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City Area Catchment Flood Study

Final Report **October** 2014

City Area Catchment Flood Study

Final Report

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FORWARD

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

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

The Policy provides for technical and financial support by the NSW State Government through the six sequential stages:

1. **Formation of a Committee**
    - Established by Council and includes community group representatives and State agency specialists.
2. **Data Collection**
    - Past data such as flood levels, rainfall records, land use, soil types etc.
3. **Flood Study**
    - Determines the nature and extent of the flood problem.
4. **Floodplain Risk Management Study**
    - Evaluates management options for the floodplain in respect of both existing and proposed developments.
5. **Floodplain Risk Management Plan**
    - Involves formal adoption by Council of a plan of management for the floodplain.
6. **Implementation of the Floodplain Risk Management Plan**
    - Construction of flood mitigation works to protect existing development. Use of local environmental plans to ensure new development is compatible with the flood hazard.

This study represents Stages 2 and 3 of this process and aims to provide an understanding of existing and future flood behaviour within the City Area catchment.

EXECUTIVE SUMMARY

Introduction

The Sydney City Area Catchment Flood Study has been prepared for the City of Sydney to define the existing flood behaviour in the City Area catchment and establish the basis for subsequent floodplain management activities.

The study is being prepared to meet the objectives of the NSW State Government's Flood Prone Land Policy.

The primary objective of the Flood Study is to define the flood behaviour within the City Area catchment through the establishment of appropriate numerical models. The study has produced information on flood flows, velocities, levels and extents for a range of flood event magnitudes under existing catchment conditions. Specifically, the study incorporates:

- Compilation and review of existing information pertinent to the study;
- Development and calibration of appropriate hydrologic and hydraulic models;
- Determination of design flood conditions for a range of design events including the 2 year ARI, 5 year ARI, 10% AEP, 5% AEP, 2% AEP, 1% AEP, 0.2% AEP and PMF event; and
- Presentation of study methodology, results and findings in a comprehensive report incorporating appropriate flood mapping.

Catchment Description

The catchment is fully developed and comprises predominantly high-density housing and commercial development. There are some large open spaces within the catchment including Observatory Park and part of Hyde Park.

The catchment covers an area of about 199 ha and drains into the Sydney Harbour at various locations with the majority of the catchment discharging to Sydney Cove via Sydney Water's main trunk drainage system. This trunk drainage network is connected to Council's minor stormwater drainage system which comprises covered channels, pipes, culverts and pits. There are no open channel reaches within the City Area catchment.

The topography within the City Area catchment varies from steep surface slopes in excess of 15% on the western sides to the near flat lower catchment near Circular Quay and the other Sydney Harbour shoreline locations. The catchment therefore has regions where surface water runoff within the road network has high velocity with shallow depths, whilst in the lower catchment surface water is more likely to pond in sag points with typically lower flow velocities. The lower reaches of the catchment fringing Sydney Harbour are potentially affected by elevated water levels within the Harbour.

Within the catchment there are various excavation and cuttings, resulting in some vertical drops of over 10m.

The entire catchment is highly developed with little opportunity for water to infiltrate due to the high degree of impervious surfaces. It has been calculated that the combined area of roofs and roads is in excess of 50% of the catchment area. As a sign of the age of the region and high density nature, most residential properties are brick or sandstone construction with common walls to neighbours. In the central business district area numerous high rise buildings are built above the surrounding ground levels providing clear flow obstructions. There are very few opportunities for flow to pass through or between properties and as a result the roads form the primary overland flow paths.

Historical Flooding

Council has indicated that flooding within the catchment occurs at various locations in rainfall events exceeding 2 year ARI. June 1949, November 1961, March 1973, November 1984, January 1991 and February 2001 are noted historic major storm events which resulted in extensive flooding. Rainfall analysis was undertaken for these months using the Observatory Hill rain gauge. The November 1984 rainfall event was the largest analysed and was in excess of a 0.2 % AEP (500 year ARI) event.

It should be noted that the most recent of these key flood events (2001) occurred over 10 years ago and given the amount of time that has since passed it has been difficult obtaining records of flood behaviour for any of these events, specifically:

- Peak flood level survey data are not available for any of these events;
- Review of archived newspaper articles has found limited reports of the 1949 and other events. This data is useful, though due to its anecdotal nature it has limited value with respect to quantitative calibration data (e.g. observed flood levels and depths);
- Limited data has been recorded in the Sydney Water flooding database; and
- The median term of residency determined from the community consultation (refer to Section 3) is 8 years, indicating that many of the current residents did not experience any of these historic flooding events.

Community Consultation

Community consultation has been an important component of the current study. The consultation has aimed to inform the community about the development of the flood study and its likely outcome as a precursor to subsequent floodplain management activities. It has provided an opportunity to collect information on community members' flood experiences in the catchment and to collect feedback on concerns regarding flooding.

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

- Distribution of a questionnaire to landowners, residents and businesses within the study area via mail delivery and online from the City of Sydney website;
- Regular presentations of progress to the Floodplain Management Committee, which includes community representatives and Council staff; and
- Review of the draft Flood Study by the Floodplain Management Committee.

Model Development

Development of hydrologic and hydraulic models have been undertaken to simulate flood conditions in the catchment. Traditionally the hydrological model provides for simulation of the rainfall-runoff processes. The hydraulic model, utilising established flows from the hydrologic model, simulates flood depths, extents and velocities.

The hydrologic and hydraulic modelling has been combined in TUFLOW two dimension (2D) software developed by BMT WBM, using the “direct-rainfall” approach (also referred to as “rainfall-on-grid”). A direct-rainfall approach models at the resolution of the grid all the minor flow features and also spatial variability in land uses categories which define rainfall infiltration potential and resistance to flow. Verification of the direct-rainfall approach has been undertaken by comparing results obtained using tradition hydrological modelling (WBNM) techniques.

The entire City Area catchment is modelled in the 2D domain while approximately 27 km of sub-surface pipe network is modelled as 1D elements dynamically linked to the 2D domain. The dynamically linked 1D pit and pipe network means that pit inlets and pipe surcharging is modelled to allow interaction with overland flows.

The 1D/2D modelling approach is suited to model the complex interactions between overland flows and sub-surface stormwater network and the converging and diverging flows through the urban environment.

The Digital Terrain Model (DTM) which underpins the 2D model was defined using aerial survey data provided by Council.

Model Calibration and Validation

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

Review of the available data for the City Area catchment, including rainfall and tidal data, community consultation data, archived newspaper articles and Sydney Water flooding database, showed there are very few events with any recorded flood levels or observations of flood behaviour within the catchment.

Following assessment of available data and community consultation feedback, the 8 November 1984 and 26 January 1991 events were selected for the model calibration and verification process. To maximise the value of the community consultation, the 8 March 2012 event has also been used to verify general flooding behaviour reports within the City Area catchment.

The model was found to provide a good representation of the observed flood behaviour in the catchment.

Design Event Modelling and Output

The developed model has been applied to derive design flood conditions for the City Area catchment. Design rainfall depth is based on the generation of intensity-frequency-duration (IFD) design rainfall curves utilising the procedures outlined in AR&R (2001). A range of storm durations using standard

AR&R (2001) temporal patterns, were modelled. The design results represent the maximum envelope of all the durations assessed for the given design event frequency.

The design events considered in this study include the 2 year ARI, 5 year ARI, 10% AEP, 5% AEP, 2% AEP, 1% AEP, 0.2% AEP and PMF events. The model results for the design events considered have been presented in a detailed flood mapping series for the catchment (Appendix A). The flood data presented includes design flood inundation, peak flood water levels and depths and peak flood velocities.

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

Flood Emergency Response Planning Classifications (DECC, 2007) have been prepared for the range of design events considered.

Sensitivity Testing and Climate Change

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

- The impact of potential future climate change, including sea level rise and increased rainfall intensities;
- Changes in the adopted design rainfall loss parameters;
- Changes in the adopted roughness parameters; and
- Stormwater drainage system blockages.

Results were shown to be generally insensitive to the values adopted for deriving the design flood levels and extents for the hydraulic roughness and rainfall losses tests. Higher sensitivity was exhibited for stormwater drainage system blockages for frequent events at trapped low points.

The most significant impacts of climate change within the study area are associated with increased rainfall intensities.

Conclusion

The primary objective of the Flood Study was to define the flood behaviour of the City Area catchment through the establishment of an appropriate numerical model. The principal outcome of the flood study is an understanding of flood behaviour in the catchment and in particular the design flood level information that will be used to set appropriate flood planning levels. The flood study forms the basis for the subsequent floodplain risk management activities, being the next stage of the floodplain management process. Accordingly, the adoption of the flood study and predicted design flood levels is recommended.

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GLOSSARY

annual exceedance probability (AEP)	The chance of a flood of a given size (or larger) occurring in any one year, usually expressed as a percentage. For example, if a peak flood discharge of 500 m^3/s has an AEP of 5%, it means that there is a 5% chance (i.e. a 1 in 20 chance) of a peak discharge of 500 m^3/s (or larger) occurring in any one year. (see also average recurrence interval)
Australian Height Datum (AHD)	National survey datum corresponding approximately to mean sea level.
Astronomical Tide	Astronomical Tide is the cyclic rising and falling of the Earth's oceans water levels resulting from gravitational forces of the Moon and the Sun acting on the Earth.
attenuation	Weakening in force or intensity.
average recurrence interval (ARI)	The long-term average number of years between the occurrence of a flood as big as (or larger than) the selected event. For example, floods with a discharge as great as (or greater than) the 20 year ARI design flood will occur on average once every 20 years. ARI is another way of expressing the likelihood of occurrence of a flood event. (see also annual exceedance probability)
calibration	The adjustment of model configuration and key parameters to best fit an observed data set.
catchment	The catchment at a particular point is the area of land that drains to that point.
design flood event	A hypothetical flood representing a specific likelihood of occurrence (for example the 100 year ARI or 1% AEP flood).
development	Existing or proposed works that may or may not impact upon flooding. Typical works are filling of land, and the construction of roads, floodways and buildings.
discharge	The rate of flow of water measured in tems of vollume per unit time, for example, cubic metres per second (m^3/s). Discharge is different from the speed or velocity of flow, which is a measure of how fast the water is moving for example, metres per second (m/s).
flood	Relatively high river or creek flows, which overtop the natural or artificial banks, and inundate floodplains and/or coastal inundation resulting from super elevated sea levels and/or waves overtopping coastline defences.
flood behaviour	The pattern / characteristics / nature of a flood.
flood fringe	Land that may be affected by flooding but is not designated as floodway or flood storage.
flood hazard	The potential risk to life and limb and potential damage to property resulting from flooding. The degree of flood hazard varies with circumstances across the full range of floods.

flood level	The height or elevation of floodwaters relative to a datum (typically the Australian Height Datum). Also referred to as "stage".
flood liable land	see flood prone land
floodplain	Land adjacent to a river or creek that is periodically inundated due to floods. The floodplain includes all land that is susceptible to inundation by the probable maximum flood (PMF) event.
floodplain management	The co-ordinated management of activities that occur on the floodplain.
floodplain risk management plan	A document outlining a range of actions aimed at improving floodplain management. The plan is the principal means of managing the risks associated with the use of the floodplain. A floodplain risk management plan needs to be developed in accordance with the principles and guidelines contained in the NSW Floodplain Management Manual. The plan usually contains both written and diagrammatic information describing how particular areas of the floodplain are to be used and managed to achieve defined objectives.
Flood planning levels (FPL)	Flood planning levels selected for planning purposes are derived from a combination of the adopted flood level plus freeboard, as determined in floodplain management studies and incorporated in floodplain risk management plans. Selection should be based on an understanding of the full range of flood behaviour and the associated flood risk. It should also take into account the social, economic and ecological consequences associated with floods of different severities. Different FPLs may be appropriate for different categories of landuse and for different flood plans. The concept of FPLs supersedes the "standard flood event". As FPLs do not necessarily extend to the limits of flood prone land, floodplain risk management plans may apply to flood prone land beyond that defined by the FPLs.
flood prone land	Land susceptible to inundation by the probable maximum flood (PMF) event. Under the merit policy, the flood prone definition should not be seen as necessarily precluding development. Floodplain Risk Management Plans should encompass all flood prone land (i.e. the entire floodplain).
flood source	The source of the floodwaters.
flood storage	Floodplain area that is important for the temporary storage of floodwaters during a flood.
floodway	A flow path (sometimes artificial) that carries significant volumes of floodwaters during a flood.
freeboard	A factor of safety usually expressed as a height above the adopted flood level thus determing the flood planning level. Freeboard tends to compensate for factors such as wave action, localised hydraulic effects and uncertainties in the design flood levels.
geomorphology	The study of the origin, characteristics and development of land forms.

gauging (tidal and flood)	Measurement of flows and water levels during tides or flood events.
historical flood	A flood that has actually occurred.
hydraulic	Relating to water flow in rivers, estuaries and coastal systems; in particular, the evaluation of flow parameters such as water level and velocity
hydrodynamic	Pertaining to the movement of water.
hydrograph	A graph showing how a river or creek's discharge changes with time.
hydrographic survey	Survey of the bed levels of a waterway.
hydrologic	Pertaining to rainfall-runoff processes in catchments
hydrology	The term given to the study of the rainfall-runoff process in catchments.
hyetograph	A graph showing the distribution of ranfall over time.
Intensity Frequency Duration (IFD) Curve	A statistical representation of rainfall showing the relationship between rainfall intensity, storm duration and frequency (probability) of occurrence.
isohyet	Equal rainfall contour.
morphological	Pertaining to geomorphology.
peak flood level, flow or velocity	The maximum flood level, flow or velocity that occurs during a flood event.
pluviometer	A rainfall gauge capable of continously measuring rainfall intensity
probable maximum flood (PMF)	An extreme flood deemed to be the maximum flood likely to occur.
probability	A statistical measure of the likely frequency or occurrence of flooding.
riparian	The interface between land and waterway. Literally means "along the river margins"
runoff	The amount of rainfall from a catchment that actually ends up as flowing water in the river or creek.
stage	See flood level.
stage hydrograph	A graph of water level over time.
sub-critical	Refers to flow in a channel that is relatively slow and deep
topography	The shape of the surface features of land

velocity	The speed at which the floodwaters are moving. A flood velocity predicted by a 2D computer flood model is quoted as the depth averaged velocity, i.e. the average velocity throughout the depth of the water column. A flood velocity predicted by a 1D or quasi-2D computer flood model is quoted as the depth and width averaged velocity, i.e. the average velocity across the whole river or creek section.
validation	A test of the appropriateness of the adopted model configuration and parameters (through the calibration process) for other observed events.
water level	See flood level.

