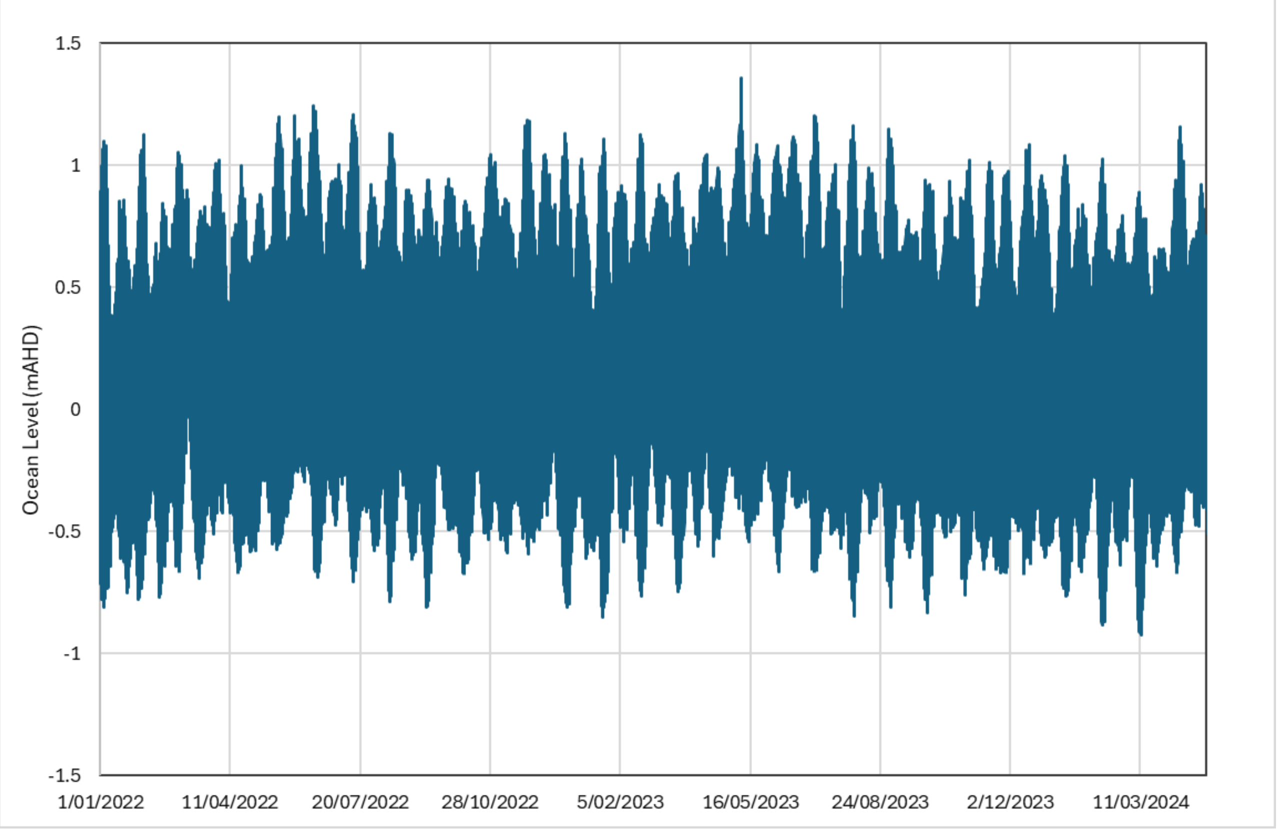

Figure 3.3 Water level at Sydney monitoring station

3.4 Stormwater drainage network

Stormwater network data was made available for this study by Council. The dataset contained the following GIS layers:

- Closed conduits,
- Open conduits,
- Pits, and
- Stormwater Quality Improvement Devices (SQIDs).

To ensure the modelled stormwater system accurately represents ground conditions, MHL conducted field verification to confirm the details of key stormwater pipes. Based on the findings from field investigations, the configuration of the stormwater system, land elevation and slope and satellite imagery stormwater pipes with a diameter greater than 300 mm, along with their associated pits, were updated and included in the flood model. Stormwater drainage pits and pipes are illustrated in **Figure C.3** in **Appendix C**

A review of topographic data for these areas indicates that they generally slope towards the bay and are unlikely to contribute any significant overland flow to surrounding areas during flood events. Therefore, flooding in adjacent areas is not expected to be influenced by these sites, and the absence of pipe network data does not affect the findings of this study.

3.5 Other relevant GIS information

A selection of digitally available information current upon receipt (19 May 2023) was provided by the Council in the form of GIS datasets for use in this study. The following Council GIS data have been utilised:

- Cadastre,
- Kerb and gutter, and
- Roads.

These datasets were utilised for flood modelling and for flood mapping purposes. The roads layer was used to incorporate appropriate roughness along the roads, and the cadastre layer was used to account for losses due to fences along lot boundaries.

4 Community consultation

A key element in the success of the flood risk management process is the effective engagement of the community. During this phase, community consultation was aimed at reaching out to residents to inform about the flood study, request information from them about historic flooding events, address flooding concerns, and gather ideas on potential flood risk management measures.

Consultation for this study included interactions with multiple community members in response to the distributed questionnaire to residents at the commencement of the project and the placement of the Draft Flood Study on Public Exhibition prior to finalising the study. Both items are further described below.

4.1 Community flood questionnaire

A primary component of this consultation process included hosting, collation, and review of an electronic Community Flood Questionnaire. MHL, with Councils input, developed an online questionnaire using SurveyMonkey to collect recent flood information. In late 2023 Council distributed notification letters to residents via a letter box drop to approximately 16,250 households being the whole of the Mosman LGA; the letters included a QR code link to the questionnaire. The questionnaire was accessible for more than 6 weeks, allowing sufficient time for the local community to respond. A dedicated webpage was created on Mosman Council's website and an advertisement was placed on the front page of Council website with a link to this dedicated page. The dedicated webpage contained information about the flood study and flood risk management process as well as a FAQ section. Links to the questionnaire as well as contact information to a 1800 number and a dedicated flood study email address were provided. In response to the above, 237 responded to the questionnaire, 18 people emailed the dedicated email address and 2 people called the 1800 number between December 2023 and June 2024.

The questionnaire sought to identify flood concerns within the catchment, acquire reliable flood information for flood model calibration and validation, and gather preliminary information on future flood risk management measures. This approach not only promoted flood risk awareness but also helped describe the NSW flood risk management process. The results of the Community Flood Questionnaire were processed and summarised in graphical and tabular formats. Details are provided in **Appendix B** .

A total of 237 responses were received, with all responses provided through the Community Flood Questionnaire, except for two responses submitted via email. The spatial distribution of responses is mapped in **Figure B.2** with five locations of respondents not identified. The respondents were well distributed across the study area and not concentrated in any specific location. Approximately 55% of respondents reported that their property had been affected by flooding, including yard flooding.

The flood study team and Council are very grateful for the valuable contributions from the community to this report and its data and for offering their photographic records.

Community feedback indicated that the study area is primarily prone to flash flooding. The majority (approximately 67%) described flooding events as lasting less than an hour up to 6 hours. About 23% described flooding lasting between 6 to 24 hours, while the remainder (10%) described flooding lasting between 24 to 48 hours. The primary sources of flooding were identified by community as follows:

- Water flowing from the road or other public land
- Overflow from neighbouring properties
- Local rainfall-runoff
- Overflow from drainage channels
- Coastal inundation

Community main concerns and suggestions regarding flooding included:

- Inadequate drainage system maintenance and cleaning
- Need for an upgraded drainage system
- Flooding from neighbouring properties
- Impact of local development/new properties
- Properties located at a topographic low point (sag point)

70 respondents indicated that they had information about historical flooding, primarily between 2018 and 2023 (refer to **Figure B.3** for spatial distribution of respondents). Of these, 28 provided the year and estimated flood depth, 12 did not mention the flood depth, and the remaining 30 did not specify any further information about the flooding (**Table 4.1**). The highest number of reports (33) came from residents affected in February 2023, followed by 26 in March 2022 and 22 in November 2018 with some respondents reporting flooding in multiple years. This valuable information has been incorporated into the study to help calibrate and validate the flood model.

Additionally, many respondents mentioned possessing photographs or videos of historical flood events within the study area. This substantial archive of potential flood data is crucial for flood model calibration and validation and strengthens community engagement in the Mosman LGA Flood Study. Consequently, further communication was carried out with these respondents to collect this additional information and photos, with the results included in **Section 5.2**. Photos provided by residents have also been used through this document.

For more information on the Community Flood Questionnaire, refer to **Appendix B** .

Table 4.1 Summary of historical flood information from Community Flood Questionnaire

Description	No of Respondents	Comments
Responses with year and estimated flood depth	28	Includes year and depth reported at property level
Responses with year only (no flood depth)	12	Partial information

Description	No of Respondents	Comments
Responses without year and depth of flooding	30	Limited detail
Total number of responses indicating flood experience	**70**	Further communication was undertaken to collect additional flood information, see **Section 5.2**

4.2 Public exhibition

The Draft Flood Study was placed on public exhibition between 14 August 2025 and 30 September 2025. The notification to inform the community about the public exhibition was organised via multiple means including a dedicated Council webpage, posters, flood study information leaflet distribution to all properties, letters to owners of properties identified as being within the Preliminary Flood Planning Area (FPA) and advertisements in 'Mosman Daily'.

The dedicated webpage offered information and the ability to ask questions or make a submission. During the public exhibition period, there were approximately 2,400 visits to the website, 38 meetings with residents at one-on-one sessions held at Barry O'Keefe Library and 20 interactions with Council's pop-up stand at the September 2025 Mosman Markets.

A total of 115 written correspondences were received including 91 submissions where 70 challenged the fact that the properties were identified as being within the Preliminary FPA, 13 general questions about the study and 11 comments.

Following a review of all responses received, an assessment of each submission concerning their properties being included within the Preliminary FPA was undertaken to determine the validity of the claim. When assessing each property, two key factors were identified which impacted a properties inclusion in the Preliminary FPA. These were the localised anomalies associated with the Digital Elevation Model (DEM) and the property being only marginally within the Preliminary FPA.

To address the issues in relation to the DEM used for the flood model, minor elevation adjustments were required to more accurately reflect the localised ground levels that may have been impacted by the removal of trees and other obstructions. To minimise these impacts on the flood model, the elevation dataset used for the entire LGA was checked with adjustments made accordingly.

Subsequent to applying the adjustments, the model was rerun for all design events and results were remapped accordingly.

To address the issues in relation to the property being only marginally within the Preliminary FPA, a buffer was applied prior to identifying the property as being within the Preliminary FPA.

5 Field investigation

5.1 Survey of stormwater networks

To ensure the modelled stormwater system accurately represents ground conditions, MHL conducted field verification to confirm the dimensions of key stormwater pipes. 67 locations were identified for ground truthing. MHL staff conducted site inspections on 25 September 2023, 10 January 2024 and 10 May 2024 to confirm pipe sizes as documented in Council's stormwater database.

Thorough photographic evidence and measurements were taken during the visits, capturing a total of 182 features. Based on the outcomes of the field investigation, configuration of the stormwater system and recent topographic data, stormwater pipe and pit networks were included in the model.

5.2 Survey and/or processing of flood information

During the Community Flood Questionnaire, 70 respondents indicated that they had information about historical flooding. Consequently, each respondent was contacted individually via email and text message. Out of these 70 respondents, 40 replied, with 28 providing information on past flood events. To gain further insight into flood behaviour within Mosman, a field survey was conducted on 10 May 2024, at 11 specific locations. Key outcomes from the investigation and field survey are summarised below,

- Several respondents provided photos showing road flooding, which were processed and analysed to estimate likely flood depths.
- A number of properties are situated on slopes within hilly areas. Due to the natural gradient, rainfall runoff flows along these slopes and through some properties.
- Some properties are situated at low points or sag areas along sloped roads. During heavy rainfall, floodwater travels along these roads and overtops the kerb when the gutter's conveyance capacity is exceeded or when obstructions, such as parked cars, impede the flow.
- Some photographs showed inundation inside properties.

Following a thorough review of the provided flood information and field investigation results, flood photographs from 8 locations were deemed suitable for use for flood model calibration and validation purposes. Other provided flood photographs were considered unsuitable for calibration or validation, primarily because they either could not be used to estimate flood depths (e.g., on roads or outside building footprints) or were recorded outside the selected events used for flood model calibration and validation. It should be noted that this is a catchment-wide flood model, and as such does not account for obstructions within roads, such as cars, bins, utility poles, or blockages within property boundaries due to features like swimming pools or storage.

6 Flood model development

6.1 Introduction

A one dimensional – two dimensional (1D-2D) coupled hydraulic model was developed using TUFLOW software covering the entire Mosman LGA in accordance with recent guidelines, AR&R 2019 and the NSW Flood Risk Management Manual 2023. A schematic diagram of the TUFLOW hydraulic model is presented in **Figure C.1** in **Appendix C** with further details documented below.

6.2 Development of TUFLOW hydraulic model

6.2.1 Hydraulic Model Selection

The latest version of TUFLOW HPC (Build 2023-03-AC at the time of the model development) was selected for this study. TUFLOW HPC is a two-dimensional (2D) fixed grid hydrodynamic solver that uses an explicit finite volume solution (TUFLOW, 2018).

6.2.2 Topographic Data

The 2D model terrain was defined by 1 m resolution LiDAR data captured in 2020. Key terrain features that may influence flood behaviour, such as small channels, gullies, and roadside kerbs, were identified using the Council's database and aerial imagery and incorporated into the model. Some inconsistencies in land elevation within lot boundaries, particularly at building footprints, were detected, which could lead to artificial ponding. These discrepancies are likely due to construction activity, the presence of water, or other significant ground changes at the time of LiDAR capture. To address these issues and minimise artificial pooling, further refinements to the topography were undertaken. During this process, elevations in the affected areas (e.g., within building footprints) were interpolated based on the surrounding ground levels. The 5 m 2018 Marine LiDAR dataset was utilised to define the bed profile of the coastline.

6.2.3 Pit and Pipe Network

Pit and pipe networks play a vital role in managing runoff, especially during frequent rainfall events, and are crucial for simulating the characteristics of overland flooding in Mosman LGA. Council provided a substantial amount of stormwater pit and pipe data for this study. Based on Council's data and additional information—including site visual inspections, previous studies, LiDAR data, and the configuration of nearby stormwater systems—the pit and pipe network was reviewed, and approximately 3,000 individual stormwater pipes with diameters larger than 300mm and about 1,750 stormwater pits (excluding manholes and junction pits) were identified and included in the flood model.

6.2.4 Representation of building and fences

The extensive urbanisation of the Mosman catchment introduces numerous obstacles to overland flow. Research indicates that buildings can significantly alter flow patterns in urban areas by redirecting water (Smith et al., 2008). Flood dynamics in urbanised areas are often complex, as water navigates through streets, over or under fences, and around buildings. This complexity is further compounded by factors such as terrain slope, fence types and failures, debris blockages, and the displacement of objects like cars. Consequently, capturing the finer details of flow behaviour around buildings and fences on a catchment-wide scale can be challenging—for example, accounting for cars or bins obstructing normal flow paths.

Smith et al. (2008) proposed several methods to account for the impact of buildings and fences in overland flood modelling. These methods include blocking flood model cells, artificially increasing bed roughness, adding extra energy losses, and partially obstructing elements near buildings and fences. Each method has its own advantages and limitations depending on the context; therefore, Smith et al. (2008) recommended that the modelling approach be selected based on site-specific conditions.

6.2.4.1 Representation of buildings

As part of this study, several techniques were explored — including partially obstructing elements, blocking out building, and high bed roughness — to represent buildings in the flood model. Of these, the partially obstructing elements approach was deemed impractical, particularly for catchment-wide flood modelling in densely urbanised areas. Instead, high bed roughness was found to be more suitable than blocking-out buildings. The selection of this approach was based on the following factors:

- Resident Feedback: Input from residents through Community Flood Questionnaire and direct communication indicated that several properties experienced local flooding during past rainfall events.
- Urban Density: Mosman LGA is a highly urbanised area with some properties having narrow gaps (e.g., less than 1 m) between them. As a result, the “blocking out building” approach would not be suitable for a 1 m grid model, as it would prevent water from flowing through/between these properties. **Figure 6.1** illustrates examples of densely packed buildings, where water can move through the narrow gaps.
- Direct Rainfall Modelling Approach: This study adopted the direct rainfall modelling approach, in which rainfall is applied directly to the grid of the 2D hydraulic model. This method is particularly suitable for highly urbanised catchments. It ensures that rainfall is accounted for as it falls on top of buildings before reaching the ground, avoiding any loss in rainfall data.
- Storage Considerations: The “blocking out building” approach does not account for the potential storage capacity within building footprints, which could lead to conservative water level estimates.