1 INTRODUCTION

The Sydney City Area Catchment Flood Study has been prepared for the City of Sydney to define the existing flood behaviour in the City Area catchment and establish the basis for subsequent floodplain management activities.

The study is being prepared to meet the objectives of the NSW State Government's Flood Prone Land Policy.

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

- Stage 1 - Collection, Compilation and Review of Available Information;
- Stage 2 – Model development, Calibration and Validation;
- Stage 3 – Design Modelling and Mapping;
- Stage 4 – Draft Flood Study Report; and
- Stage 5 – Final Flood Study Report.

An interim report outlining the methodologies, analysis and key outcomes has been provided at the completion of each stage. This report is the Stage 5 Final Flood Study Report.

1.1 The Study Location

The City Area catchment, shown in Figure 1-1, is located in Sydney's inner-city suburbs of Millers Point, Dawes Point, The Rocks, Barangaroo and Sydney. The catchment lies wholly within the Local Government Area (LGA) under the control of the City of Sydney. The catchment drains an area of approximately 199 ha (1.99 km^2).

1.2 The Need for Floodplain Management within the City Area Catchment

Historical records indicate that flooding has occurred at various locations within the City Area catchment. Prior to this current study, a comprehensive flood study has not been undertaken for this catchment to accurately determine the flood liability within the catchment. In order to reduce the risk to existing flood prone properties and manage the future land use of flood prone land, effective floodplain management strategies are required.

The City Area Catchment Flood Study includes the entire catchment and includes all sources of flooding (e.g. rainfall, tides) in a single state-of-the-art model. Current practice in floodplain management also requires consideration of the impact of potential climate change scenarios on design flood conditions. For the City Area catchment this includes increases in design rainfall intensities and sea level rise scenarios impacting on ocean and estuarine boundary conditions.

Title:
City Area Catchment Study Area Locality

Figure: 1-1

Rev: 1

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Accordingly, these potential changes will translate into increased design flood inundation in the catchment, such that future planning and floodplain management in the catchment will need to take due consideration of this increased flood risk.

1.3 The Floodplain Management Process

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

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

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

Table 1-1 Stages of the Floodplain Management Process

Stage Number	Stage Name	Description
1	Formation of a Committee	Established by Council and includes community group representatives and State agency specialists.
2	Data Collection	Past data such as flood levels, rainfall records, land use, soil types etc.
3	Flood Study	Determines the nature and extent of the flood problem.
4	Floodplain Risk Management Study	Evaluates management options for the floodplain in respect of both existing and proposed developments.
5	Floodplain Risk Management Plan	Involves formal adoption by Council of a plan of management for the floodplain.
6	Implementation of the Floodplain Risk Management Plan	Construction of flood mitigation works to protect existing development. Use of local environmental plans to ensure new development is compatible with the flood hazard.

This study represents Stages 2 and 3 of this process and aims to provide an understanding of existing and future flood behaviour within the City Area catchment.

1.3.1 Climate Change Policy

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

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

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

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

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

The potential impacts of sea level rise have been based on sea level rise projections from the 2009 NSW Sea Level Rise Policy Statement. Given that the Chief Scientist and Engineer's Report identifies the science behind these sea level rise projections is adequate, it was agreed between Council and BMT WBM that the potential impacts of sea level rise for the City Area catchment should be based on the best available information during preparation of this report.

For the City Area catchment, rising sea level is expected to increase the frequency, severity and duration of flooding in the lower reaches of the catchment.

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

In consultation with Council and the Office of Environment and Heritage (OEH), a range of climate change sensitivity tests incorporating combinations of sea level rise and increased design rainfall intensity have been formulated. The results of these sensitivity tests (refer Section 9) were then compared to the base case (i.e. models with existing sea level and climate) model results in order to assess the potential increase in flood risk due to climate change.

1.4 Study Objectives

The primary objective of the study is to define the flood behaviour under existing and future conditions (incorporating potential impacts of climate change) in the City Area catchment for a full range of design events. The study has produced information on flood levels and depths, velocities, flows, hydraulic categories and provisional hazard categories. This has been established for existing and future conditions for a full range of design flood events. The flood study has also identified the impact on flood behaviour as a result of future climate change and potential changes in the catchment. Specifically, the study incorporates:

- Compilation and review of existing information pertinent to the study;
- A community consultation and participation program to identify local flooding concerns, collect information on historical flood behaviour and engage the community in the on-going floodplain management process;
- Development and verification of appropriate hydrologic and hydraulic models;
- Determination of design flood conditions for a range of design events - including the 2 year ARI, 5 year ARI, 10% AEP (10 year ARI), 5% AEP (20 year ARI), 2% AEP (50 year ARI), 1% AEP (100 year ARI) and Probable Maximum Flood (PMF – an extreme flood event);
- Cost of flood damages for existing conditions using a full range of design flood events;
- Examination of potential impact of climate change using the latest guidelines for the 1% AEP design event; and
- Presentation of study methodology, results and findings in a comprehensive report incorporating detailed flood mapping.

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

- Outline the flood behaviour within the catchment to aid Council's strategic land use management planning; and
- Form the basis for a subsequent floodplain risk management study where detailed assessment of flood mitigation options and floodplain risk management measures will be undertaken.

1.5 About this Report

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

Section 1 introduces the study.

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

Section 3 outlines the community consultation program undertaken.

Section 4 details the development of the computer models.

Section 5 details the hydraulic model calibration and validation process.

Section 6 details the design flood conditions.

Section 7 presents the design flood results.

Section 8 presents the results of sensitivity analysis.

Section 9 presents results of climate change analysis.

Section 10 presents flood damage assessment.

2 STUDY APPROACH

2.1 The Study Area

2.1.1 Catchment Description

The catchment is fully developed and comprises predominantly high-density housing and commercial development. There are some large open spaces within the catchment including Observatory Park and part of Hyde Park.

The catchment covers an area of about 199 ha and drains into Sydney Harbour at various locations with the majority of the catchment discharging to Sydney Cove via Sydney Water's main trunk drainage system. This trunk drainage network is connected to Council's minor stormwater drainage system which comprises covered channels, pipes, culverts and pits. There are no open channel reaches within the City Area catchment.

The topography within the City Area catchment varies from steep surface slopes in excess of 15% on the western sides to the near- flat lower catchment near Circular Quay and the other Sydney Harbour shoreline locations. The catchment therefore has regions where surface water runoff within the road network has high velocity with shallow depths, whilst in the lower catchment surface water is more likely to pond in sag points and flow velocities will be lower. The lower reaches of the catchment fringing the Sydney Harbour are potentially affected by elevated water levels within the Harbour.

Within the catchment there are various excavation and cuttings, resulting in some vertical drops of over 10m.

The entire catchment is highly developed with very little opportunity for water to infiltrate due to the high degree of impervious surfaces. It has been calculated that the combined area of roofs and roads is in excess of 50% of the catchment area. As a sign of the age of the region and high density nature, most residential properties are brick or sandstone construction with common walls to neighbours. In the central business district area numerous high rise buildings are built above the surrounding ground levels providing clear flow obstructions. There are very few opportunities for flow to pass through or between properties and as a result the roads form the primary overland flow paths.

2.1.2 Stormwater Drainage System

The City Area catchment was first settled in the late 18th Century. The original natural drainage system comprised rock gullies draining to small pockets of mangroves along the shoreline. As development proceeded within the catchment, the land use changed to a higher proportion of impervious surfaces leading to increased runoff volumes and peak flows. It followed that the natural drainage lines were incorporated into the constructed drainage system of open channels. By the late 19th Century, much of the channel system was progressively covered over and piped, with much of the original system forming the backbone of the stormwater drainage system in place today.

The study area contains the Tank Stream, running between George Street and Pitt Street, which has been listed on the State Heritage Register. The Tank Stream was the first and main source of fresh water for NSW's colonial settlement from 1788, and now operates as a stormwater channel managed by Sydney Water.

Title:

City Area Catchment Study Area

Figure: 2-1

Rev: 1

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The Sydney Water Capacity Assessment Report for Drainage Area 29 (SWC, 1996) provides details of the trunk drainage components, indicating that the system is a combination of various eras of trunk drainage design and installation.

In rainfall events where flows exceed the piped system capacity, surface water runoff is generally conveyed within the road system as uncontrolled flow. When this occurs, there is potential for high hazard flooding conditions resulting from combined high flow velocities and depths.

There are no open channels within the study area to assist with drainage.

2.1.3 Known Flooding Problems

Council has indicated that flooding within the catchment occurs at various locations in rainfall events exceeding 2 year ARI. June 1949, November 1961, March 1973, November 1984, January 1991 and February 2001 are noted historic major storm events which resulted in extensive flooding. Rainfall analysis was undertaken for these months using the Observatory Hill gauge. Table 2-1 shows the results of this rainfall analysis. The November 1984 rainfall event was the largest analysed and was in excess of a 0.2 % AEP (500 year ARI) event. Review of rainfall data for the month of March 1973 and February 2001 indicated substantial gaps in data and no significant recorded rainfall event. It is therefore assumed that the gauge failed for the events.

Table 2-1 Rainfall analysis of key historic rainfall events

Event	Peak % AEP
15 June 1949	~ 20 % AEP (~5 year ARI)
18-19 November 1961	~ 5 % AEP (~20 year ARI)
March 1973	Gauge Failed
9 November 1984	< 0.2 % AEP (> 500 year ARI)
27 January 1991	~ 2 % AEP (~50 year ARI)
February 2001	Gauge Failed

It should be noted that the most recent of these key flood events (2001) occurred over 10 years ago and given the amount of time that has since passed it has been difficult obtaining records of flood behaviour for any of the events, specifically:

- Peak flood level survey data are not available for any of these events;
- Review of archived newspaper articles has found limited reports of the 1949 and other events. This data is useful, though due to its anecdotal nature it has limited value with respect to quantitative calibration data (e.g. observed flood levels and depths);
- Limited data has been recorded in the Sydney Water flooding database; and
- The median term of residency determined from the community consultation (refer to Section 3) is 8 years, indicating that many of the current residents did not experience any of these historic flooding events.

2.2 Compilation and Review of Available Data

2.2.1 Introduction

The data compilation and review was undertaken as the first stage in this flood study in order to consolidate and summarise all of the currently available data, and identify any significant data gaps that may affect the successful completion of the study. This allowed for the missing data to be collected during the initial phases of the study.

The review included:

- Previous studies undertaken within the City Area catchment;
- Available water level, tide and rainfall data; and
- Sydney Water flooding complaints register.

Council has provided digitally available information such as aerial photography, cadastral boundaries, watercourses, and drainage networks in the form of GIS datasets.

2.2.2 Previous Studies and Investigations

Comprehensive flood modelling has not previously been undertaken for the entire City Area catchment. A key Sydney Water document provides details of the trunk stormwater assets within in the study area including capacity assessment. Flood Studies in neighbouring catchments with similar topographic features and urban densities have recently been undertaken. Details of these relevant studies are summarised below.

1. **City Area SWC 29 Capacity Assessment (Sydney Water, 1996).**

This report prepared by Sydney Water assessed the quantitative performance of stormwater drainage elements within Sydney Water's City Area SWC29. The document categorises drainage elements into one of four "land use design ARI" as presented below. For each drainage element the actual performance (ARI flow required to exceed hydraulic capacity) is compared to desired performance for the land use design ARI categorisation. Further assessment and comment is made upon the likely impacts of future urban consolidation which would result in increased impervious areas and hence increased flows.

- Low density residential, minor roads and open spaces represented by a 5 year design ARI;
- Business, commercial and industrial areas, intensely developed residential areas, and local access road culverts reflected by a 10 year design ARI;
- Intense business, commercial and industrial, major secondary roads, major railway culverts, highways and freeways, 20 year design ARI: and
- Central business districts and the wider service corridors where the channel is obviously a trunk drain as designed by AR&R, a 100 year design ARI is compared to.

The drainage area SWC29 covers approximately the same extent of the City Area catchment study area.

Details of pipe capacity as well as dimensions and hydraulic parameterisation are extensively detailed within this report. These data have been digitised for the hydraulic model build of the current study.

2. Blackwattle Bay Catchment Flood Study (Final Report) (WMA, 2012a)

This flood study report prepared by WMAwater for the City of Sydney details the flooding behaviour in the Blackwattle Bay catchment. Blackwattle Bay catchment is approximately 2 km to the west of the City Area catchment.

The hydrodynamic modelling program TUFLOW was used to model both the hydrologic and hydraulic processes in the catchment (direct-rainfall). The study area covers approximately 315 ha and was modelled with a 2 m grid cell.

26^{th} January 1991 and 17^{th} February 1993 were adopted as the calibration and verification events, respectively, though very limited data were available for this process.

As part of the study a flood damage assessment was undertaken for all standard design events. Impacts of climate change and sea level rise were also considered.

A critical storm duration of 120 minutes was adopted for all non-PMF design event simulations, whilst the 1 hour event was adopted for the PMF event.