Figure 6.1 Example of high building density (left) and narrow gap between buildings (right) in the Mosman LGA

Source: SixMap; Google Street View

6.2.4.2 Representation of fences

Fences can significantly impact overland flood behaviour, and hence understanding the role fences play in obstructing flow during floods is important. Those considerable uncertainties are due to several factors as follows:

- Fence Types and Debris: The wide array of fence designs and the varying nature of debris carried by floodwaters can lead to significant differences in blockage levels. **Figure 6.2** showcases examples of a few fencing types located within Mosman LGA.
- Fence Failure Risks: Fences exposed to high floodwater depths and velocities may fail or collapse, adding another layer of uncertainty.

An extensive number of fences are located in the study area. Due to uncertainties regarding their potential failure during floods, conducting a detailed survey of each fence was deemed inappropriate. Therefore, only fences located along the main flowpaths were identified using Google Street View and modelled as appropriate (further details in **Section 7.2**).

Fences located outside the main flow paths were instead represented in the TUFLOW model as "flow constriction" lines. This approach allows a blockage factor to be applied to each cell beneath a fence line, reflecting the impediment to flow and the reduced conveyance capacity caused by fences. An automated method was used to estimate fence locations based on the cadastre database. For the purpose of this study, a 50% blockage factor was applied to fences outside the main flow paths. The impact of these fences on the overall flow behaviour is considered minor or localised, and is therefore not expected to result in significant changes to flood behaviour if a different blockage factor were used.

Figure 6.2 Example of fences within Mosman LGA

Source: Google street view

6.2.5 Representation of roadside gutter

Roadside gutters collect stormwater runoff and discharge it to an appropriate location or pit. They are very important for urban drainage systems, especially during frequent rainfall events. In this study, the gutters were included in the TUFLOW model as 'breaklines' to ensure accurate representation of the low elevations along the gutters. Their locations and alignments were determined using the kerb and gutter GIS layer from Council's database.

6.2.6 Hydraulic roughness

Hydraulic roughness coefficients (Manning's n) are used to represent the resistance to flow of different surface materials. Hydraulic roughness has a major influence on flow behaviour and is one of the primary parameters in hydraulic model calibration.

Spatial variation in hydraulic roughness was represented in TUFLOW by delineating the catchment into zones of similar hydraulic properties. The hydraulic roughness zones adopted in this study have been delineated based on consideration of the NSW Environmental Planning Instrument (EPI) - Land Zoning data set, Council's building footprint, cadastre, zoning and aerial photography data, supplemented with site observations where necessary. Factors affecting resistance to flow were of primary importance including surface material, vegetation type and density, and the presence and density of flow obstructions such as buildings and fences. Manning's 'n' values assigned to each zone were determined based on land type with reference to standard values recommended by Chow (1959) and AR&R 2019 guidelines. Land areas with light vegetation were assigned a Manning's n value of 0.03, while those areas with thick vegetation were assigned a value of 0.08. For buildings, a depth-varying roughness was adopted: 0.03 for depths up to 20 mm, increasing to 0.4 at a water depth of 100 mm. Having a low Manning's n value for shallow depths simulates fast runoff from the roof; otherwise, the water can appear to mound on the building. **Figure C.2** in **Appendix C** and **Table 6.1** below further summarise the detailed Manning's n values used in the hydraulic model.

Table 6.1 Adopted Manning's n hydraulic roughness coefficients

Material	Manning's n
2D roughness values	
Harbour water body	0.013
Creek	0.040
Open lined channel	0.011
Roadways and pavement	0.020
High density development	0.080
Light density vegetation/ open area	0.030
Medium density vegetation (i.e., shrubs)	0.050
High density vegetation (i.e., nature conservation, plantation forests, woody cover, incl. shadowed areas due to canopy cover)	0.080
Areas within lot but outside building footprint	0.060
Building footprint (depth-varying roughness)	0.030 - 0.400
1D roughness values	
Concrete channel	0.011
Pipes and culverts	0.011 – 0.013
Concrete channel with vegetation (light to dense)	0.025-0.050

6.2.7 Downstream boundary conditions for calibration and validation event

The downstream boundary condition for the hydraulic model was defined using a stage-time boundary, based on tidal gauging data recorded at the Sydney (213470) water level gauge, refer to **Section 3.3.3**. This gauge, located on the north-east side of Balmoral Beach, has been monitoring water levels in Sydney Harbour since 1987 and is the nearest and most suitable gauge for this study, providing reliable data for the selected calibration and validation rainfall events.

During the calibration event on 8 March 2022, tidal levels ranged from 0.0 m AHD to 0.6 m AHD, indicating a period of high tide. For the 9 February 2023 event, a low tide was observed, with water levels at or below 0 m AHD. Similarly, during the validation event on 12 January 2022, tidal levels were also at low tide. This boundary condition setup ensures that the model accurately reflects the tidal variations during these key rainfall events, enhancing the reliability of the simulation results along the coastline and the representation of any backwater effects resulting from elevated tidal levels.

6.3 Development of WBNM hydrologic model

6.3.1 Introduction

AR&R 2019 recommends using critical combinations of durations and temporal patterns for simulating flood behaviour. However, identifying these combinations using the TUFLOW hydraulic model can be highly inefficient, particularly with the direct rainfall modelling method. To streamline this process, a hydrologic model was proposed as per AR&R 2019 guideline to pre-select suitable durations and temporal patterns for the Mosman LGA.

Consequently, a hydrologic model was developed using WBNM (version 2017). WBNM is one of the few tools that incorporate AR&R 2019 design rainfalls and procedures, which is based on the updated 2016 Intensity-Frequency-Duration (IFD) diagrams. It requires relatively few catchment parameters compared to other runoff routing models and has been extensively used to simulate a wide range of hydrological behaviours in both natural and urban catchments.

6.3.2 Catchment delineation

The CatchmentSIM tool was utilised to delineate the catchment area of the Mosman LGA and to investigate overland flow paths using the 2020 1 m LiDAR data. Based on the distribution of these flow paths, stormwater systems, and topography, the Mosman LGA catchment was divided into 108 smaller sub-catchments with the help of CatchmentSIM. **Figure C.4** in **Appendix C** presents a map illustrating the boundaries of these sub-catchments. Investigations determined that the slopes of the sub-catchments ranged from 1% to 5% for 59 sub-catchments, from 5% to 10% for 38 sub-catchments, and above 10% for 11 sub-catchments (as detailed in **Table C.1** in **Appendix C**).

6.3.3 Model parameters

Parameters required by the WBNM model include sub-catchment area and linkage, pervious and impervious percentage, runoff lag factor, stream routing lag factor, rainfall input, initial losses and continuing losses. Details of each parameter are documented below.

6.3.3.1 Impervious areas

Using land use data and satellite images (Google, SixMap and NearMap), a weighted average of impervious and pervious areas was calculated for each sub-catchment. Urbanised and residential areas were considered to be 60% impervious outside building footprints. Building footprints, roadway corridors, and paved areas were considered 100% impervious, while the remaining areas were classified as pervious surfaces. Based on these estimates, the percentage of impervious area for each sub-catchment ranged from 5% to 88%. Notably, approximately 81 sub-catchments have an impervious area of 70% or more (refers to **Table C.1** in **Appendix C**).

6.3.3.2 Rainfall losses and Lag parameter

Rainfall losses including initial loss (IL) and continuing loss (CL), can be widely variable from storm to storm and catchment to catchment. The amount of loss is dependent on a number of factors such as catchment topography, soil, vegetation, and the antecedent soil moisture (M. El-Kafagee, 2011). It is recommended in AR&R 2019 that practitioners undertaking flood investigations in New South Wales should use a hierarchical approach to design loss estimation. The hierarchy goes from 1 (most preferred) to 5 (least preferred) as and described below. Losses adopted for WBNM model are documented in the **Section 7.4**.

1. Use the average of calibration losses from the actual study on the catchment if available.
2. Use the average calibration losses from other studies in the catchment, if available and appropriate for the study.
3. Use the average calibration losses from other studies in similar adjacent catchments, if available and appropriate for the study.
4. Use the NSW FFA-reconciled losses available through the AR&R Data Hub.
5. Use default AR&R data hub continuing losses for a location with a multiplication factor of 0.4.

This study adopted the approach outlined in item 1, and the specific losses applied are detailed in **Section 7.4**.

WBNM developers recommend lag parameter values ranging between 1.3 and 1.8 (Boyd and Bodhinayake, 2006). Lag parameter (C) is used for the conversion of rainfall to runoff on pervious surfaces. The value of the lag factor can vary based on the characteristics of the watershed, including soil type, land use, slope, and vegetation. Generally, a lag parameter value down to 1.3 is recommended for catchments with steep slopes and fast drainage and thus a peakier flow profile, while a value of up to 1.8 is suggested for catchments with a flatter flow profile (i.e., flow with a longer duration and lower peak). Calibration outcomes, as described in **Section 7.4**, revealed that a C parameter value of 1.3 appropriately replicates the flow across gauging locations. The flow paths were routed using nonlinear routing (type = R) with a value of 1.0 as recommended by Boyd et al. (2017) for natural channels and streams.

7 Calibration and validation of model

7.1 Selection of calibration and validation events

The selection of suitable historical events for calibrating the flood models largely depends on the availability of historical flood information. Gauging stations at Reid Park and Balmoral Beach (Sailing Club) have been recording continuous water levels since December 2021 (refer to **Section 3.3.1**). However, water level data for Reid Park was unavailable from July to August 2022 and December 2023 to April 2024 due to damage to the sensor.

As part of this study, a Community Flood Questionnaire was conducted as well as direct communication with residents who were able to provide further information. Based on the information received from the community consultation (refer to **Section 3.4**), water level gauge data, and data from rainfall stations, eight potential events were initially identified (**Table 7.1**) that could be used for the calibration and validation of the flood model:

- 28 November 2018
- 12 January 2022
- 08 March 2022
- 07 April 2022
- 09 July 2022
- 09 February 2023
- 02 December 2023
- 06 April 2024

Considering the availability of recorded rainfall, and the magnitude of each rainfall event, the 12 January 2022 and 8 March 2022 events were identified as the most suitable for calibrating the TUFLOW model. Meanwhile, the 9 February 2023 event has the most extensive collection of flood information from the community, making it the most suitable for validating the TUFLOW flood model.

While the 28 November 2018 event was significant and had a good collection of flood information from the Community Flood Questionnaire, it lacked pluviometer data from the Mosman BC rainfall station and no stormwater gauge data was available to validate or calibrate the flood model. Gauge data is considered as primary source for flood model calibration. Furthermore, the Mosman BC station, installed in 2021, is one of the primary stations that represents the overall rainfall behaviour within the Mosman LGA. Without pluviometer data from this station, the flood model may overestimate or underestimate flood behaviour, therefore, the 28 November 2018 event was excluded from flood model calibration and validation.

Other rainfall events, such as those in April 2022, July 2022, December 2023, and April 2024, were either minor or did not have sufficient reported flood information or had unavailability of water level gauge data, so were not included in the calibration and validation of the model.

Table 7.1 Details of potential rainfall events for flood model calibration

Rainfall event	Outcome of Community Consultation		Availability of Recorded Water level		Observed Peak Water level (mAHD)		Availability of Recorded Rainfall				Comments
	Number of respondents with depth of flooding	Number of respondents with flood photo	Reid Park	Balmoral Beach	Reid Park	Balmoral Beach	Taronga Zoo	Mosman BC	Spit Bridge	Rainfall at Mosman BC in 30 mins	
28 November 2018	22	4	No	No	~	~	Yes	No	Yes	NA	Not adopted for further study
12 January 2022	**~**	**~**	**Yes**	**Yes**	**2.2**	**2.1**	**Yes**	**Yes**	**Yes**	**32 mm (equivalent to 30% AEP)**	**Adopted as calibration event**
08 March 2022	**~10**	**3**	**Yes**	**Yes**	**2.0**	**2.5**	**Yes**	**Yes**	**Yes**	**36 mm (equivalent to 20% AEP)**	**Adopted as calibration event**
07 April 2022	~	~	Yes	Yes	1.6	2.4	Yes	Yes	Yes	21 mm	Not adopted for further study
09 July 2022	2	~	Yes	Yes	0.8	1.2	Yes	Yes	Yes	16 mm	Not adopted for further study
09 February 2023	**~33**	**5**	**No**	**Yes**	**~**	**2.5**	**Yes**	**Yes**	**Yes**	**64 mm (equivalent to 1% AEP)**	**Adopted as validation event**
02 December 2023	4	~	No	Yes	~	1.7	Yes	Yes	Yes	12 mm	Not adopted for further study
06 April 2024	~	~	Yes	Yes	~	2.5	Yes	Yes	Yes	28 mm	Not adopted for further study

7.2 Simulation of TUFLOW hydraulic model for calibration and validation events

7.2.1 General approach to TUFLOW model for calibration and validation

TUFLOW hydraulic simulations were carried out for the calibration events on 12 January 2022 and 8 March 2022, using recorded rainfalls at Mosman BC, Taronga Zoo and Spit Bridge (refer to **Section 3.3.1** for the description of rainfall stations). Rainfall depths at 5 minutes interval were incorporated into the TUFLOW model and the direct rainfall modelling approach was applied. Multiple iterations were performed to ensure the TUFLOW hydraulic model could produce results closely aligned with observed data.

The investigation highlighted that accurately representing rainfall distribution was one of the main critical factors in simulating historic flood behaviour in the Mosman LGA, as rainfall patterns can vary significantly over short distances (**Table 3.3**). Consequently, the representative areas for rainfall stations were evaluated using weather radar data, as detailed in **Section 7.2.2**.

Additionally, fences along the flow path were found to significantly alter overland flow distribution, making them essential to incorporate for realistic flood simulations. Key fences were therefore identified using Google Street View and included in the model with appropriate blockage parameters. Example of typical fences along flow path is illustrated in **Figure 7.1**.

By adopting initial losses of 10 mm and continuing losses of 2.5 mm/hr for pervious areas with 0 mm/hr for impervious areas, the model generated best outcomes for both calibration events. Once the TUFLOW model produced flood behaviour similar to observed for the calibration events, the February 2023 event was simulated to validate the model. Continuing loss adopted for the validation event was the same as the calibration events, but initial loss was chosen to be zero as this event followed a series of rainfall episodes.

The results of both the calibration and validation events indicated that the TUFLOW flood model was able to represent the historical events to a reasonable level, providing confidence in the model to simulate flood behaviour for design flood events. A summary of each of the calibration and validation events is documented in the following sections with further detailed in **Appendix D** .

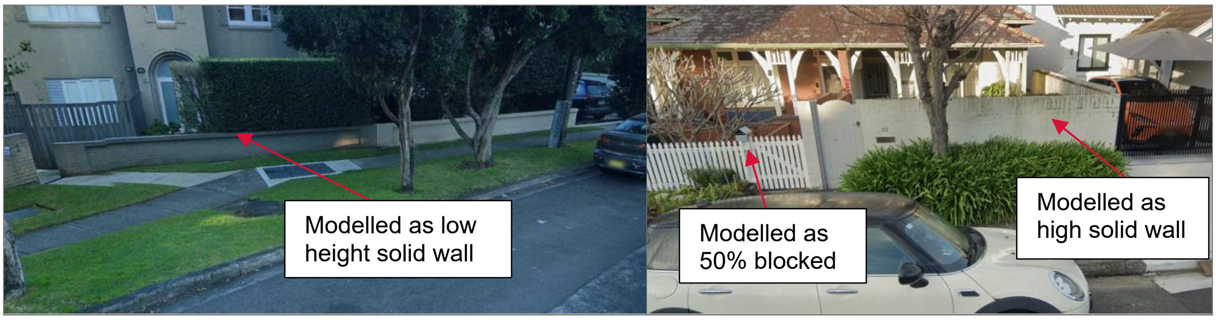

Figure 7.1 Examples of modelling of typical fences along flow path

Source: Google Street View

7.2.2 Processing of rainfall data for TUFLOW model calibration and validation

The Taronga Zoo, Mosman BC, and Spit Bridge rainfall stations are located within a short distance of approximately 4.5 km. Specifically, the distance between Taronga Zoo and Mosman BC is 1.5 km, while the distance between Taronga Zoo and Spit Bridge is about 4.5 km. Despite their proximity, significant variations in historical rainfall data recorded at these stations suggest that the rainfall pattern in Mosman LGA can vary considerably over short distances and timeframes (see **Table 3.3**).