Design rainfall losses adopted were as follows:

- Pervious areas: Initial Loss 10 mm; Continuing Loss 2.5 mm/h
- Impervious areas: Initial Loss 1.5mm; Continuing Loss 0mm/h

3. Johnstons Creek Catchment Flood Study (Final Report) (WMA, 2012b)

This flood study report prepared by WMAwater for the City of Sydney details the flooding behaviour in the Johnstons Creek catchment. Johnstons Creek catchment is immediately adjacent (to the west) of the Blackwattle Bay Catchment and is approximately 3 km from the City Area catchment.

The hydrodynamic modelling program TUFLOW was used to model both the hydrologic and hydraulic processes in the catchment (direct-rainfall). The study area covers approximately 224 ha and was modelled with a 2 m grid cell.

Model calibration was not undertaken since surveyed records of flooding were unavailable and there is no flow monitoring within the catchment. Model verification therefore focused on simulating flood hot-spots and generating a similar specific yield to neighbouring calibrated catchments.

As part of the study a flood damage assessment was undertaken for all standard design events. Impacts of climate change and sea level rise were also considered.

A critical storm duration of 120 minutes was adopted for all non-PMF design event simulations whilst the 3 hour event was adopted for the PMF event.

Design rainfall losses adopted were as follows:

- Pervious areas: Initial Loss 10 mm; Continuing Loss 2.5 mm/h
- Impervious areas: Initial Loss 1.5mm; Continuing Loss 0mm/h

2.2.2.1 Summary of Previous Studies

Very little flood modelling has been undertaken in the City Area catchment, with no existing models which are suitable to adapt for this study.

Council commissioned Flood Studies have been completed for the neighbouring Blackwattle Bay and Johnstons Creek. In order to provide consistency for Council across the LGA, the current study has, were possible, ensure consistency between these studies with respect to modelling approach and parameterisation.

2.2.3 Rainfall Data

There is an extensive network of rainfall gauges across the Sydney area, many of which are operated by the Bureau of Meteorology (BoM) and Sydney Water Corporation (SWC). The closest BoM station, located at Observatory Hill, is within the City Area catchment. This rainfall station records continuous rainfall (pluviometer) and has a long period of record, commencing in 1858.

There are two more daily rainfall stations located in close proximity to the study area, resulting in a suitable density of daily rainfall stations to define historic rainfall. A list of these relevant rainfall stations with their respective period of record is shown in Table 2-2, with the spatial distribution of the rainfall stations shown in Figure 2-2. This combination of daily rainfall stations and the Observatory Hill pluviometer to define the temporal pattern of rainfall presents a high quality rainfall data set for use in this Flood Study.

Table 2-2 Rainfall stations in the City Area catchment locality area

Station #	Name	Record Period	Type
066006	Sydney Botanic Gardens	1885 – 2011	Daily
066062	Sydney (Observatory Hill)	1858 – 2013	Daily/Pluviometer
066160	Sydney Centennial Park	1990 - 2010	Daily

2.2.4 Stream Gauge Data

There are no stream gauging data within the study area. This is a common data deficiency in urban catchments.

2.2.5 Harbour Water Level Data

The City Area catchment primarily flows into Sydney Harbour via Sydney Cove. Consequently, the water level within Sydney Harbour can act as a significant downstream control for both overland and piped flows under flooding conditions resulting from rainfall events.

Consideration of the most appropriate tailwater condition is required for the historic event calibration and design event modelling. For all calibration events, a dynamic tailwater boundary for Sydney Harbour has been adopted based on water level records from Fort Denison (see Figure 2-2). This data has been obtained from the Bureau of Meteorology's National Tidal Centre. Design event water levels within Sydney Harbour comprise a constant water level based on a frequency analysis of Fort Denison's water level records. Table 2-3 presents the design peak water levels for Sydney Harbour (DECC, 2008). Discussion in later sections presents the assumed joint probability of rainfall events with elevated harbour tailwater level.

Table 2-3 Sydney Harbour design still water levels

Frequency	Maximum Water Level (m AHD)
0.02 year ARI	0.965
0.05 year ARI	1.045
0.1 year ARI	1.095
1 year ARI	1.235
2 year ARI	1.275
5 year ARI	1.315
10% AEP	1.345
5% AEP	1.375
2% AEP	1.415
1% AEP	1.435
0.5% AEP	1.455

2.2.6 Flood Level Data

No peak flood level survey of historic flooding is available for this study. Model calibration has therefore relied on information received from community recollections of flooding via the community engagement process and from the Sydney Water Corporation (SWC) Historical Database of flooding incidents.

2.2.7 Topographic Data

Aerial topographic survey, also known as ALS (Airborne Laser Scanning) covering the study area has been provided by Council. ALS data typically has a vertical accuracy of +/- 0.15m with 68% confidence and horizontal accuracy of +/- 0.55m with 68% confidence.

The ALS data set has been provided as filtered data, where a filtering routine has been applied to remove non-ground features such as buildings and vegetation to provide a representation of the ground surface. The data set has been converted into a 1m resolution digital terrain model (DTM) using terrain modelling software. Non ground points have been provided as a separate dataset.

Section 4 discusses detailed interpretation of the ALS data and how the data has been enhanced for use in this study by applying post-processing methods since numerous large buildings and bridges within the study area influence the data provided.

Title:

City Area Catchment
BOM Rainfall Stations

Figure: 2-2

Rev: 1

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Approx. Scale

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Figure 2-3 shows the DTM developed for the study area, providing a visualisation of potential flow paths. The flow path with the largest contributing catchment is along Pitt Street. The average slope of this flow path is 1-2% and overlays Tank Stream. West of the Tank Stream catchment there is a ridge and flows fall quickly to the West into Darling Harbour.

2.2.8 Council GIS Data

Digitally available Geographical Information Systems (GIS) data such as aerial photography, cadastral boundaries, details on the Sydney Local Environmental Plan (LEP) zones, park streetscapes, and building footprints, have been provided by Council. These data provide a means to distinguish between land-use types across the study area to allow spatial variation of distinct hydrologic (e.g. rainfall losses) and hydraulic (e.g. Manning's roughness parameter '*n*') properties.

Roads layers have not been provided and have been manually digitised for this study.

2.2.9 Stormwater Drainage Network

An extensive network of stormwater infrastructure exists in the study area to provide drainage to City Area. This infrastructure is primarily comprised of a 'pit and pipe' stormwater network and does not include open channels as part of the trunk drainage system. Detail of the stormwater drainage network has been compiled from the following sources:

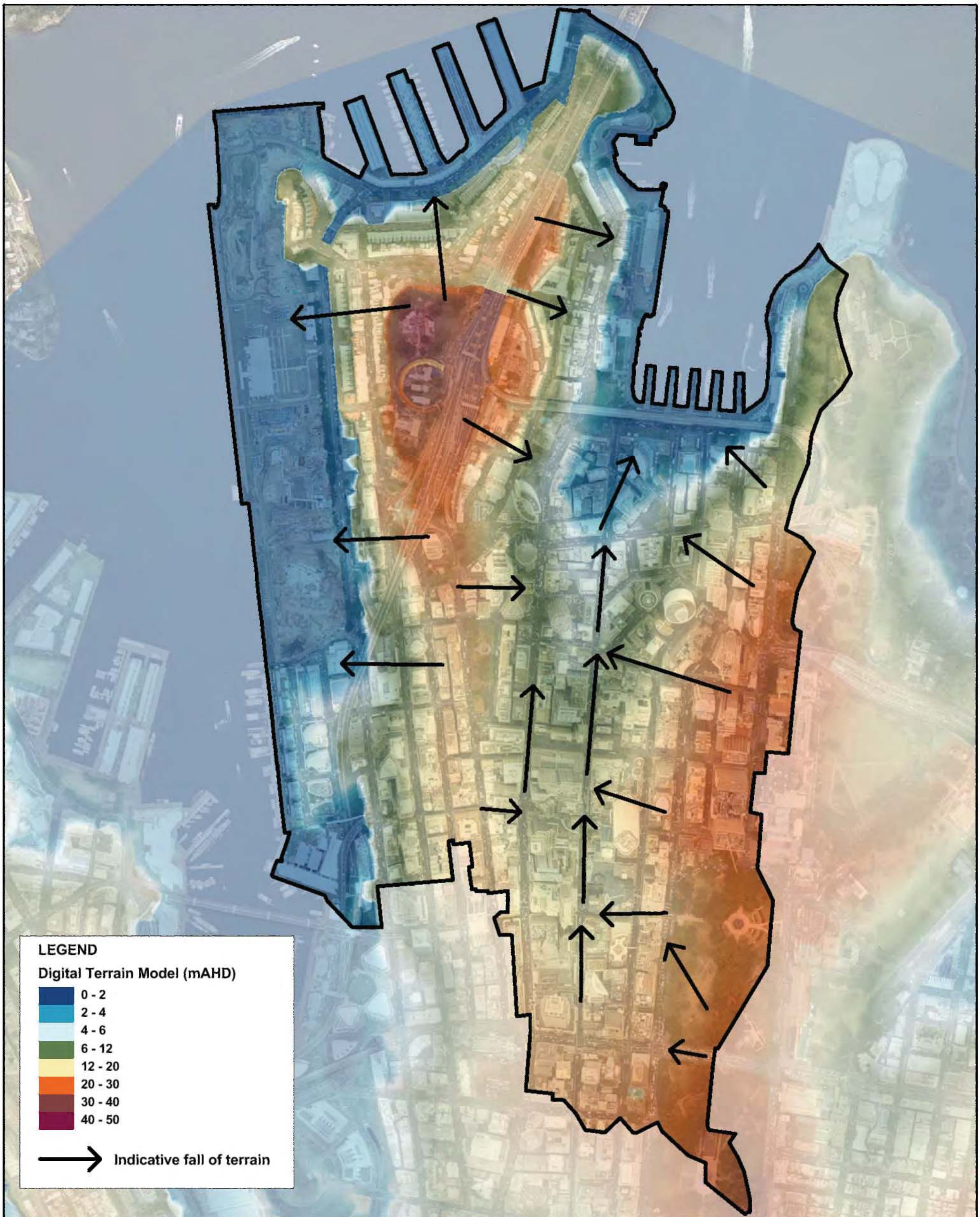
- Council's GIS database; and
- Details contained in the Sydney Water Capacity Assessment reports (SWC, 1996).

Council's GIS database of the pit and pipe data is the primary data set used to build the pipe drainage features of the hydraulic model. The data set includes details such as upstream and downstream pipe inverts, pipe dimensions, inlet dimensions for pits, pit surface levels and pit depths. Further details of stormwater drainage network are provided in Section 4.

Pipe types within the study area include circular, rectangular and oviform pipes. Circular and rectangular pipes are modern extruded concrete or clay pipes in circular and rectangular dimensions. Dimensions of these pipes were provided in electronic format and are easily defined in the hydraulic model by diameter of a circular pipe or the height and width of a rectangular pipe.

The oviform pipes are a special class and refer to the very old pipes build in the late 1800's as part of the combined sewerage and stormwater system which now functions solely for stormwater. The dimensions of the oviform are irregular. Figure 2-4 shows examples of oviform pipes within the study area.

Dimensions of the various irregular pipes throughout the stormwater drainage network were not provided in an electronic format and the dimensions have been manually digitised from drawings in the Sydney Water Capacity Assessment reports. The irregular pipes have been represented in the hydraulic model by manually calculating the "water depth versus flow area" and the "water depth versus wetted perimeter" values.



Title:

City Area Catchment
Digital Terrain Model

Figure: 2-3

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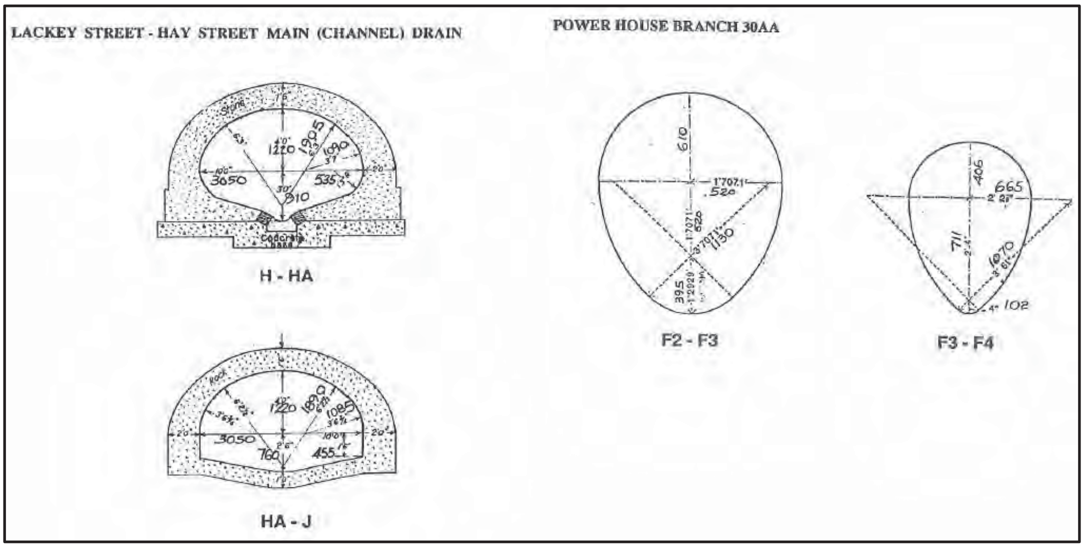

Figure 2-4 Oviform Pipe Examples (SWC, 1996)

Table 2-4 provides a summary of the stormwater infrastructure and Figure 2-5 shows the location of this infrastructure.

Table 2-4 Summary of stormwater infrastructure elements in hydraulic model

Stormwater Infrastructure Type	Number of Elements
Circular	1959
Rectangular	119
Oviform	224
Other*	94
Undefined**	48
TOTAL PIPES	**2444**
Pits	1314
Nodes	651
Connective Nodes***	444
TOTAL NODES/PITS	**2409**

* Not all pipes in Council's GIS database have defined dimensions. These pipes are likely hidden pipes unable to be surveyed. The pipes are classified as "Undefined". Dimensions of these pipes have been assumed based on connected pipe dimensions.

**Small sections of pipes illogically ended or failed to be connected to upstream pits. New pipes have been drawn to connect these stormwater elements. Dimensions of these pipes have been assumed based on connected pipe dimensions. These newly drawn pipes are classified as "Assumed".

*** In order to configure the hydraulic model, nodes were required at all pipe junctions. Nodes manually drawn to satisfy this requirement are referred to as "Connective Nodes".

Title:

City Area Catchment Stormwater Pit/Pipe Dataset

Figure: 2-5

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2.3 Sydney Water Corporation Historical Flood Database

Sydney Water Corporation (SWC) maintains a register documenting reports of flooding. The earliest record in this database within the study area is from 1943 and the database is still maintained for current events. The database has very little flood level data (AHD or similar) though can still provide useful information of the locations of flooding hot-spots and the storm events which triggered the reported flooding.

Figure 2-6 shows the locations of all flood reports available for the study area noting also the date of the incident.

The earliest reports of flooding hold diminished value to this current study since the catchment conditions which resulted in the flooding are unknown. Table 2-5 lists the relevant storm events from 1984 up to the most current and list the number of reported locations with flooding for each event. As shown the most recent entry in the flood database is over 20 years old and only has a single flooding report location. The 1983 event has 2 reported locations of flooding available for model result calibration though is over 30 years old.

Table 2-5 Sydney Water flood database for the City Area catchment

Storm Event	Number of Locations with Reported Flooding
22 August 1984	1
5 November 1984	2
8 November 1984	6
6 January 1989	3
26 January 1991	3
9 February 1992	1

Inspection of the Observatory Hill rainfall gauge data showed that the August 1984 and February 1992 events were not recorded.

To gain an appreciation of the significance of the January 1989, January 1991 and 8 November 1984 events, the recorded rainfall depths for various storm durations is compared with the design Intensity-Frequency-Duration (IFD) data for the catchment as shown in Figure 2-7. For a 30 minute duration the January 1989, January 1991 and 8 November 1984 exceeded the 5 year ARI (20% AEP), 20 year ARI (5% AEP) and 500 year ARI (0.02% AEP) respectively.

Title:

SWC Historical Flood Database
City Area Catchment Records

Figure: 2-6

Rev: -

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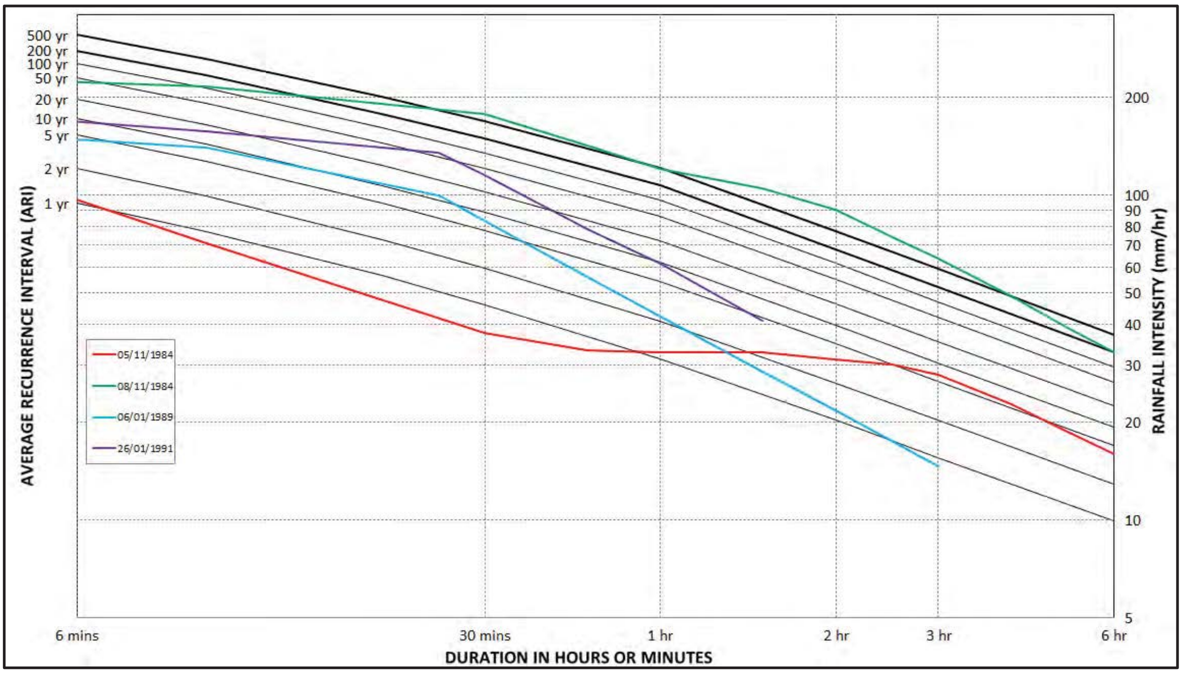


Figure 2-7 Rainfall analysis for SWC historical flood database events

2.4 Review of Historical Newspaper Articles (TROVE)

Newspaper articles can provide a valuable insight to key historic flood events and flooding behaviour. A literature review of available archived Australian media publications on the TROVE database maintained by the National Library of Australia was undertaken to obtain anecdotal information of flooding.

Over 15 relevant articles were found dating from as far back as 1877. Appendix B presents the full list of articles found and includes a more detailed account of the findings, with results of the review summarised in Figure 2-8. This figure shows the areas documented to be flood affected which are:

- Circular Quay – 1-4 feet deep;
- Pitt Street – reported flooded in 1912, 1913, 1938, 1949;

Other details taken from the articles are as follows:

- Main flow paths have been identified at Market Street, Elizabeth Street and Park Street from Hyde Park.

Results of the historical newspaper review cannot be relied upon to provide quantitative model calibration as wide-spread land use and stormwater infrastructure changes across the catchment will have altered the flood behaviour. Furthermore, the reports are anecdotal and referenced to general areas rather than precise addresses. However, these articles provide a valuable data set for model verification and identifying key areas where some flood affectation would still be anticipated today.

2.5 Site Inspections

A number of site inspections were undertaken throughout the course of the Flood Study to gain a better appreciation of local features influencing flood behaviour. Some of the key observations accounted for during the site inspections include:

- Presence of local structural hydraulic controls;
- Location and characteristics of surface drainage pits and pipes;
- Location of existing development and infrastructure on the floodplain;
- General nature of the contributing catchment.

This visual assessment was useful for defining hydraulic properties within the hydraulic model and ground-truthing of topographic features identified from the ALS data.

2.6 Community Consultation

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

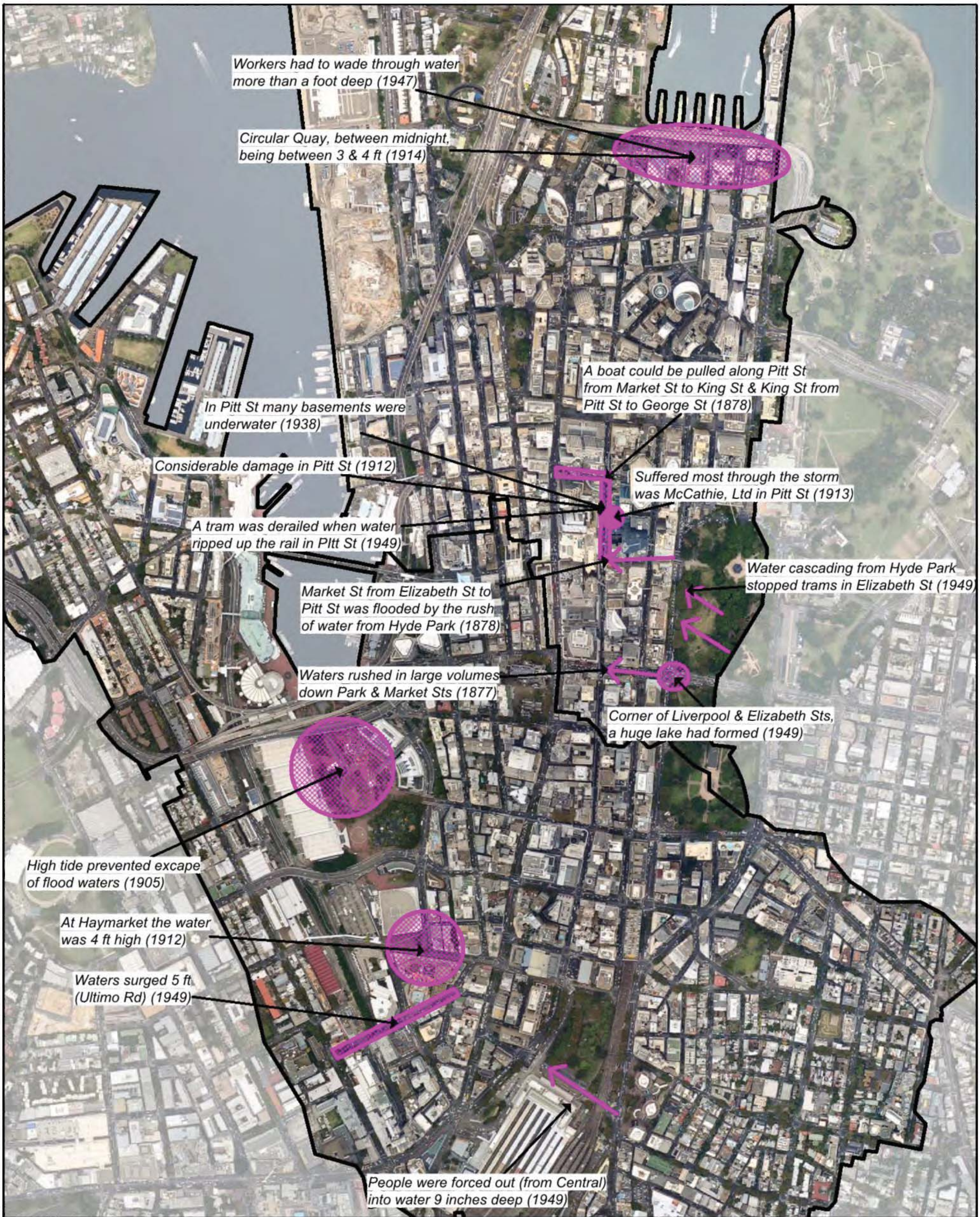
The key elements of the consultation program undertaken for the study are discussed in Section 3.

2.7 Development of Computer Models

2.7.1 Hydrological Model

Traditionally, for the purpose of the Flood Study, a hydrologic model is developed to simulate the rate of storm runoff from the catchment. The output from the hydrologic model is a series of flow hydrographs at selected locations such as at stormwater drainage pit inlets, which form the inflow boundaries to the hydraulic model.

In recent years the advancement in computer technology has enabled the use of the direct-rainfall approach as a viable alternative (also referred to as rainfall-on-grid). With the direct-rainfall method the design rainfall is applied directly to the individual cells of the 2D hydraulic model. This is particularly useful for overland flow studies where model results are desired in areas with small contributing catchments. This study has adopted the direct-rainfall approach for modelling hydrology, details of which are discussed in Section 4. Verification of the direct-rainfall approach against traditional hydrological modelling is shown in Section 5.9.



Title:

Darling Harbour and City Area Catchment Historic Reports of Flooding (TROVE)

Figure: 2-8

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2.7.2 Hydraulic Model

The TUFLOW hydraulic model (discussed in Section 4) developed for this study includes:

- two-dimensional (2D) representation of the entire City Area catchment; and
- one-dimensional (1D) representation of the stormwater pit/pipe network.

The hydraulic model has been applied to determine flood levels, velocities and depths across the study area for historical and design events.

2.8 Model Calibration/Validation and Sensitivity Analysis

The hydraulic model has been validated against available historic flood event data to establish the values of key model parameters and to confirm that the model is adequately representing the runoff processes within the catchment.

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

- The availability, completeness and quality of rainfall and flood level event data;
- The amount of reliable data collected during the historical flood information survey; and
- The variability of events – preferably events would cover a range of flood sizes.

Since the amount of reliable historic flood level data was limited, a full model calibration has not been possible for this study. Flood information collected from the community questionnaire that is not specific to particular rainfall and flood events has been used to aid the model validation process. The validation of the hydraulic model is presented in Section 5.

A series of sensitivity tests have also been carried out to evaluate the model. These tests have been conducted to examine the performance of the model and determine the relative importance of different hydrological and hydraulic parameters. The sensitivity testing of the model is presented in Section 8.

2.9 Establishing Design Flood Conditions

Design floods are statistical-based events which have a particular probability of occurrence. For example, the 1% Annual Exceedance Probability (AEP) event, which is sometimes referred to as the 1 in 100 year Average Recurrence Interval (ARI) flood, is the best estimate of a flood with a peak discharge that has a 1% (i.e. 1 in 100) chance of occurring in any one year. For the City Area catchment, design floods have been based on design rainfall estimates according to Australian Rainfall and Runoff (Pilgrim, DH, 2001).

The design flood conditions form the basis for floodplain management in the catchment and in particular design planning levels for future development controls. The estimated design flood conditions are presented in Section 7.

2.10 Mapping of Flood Behaviour

Design flood mapping is undertaken using output from the hydraulic model. Maps are produced showing water level, water depth and velocity. The maps present the peak value of each parameter. Provisional flood hazard categories and hydraulic categories are derived from the hydraulic model results and are also mapped. The mapping outputs are described in Section 7 and presented in Appendix A.

2.11 Conclusion

The City Area catchment is heavily urbanised and is predominantly comprised of residential and commercial development. Low rise and high rise buildings, which pose as significant flow obstructions, are common features in the central business area. The natural overland drainage features have been heavily modified and the entire catchment is now drained by an extensive stormwater drainage network. There are no open channels within the study area. When the capacity of the stormwater drainage network is exceeded, overland flow will occur predominantly along the road network.