For example:

- In the January 2022 event, the Taronga Zoo gauge recorded 250% more rainfall than the Spit Bridge gauge.
- During the March 2022 event, rainfall recorded at the Spit Bridge gauge was 30% higher than the rainfall recorded at the Mosman BC gauge and 140% higher than at the Taronga Zoo gauge.
- During the February 2023 event, rainfall at the Mosman BC gauge was about 50% higher than at the Taronga Zoo gauge and 35% higher than at the Spit Bridge gauge.

Rainfall patterns can vary significantly across the Mosman catchments. Rainfall radar was used to develop a better understanding of the rainfall patterns in Mosman. Further investigation into historical rainfall distribution patterns adopted for flood model calibration and validation is documented in **Appendix D** .

7.3 Outcomes of calibration and validation of TUFLOW hydraulic model

7.3.1 Key outcomes of calibration event – 12 January 2022

7.3.1.1 Comparison with stormwater gauge data

<u>At Reid Park Gauge</u>

- There is a good correlation between the simulated and recorded water levels at Reid Park monitoring station. Comparison between the two datasets is presented **Figure 7.2**.
- The model simulated peak water levels align well with the recorded levels, with modelled levels typically within 0.1 m of the observed levels. These results can be considered within a reasonable limit.
- To assess typical outcomes of flood model calibration for overland flood studies across the wider industry, a review of other flood studies was conducted. The outcomes of selected studies are summarised below:
  - ➢ The Ourimbah Creek Flood Study (Catchment Simulation Solutions, 2013) reported differences of up to 0.15 m between observed and simulated water levels.
  - ➢ The Little Creek Catchment Overland Flow Flood Study (WMAwater, 2017) reported differences of up to 0.26 m between observed and simulated water levels.
  - ➢ The Cabravale Overland Flow Flood Study (Catchment Simulation Solutions, 2023) recorded differences of up to 0.14 m between observed and simulated water levels.

- Additionally, the model satisfactorily simulates the general shape of the hydrograph, including both the rising and falling limbs.

  At Balmoral Beach Gauge

- **Figure 7.3** shows that the flood model slightly overestimates the peak water level. Discrepancies at the peak may be the result of multiple factors such as potential blockage in the system or the model allowing slightly more water to flow through the Balmoral Sailing Club Building than in the recorded data or the rainfall data applied to the model may not be highly representative for the Balmoral Catchment. The discrepancy may also be associated with other uncertainties, as explained in **Section A.2.2**.

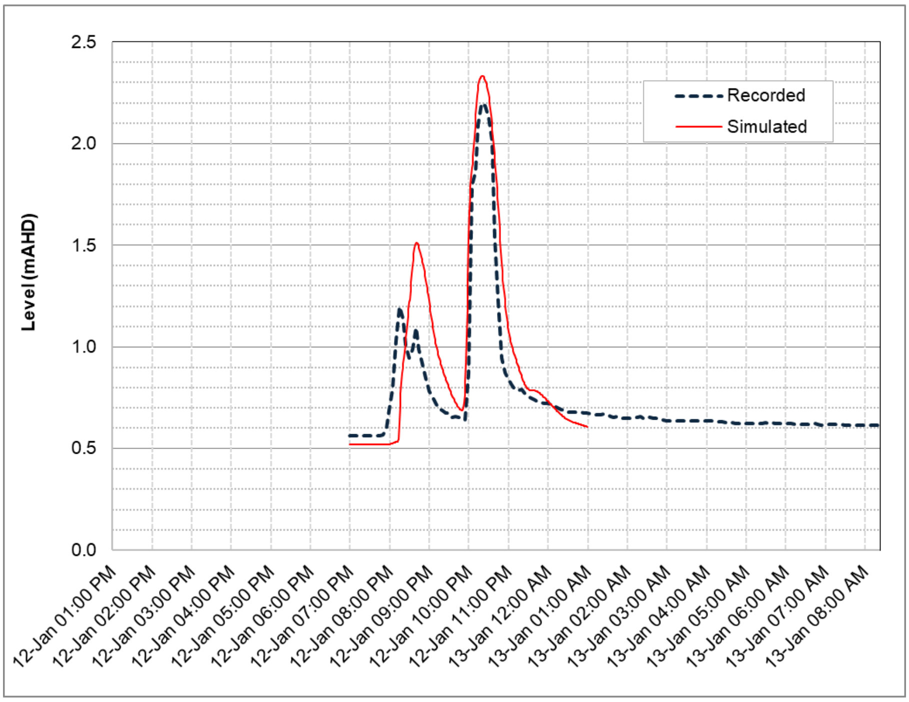

Figure 7.2 Simulated vs recorded water levels at Reid Park – 12 January 2022

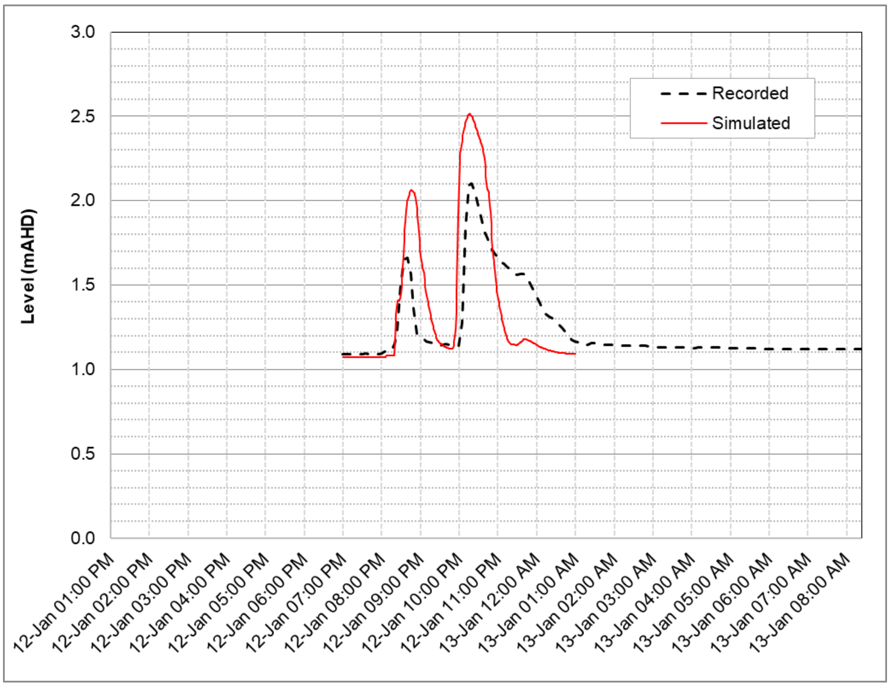

Figure 7.3 Simulated vs recorded water levels at Balmoral Beach – 12 January 2022

7.3.1.2 Comparison with flood photos and community information

There are no historical photographs or community information available for the January 2022 events which can be utilised for flood model validation. During the Community Flood Questionnaire, the community mentioned experiencing flooding in the year 2022 but it was unclear whether it was on 12 January 2022 or not.

7.3.2 Key outcome of calibration event – 8 March 2022

7.3.2.1 Comparison with stormwater gauge data

<u>At Reid Park Gauge</u>

- Similar to the January 2022 event, there is a good correlation between the simulated and recorded water levels at Reid Park monitoring station. Comparison between the two datasets is presented in **Figure 7.4**.
- During this event, two similar rainfall peaks occurred within five hours. The simulated peak water levels for both events align well with the recorded levels, with modelled levels typically within 0.1 m of the recorded levels. This is considered acceptable considering the uncertainty in the rainfall data due to the localised storm behaviour and the responsiveness of the catchment to heavy rainfall.
- The model simulates the general shape of hydrograph satisfactorily, including both the rising and falling limbs.

<u>At Balmoral Beach Gauge</u>

- The comparison (**Figure 7.5**) indicates that the simulated peak water levels match well with recorded levels, especially above 2 m AHD.
- The flood model, however, underestimated water level within the culverts. This discrepancy is likely attributed to blockages inside the culvert and the complexity of the network system, as explained in **Section A.2.2**.
- The primary objective of this study is to assess above-surface flooding. Therefore, the model is considered capable of simulating water levels for 8 March 2022 event within a reasonable level of accuracy.

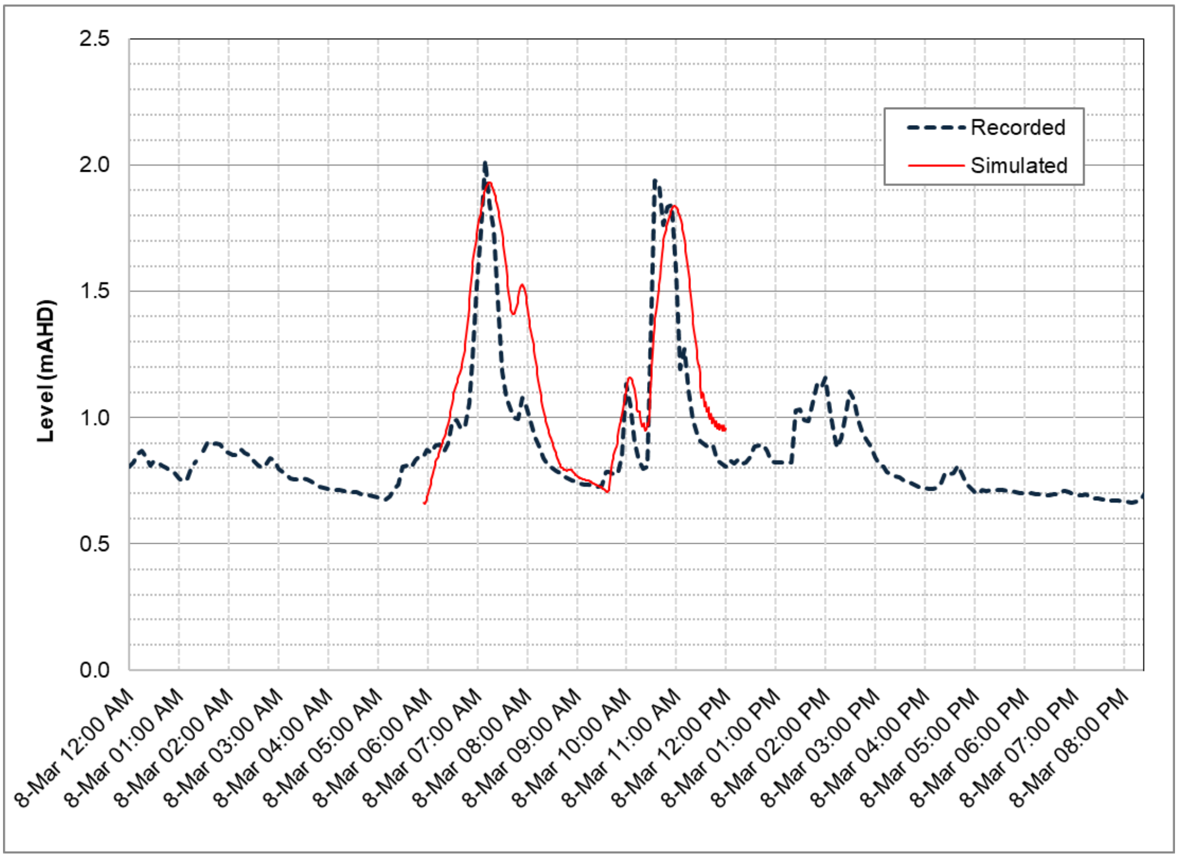

Figure 7.4 Simulated vs recorded water levels at Reid Park – 8 March 2022

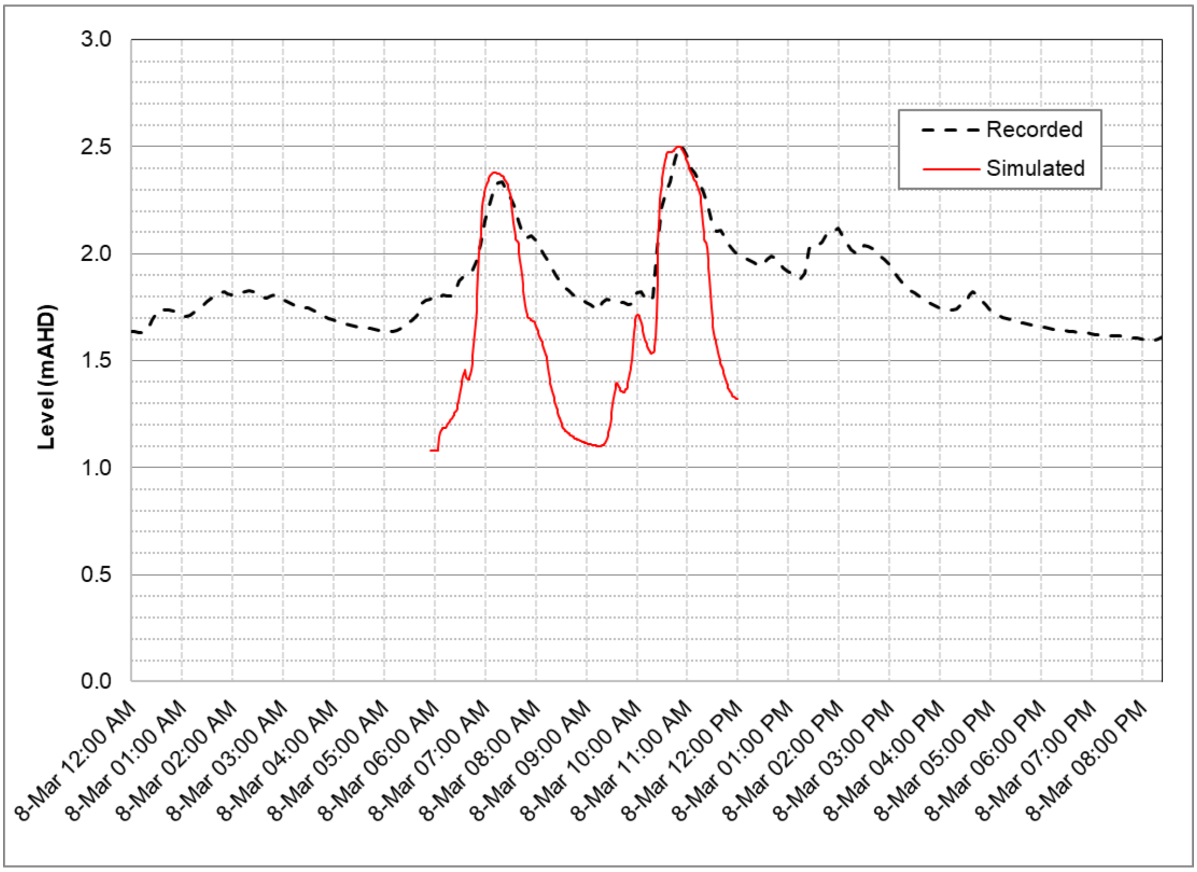

Figure 7.5 Simulated vs recorded water levels at Balmoral Beach – 8 March 2022

7.3.2.2 Comparison with flood photos and community information

Validation of flood extents and flood depths against historical photographs and videos is presented in **Appendix D.2**, with a summary provided in **Table 7.2**. The comparison indicates that the simulated flood depths and extents closely align with the documented flood photographs and information.

It is important to note that there is inherent uncertainty in measuring flood depths and extents from historical photographs, as these images are not to any scale and the timing of the photographs may be unknown. Consequently, the estimated flood depths may vary due to these uncertainties. Therefore, differences between the estimated and simulated flood depths, which are less than 0.1 m, are considered acceptable within this context.