Availability of historical flooding and flood data in the City Area catchment is limited. The largest historical event identified in the catchment occurred in November 1984.

3 COMMUNITY CONSULTATION

3.1 The Community Consultation Process

Community consultation has been an important component of the current study. The consultation has aimed to inform the community about the development of the flood study and its likely outcome as a precursor to subsequent floodplain management activities. It has provided an opportunity to collect information on community members' flood experiences in the catchment and to collect feedback on concerns regarding flooding.

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

- Distribution of a questionnaire to landowners, residents and businesses within the study area via mail delivery and online from the City of Sydney website;
- Regular presentations of progress to the Floodplain Management Committee, which includes community representatives and Council staff; and
- Review of the draft Flood Study by the Floodplain Management Committee.

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

3.2 Community Questionnaire

Council distributed a questionnaire in May 2013 to all residential properties and businesses within the study area to collect information on their previous flood experience and flooding issues. The focus of the questionnaire was historical flooding information that may be useful for correlating with predicted flooding behaviour from the modelling. A copy of the questionnaire is provided in Appendix C.

A total of 21,250 community questionnaires were mailed to residents and businesses within the combined study areas of Darling Harbour and the City Area. A total of 358 responses were received equating to a response rate of 2%, with 58 of the responses from the City Area catchment.

The responses have been compiled into a database to allow for a quantitative assessment of flooding experiences. Questions 2 to 6 are particularly useful in characterising the respondents and their flood affectation. The charts provided in Figure 3-1 present the results of these questions.

It is noted that some respondents did not fully complete the questionnaire though effort was made to most fully utilise the responses.

Figure 3-1 Results from the Community Consultation

Results of the community consultation indicate that the median period of residency is 8 years. The largest historic rainfall event occurred in November 1984 which is almost 30 years ago and the most recent of the historic rainfall events is February 2001 which is over 10 years ago. Accordingly, residents were unlikely to have been living at their current address during the key historic rainfall events and this is potentially why responses failed to obtain significant new information on these events.

Approximately 40% of residents are at least aware of flooding in there catchment and street (Qu4&5), though the flooding is rarely dangerous or above floor level and is mostly reported as regular (Qu6). The responses suggest minor nuisance flooding rather than flooding from the key identified historic flood events. Only 2 responses indicated above floor level inundation, however, the respondents failed to identify the event for these occurrences.

Regarding the historic events which caused reports of flooding, respondents rarely reported the precise time and date of the flooding. For the instances where a month and year were reported, historic rainfall records where reviewed to determine the likely magnitude of the contributing event. To gain an appreciation of the significance of the identified events, the recorded rainfall is compared with the design IFD data for the catchment as shown in Figure 3-2.

The most significant events reported include:

- 12 February 2010 ~10% AEP (10 year ARI),
- 8 March 2012 ~2 year ARI,
- 3 April 2013 ~1 year ARI.

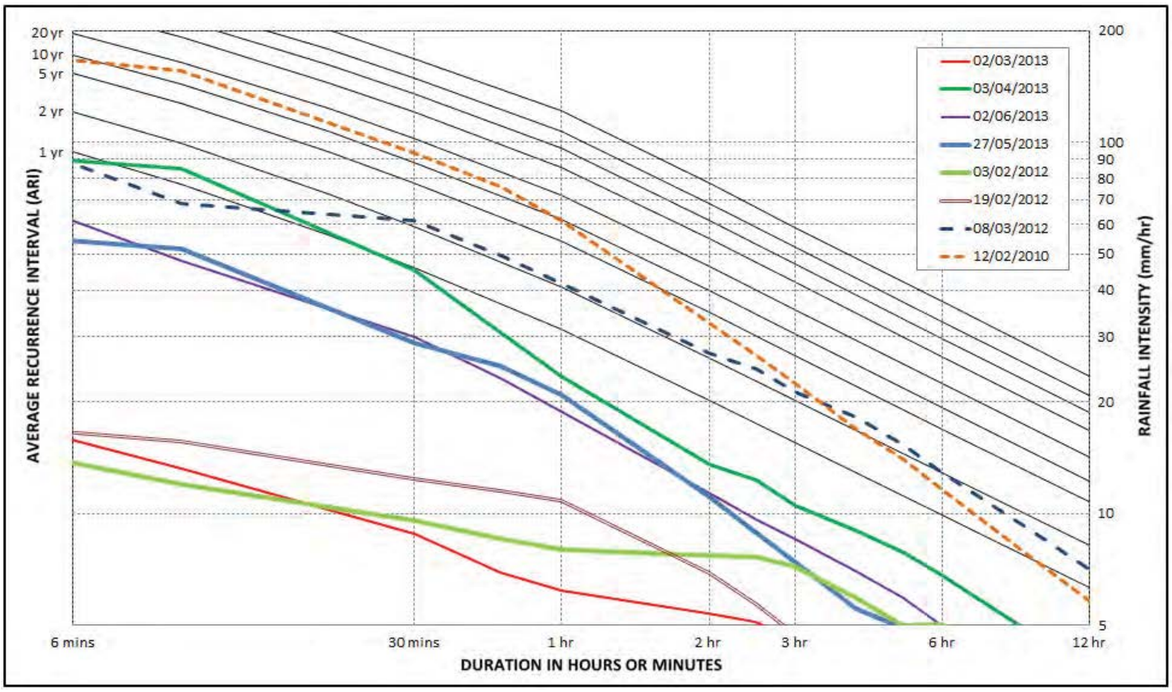

Figure 3-2 IFD analysis of events identified in community consultation

The locations of all respondents, including whether or they are flood affected, are shown in Figure 3-3. This has been prepared by linking the addresses of respondents with the addresses in Council's cadastre database.

Title:

City Area Catchment
Location of Community Consultation Respondents

Figure: 3-3

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3.3 Conclusion

Community Consultation undertaken during the study has aimed to collect information on historical flooding and previous flooding experiences, and to inform the community about the development of the flood study and its likely outcome as a precursor to floodplain management activities to follow. The key element of the consultation process involved the distribution of a questionnaire relating to historical flooding. The number of responses from the questionnaire was very low (2%) with minimal additional historical flood information obtained. This is likely to be representative of a combination of the following:

- The relatively low number of significant rainfall and flooding events within the City Area catchment in recent years;
- The relatively low median period of residency.

Demographic statistics were explored to help understand the low return rate of questionnaire and also the low median period of residency. Basic Community Profile data was obtained from the 2011 Census for the postcode area 2000 (ABS, 2011) which supports the assumption that the population is transient. Only 55% of residents in the 2011 Census reported living in the same address 1 year prior and this number reduced to 23% when reporting if living in the same address 5 years prior. Short term residents are generally unable to contribute long term accounts of flooding. Furthermore, short term residents are likely to be less interested in the outcomes of the Flood Study and subsequent Floodplain Risk Management Study and Plan and may not have participated in the consultation process.

4 MODEL DEVELOPMENT

4.1 Introduction

In the absence of long term stream flow data, computer models are usually the most accurate, cost-effective and efficient tools to assess a catchment's flood behaviour. Traditionally, for the purpose of the Flood Study, a hydrologic model and a hydraulic model are developed.

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

The **hydraulic** model simulates the flow behaviour of the drainage network and overland flow paths, producing flood levels, flow discharges and flow velocities.

In recent years the advancement in computer technology has enabled the use of the direct-rainfall approach as a viable alternative over the use of "traditional" hydrological models (e.g. XP-RAFTS, WBNM). With the direct-rainfall method the rainfall depths are applied directly to the individual cells of the 2D hydraulic model. This is particularly useful for overland flow studies where model results are desired in areas with small contributing catchments. This study has adopted the direct-rainfall approach for modelling the catchment hydrology and therefore only a single TUFLOW model has been developed which implicitly performs both hydrologic and hydraulic computation. The TUFLOW model developed for this study has been calibrated by addressing hydrological and hydraulic aspects of the calibration interactively.

Information on the topography and characteristics of the catchment, drainage network and floodplain are built into the model. Recorded historical flood data, including rainfall and flood levels, are used to simulate and validate the model. The model produces as output, flood levels, flows rates and flow velocities.

Development of a hydraulic model follows a relatively standard procedure:

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

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

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

4.2 Hydrological Model

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

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

A direct-rainfall (also referred to as rainfall-on-grid) approach has been adopted in the TUFLOW hydraulic model (refer to Section 4.3 for details of the model setup). The factors given above have been represented in the model by:

- The runoff routing and hydrological response of the catchment within the 2D model is driven by the surface type and underlying topography. Where appropriate, runoff is diverted into 1D pipe domains of the 2D/1D model (more detail is provided in Section 4.3).
- The amount and intensity of rainfall can be varied across the catchment based on available data and information.
- The antecedent moisture conditions are modelled by varying the amount of rainfall which is “lost” into the ground and “absorbed” by storages. For very dry antecedent moisture conditions, there is typically a higher initial rainfall loss.

The general modelling approach and adopted parameters are discussed in the following sections.

4.2.1 Catchment Delineation

The City Area catchment drains an area of approximately 1.99 km^2 via a piped stormwater drainage network to Sydney Harbour.

Discretisation of the study area into sub-catchments has not been required for this study given that rainfall is being applied directly to the 2D domain and traditional rainfall-runoff modelling is not being used. However, the delineation of the overall catchment boundary is important for defining the limits of the hydraulic model and the associated direct-rainfall input. The precise study area catchment boundary is not clearly or easily defined due to the presence of some low points at the catchment boundaries. During significant rainfall events these low points collect runoff which cannot be adequately drained by the formalised drainage network. The low points act as storages which can overflow to the Darling Harbour catchment, the neighbouring catchments or both during significant rainfall events.

The hydrologic catchment boundary and the hydraulic model extent have been sufficiently extended to account for the potential interactions with the neighbouring catchments.

4.2.2 Rainfall Data

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

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

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

The procedure for defining these properties is different for historical and design events. For historical events, the recorded hyetographs at continuous rainfall gauges provide the observed rainfall depth and temporal pattern (refer to Figure 2-2 for rainfall gauge locations).

For design events, rainfall depths are most commonly determined by the estimation of intensity-frequency-duration (IFD) design rainfall curves for the catchment. Standard procedures for derivation of these curves are defined in Australian Rainfall and Runoff (AR&R) (EA, 1987). Similarly AR&R defines standard temporal patterns for use in design flood estimation.

The rainfall inputs for the historical calibration/validation events are discussed in further detail in Section 5 with design events discussed in Section 6.

4.2.3 Rainfall Losses

The antecedent catchment condition reflecting the degree of wetness of the catchment prior to a major rainfall event directly influences the magnitude and rate of runoff.

The total rainfall which falls in an event does not all contribute to run-off. Many precipitation loss processes occur which reduce the effective rainfall converted to run-off. Some rainfall fills depression storages on the ground surface, some is lost by interception from vegetation while some infiltrates into the ground. A conceptual model known as the “Initial Loss – Continuing Loss model” is widely used in Australia and is adopted for this study.

The initial loss component represents a depth of rainfall effectively lost from the system and not contributing to runoff and simulates the wetting up of the catchment to a saturated condition. The continuing loss represents the rainfall lost through soil infiltration once the catchment is saturated and is applied as a constant rate (mm/hr) for the duration of the runoff event.

To determine the correct volume of rainfall run-off, the two most important land categories in this study are roads and roof tops which together represent greater than 55% of the total area.

The remaining land categories for defining rainfall losses have been derived based on the City of Sydney Local Environmental Plan (LEP) Zones.

The rainfall loss parameters for the historical calibration/validation events and design events are discussed in further detail in Section5.

4.3 Hydraulic Model

BMT WBM has applied the fully-2D software modelling package TUFLOW. The 2D model has distinct advantages over 1D and quasi-2D models in applying the full 2D unsteady flow equations. This approach is necessary to model the complex interaction between watercourses and floodplains and converging and diverging of flows through structures. The floodplain topography is defined using a high resolution Digital Terrain Model (DTM) for greater accuracy in predicting flows and water levels and the interaction of stormwater drainage network and floodplain areas.

4.3.1 Topography

The ability of the model to provide an accurate representation of the flow distribution on the floodplain ultimately depends upon the quality of the underlying topographic model. For the City Area catchment, a 2m by 2m gridded DTM has been derived from the ALS survey provided by Council.

The ground surface elevation for the TUFLOW model grid points are sampled directly from the DTM. It is a representation of the ground surface and does not include features such as buildings or vegetation. In the context of the overland flow path study, a high resolution DTM is important to suitably represent available flow paths, such as roadway flows that are expected to provide significant flood conveyance within the study area. Experience has proved this to be a successful approach and enables detailed simulation of flooding from overland flow paths.

Owing to some limitations of the ALS data capture method, preparation of the DTM for the City Area study area required additional ground level points and breaklines to be defined to ensure a coherent and correct DTM was achieved for this study. In particular, focus was given to ensuring that the full flow width along the road network was correctly defined.

The resulting topography of the hydraulic model is illustrated in Figure 2-3.

4.3.2 Buildings

The influence of buildings and other obstacles to the passage of flow in urban floodplains is an important issue in the context of urban floodplain management (Engineers Australia, 2012a). In a typical urban floodplain, some buildings will be elevated on fill and totally obstruct the passage of floodwater, others may be inundated with floodwater ponding inside the building, whilst others may be elevated on piers allowing flow under the building.

Based on a visual assessment of the range of buildings throughout the City Area catchment and the likely effect of buildings on the passage of floodwater, buildings have been represented in the TUFLOW model by removing the building footprints from the active model area. This assumption means that floodwater does not pass through and must flow around buildings.

The building footprints across the study area have been based on the footprints provided by Council. Buildings not contained within Council's building footprint dataset have been manually defined using available NearMap aerial photography dated July 2013.