Table 7.2 Summary of simulated vs estimated flood depths - 8 March 2022

Address	Estimated water level from photos/ flood marks	Simulated water level
3 Bullecourt, Avenue	420 mm	480 mm
12 Somerset Street	Back yard flooding	Model shows flood water overtopped kerb and inundated back yard
74 Bay Street	420 mm	400 mm

A further comparison was conducted between the simulated flood depths and the flood depths reported by the community during the Community Flood Questionnaire. There are several uncertainties associated with the community-reported flood depths, including the timing of the measurement, the precise location of the reported depths, the method used for measurement (e.g., visual estimation or scaling), and subjectivity of the assessment. These uncertainties make the reported depths unsuitable for exact comparison but provide a general indication of the flood behaviour.

Therefore, a range of simulated flood depths within each lot, but outside the building footprint, was extracted from the TUFLOW model results and compared with the reported flood depths, as shown in **Figure D.1** in **Appendix D**. At 7 out of 10 lots, the reported flood depths were within the simulated range. However, at the remaining three lots, the reported depths deviated from the simulated range. This discrepancy may be due to localised factors or other uncertainties mentioned in previous sections, which is beyond the scope of this flood study.

7.3.3 Key outcomes of validation event – 9 February 2023

7.3.3.1 Comparison with stormwater gauge data

<u>At Reid Park Gauge</u>

- Due to damage to sensor of the monitoring station, no data is available for model validation.

<u>At Balmoral Beach Gauge</u>

- The comparison (**Figure 7.6**) indicates that the simulated peak water levels match well with recorded levels, with maximum difference in peak water level reaching up to approximately 0.15 m.

- This discrepancy is likely attributed to blockages in the system, as explained in **Section A.2.2**, or rainfall data captured in the rain gauge station is not fully representative for the Balmoral Catchment.
- The flood model can be considered capable of simulating water levels for the February 2023 with a reasonable level of accuracy.

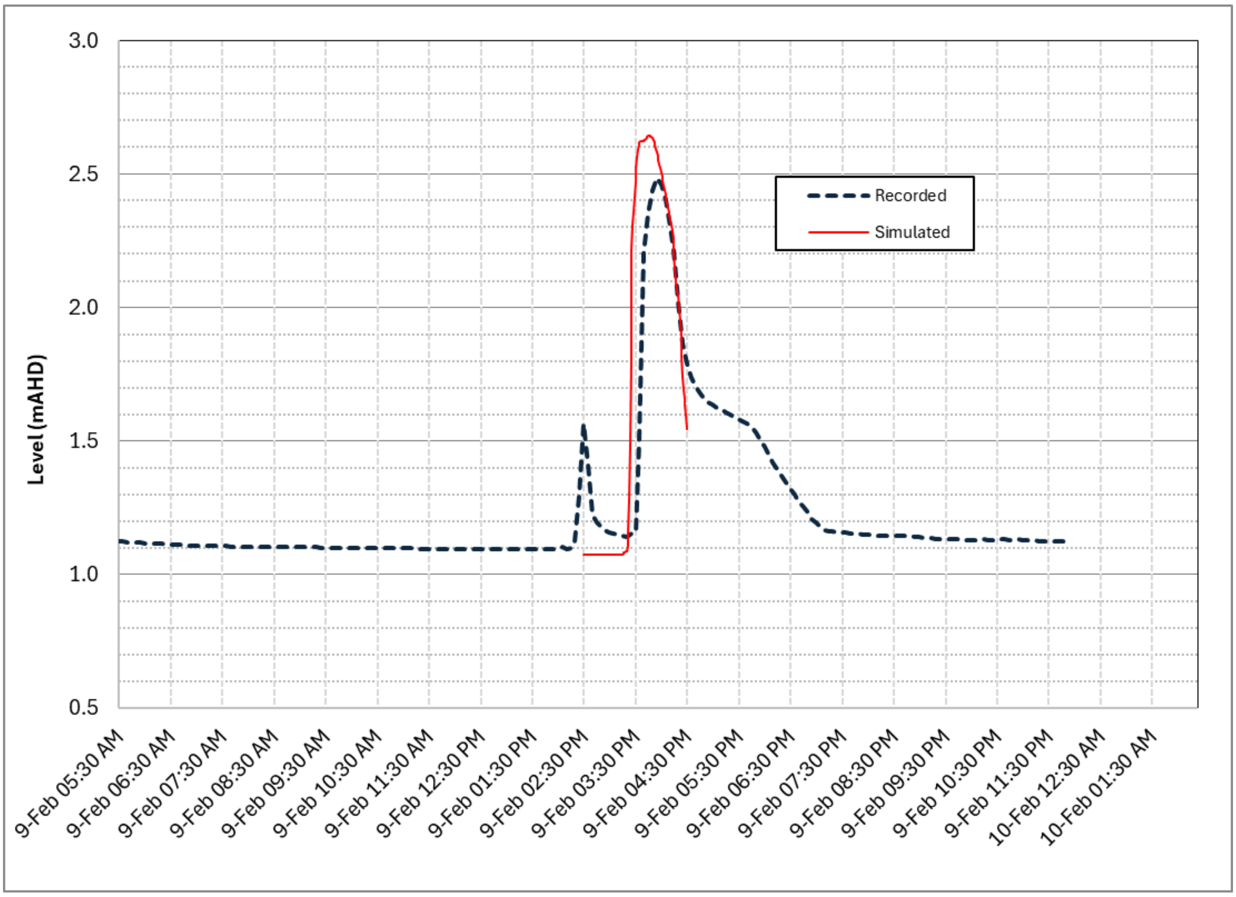

Figure 7.6 Simulated vs recorded water levels at Balmoral Beach – 9 February 2023

7.3.3.2 Comparison with flood photos and community information

Appendix D.3 details the comparison between the simulated flood depths and the flood photographs received from the community and a summary is provided in **Table 7.3**. The comparison indicates a good agreement between the two datasets. Though there is inherent uncertainty in measuring flood depths and extents from historical photographs, as these images are not to any scale and the timing of the photographs may be unknown, differences between the estimated and simulated flood depths, which are less than 0.1 m, considered acceptable within this context.

Table 7.3 Summary of simulated vs estimated flood depths - 9 February 2023

Address	Observed water level	Simulated water level
20 Bond Street	Yard flooding	Modelled floodwater just overtops kerb
2 Cabramatta Road	250 mm	250 mm
121 Raglan Street	200 mm	230 mm
6 Reginald Street	Just overtop footpath/ kerb	180 mm
Balmoral Sailing Club	620 mm	700 mm

A further comparison was conducted between the simulated flood depths and the flood depths reported by the community during the Community Flood Questionnaire. Similar to previous event, a range of simulated flood depths within each lot was extracted from the TUFLOW model results and compared with the reported flood depths, as shown in **Figure D.2**. At 33 out of 38 lots, the reported flood depths were within the simulated range of flood depths. In the remaining five lots, the reported flood depths deviated from the simulated range. This discrepancy may be attributed to localised factors or other uncertainties mentioned in previous sections, which falls outside the scope of this flood study.

The outcome of the calibration and validation process indicates that the TUFLOW flood model can simulate historical flood behaviour with a reasonable level of accuracy. Therefore, it is suitable for simulating the flood behaviour of design events.

7.4 Calibration of WBNM hydrology model

Model calibration is a crucial step to ensure that a hydrologic model can accurately simulate historical events. It relies on reliable recorded flow data, making the choice of calibration events dependent on the availability and quality of this information.

Given the lack of dependable flow data (**Section A.2.3**), the WBNM hydrologic model was instead calibrated using flows simulated by the validated TUFLOW flood model for the January 2022 and March 2022 events. Pluviometer data from Taronga Zoo, Mosman Bowling Club, and Spit Bridge were incorporated in the WBNM model to generate hydrographs for various sub-catchments. To account for the spatial distribution of rainfall for the selected historic events, representative areas for each rainfall station were adopted based on observed radar information as discussed in **Section 7.2.2**. The WBNM outputs were then compared with corresponding TUFLOW results for the Reid Park, and Balmoral Beach catchments.

A lag parameter of 1.3 was adopted to account for the steep slopes and fast drainage characteristics of the Mosman LGA. The initial model parameters were set similarly to those used for TUFLOW model calibration and validation, which included a continuing loss (CL) of 2.5 mm/h and an initial loss (IL) of 10 mm. No losses were applied to impervious areas. The adopted parameters produced the best match between the WBNM and TUFLOW outputs.

The comparison of the two models for January 2022 is shown in **Figure 7.7** and **Figure 7.8**, and for March 2022 in **Figure 7.9** and **Figure 7.10**. The close agreement between WBNM and TUFLOW indicates that the WBNM model is suitable for simulating design events and identifying critical durations and temporal patterns. The calibrated parameters were subsequently used in the WBNM model for design event simulation.

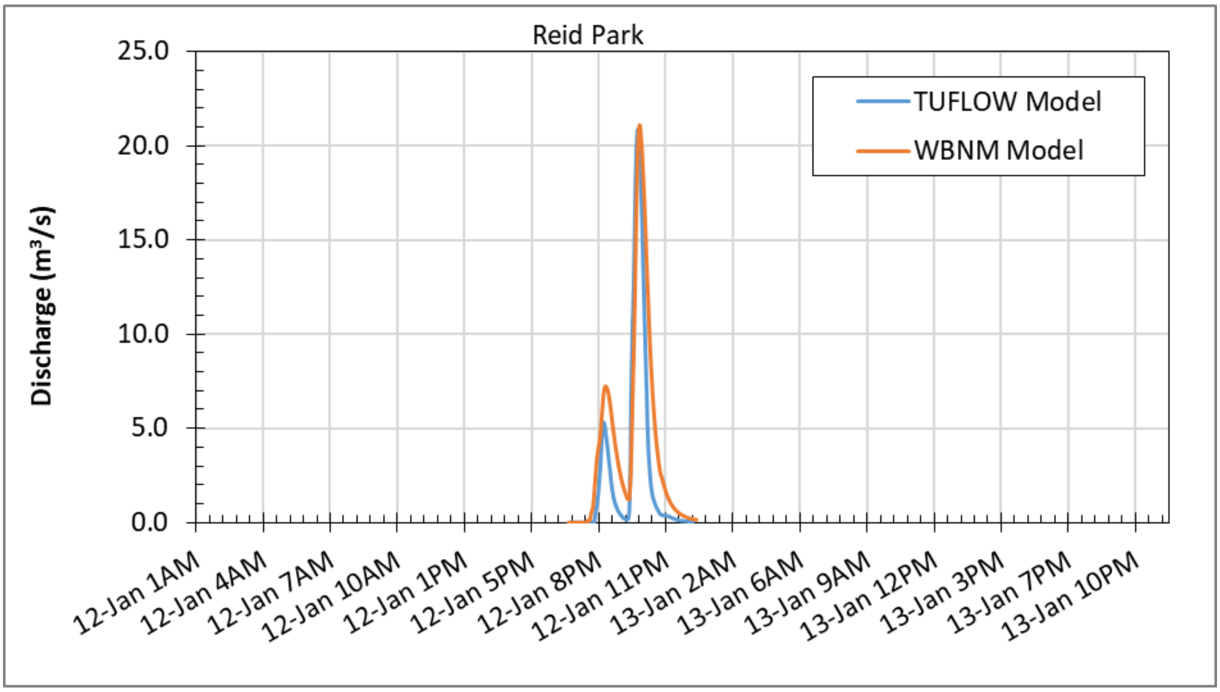

Figure 7.7 WBNM vs TUFLOW model results at Reid Park – 12 January 2022

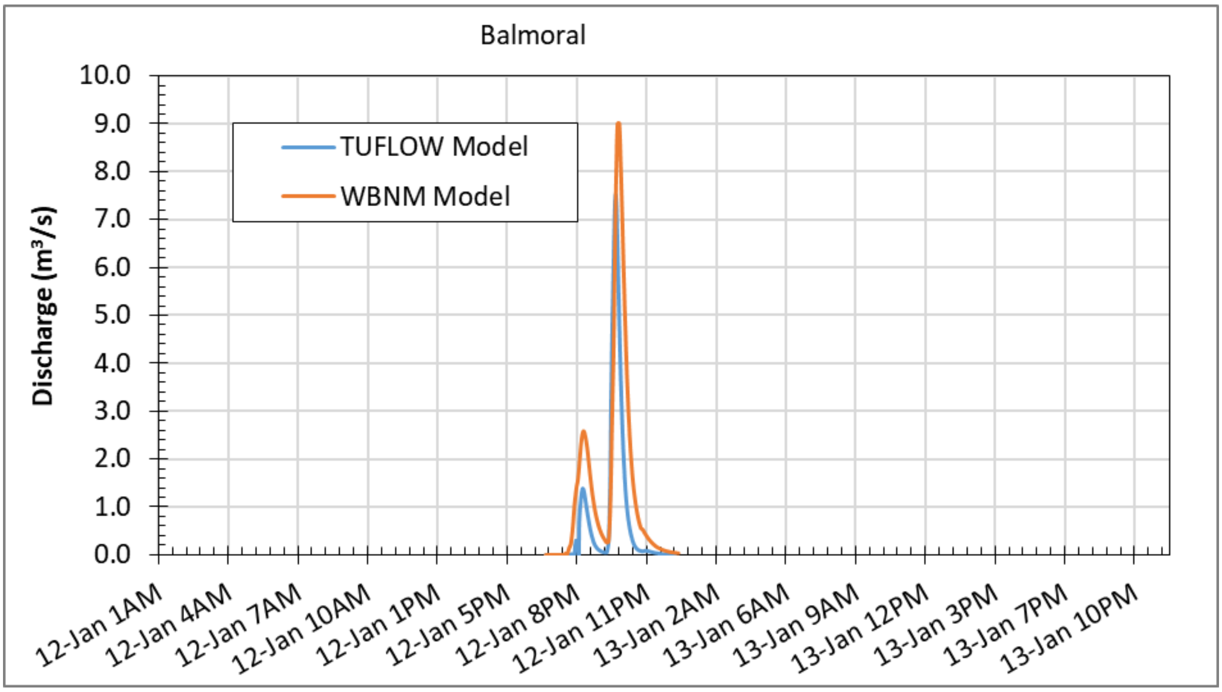

Figure 7.8 WBNM vs TUFLOW model results at Balmoral Beach – 12 January 2022

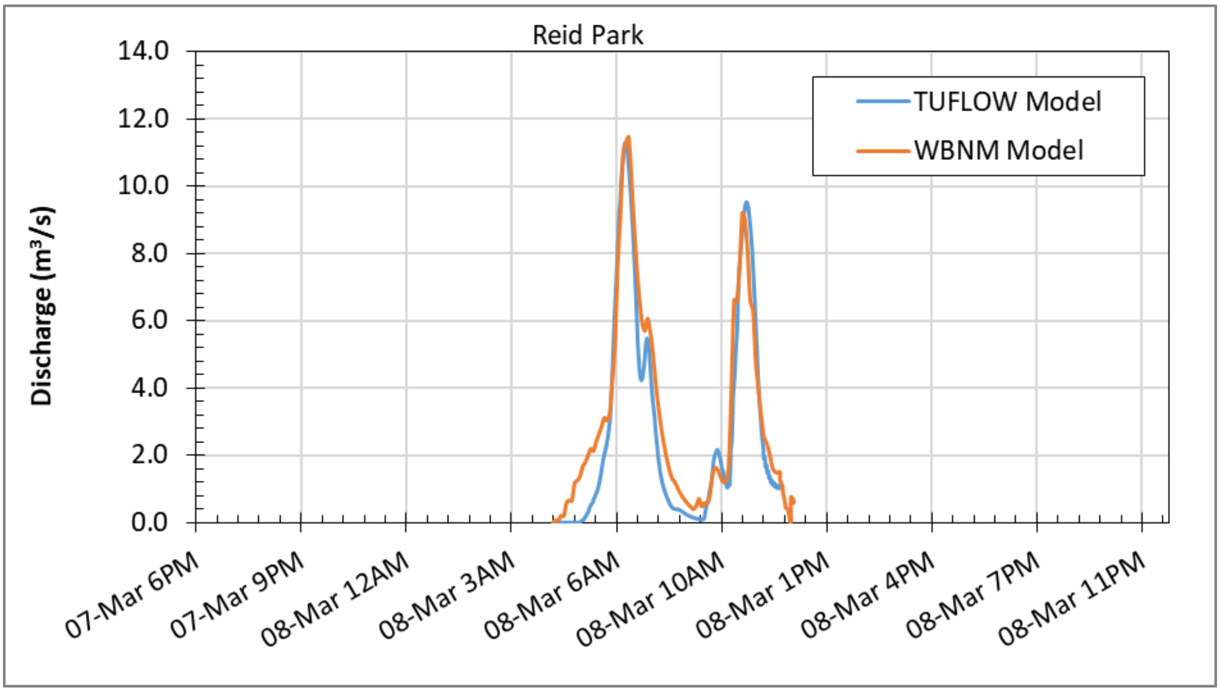

Figure 7.9 WBNM vs TUFLOW model results at Reid Park – 8 March 2022

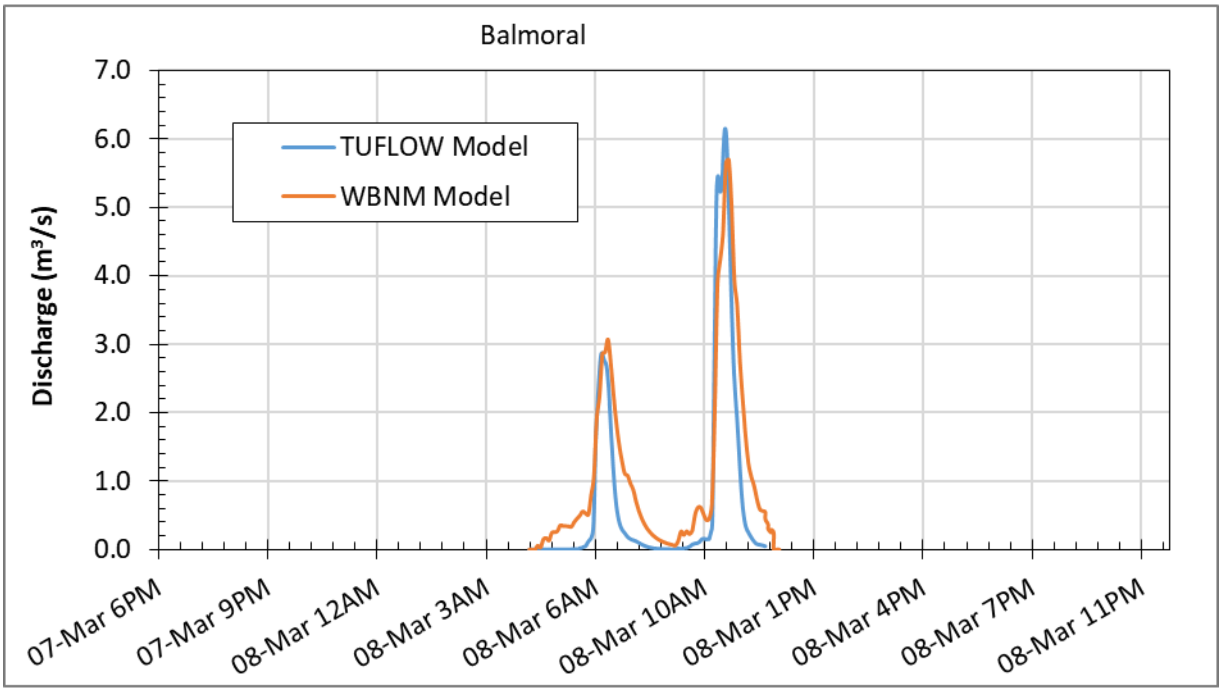

Figure 7.10 WBNM vs TUFLOW model results at Balmoral Beach – 8 March 2022

8 Design event simulation

8.1 AR&R 2019 rainfall database for design events

For design event simulation, rainfall data and parameter were incorporated in calibrated and validated hydrologic and hydraulic model in accordance with the new Australian Rainfall and Runoff 2019 (AR&R 2019) Guidelines. The AR&R 2019 Data Hub was accessed to derive design rainfall inputs for 20%, 10%, 5%, 2%, 1%, and 0.5% AEP (1 in 200) using AR&R 2019 guidelines. The Data Hub also includes links to relevant data sources, including the Bureau of Meteorology Design Rainfall Data System which is used to source 2016 Intensity Frequency Duration (IFD) design rainfall depths. Data was extracted at the centroid of the study area. In accordance with AR&R 2019 for catchments with an area less than 75 km^2, the “point” temporal patterns rather than “areal” temporal patterns were selected to describe the temporal variation in rainfall, Refer to **Appendix E** for IFD and other rainfall parameters.

Rainfall continuing losses for various land types were adopted based on the calibration results as per guidance of AR&R 2019. Continuing losses of 2.5 mm/hr for pervious areas and 0 mm/hr for impervious areas have been found appropriate for Mosman LGA during the calibration process (refer to **Section 7**).

The AR&R 2019 guideline was also applied to estimate the initial loss and pre-burst rainfall for each duration and temporal pattern. AR&R 2019 introduces the concept of pre-burst rainfall, which accounts for rainfall that occurs prior to the main burst of a storm. This pre-burst rainfall effectively saturates the catchment, reducing the initial loss required for runoff to occur in subsequent rainfall events. By incorporating pre-burst rainfall, the guideline provides a dynamic approach that ensures initial loss values accurately reflect the catchment's conditions at the onset of each storm.

8.2 Determination of critical duration and temporal pattern for design events

8.2.1 Representative critical duration using WBNM hydrologic model

To select representative critical durations and temporal patterns for simulating the direct rainfall TUFLOW model, the WBNM model was run for design events with AEP of 20%, 10%, 5%, 2%, 1%, and 1 in 200 AEP, using durations ranging from 10 minutes to 6 hours. Ensemble modelling methods were employed in accordance with the AR&R 2019 Guidelines, involving the simulation of 10 different temporal patterns (TPs) for each design event and storm duration.

To identify consistent temporal pattern outcomes, the design storms were categorised into temporal pattern bins. Each bin was associated with a distinct set of 10 temporal patterns. For this study, the 20%, 10%, and 5% AEP events were classified within the 'Intermediate' temporal pattern bin, while the 2%, 1%, and 1 in 200 AEP events were grouped under the 'Rare' temporal pattern bin.

Outputs from the WBNM model were investigated in detail to identify representative critical durations and temporal patterns. Following AR&R 2019 guidance, the temporal pattern that generated the peak discharge closest to, or slightly above the median discharge of the 10 temporal patterns was selected as the "representative" temporal pattern for each sub-catchment.

The results showed a wide variety of critical durations and temporal patterns across the WBNM model area. For the 'Rare' bin group, critical durations ranged from 10 to 45 minutes (specifically 10, 15, 20, 25, 30, and 45 minutes), while for the 'Intermediate' bin group, the critical durations were 15, 20, 30, and 45 minutes. With various critical temporal patterns corresponding to each critical duration, over 40 distinct combinations were identified across the 108 sub-catchments.

Given this large number of combinations, it was impractical to apply all of them in the TUFLOW model. Therefore, the most frequently occurring temporal patterns for each identified critical duration were selected based on their prevalence across the sub-catchments. Additionally, to ensure consistency across design events and account for potential inaccuracies in representing 2D storage areas and slopes within the WBNM model, representative temporal patterns were also chosen for durations outside the critical durations identified by the WBNM model (e.g., 60, 90, 120 and 180 minutes). Similar temporal patterns were selected for each duration and bin group to maintain consistency.

The final selected durations and temporal patterns to be used to simulate TUFLOW flood model are summarised in **Table 8.1**. An example of selecting critical duration of a sub-catchment (ID-50) located upstream of Reid Park is presented in **Figure 8.1**.

Table 8.1 Representative critical duration and temporal pattern extracted from WBNM hydrologic model

Selected Duration (minutes)	Selected Event ID*/Temporal Pattern (TP)	
	Intermediate Bin Group (20% 10% and 5% AEP)	Rare Bin Group (2%, 1% and 1 in 200 AEP)
010	4376 (TP07)	4364 (TP07)
015	4410 (TP04)	4401 (TP08)
020	4440 (TP08)	4433 (TP10)
025	4473 (TP06) and (TP05)	4460 (TP05)
030	4513 (TP08)	4498 (TP05)
045	4542 (TP08)	4534 (TP09)
060	4572 (TP09)	4405 (TP02)
090	4590 (TP04)	4430 (TP02)
120	4624 (TP04) and (TP01)	4431 (TP01)
180	4639 (TP02)	4599 (TP02)

**Note: Event/pattern IDs and temporal patterns (TP) are extracted from the AR&R 2019 temporal pattern database.*

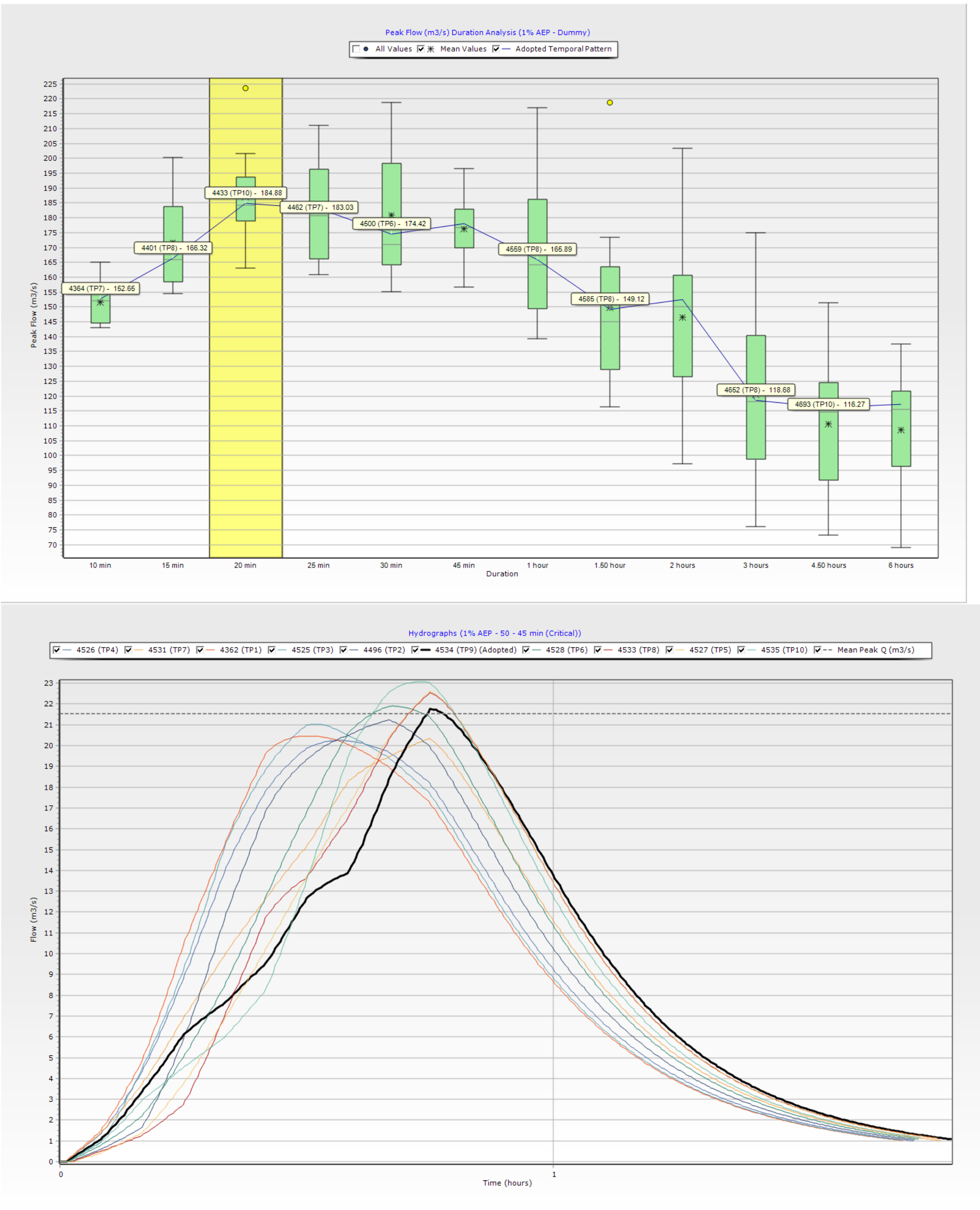

Figure 8.1 Example of selecting the critical duration and temporal pattern for a sub-catchment

8.2.2 Selection of critical duration and temporal pattern for simulating flood behaviour using TUFLOW

The calibrated and validated TUFLOW flood model was simulated for the 20%, 10%, 5%, 2%, 1%, and 1 in 200 AEP design events using the representative critical durations and temporal patterns documented in **Table 8.2**. More specifically, the TUFLOW model was simulated for 12 combinations of TPs and durations for the 20%, 10% and 5% AEP events, and 10 combinations for the 2%, 1% and 1 in 200 AEP events.

Results produced for each event were investigated to identify the design critical duration and temporal patterns. The most prevalent durations were selected for each temporal bin group to evaluate flood behaviour within the Mosman LGA (refer to **Table 8.2**). the critical duration for each design event was mapped (refer to **Figure F.1** to **Figure F.5** in **Appendix F** for mapping).

Table 8.2 Selected critical durations for design flood behaviour assessment

<table>
<tr><th>Design Events (AEP)</th><th>Dominant Critical Duration</th><th>Selected Critical Duration</th></tr>
<tr><td>20%</td><td>180min, 60min, 45min, 10min</td><td rowspan="3">180min, 60min, 45min, 20min, and 15min</td></tr>
<tr><td>10%</td><td>60min, 20min, 15min</td></tr>
<tr><td>5%</td><td>60min, 20min, 15min</td></tr>
<tr><td>2%</td><td>180min, 45min, 30min, 25min, 15min, 10min</td><td rowspan="3">180min, 45min, 30min, 25min, and 10min</td></tr>
<tr><td>1%</td><td>180min, 45min, 30min, 25min, 10min</td></tr>
<tr><td>1 in 200</td><td>180min, 45min, 25min, 15min, 10min</td></tr>
</table>

8.3 Probable Maximum Flood event

The Probable Maximum Precipitation (PMP) is used to derive the Probable Maximum Flood (PMF) event. The theoretical definition of PMP is "the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of year" (Pilgrim, D.H., 2001). The AEP of a PMP/PMF event ranges between 10^{-5} % and 10^{-9} % AEP for a catchment the size of Mosman LGA (**Figure 8.2**). The PMP has been estimated using the Generalised Short Duration Method (GSDM), developed by the Bureau of Meteorology. This method is suitable for durations of up to six hours and is considered appropriate for small catchments such as those in the Mosman LGA.

To determine the critical duration for the PMF event, the model was simulated for all standard durations up to 90 min. The analysis found that a 15-min duration was critical for most areas in Mosman, refer to **Figure F.6** in **Appendix F**.