Removing the buildings from the active model area impacts on the underlying assumptions with using the direct-rainfall approach adopted for the hydrological modelling component of the City Area model, whereby the model will not account for rain falling on model cells within the building footprints. Flow originating from rainfall on buildings has been included in the model using the methods described in Section 4.3.6.

4.3.3 Underground Carparks

The Sydney City Area catchment has numerous underground car parks. In large flood events the car parks may be inundated and act as temporary flood storages if the entrance level is below the flood level. Car parks however are not intended to be inundated in large floods and therefore have not been included in the modelling.

Upon delivery of this flood study, future works can assess the suitability of current flood protection afforded by car park entrance levels and recommend upgrades if necessary to make the car parks flood free.

4.3.4 Stormwater Drainage Network

This study required the modelling of the stormwater drainage system across the catchment. Information on the pit and pipe drainage network has been compiled from various sources, as discussed in Section 2.2.9.

The review of the available stormwater drainage system found the data to be largely complete along the main drainage lines. In areas where no pipe survey was available pipe size details were assumed from upstream and downstream configurations. The invert levels were interpolated between known locations, maintaining the upstream and downstream pipe gradients where appropriate. These were then cross-checked against the DTM elevations to take account of any local topographic features and to maintain minimum cover levels. Model results demonstrate limited sensitivity to adopted conduit parameters (Section 8) and therefore the pipe assumptions are considered to provide an appropriate representation of the pipe system.

Tank Stream from Martin Place downstream to Sydney Cover is presented as a sample longitudinal profile in Figure 4-1. This figure depicts the invert and obvert levels according to culvert dimensions, the ground surface level as derived from the DTM, and a minimum cover level of 500mm.

All known stormwater pits and pipes within the study area have been included in the TUFLOW model. The study area contains a number of locations that would drain poorly without the inclusion of the pipe network. Modelling all pipes ensures that the drainage of these areas is well represented.

The pipe network, represented as a 1D layer in the model, is dynamically linked to the 2D domain at specified pit locations for inflow and surcharging, as illustrated in Figure 4-2.

The modelled pipe network, comprising approximately 2440 pipes and has a combined run length of over 27km, is shown in Figure 2-5.

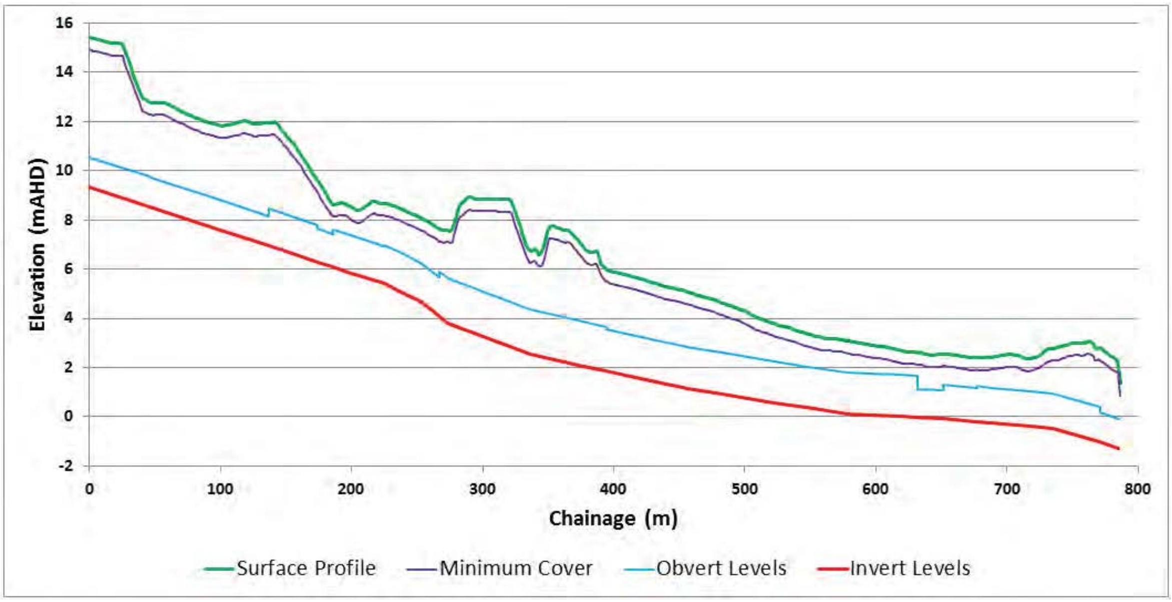


Figure 4-1 Sample Stormwater Drainage Line Longitudinal Profile

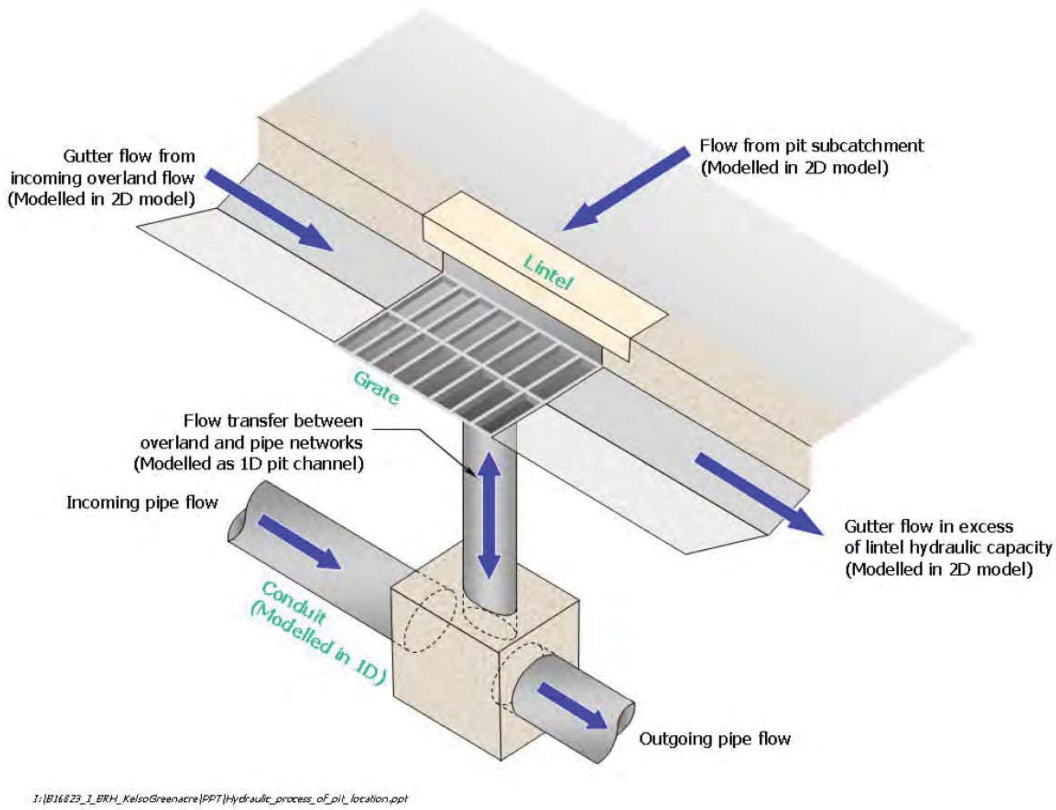


Figure 4-2 Linking underground 1D stormwater drainage network to the overland 2D domain

Pit inlet capacities have been modelled using lintel opening lengths and grate sizes based on the collected data. Pit inlet dimensions have been assumed where data were not available, based on site inspections and nearby pits. Pit inlet curves have been developed using an industry standard approach which rely on laboratory tests by the NSW Department of Main Roads and are considered sufficiently reliable for the purpose of this study. The pit inlet curves for a number of lintel opening and grate sizes, as applied in the TUFLOW model, are presented in Appendix D.

For the magnitude of events under consideration in the study, the pipe drainage system capacity is anticipated to be exceeded with the major proportion of flow conveyed in overland flow paths. Therefore any limitations in the available pipe data or model representation of the drainage system is expected to have little effect on results (see Section 8 full pit blockage sensitivity analysis).

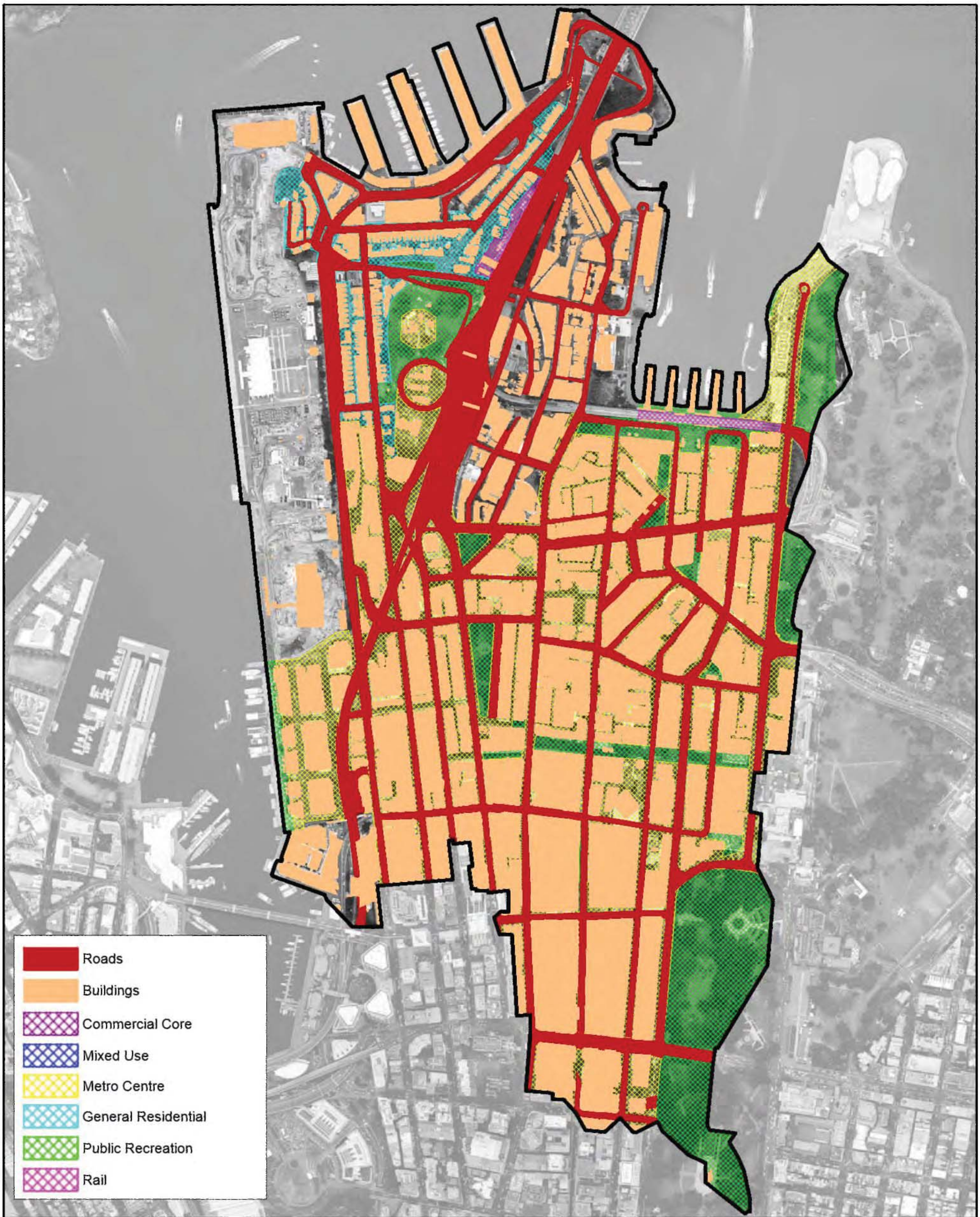
4.3.5 Hydraulic Roughness

The development of the TUFLOW model requires the assignment of different hydraulic roughness (Manning's 'n') zones. These zones are delineated from aerial photography and cadastral data identifying different land uses (e.g. vegetation, cleared land, roads, urban areas, etc.) for modelling the variation in flow resistance. The GIS layers and aerial photography supplied by Council has been used to generate the land use surface types and roughness zones for the study area. The base land use map used to assign the different hydraulic roughness zones across the model is shown in Figure 4-3.

The Manning's 'n' hydraulic roughness values adopted for each land use category are given in Table 4-1.

Table 4-1 Adopted Manning's 'n' hydraulic roughness values

Land Use Category	Manning's '*n*'
Roads	0.02
Public Recreation	0.05
Metro Centre	0.04
Rail Corridor	0.04
General Residential	0.04
Mixed Use	0.04
Commercial Core	0.04
Underground Pipes/Culverts	0.015



Title:

City Area Catchment Land Use Categories

Figure: 4-3

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

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4.3.6 Boundary Conditions

The model boundary conditions are derived as follows:

- Inflow – the catchment runoff is determined through the hydrological component of the model. With the direct-rainfall approach, rainfall is applied directly to every cell in the hydrologic catchment extent, where it is routed as sheet flow until the runoff contribution is substantial enough to generate an overland flow path. Flow is automatically transferred to the 1D domain where sufficient pipe and inlet capacity is available. Surcharging will then occur from the 1D to the 2D domain once the pipe capacity has been exceeded.
- Downstream Water Level – the downstream model limit corresponds to the tidal water level in Sydney Harbour. A water level boundary has been applied at this location for the duration of the modelled events to both 1D and 2D model components.

As discussed in Section 4.2, a direct-rainfall approach has been adopted in the TUFLOW hydraulic model to determine the catchment inflows. As buildings have been removed from the TUFLOW model (refer to Section 4.3.2), rainfall volume corresponding to each building footprint is therefore not accounted for in the direct-rainfall input. Rain falling on buildings has been accounted for in the TUFLOW model by using appropriate boundary features to calculate the runoff from each building, allocating the calculated flow around the perimeter of each building. This method has ensured that all rain falling on the buildings has been accounted for and represented as contributing to overland flow.