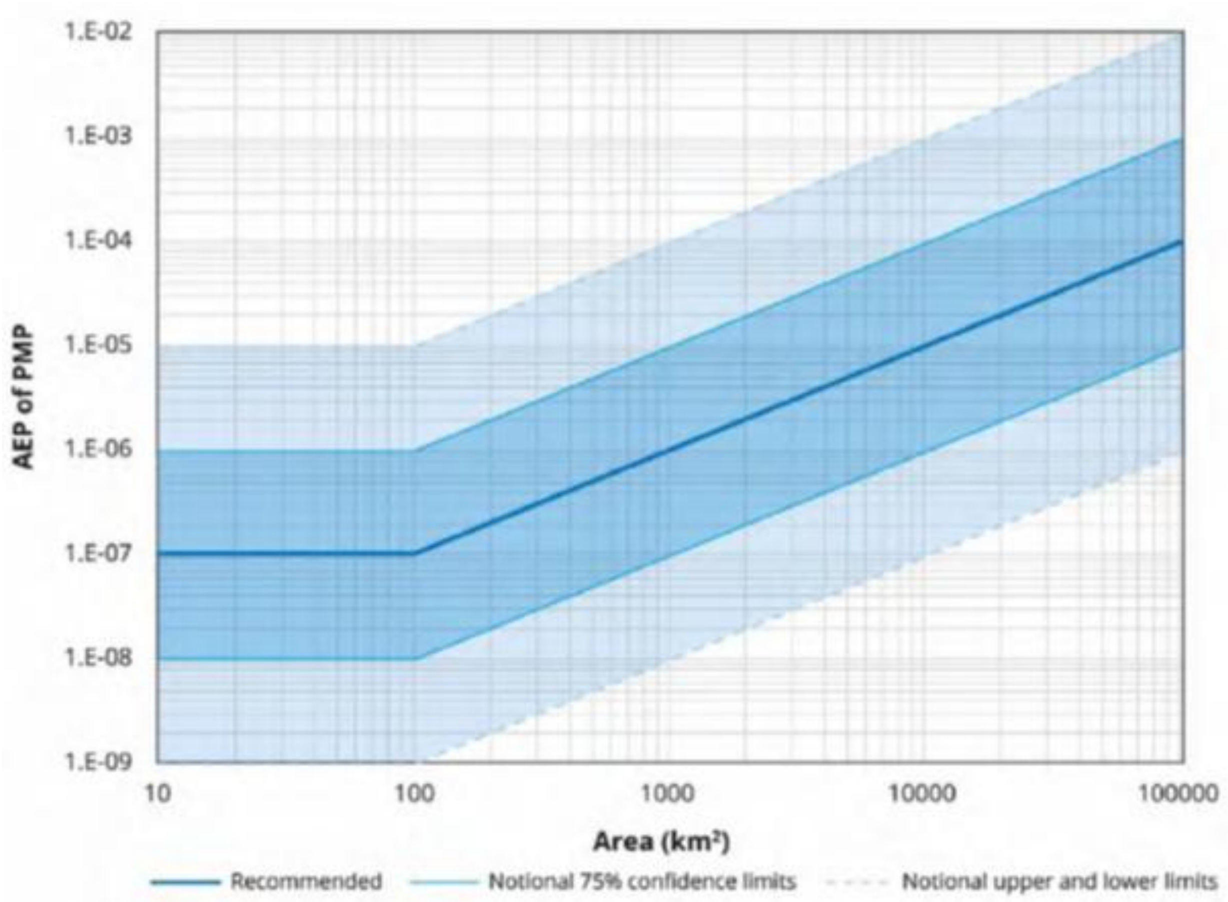

Figure 8.2 Recommended regional estimates for the AEP of PMP (Ball, 2019)

8.4 Downstream water level for design event

Water levels of Middle Harbour for the design event simulation were determined based on the "Modelling the Interaction of Catchment Flooding and Oceanic Inundation in Coastal Waterways" (NSW Office of Environment and Heritage (OEH), 2015). According to the guideline, the waterway entrance for the Mosman LGA can be classified as a Type A entrance, located south of Crowdy Head. Consequently, the design peak ocean level for a 1% AEP event is 1.45 m AHD, and for a 5% AEP event, is 1.40 m AHD (as outlined in Table 5.2 of OEH, 2015).

Catchment flooding and oceanic inundation can be triggered by the same storm cell; therefore, the design water levels in a lower coastal waterway will be influenced by a combination of these sources. However, although the majority of the Mosman LGA is situated above the high tide level, a general and detailed approach was adopted to investigate the coincidence of ocean and catchment flooding, as recommended in Table 8.1 of the OEH, 2015. The High High-Water Springs (Solstice Spring) (HHWS(SS)) level for Mosman LGA is 1.25 m AHD (Appendix C of the OEH, 2015). The adopted combination of design flood events is detailed in **Table 8.3**.

Table 8.3 Adopted combinations for catchment flooding and oceanic inundation scenario

Design AEP for peak levels/velocities	Catchment Flood Scenario	Harbour/Ocean Water Level Boundary
20%	20%	HHWS(SS)
10%	10%	HHWS(SS)
5%	5%	HHWS(SS)
2%	2%	5% AEP
1% envelope level*	1%	5% AEP
	5%	1% AEP
1 in 200	1 in 200	1% AEP
PMF	PMF	1% AEP

**Note: The "1% envelope level" represents the maximum flood level obtained from both simulated 1% AEP scenarios (e.g., catchment-driven and ocean-driven events).*

8.5 Scenarios for design event simulation

Three blockage design scenarios were selected to simulate flood behaviour for the Mosman LGA. These combinations are consistent with industry standards and the recommendations provided in the AR&R 2019 guidelines. Each design scenario was simulated for all critical durations identified for each design event, as outlined in **Table 8.2**. The design scenarios are:

- Design scenario I: Zero blockage for stormwater system and for culverts/bridges
- Design scenario II: 50% blockage for stormwater system and AR&R 2019 design blockage for culverts/bridges
- Design scenario III: 100% blockage for stormwater system and double (2x) AR&R 2019 design blockage for culverts/bridges

In addition, as per the OEH guideline (**Table 8.3)**, the 1% AEP flood behaviour was determined based on the envelope of two scenarios:

- Tailwater level scenario A: 1% AEP catchment flood combined with 5% AEP tail water level in harbour.
- Tailwater level scenario B: 5% AEP catchment flood combined with 1% AEP tail water level in harbour.

Tailwater level combinations were simulated for all three design blockage scenarios.

For the PMF event, the model was run under all three design scenarios and Tailwater Level Scenario A, using critical durations of 15, 30, and 45 minutes. Enveloped PMF maps were then generated based on these model results.

9 Sensitivity analysis

9.1 Scenarios for sensitivity analysis

Sensitivity analysis is a critical component of flood modelling as it evaluates the influence of key variables on model outcomes, ensuring the reliability and robustness of predictions. It is an important step recommended in the latest NSW Flood Risk Management Manual. For Mosman LGA, understanding the sensitivity of the model to factors such as stormwater blockage, roughness coefficients, tide levels, and climate change projections is vital. These factors can significantly alter flood behaviour, affecting the accuracy of flood extent, depth, and hazard predictions. **Table 9.1** presents the various scenarios selected for the sensitivity analysis of each individual parameter for the Mosman LGA Flood Study. For the analysis of the sensitivity of each parameter, the 1% AEP catchment flood combined with a 5% AEP tailwater level was adopted as the base scenario.

By analysing these sensitivities, Council can identify the parameters most impactful to flood risks, enabling informed decision-making in the development of flood mitigation strategies. For instance, assessing stormwater blockage highlights the vulnerability of drainage infrastructure, while examining roughness coefficients ensures appropriate representation of land use and vegetation. Similarly, low tide sensitivity and climate change scenarios allow the model to incorporate future uncertainties, making it a robust tool for long-term planning and resilience. **Table 9.1** shows scenarios for sensitivity analysis adopted for each parameter for the Mosman LGA Flood Study. Results of the sensitivity analysis for each parameter individually assessed are presented in the following section.

Table 9.1 Adopted parameters and assumptions for sensitivity analysis

Parameter	Sensitivity Assumptions
Rainfall losses	• Zero initial and continuing loss (IL and CL) • 2 x design IL and CL
Hydraulic roughness	• 20% more roughness • 20% less roughness
Tailwater level	• -0.95 m AHD (ISLW, Indian Springs Low Water)
Climate change	• RCP-8.5 2050 • RCP-8.5 2100 • RCP-8.5 2100 95 percentile
Blockage	• Design blockage vs no blockage • Double design blockage vs design blockage

9.2 Sensitivity analysis results

9.2.1 Rainfall losses

The TUFLOW model was used to re-simulate the 1% AEP flood under two different loss scenarios: (1) with zero continuing or initial loss, and (2) with double the design continuing and initial losses. Water level difference maps comparing the sensitivity analysis results with existing flood behaviour were generated and are presented in **Figure F.7** and **Figure F.8** in **Appendix F** . The analysis indicated that changes in rainfall losses had a negligible impact on peak water levels, with variations in almost all instances being less than 0.02 m.

Overall, the sensitivity analysis confirms that the TUFLOW model is insensitive to variations in loss rates. Therefore, any uncertainties related to the adopted loss rates are not expected to significantly affect the model's results.

9.2.2 Hydraulic roughness

Manning's "n" roughness coefficients describe the resistance to water flow due to different land uses and surface conditions across the catchment. However, these values may fluctuate based on various factors, such as vegetation changes, or change in land usages or change in topographic features. For instance, vegetation tends to be denser in summer than in winter, resulting in higher Manning's "n" values. To evaluate the potential impact of these variations, additional analyses were carried out to determine how uncertainties in Manning's "n" values might influence predicted flood behaviour.

The TUFLOW model was modified to test the effects of a 20% increase and a 20% decrease in the adopted Manning's "n" values, followed by simulations of the 1% AEP design event. Water level difference maps were generated by comparing the sensitivity analysis results with existing flood conditions, as detailed in **Figure F.9** and **Figure F.10** in **Appendix F** .

The findings show that adjustments to Manning's "n" values can cause both increases and decreases in predicted 1% AEP water levels, primarily in localised areas. However, the overall impact is minimal, with variations generally remaining under 0.05 m. This indicates that the model is not highly sensitive to changes in Manning's "n" values. Therefore, any uncertainties related to the adopted roughness coefficients are unlikely to have a significant effect on the model's outcomes.

9.2.3 Tailwater level

The sensitivity analysis of tailwater levels indicated a minimal impact on flooding in the Mosman LGA, as presented in **Figure F.11** in **Appendix F**

9.2.4 Stormwater system blockage

Sensitivity analysis of blockage helps assess how stormwater and culvert obstructions influence flood behaviour and identify key areas affected by these changes. An analysis was conducted for the 1% AEP event by comparing a design blockage scenario with a no-blockage scenario, as well as a double-blockage scenario with the design blockage scenario. The results of this analysis are presented in **Figure F.12** and **Figure F.13** in **Appendix F** .

The design blockage scenario assumes design blockage per AR&R for culverts and 50% blockage for stormwater pipes, while the double-blockage scenario assumes double the AR&R blockage for culverts and complete blockage of stormwater pipes. The sensitivity analysis indicated that blockages could impact 1% AEP water levels. The complete obstruction of stormwater pipes is expected to increase water levels along the main overland flow paths, typically by between 0.05 to 0.15 m. However, in some localised areas—particularly within lots and around building footprints—water levels were found to increase by up to 0.3 m. These areas are primarily located along the Reid Park catchment's overland flow paths, including sections near Avenue Road, Cabramatta Road, and Wolger Road. This analysis highlights that, although the stormwater system may have a relatively limited capacity, it still plays a crucial role in reducing flood severity during most flood events.

9.2.5 Climate change

Climate change has the potential to influence flood behaviour. In the Mosman LGA this is most likely to occur through impacts on rainfall and / or sea level rise. Following discussions with DCCEEW, it was determined that a sensitivity analysis on rainfall and the downstream boundary was the most appropriate approach to assess the potential changes to the flood behaviour as a result of climate change. This sensitivity analysis is useful to understand the potential variance in water levels, flood behaviour and associated planning under climate change conditions.

Three scenarios were assessed in the analysis:

- 2050 scenario: 9% increase in rainfall and a 0.4 m rise in ocean water level.
- 2100 scenario: 22% increase in rainfall and a 0.78 m rise in ocean water level.
- 2100 (95th percentile) scenario: 30% increase in rainfall and a 1.3 m rise in ocean water level.

Peak floodwater levels were extracted from the climate change scenarios and compared against peak water levels of the existing flood behaviour (refer to **Figure F. 14** to **Figure F.16** in **Appendix F**). The results of the climate change simulations indicate that increases in rainfall intensity do have the potential to increase existing 1% AEP water levels. Across most areas, the increases are predicted to not generally exceed 0.05 m for the 2050 scenario, 0.1 m for the 2100 scenarios and 0.2 m for 2100 (95th percentile) scenario. However, some localised areas, particularly along the edges of the Mosman LGA in low-lying regions near the harbour, may experience more significant water level increases.

10 Flood model outcomes

10.1 Map filtering

Mosman LGA Flood Study adopted the direct rainfall modelling approach. Flood maps generated by this approach would include several puddles and shallow/sheet flow. Therefore, a filtering approach was adopted to remove shallow depths areas from flood maps. A sensitivity analysis was undertaken to assess the impact of removing small puddle areas from the flood maps, with the aim of identifying the most appropriate filtering method for the Mosman LGA. Various threshold values for depth, velocity, and the product of depth and velocity were tested for the study area, being a highly urbanised area subject to local overland flow. The results were discussed with DCCEEW, and the following criteria were adopted for flood mapping in Mosman:

- Depth > 0.10 m; OR
- Depth > 0.05 m AND Velocity × Depth > 0.025 m^2/s; OR
- Velocity > 2 m/s.

Following application of the above criteria, “puddles” smaller than 100 m^2 were also excluded from the flood extent.

The filtering criteria were determined through MHL’s experience, consultation with DCCEEW, and review of industry practice in other overland flow flood studies. Key reference studies included:

- Middle Harbour Southern Catchments Flood Study (BMT, 2023), Ku-ring-gai Council.
- Redbank Creek Flood Study (MHL, 2024), Hawkesbury City Council.
- The Little Creek Catchment Overland Flow Flood Study (WMAwater, 2017), Penrith City Council.

10.2 Peak flood depth, water levels, velocity

Flood extent maps showing peak flood depths, peak water level contours and peak flood velocities for the 20%, 5%, 2%, 1% AEP, 1 in 200 AEP and PMF design flood events are provided in **Figure G.1** to **Figure G.18** in **Appendix G** .

Table 10.1 presents the peak water levels at the Reid Park and Balmoral Beach gauge stations based on model simulation results for a range of design flood events. At Reid Park, the simulated peak water level for the 20% AEP event is 2.39 m AHD, increasing to 2.55 m AHD for the 1% AEP event. Similarly, at Balmoral Beach, the 20% AEP water level is 2.56 m AHD, rising to 2.70 m AHD for the 1% AEP event. For the rarer events, the simulated water levels further increase to 2.60 m and 3.51 m AHD at Reid Park, and 2.73 m and 3.42 m AHD at Balmoral Beach, for the 1 in 200 AEP and PMF events respectively.

Table 10.1 Simulated peak water levels at key gauge locations for design flood events

Design Event	Reid Park Gauge (m AHD)	Belmoral Beach Gauge (m AHD)
20% AEP	2.39	2.56
10% AEP	2.40	2.59
2% AEP	2.51	2.66
1% AEP	2.55	2.70
1 in 200 AEP	2.60	2.73
PMF	3.51	3.42

10.3 Flood hazard classification

Flood hazard vulnerability classification is determined through a relationship developed between the depth and velocity of floodwaters and is based strictly on hydraulic considerations. Flood hazard can inform emergency and flood risk management for existing communities, and strategic and development scale planning for future areas. Flood hazard categories for this study were determined based on flood risk management guideline (FB03) (DPE, 2023c). The guidelines present a set of hazard vulnerability curves shown in **Figure 10.1**. This shows how flood depths, velocities and depth-velocity product affect the stability of vehicles, pedestrians and buildings.