5 MODEL CALIBRATION AND VERIFICATION

5.1 Introduction

A key stage of the model development is calibration and verification. This demonstrates the models ability to replicate flooding using recorded inputs from real historic storms.

In order to undertake a full calibration process, the two types of required information could be summarised as model inputs and accounts of flood behaviour.

Model Inputs

Model inputs include historic rainfall depths recorded from pluviometers and corresponding historic records of Harbour water levels. Land use conditions and details of the stormwater network current for each historic event are also required.

Accounts of Flood Behaviour

Accounts of flood behaviour include gauged flows at downstream catchment locations and surveyed peak water levels marks across the catchment. Anecdotal descriptions of flood behaviour are also important though can be a less reliable record of flooding.

For the City Area catchment, model inputs for the majority of key historic flood events are well known. Observatory Hill has a long record of rainfall data and long records of Harbour water levels recorded at Fort Denison are available. What is limiting, is the accounts of flood behaviour. The value of the calibration process in simulating historic flood events in the Flood Study model may be limited if the results cannot be compared with reliable accounts of the actual flood behaviour.

In the City Area catchment, there are not any flow gauges in the catchment to compare modelled flows and no survey of peak flood levels have been undertaken following historic flooding. Anecdotal accounts of flooding are available from Sydney Water records and from community consultation undertaken during the study.

5.2 Selection of Calibration Events

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

Review of the available data for the City Area catchment, including the community consultation data, showed there are very few events with any recorded flood levels or observations of flood behaviour within the catchment. Table 5-1 summarises specific rainfall events identified from the community consultation which resulted in flooding of property in addition to events extracted from the Sydney Water Corporation Historic Flood Database. In most instances, exact dates were not reported by community respondents requiring the date to be assumed following analysis of available rainfall data.

Table 5-1 Available calibration data for the City Area catchment

Storm Event	Locations with Reported Flooding	Community Consultation	Sydney Water Corporation Database
March 2012	1	✓	
June 2013	1	✓	
22 August 1984	1		✓
5 November 1984	2		✓
8 November 1984	6		✓
6 January 1989	3		✓
26 January 1991	3		✓

Following assessment of available rainfall and tidal data and the events listed in Table 5-1, the 8 November 1984 and 26 January 1991 events were selected for the model calibration and verification process. Whilst there were no specific reports of flooding associated with the event, the 8 March 2012 event has been used to verify general flooding behaviour within the City Area catchment.

Referring to the feedback received from the community consultation exercise, not all respondents indicated the dates upon which the reported flooding behaviour occurred. To maximise the value of the community consultation, it was desirable to consider all reports of flooding from residents even when the flood event was not specified. Accordingly, reports of general flooding behaviour and observed flow paths, not attributed to any specific storm event, were considered in the model validation process. The 8 March 2012 was simulated as an additional model validation event for comparison with the community observations in relation to flow paths and general flooding behaviour.

The distribution of rainfall gauge locations in the vicinity of the City Area catchment is shown in Figure 2-2. Given the proximity of the Observatory Hill gauge to the City Area catchment, the rainfall data from Observatory Hill has been applied uniformly across the City Area catchment for all events assessed.

5.3 Model Parameters Adopted for Calibration

For all calibration events modelled, the same parameter values have been adopted for rainfall losses and hydraulic roughness. Given the paucity of calibration data across the study area, there was insufficient justification for varying values for these parameters between the different events being modelled. The values adopted for these parameters are summarised in Section 5.10.

5.4 Model Calibration – 8 November 1984

5.4.1 Rainfall and Harbour Water Level Data

Figure 5-1 shows the recorded Harbour water levels at Fort Denison and rainfall depths recorded at Observatory Hill. A total rainfall depth of approximately 190 mm fell over a 3 hour period with the peak of the rainfall occurring at 10:00 PM, coinciding with a low tide level of 0.4m AHD.

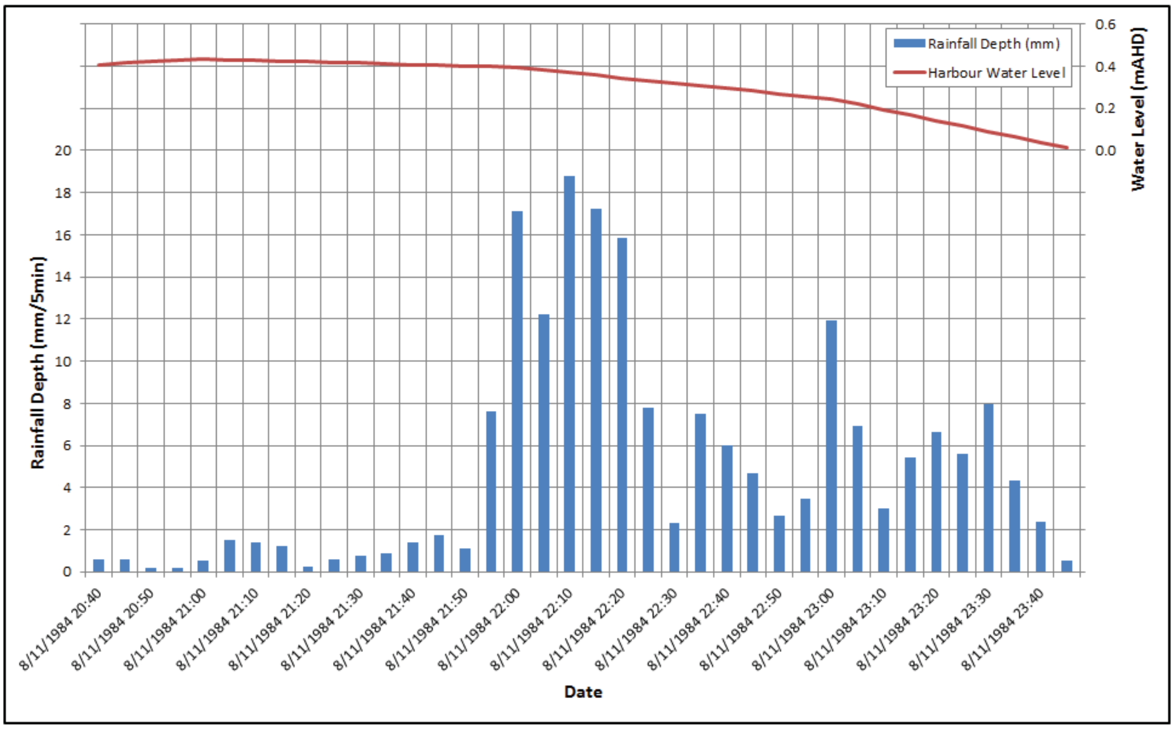


Figure 5-1 Recorded rainfall and harbour water level – 8 November 1984

The recorded rainfall depths at the Observatory Hill rainfall gauge have been compared with the design IFD data, as shown in Figure 5-2. This indicates that the rainfall event was of a magnitude comparable with a 500 year ARI design rainfall event for durations between 30 minutes and 3 hours. In the 4 days prior to the event, 220 mm of rainfall was recorded at Observatory Hill. This rainfall largely fell as part of the 5 November 1984 event which was noted in Table 5-1.

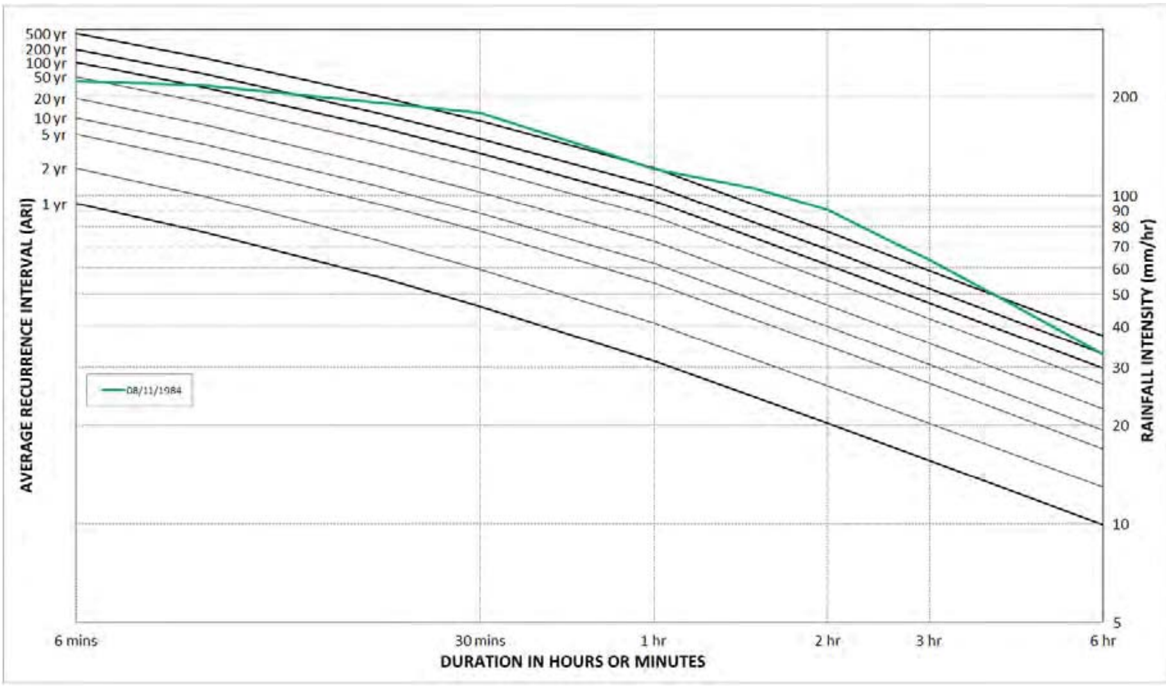


Figure 5-2 Comparison of 8 November 1984 rainfall with IFD relationships

5.4.2 Observed and Simulated Flood Behaviour

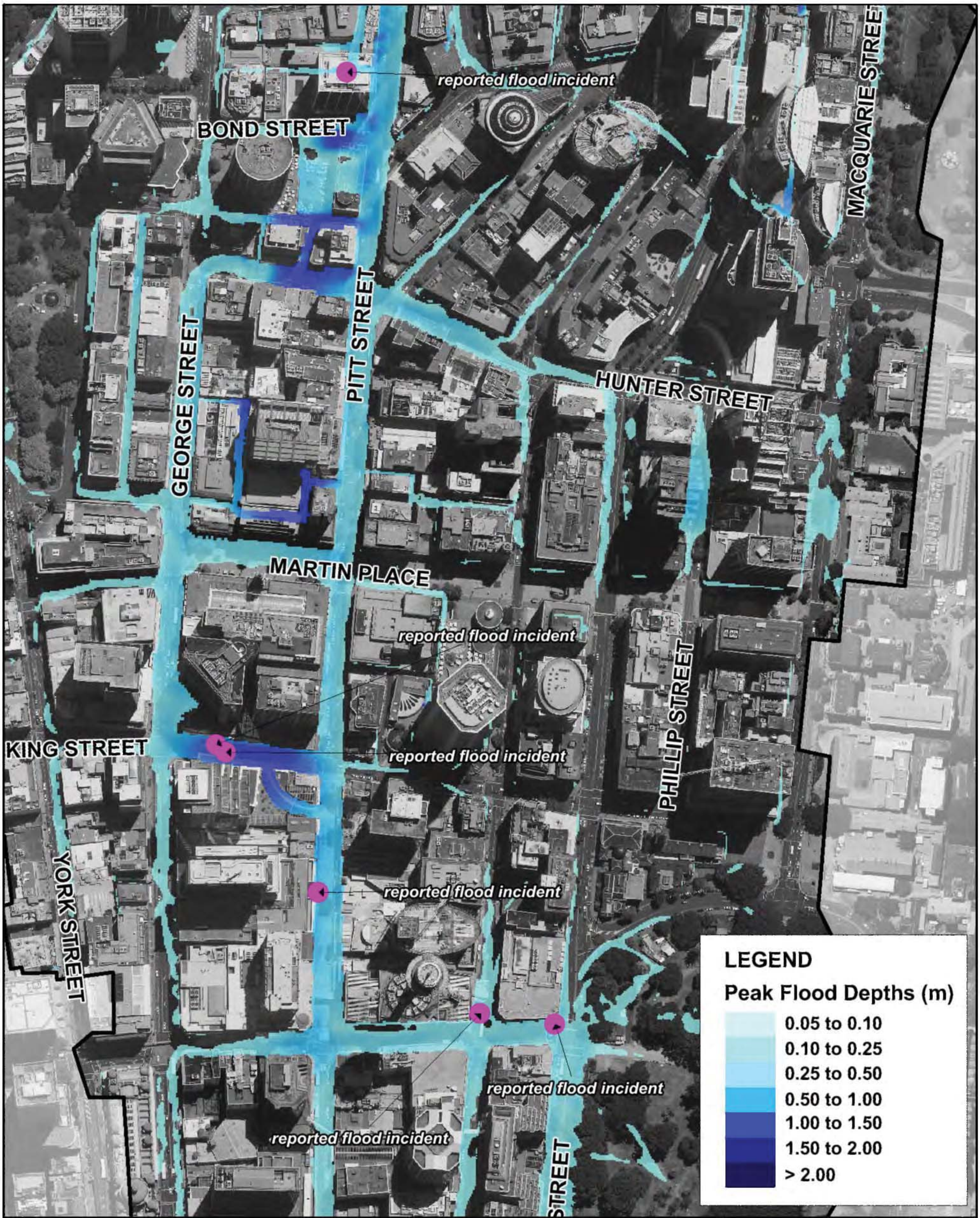
Six reports of flood behaviour for the 8 November event are available in the City Area catchment. These flooding reports are sourced from the Sydney Water Corporation Historic Flood Database and are presented below. Figure 5-3 shows the peak depth results from this calibration event and shows locations of each of these reports of flooding.