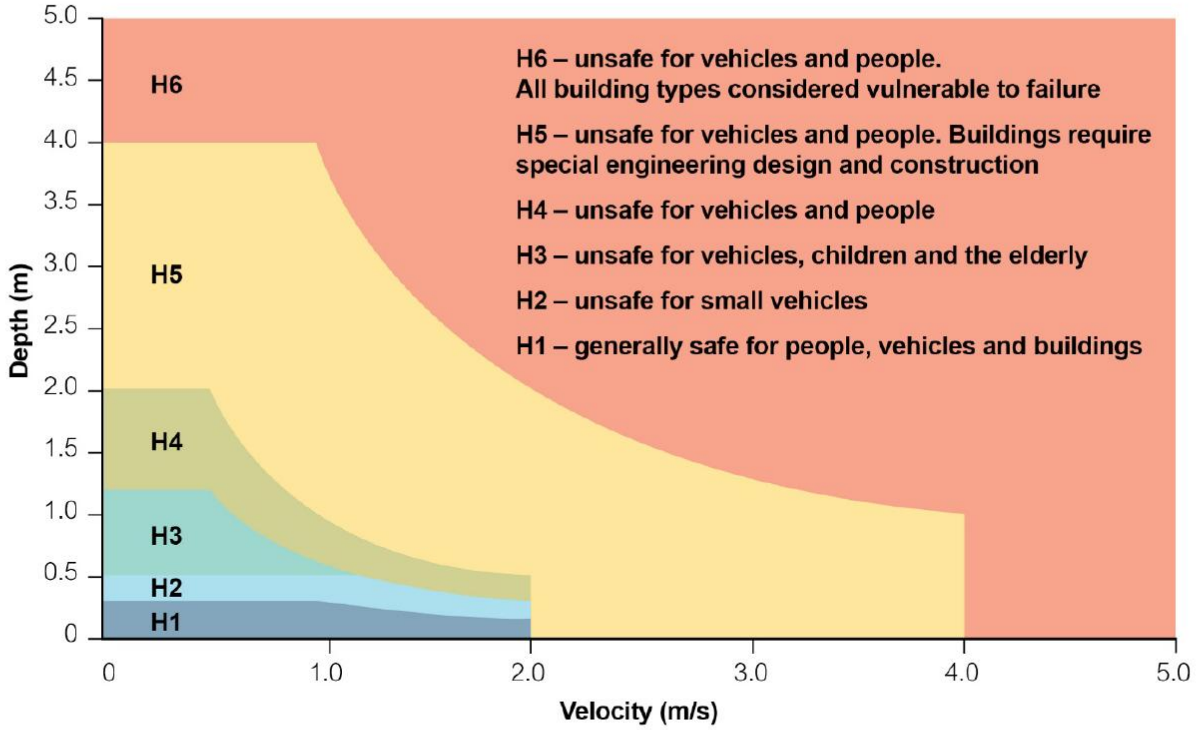

Figure 10.1 General flood hazard vulnerability curves; Source: (DPE, 2023)

Maps for flood hazard vulnerability classification for Mosman LGA for the 20%, 10%, 2%, 1%, and 1 in 200 AEP and PMF are included in **Figure G.19** to **Figure G.24** in **Appendix G** . The extent of hazard conditions between H3 and H6 remain typically concentrated along main overland flow path, while the majority of the LGA flooding is classified as H1 or H2 hazard category. The H1 and H2 hazard are generally safe for people, larger vehicles and buildings.

10.4 Preliminary Flood Planning Area

Land use planning is essential for mitigating flood risk and minimising damage caused by flooding. The Flood Planning Area (FPA) is designated to enforce flood-related development controls, while the Flood Planning Level (FPL) establishes the minimum floor level for developments within the FPA. To effectively manage flood risk, the FPA should include areas where future development may influence flood behaviour, as well as areas where controls are required to minimise risk to future development. The FPL is set to reduce the likelihood of over-floor flooding and minimise flood damage. According to the Flood Risk Management Manual 2023, the FPL is typically based on defined flood event plus an appropriate freeboard.

This study has identified a preliminary FPA, which will be subject to refinement during the Flood Risk Management Study phase. The definition of FPL is not part of the scope of this study as this will be undertaken as part of the next stages of the Flood Risk Management Process.

To identify the most appropriate method for defining the preliminary FPA in Mosman LGA, a sensitivity analysis was undertaken as part of this flood study. The investigation assessed several scenarios, including the 1% AEP flood extent with added freeboards of 0.3 m and 0.5 m (refined to not exceed the PMF extent), as well as the 1 in 200 AEP and 1 in 500 AEP flood extents. The outcomes were reviewed and discussed with DCCEEW, and it was concluded that the 1 in 200 AEP extent is the most suitable for defining the preliminary FPA.

This approach offers a practical balance between flood risk management and development feasibility. Many areas within the Mosman catchment are subject to only shallow flooding, and applying a uniform freeboard—or adopting the 1 in 500 AEP or PMF flood extents—could significantly overestimate flood-affected areas. This may lead to overly conservative planning controls and unnecessary restrictions on development. In contrast, using the 1 in 200 AEP extent provides a more realistic, yet still conservative, basis for planning. It captures extreme rainfall variability and accounts for potential future climate impacts, while helping to avoid overregulation. Accordingly, a preliminary FPA for Mosman LGA was developed based on the 1 in 200 AEP flood extent (refer to **Figure H.1** in **Appendix H**), with a recommendation to develop and define the final FPA during a future Flood Risk Management Plan/Study. **Figure H.1** in **Appendix H** shows approximately 2,100 properties located within Preliminary Flood Planning Area (FPA) extents.

The review of submissions received during the public exhibition period noted that numerous properties were only marginally impacted or brushed by the Preliminary FPA. To minimise the impacts, a buffer at the perimeter of the property was applied. The buffer was selected considering factors such as the resolution of the model, flood impacts and flood risks in consultation with DCCEEW and Council. Accordingly, a buffer of 900 mm was applied prior to identifying the property as being within the preliminary FPA.

This process resulted in a reduction in the number of properties being identified as being within the Preliminary FPA to approximately 1,700. Even after this process, a number of properties challenging their inclusion in the Preliminary FPA remained within the Preliminary FPA extent. However, in the final Mosman LGA Flood Study, the FPA still remains preliminary and will be assessed in further detail during the Flood Risk Management Study and Plan.

10.5 Key flood-prone areas

Total number of properties located within the 1% AEP flood extent is approximately 1,970, increasing to approximately 5,940 during PMF events. This count includes any part of the property located within the flood extent, as determined using the map filtering criteria outlined in **Section 10.1.**

Below is a list of selected locations where roads and/or properties may experience significant flood impacts.

HS-01: The Esplanade near Raglan Street

This low point is located slightly north of the intersection between The Esplanade and Raglan Street. The Esplanade near Raglan Street is expected to be impacted from a 20% AEP flood event. The expected maximum depth of flooding on the road in a 20% AEP event is approximately 1.3 m, increasing to 1.4 m in a 1% AEP event and 1.6 m in a PMF event. The hydraulic hazard category for The Esplanade can reach H3 during a 20% AEP event, escalating to H5 during a PMF event. Overland flow contributions to this point travel mainly along Botanic Road and Raglan Street and drain to this low point. Several properties in close proximity of this location may become isolated and/or submerged during a flood event similar to or more severe than a 20% AEP event.

HS-02: Cowles Road near Holt Avenue

The depth of flooding on Cowles Road is approximately 0.7 m in a 20% AEP event, increasing to 0.9m in a 1% AEP event and 1.9 m in a PMF event. The road reaches a hazard category of H5 during a 20% AEP event, escalating to H6 during a PMF event. Several properties may become isolated and submerged during a flood event similar to or more severe than a 20% AEP event.

HS-03: The Esplanade near Mandolong Road

This is another low point on The Esplanade, located slightly north of the intersection between The Esplanade and Mandolong Road. The depth of flooding on the road in a 20% AEP event is approximately 0.5 m, increasing to 0.6 m in a 1% AEP event and 0.9 m in a PMF event. The flood hazard category is H2 in a 20% AEP event, increasing to H3 in a 1% AEP event and H5 in a PMF event. Overland flow contributions to this point originate from the area between Mandolong Road and Awaba Street. A few upstream properties near this location may become isolated and submerged during a flood event similar to or more severe than a 20% AEP event.

HS-04: Julian Street near Joel's Reserve

The depth of flooding on Julian Street is approximately 0.4 m in a 20% AEP event, increasing to 0.5 m in a 1% AEP event and 1.1 m in a PMF event. The road is classified as H2 during a 20% AEP event, increasing to H3 in a 1% AEP event, and reaching H5 in a PMF event. Several properties may become isolated and submerged during a flood event similar to or more severe than a 20% AEP event.

HS-05: Bay Street near Glen Street Reserve

The depth of flooding on Bay Street is approximately 0.2 m in a 20% AEP event, increasing to 0.3 m in a 1% AEP event and 1.2 m in a PMF event. The road is expected to be cut off during a 20% AEP event and rarer events as flood hazard reaches H5. Several properties may become isolated and submerged during a flood event similar to or more severe than a 20% AEP event.

HS-06: Killarney Street near Glen Street

The depth of flooding on Killarney Street is approximately 0.4 m in a 20% AEP event, increasing to 0.5 m in a 1% AEP event and 1.0 m in a PMF event. The road is classified as H2 during a 20% AEP event, increasing to H4 during a 1% AEP event, and reaching H5 during a PMF event. Several properties may become isolated and submerged during a flood event similar to or more severe than a 20% AEP event.

HS-07: Pearl Bay Avenue near Figtree Lane

This low point is located south of the intersection between Pearl Bay Avenue and Figtree Lane. The depth of flooding on Pearl Bay Avenue is approximately 0.3 m in a 20% AEP event, increasing to 0.4 m in a 1% AEP event and 1.0 m in a PMF event. The road is expected to be cut off during a 10% AEP event and rarer events as flood hazard on the road reaches H5. A few properties in close proximity of this location may be affected by flooding similar to or more severe than a 10% AEP event, but none are likely to be fully submerged.

HS-08: Wolger Road near Ian Craig Park

The depth of flooding on Wolger Road is approximately 0.4 m in a 20% AEP event, increasing to 0.5 m in a 1% AEP event and 0.8 m in a PMF event. The road is classified as H2 during a 20% AEP event, increasing to H4 during a 1% AEP event, and reaching H5 in a PMF event. A few properties in proximity of this location may be affected by flooding, but none are likely to be fully submerged.

HS-09: Wyong Road near Congewoi Road

The depth of flooding on Wyong Road is approximately 0.2 m in a 1% AEP event, increasing to 0.7 m in a PMF event. Although the depth of flooding is relatively low, the road still reaches a hazard category of H5 during a 20% AEP event and other rare events. A few properties in proximity of this location may be affected by flooding, but none are likely to be fully submerged.

HS-10: Kiora Avenue near Rosherville Reserve

Several properties in close proximity of this location may become isolated during rare flood events. The road is expected to be cut off during a PMF event. The primary contributing catchment area lies between Stanton Road and Kiora Avenue.

10.6 Preliminary flood function (hydraulic categorisation)

Identifying the hydraulic categories/ flood functions of the floodplain is a key deliverable of this flood study and is required for best practice flood risk management in Australia, because it is essential to understanding flood behaviour. Flood function - Flood risk management guideline FB02 (DPE, 2023b) describes the following three hydraulic categories of flood-prone land:

- **Floodway / Flow Conveyance:** Flow conveyance areas are defined as those areas where a significant flow of water occurs. They typically flow continuously from the upper reaches of waterways and flow paths within the catchment to the outlet during a flood. These flows often align with naturally defined channels. They are areas that, even if only partially blocked by changes in topography or development, cause a significant redistribution of flood flow or a significant increase in water levels. They are often, but not necessarily, areas of deeper flow or areas where higher velocities occur.

- **Flood Storage:** During a flood event, significant amounts of floodwater can also extend into, and be temporarily stored in, areas of the floodplain. This water flows downstream as the flood recedes. Where storage is important in attenuating downstream flood flows and levels, areas storing this water are classified as flood storage areas. Filling of flood storage areas reduces their ability to attenuate downstream flood flows and, as a result, flood flows and water levels may increase.
- **Flood Fringe:** Flood-fringe areas make up the remainder of the flood extent for the particular event. It is the area where the effects on flood function are not a constraint. Developing in flood-fringe areas is unlikely to significantly alter flood behaviour, beyond the broader impact of changes to run-off because of urbanisation within the catchment. However, other flood-related constraints may exist in flood-fringe areas.

These qualitative descriptions do not prescribe specific thresholds for determining the hydraulic categories in terms of model outputs, and there is no “one size fits all approach” to hydraulic category / flood function definition. For the purposes of the Mosman LGA Flood Study and following sensitivities on each criteria, flood functions/hydraulic categories have been defined as per the criteria listed in **Table 10.2**.

Table 10.2 Hydraulic category criteria

Hydraulic Category	Criteria	Description
Floodway	Velocity x Depth > 0.25 m^2/s	Flow paths and channels where a significant proportion of flood flows are conveyed
Flood Storage	Depth ≥ 0.3 m, Not Floodway	Areas that temporarily store floodwaters and attenuate flood flows
Flood Fringe	Depth < 0.3 m, Not Floodway or Flood Storage	Generally shallow, low velocity areas within the floodplain that have little influence on flood behaviour

Hydraulic Categories/flood functions for the 1% AEP and PMF events as determined by the above methods are provided in **Figure H.1** and **Figure H.2** in **Appendix H** .

10.7 Preliminary flood emergency response classification

To aid in the planning and implementation of response strategies, DCCEEW developed the support for emergency management planning guideline (EM01) to classify communities according to the ease of evacuation (DPE, 2023d). These guidelines establish Flood Emergency Response Classifications of Communities (FERCC), as shown in **Figure 10.2**, with classifications determined based on the PMF or a similar extreme flood. Isolated areas, known as flood islands, are regions surrounded solely by floodwaters. Those that become completely submerged during a PMF event are classified as low-flood islands, while those with elevated areas remaining above the PMF are referred to as high-flood islands.

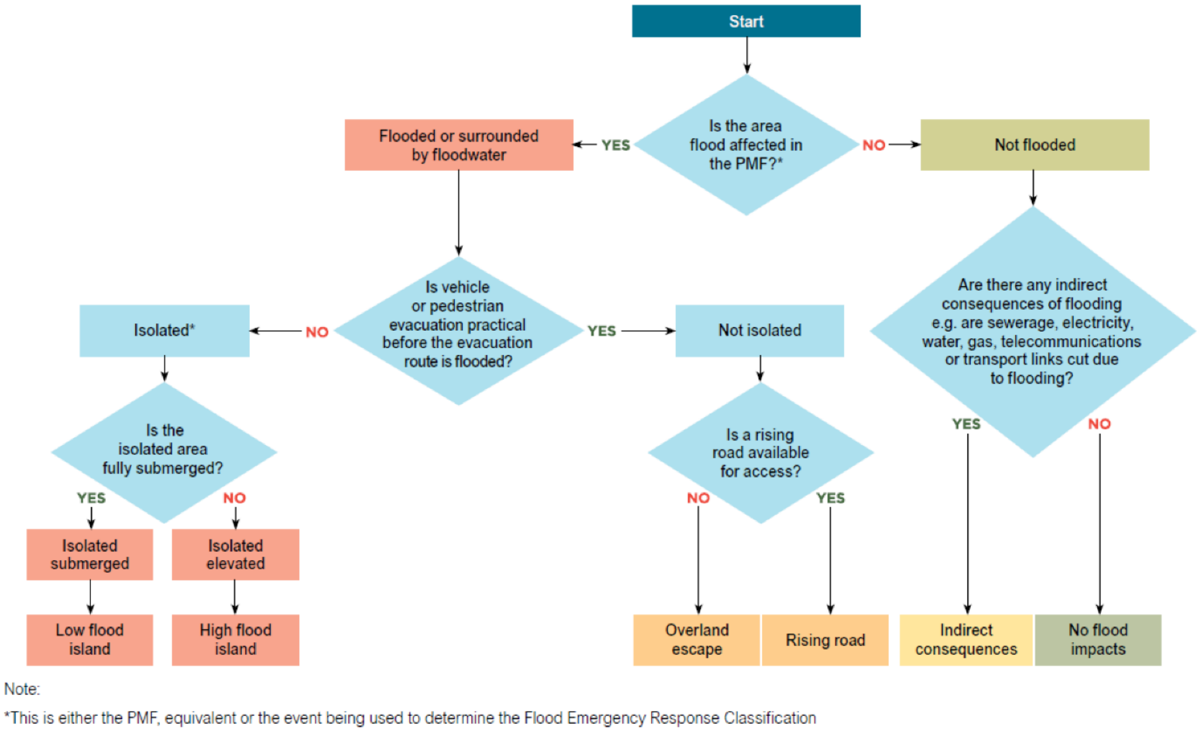

Figure 10.2 Flow chart for determining flood emergency response classifications (DPE, 2023)

Each allotment within the Mosman LGA was classified using the FERCC flowchart for both the 1% AEP flood and the PMF, with maps provided in **Figure H.3** and **Figure H.4** in **Appendix H** . This classification was undertaken using TUFLOW model results, a digital elevation model, and a road network GIS layer, considering the following factors:

- Whether evacuation routes or roadways are "cut off" due to flooding *(flood hazard maps were used to define a "cut" road).* A "cut-off road" refers to a road that becomes impassable when the flood hazard classification reaches H2 or higher (**Section 10.3**).
- Whether evacuation routes continuously rise out of the floodplain.
- If vehicular evacuation is not possible, whether evacuation on foot is feasible *(flood hazard maps were used to determine if pedestrian routes are safe).*
- "Rising road" refers to an evacuation route that gradually increases in elevation, allowing safe passage out of the floodplain without entering deeper floodwaters.

The ERC maps for the Mosman LGA identify areas that are likely to be at risk during severe flooding. Some areas have been classified as "Low Flood Island," indicating a real risk of injury or death if residents become trapped in their homes during a flood. These classifications support emergency response planning by identifying areas where evacuation strategies or additional safety measures may be required, particularly where early evacuation is not possible. The classifications also guide land use planning by identifying areas that are significantly constrained.

In Mosman, flash flooding from local catchments and overland flow can occur suddenly in response to intense rainfall, often with little to no warning. In such cases, remaining inside a home or building may be safer than attempting to drive or wade through floodwaters, as flow velocities and depths tend to be higher on roadways. During a flood event, some streets may become impassable, blocking vehicular access and causing inconvenience or risks in emergencies, such as when urgent medical care is required. However, flood isolation in Mosman is generally less critical, as access is unlikely to be cut off for extended periods.

It is noted that the ERC are preliminary and will be refined as part of the next stage of the flood risk management process, the flood risk management study and plan (FRMSP) in conjunction with SES.

10.8 Preliminary Flood Planning Constraint Categories (FPCC)

Flood Planning Constraint Categories (FPCC) are essential tools in land-use planning, providing a structured approach to identifying flood-related constraints that influence development and risk management decisions. These categories are defined based on factors such as flood exposure frequency, flood function, hazard levels, flood extent, and isolation from safety. They serve as a framework for assessing flood-related constraints and ensuring effective flood risk management across different areas of the floodplain.

Flood risk management guideline FB01 (DPE, 2023a) outlines the development of FPCCs, which are typically categorised as follows:

- FPCC1: Areas highly constrained by flooding, often unsuitable for intensified development due to significant flood hazards or functions, such as key flow conveyance or storage areas.
- FPCC2: Areas with considerable flood constraints where certain types of development may be limited, and existing development may require risk management strategies.
- FPCC3: Areas with moderate flood constraints where increased development density is possible, provided that appropriate flood-related development controls are implemented.
- FPCC4: Areas with minimal flood constraints, typically suitable for most types of development with standard planning considerations.

These classifications help inform land-use planning decisions, ensuring that development aligns with flood risk management objectives. To develop the FPCC map for Mosman LGA, the flood hydraulic categories map, flood hazard map for the Defined Flood Event (DFE), emergency response classification maps, and flood extent maps for the DFE or rarer events were reviewed, in accordance with the criteria outlined in **Table H.1** in **Appendix H** . The resulting FPCC map is presented in **Figure H.6** in **Appendix H** .

10.9 Road closure

An assessment of the frequency and hazard of road inundation is important to understand the risk of vehicles becoming unstable, posing a risk to life for their drivers and passengers. It is also important in order to understand evacuation risks and informing the classification of communities according to flood emergency response planning considerations. Road closure was assumed as occurring when flood hazard is H2 or higher. **Figure G.28** and **Figure G.29** in **Appendix G** illustrate the roads that are likely to become unsuitable for vehicles during the 1% AEP and PMF events, respectively. This flood study identified several roads that may become untrafficable even during minor flood events. These include Belmont Road (sag point near Mosman Public School), Botanic Road, Cabban Street, Cabramatta Road (sag point), Coronation Avenue, the southern part of Cowles Road, Glover Street (sag point), Killarney Street, Lindsay Lane (sag point), Rangers Avenue (near Park Avenue), Reginald Street (near Royalist Road), Sirius Cove Road, the junction of Stanley Avenue and Awaba Street, The Esplanade, Wolger Road (near Noble Street), and the junction of Wyong Road and Congewoi Road.

11 Conclusion

The Mosman LGA Flood Study was completed to provide a detailed assessment of flooding within the Mosman LGA. Its primary objective is to enhance understanding of flood behaviour and impacts, and to inform better flood risk management in the study area, particularly in relation to local overland flooding mechanisms. Valuable contributions from the community through survey responses, emails, and phone calls played an important role in shaping this Flood Study and are sincerely acknowledged.

This report presents the outcomes of investigations aimed at quantifying flood behaviour across the Mosman LGA. It includes information on design water levels, depths, velocities, and flood hazard classifications for a range of flood events. Flood behaviour was defined using a direct rainfall hydraulic model developed with TUFLOW software, which represented the stormwater drainage system, including culverts, as well as major overland flow impediments such as buildings, fences, and roads. Calibration and validation were carried out using stormwater gauging data and community-reported observations from the 2022 and 2023 floods.

Following successful calibration and validation, the model was used to simulate design flood events ranging from 20%, 10%, 2%, and 1% AEP to the 1 in 200 AEP floods, as well as the PMF. The flood maps appended to this report present the envelope of adopted critical durations and temporal patterns for the Mosman LGA.

Key findings from the study include:

- Flooding in the Mosman LGA is primarily driven by heavy rainfall, resulting in flash flooding as water flows overland before draining into the harbour.
- Critical flood durations are generally short and often occur with little or no warning; storms of 15 to 45 minutes rainfall duration typically produce the worst-case flooding conditions.
- Several roadways are predicted to be overtopped even during minor events, with impacts becoming more extensive during a 1% AEP flood event and further increasing in a PMF event.
- The Mosman LGA is generally less affected by tidal flooding.
- Blockage sensitivity analyses show that upstream flooding severity can increase when drainage structures become blocked, highlighting the importance of ongoing infrastructure maintenance.

The findings of this study will serve as a foundation for a future Floodplain Risk Management Study and the development of a Floodplain Risk Management Plan, helping guide effective flood mitigation strategies for the most affected areas in the study region.

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Glossary

Annual Exceedance Probability (AEP)	The probability that a given parameter (e.g., rainfall depth, water level) will be exceeded in any one year. E.g., if a peak flood discharge of 500 m3/s has an AEP of 5%, it means that there is a 5% chance (that is one-in-20 chance) of a 500 m3/s or larger events occurring in any one year (see ARI).
Australian Height Datum (AHD)	A common national surface level datum approximately corresponding to mean sea level.
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 20-year ARI flood event will occur on average once every 20 years. ARI is another way of expressing the likelihood of occurrence of a flood event.
Building	The principal structure on a property intended for occupancy or functional use. This includes residential dwellings, as well as commercial, industrial, or other primary use buildings. It excludes ancillary structures such as sheds, garages, or non-habitable outbuildings.
Design Blockage	Blockage is an obstruction which makes movement of flood water or flow through a drainage system difficult or impossible. Design blockage is the blockage obtained following the Australian Rainfall and Runoff 2019 recommendations. Blockage is defined as a percentage of reduction in flow capacity through a drainage structure (e.g., pit, pipe, culvert, bridge, etc.)
Double Design Blockage	Minimum of double of the design blockage for culvert or 100% blockage for stormwater pipes (i.e. fully blocked)
Catchment	The land area draining through the mainstream, as well as tributary streams, to a particular site. It always relates to an area above a specific location.
Computer Models	The mathematical representation of the physical processes involved in runoff generation and stream flow. These models are often run on computers due to the complexity of the mathematical relationships between runoff, stream flow and the distribution of flows across the floodplain.
Consent Authority	The council, government agency or person having the function to determine a development application for land use under the EP&A Act. The consent authority is most often the council, however legislation or an EPI may specify a Minister or public authority (other than a council), or the Director General of OEH, as having the function to determine an application.
Defined flood event (DFE)	The flood event selected for the management of flood hazard for the location of specific development as determined by the appropriate authority.
Development	"Is defined in Part 4 of the Environmental Planning and Assessment Act (EP&A Act). Infill Development refers to development of vacant blocks of land that

	are generally surrounded by developed properties and is permissible under the current zoning of the land. Conditions such as minimum floor levels may be imposed on infill development. New Development: refers to development of a completely different nature to that associated with the former land use. For example, the urban subdivision of an area previously used for rural purposes. New developments involve rezoning and typically require major extensions of existing urban services, such as roads, water supply, sewerage and electric power. Redevelopment: refers to rebuilding in an area. For example, as urban areas age, it may become necessary to demolish and reconstruct buildings on a relatively large scale. Redevelopment generally does not require either rezoning or major extensions to urban services."
Discharge	The rate of flow of water measured in terms of volume per unit time, for example, cubic metres per second (m3/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).
Emergency Management	A range of measures to manage risks to communities and the environment. In the flood context it may include measures to prevent, prepare for, respond to and recover from flooding.
Finished floor level	The uppermost surface of the finished floor, not including any floor covering such as carpet, tiles and the like.
Flash Flooding	Flooding which is sudden and unexpected. It is often caused by sudden local or nearby heavy rainfall. Often defined as flooding which peaks within six hours of the causative rain.
Flood Awareness	Awareness is an appreciation of the likely effects of flooding and a knowledge of the relevant flood warning, response and evacuation procedures.
Flood Control Lot	Property (or Lot) located within the flood planning area and subject to flood-related development controls.
Flood Fringe Areas	The remaining area of flood prone land after floodway and flood storage areas have been defined.
Flood Liable Land	Is synonymous with flood prone land, i.e., land susceptible to flooding by the PMF event. Note that the term flood liable land covers the whole floodplain, not just that part below the FPL (see flood planning area).
Flood Planning Area	Area that defines when a property is classified as a flood control lot.
Flood Planning Levels (FPLs)	Are the combinations of water levels (derived from significant historical flood events or floods of specific AEPs) and freeboards selected for floodplain risk management purposes, as determined in management studies and incorporated in management plans.
Flood Prone Land	Land susceptible to flooding by the PMF event. Flood prone land is synonymous with flood liable land.
Flood Risk	Potential danger to personal safety and potential damage to property resulting from flooding. The degree of risk varies with circumstances

	across the full range of floods. Flood risk in this manual is divided into 3 types, existing, future and continuing risks. They are described below. Existing Flood Risk: the risk a community is exposed to as a result of its location on the floodplain. Future Flood Risk: the risk a community may be exposed to as a result of new development on the floodplain. Continuing Flood Risk: the risk a community is exposed to after floodplain risk management measures have been implemented. For a town protected by levees, the continuing flood risk is the consequences of the levees being overtopped. For an area without any floodplain risk management measures, the continuing flood risk is simply the existence of its flood exposure.
Flood Storage Areas	Those parts of the floodplain that are important for the temporary storage of floodwaters during the passage of a flood. The extent and behaviour of flood storage areas may change with flood severity, and loss of flood storage can increase the severity of flood impacts by reducing natural flood attenuation. Hence, it is necessary to investigate a range of flood sizes before defining flood storage areas.
Flood Study	Is a technical investigation of flood behaviour in the study area. It describes the extent, depth and velocity of flood waters as well as the variation in flood hazard during a range of historical as well as hypothetical 'design' floods. The 'design' floods are based on statistical analysis of flooding that has occurred in the past.
Floodplain	Area of land which is subject to inundation by floods up to and including the probable maximum flood event, that is, flood prone land.
Floodplain Risk Management Plan	A management plan developed in accordance with the principles and guidelines in this manual. Usually includes both written and diagrammatic information describing how particular areas of flood prone land are to be used and managed to achieve defined objectives.
Floodway Areas	Those areas of the floodplain where a significant discharge of water occurs during floods. They are often aligned with naturally defined channels. Floodways are areas that, even if only partially blocked, would cause a significant redistribution of flood flow, or a significant increase in water levels.
Freeboard	Provides reasonable certainty that the risk exposure selected in deciding on a particular flood chosen as the basis for the FPL is actually provided. It is a factor of safety typically used in relation to the setting of floor levels, levee crest levels, etc. Freeboard is included in the flood planning level.
Ground truthing	Refers to the process of verifying or confirming information, by gathering real-world observations and measurements on the ground.
Hazard	A source of potential harm or a situation with a potential to cause loss. In relation to this study the hazard is flooding which has the potential to cause damage to the community.
Heavily Parallelised Compute (HPC)	In the context of the TUFLOW software, HPC is a solver which allows for the parallelisation of the hydraulic calculations within a single model. This allows a single model to run across numerous computational cores in parallel, which can significantly reduce model run times.

Historical Flood	A flood which has actually occurred.
Hydraulics	Term given to the study of water flow in waterways; in particular, the evaluation of flow parameters such as water level and velocity.
Hydrograph	A graph which shows how the discharge or stage/water level at any particular location varies with time during a flood.
Hydrology	Term given to the study of the rainfall and runoff process; in particular, the evaluation of peak flows, flow volumes and the derivation of hydrographs for a range of floods.
Impervious lag factor	The impervious lag factor is a coefficient used in WBNM to reduce the lag parameter for impervious surfaces to consider the fact that impervious surfaces allow for faster response in flow than pervious surfaces.
Lag Parameter	The lag parameter C in the runoff routing model WBNM has been derived from recorded storms on 54 catchments in Queensland, NSW, Victoria and South Australia. Parameter C was found to be independent of flood size, catchment area, stream slope, and various storm and catchment characteristics.
Local Overland Flooding	Inundation by local runoff rather than overbank discharge from a stream, river, estuary, lake or dam.
Mainstream Flooding	Inundation of normally dry land occurring when water overflows the natural or artificial banks of a stream, river, estuary, lake or dam.
Minimum Floor Level (MFL)	Minimum floor level at which a building should be constructed. Also named Flood Hazard Level (FHL).
Minor, Moderate and Major Flooding	Both the State Emergency Service and the Bureau of Meteorology use the following definitions in flood warnings to give a general indication of the types of problems expected with a flood. Minor flooding: Causes inconvenience such as closing of minor roads and the submergence of low level bridges. The lower limit of this class of flooding on the reference gauge is the initial water level at which landholders and townspeople begin to be flooded. Moderate flooding: Low lying areas are inundated requiring removal of stock and/or evacuation of some houses. Main traffic routes may be covered. Major flooding: Appreciable urban areas are flooded and/or extensive rural areas are flooded. Properties, villages and towns can be isolated.
Peak Discharge	The maximum discharge occurring during a flood event.
Probability	A statistical measure of the expected chance of flooding (see annual exceedance probability).
Probable Maximum Flood (PMF)	The PMF is the largest flood that could conceivably occur at a particular location, usually estimated from probable maximum precipitation, and where applicable, snow melt, coupled with the worst flood producing catchment conditions. Generally, it is not physically or economically possible to provide complete protection against this event. The PMF defines the extent of flood prone land, that is, the floodplain. The extent, nature and potential consequences of flooding associated with a range of events rarer than the flood used for designing mitigation works and controlling development, up to and including the PMF event should be addressed in a floodplain

	risk management study.
Probable Maximum Precipitation (PMP)	The PMP is the greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends (World Meteorological Organisation, 1986). It is the primary input to PMF estimation.
Properties	A land parcel or lot that may include various elements such as a dwelling, sheds, yards, driveways, and landscaped areas. For the purposes of this study, "property" refers to the entire lot boundary and all features within it.
Risk	Chance of something happening that will have an impact. It is measured in terms of consequences and likelihood. In the context of the NSW Flood Risk Management Manual, it is the likelihood of consequences arising from the interaction of floods, communities and the environment.
Runoff	The amount of rainfall which actually ends up as streamflow, also known as rainfall excess.
Stage	Equivalent to water level (both measured with reference to a specified datum).
TUFLOW	A 1-dimensional and 2-dimensional flood simulation software. It simulates the complex movement of floodwaters across a particular area of interest using mathematical approximations to derive information on floodwater depths, velocities and levels.
Velocity	The speed or rate of motion (distance per unit of time, e.g., metres per second) in a specific direction at which the flood waters are moving.
Water Surface Profile	A graph showing the flood stage at any given location along a watercourse at a particular time.
WBNM	Watershed Bounded Network Model. The WBNM is a conceptual, event-based, model developed for simulation of flood hydrographs and estimation of design floods

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