- Pitt Street (between Bond Street and Abercrombie Lane), Sydney: Build-up of water in the street that subsequently swept into the reported property.
- Pitt Street Mall, Sydney: Water flowed down Pitt Street above the footpath level and flooded shops on the George Street side. Water depths of at least 300 mm were observed.
- King Street (between George and Pitt Streets), Sydney: In King Street between George Street and Pitt Street: Water ponded in the sag to a depth exceeding the footpath level.
- Corner of Market Street and Elizabeth Street, Sydney: Flooding above footpath.
- Castlereagh Street (near Market Street), Sydney: Flooding above footpath.
- King Street (between George and Pitt Streets), Sydney: Build-up of water in King Street sag. Flood level exceeded entry level of car park for property associated to flooding incident.

As shown in Figure 5-3, the results of the 8 November 1984 calibration event compares well with the observed flooding behaviour, summarised as follows:

- On Market Street at its intersection with both Castlereagh Street and Elizabeth Street, the peak flood depth is approximately 0.2 m which would result in above kerb flooding.
- The flood depth along Pitt Street Mall ranges from 0.2 m to 0.5 m. This modelled depth correlates well with the estimated depth of 0.3 m reported in the Flood Database.
- At the sag on King Street between Pitt Street and George Street, the model is predicting a peak depth of 1.2 m. As discussed in Section 4, car parks have not been explicitly considered in this study; however the predicted peak flood depth at this location is likely to be sufficient to cause flooding of the car park.
- The flood level which resulted in the reported flooding at Pitt Street between Bond Street and Abercrombie Lane is not known. The modelling shows that over 0.5 m depth of water ponded in front of the building for this event.

Based on the available data, the model is considered to be adequately representing the observed flooding behaviour for the 8 November 1984 event.



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Peak Flood Depth - Verification Event 8 November 1984	5-3	A

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5.5 Model Calibration – 26 January 1991

5.5.1 Rainfall and Harbour Water Level Data

Figure 5-4 shows the recorded Harbour water levels at Fort Denison and rainfall depths recorded at Observatory Hill. A total rainfall depth of approximately 65 mm fell over a 1 hour period with the peak of the rainfall occurring at 2:55 PM which coincided with a low tide level of -0.1m AHD.

The recorded rainfall depths at the Observatory Hill rainfall gauge have been compared with the design IFD data, as shown in Figure 5-5. This indicates that the rainfall event was of a magnitude comparable with a 50 year ARI design rainfall event for a 25 minute duration.

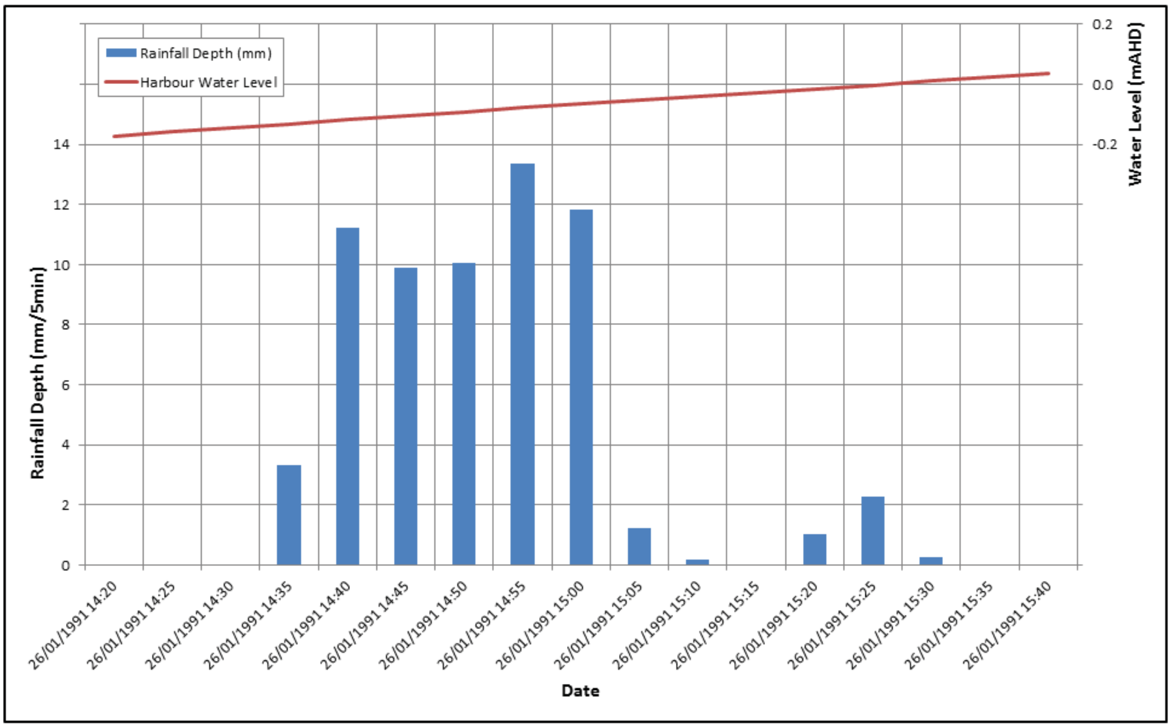


Figure 5-4 Recorded rainfall and harbour water level – 26 January 1991

5.5.2 Observed and Simulated Flood Behaviour

Three reports of flood behaviour for the 26 January 1991 event are available in the City Area catchment. These flooding reports are sourced from the Sydney Water Corporation Historic Flood Database and are presented below. Figure 5-6 shows the peak depth results from this verification event and shows locations of each of these reports of flooding.

- King Street (between George and Pitt Streets), Sydney: Build-up of water in King Street sag. Flood level exceeded entry level of car park for property associated to flooding incident.
- Bond Street, Sydney: Water flowed down the car park ramp in Bond Street.
- Macquarie Place (corner of Alfred and Loftus Streets), Sydney: Water ponded above the kerb level to approximately ankle depth.

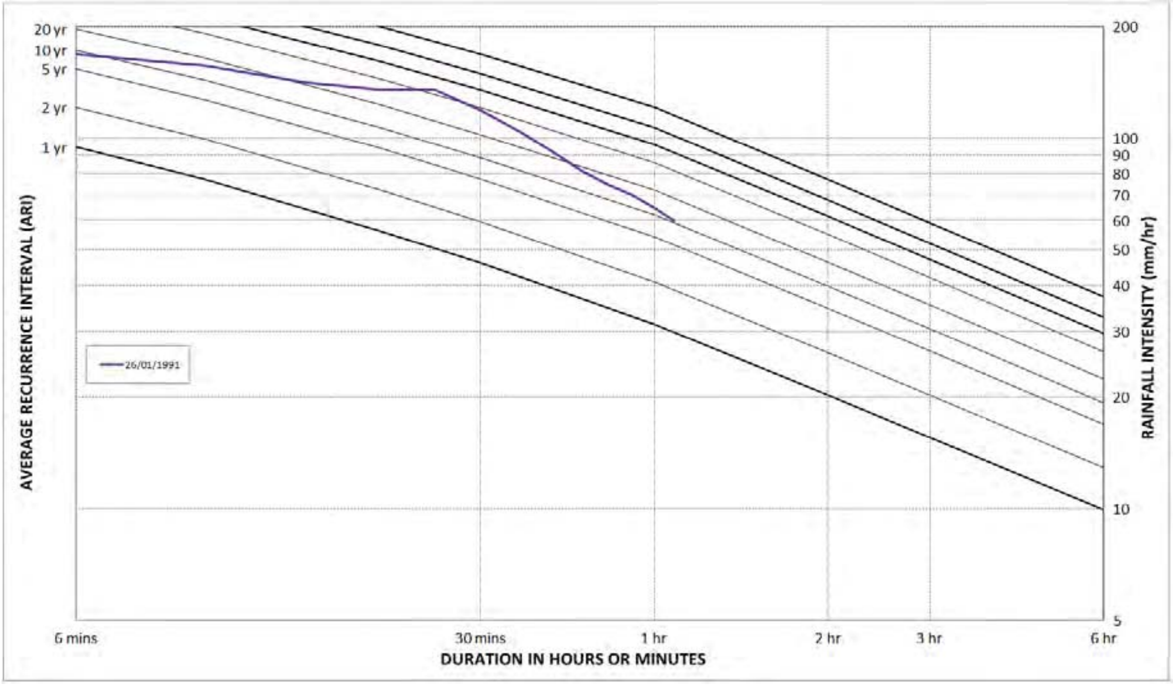


Figure 5-5 Comparison of 26 January 1991 rainfall with IFD relationships

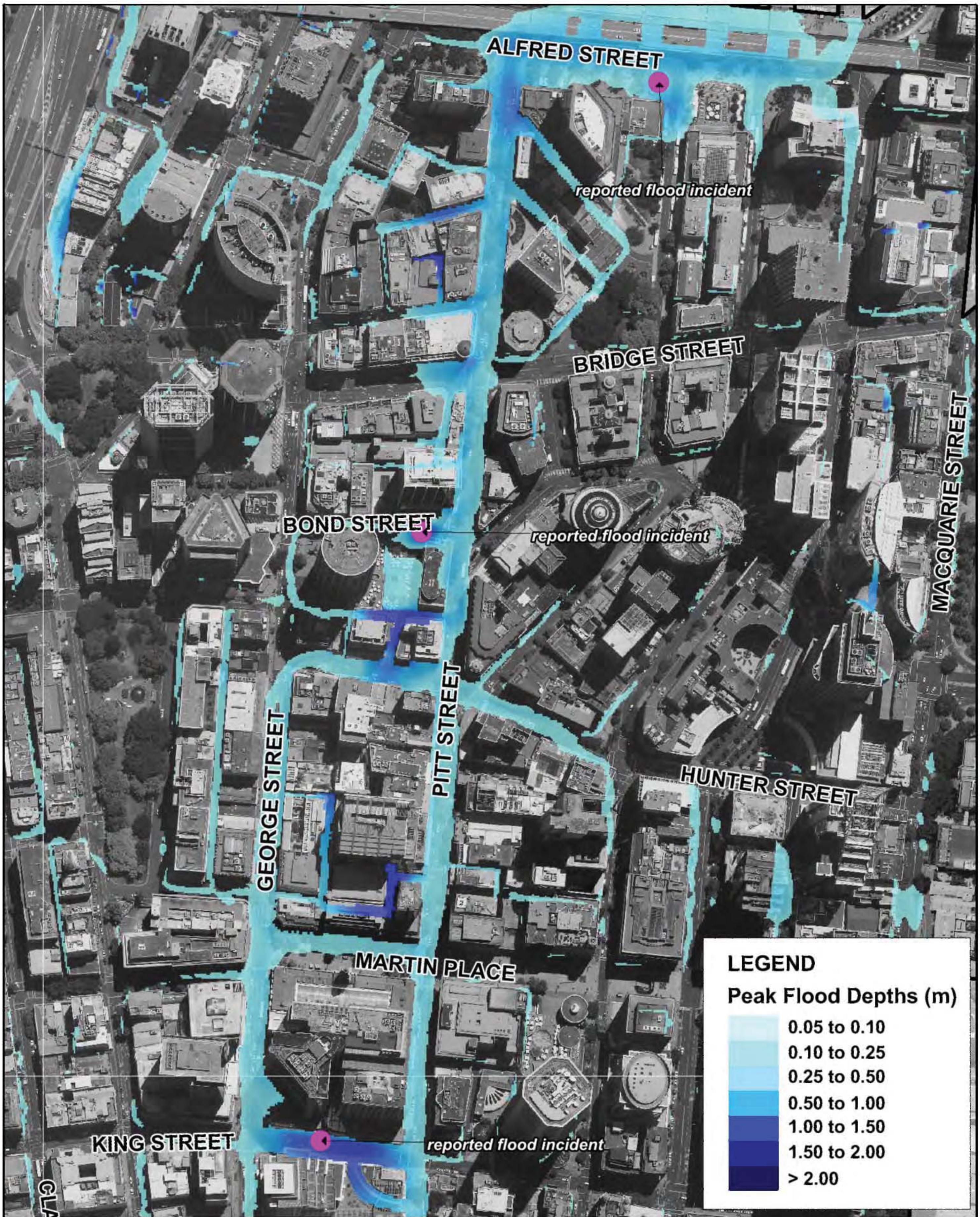
As shown in Figure 5-6, the TUFLOW model results of the 26 January 1991 calibration compares well with observed flooding behaviour, summarised as follows:

- The sag on King Street between Pitt Street and George Street was flooded in the January 1991 event as well as the November 1984 event. Calibration modelling for the January 1991 modelling shows that a peak depth of 1.1 m was is being predicted at this low point which is only 0.1 m less than occurred in the November 1984 event. The predicted peak flood depth at this location is likely to be sufficient to cause flooding of the car park.

- The water in Bond Street reached a maximum depth of 0.9 m in front of the entrance to the car park. This level is considered sufficient to trigger the reported filling of the car park

- At the corner of Alfred Street and Loftus Street, the model is predicting a depth of 300 mm which is slightly higher than the ankle deep estimate provided at this location.

Based on the available data, the model is considered to be adequately representing the observed flooding behaviour for the 26 January 1991 event.



Title:

Peak Flood Depth - Verification Event 26 January 1991

Figure: 5-6

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5.6 Model Calibration – 8 March 2012

5.6.1 Rainfall and Harbour Water Level Data

Figure 5-7 shows the recorded Harbour water levels at Fort Denison and rainfall depths recorded at Observatory Hill. A total rainfall depth of approximately 74mm fell over an 8 hour period with the rainfall event generally coinciding with a high tide level of 1.11m AHD.

The recorded rainfall depths at the Observatory Hill rainfall gauge have been compared with the design IFD data, as shown in Figure 5-8. This indicates that the rainfall event was of a magnitude comparable with a 2 year ARI design rainfall event for durations between 30 minutes and 6 hours.

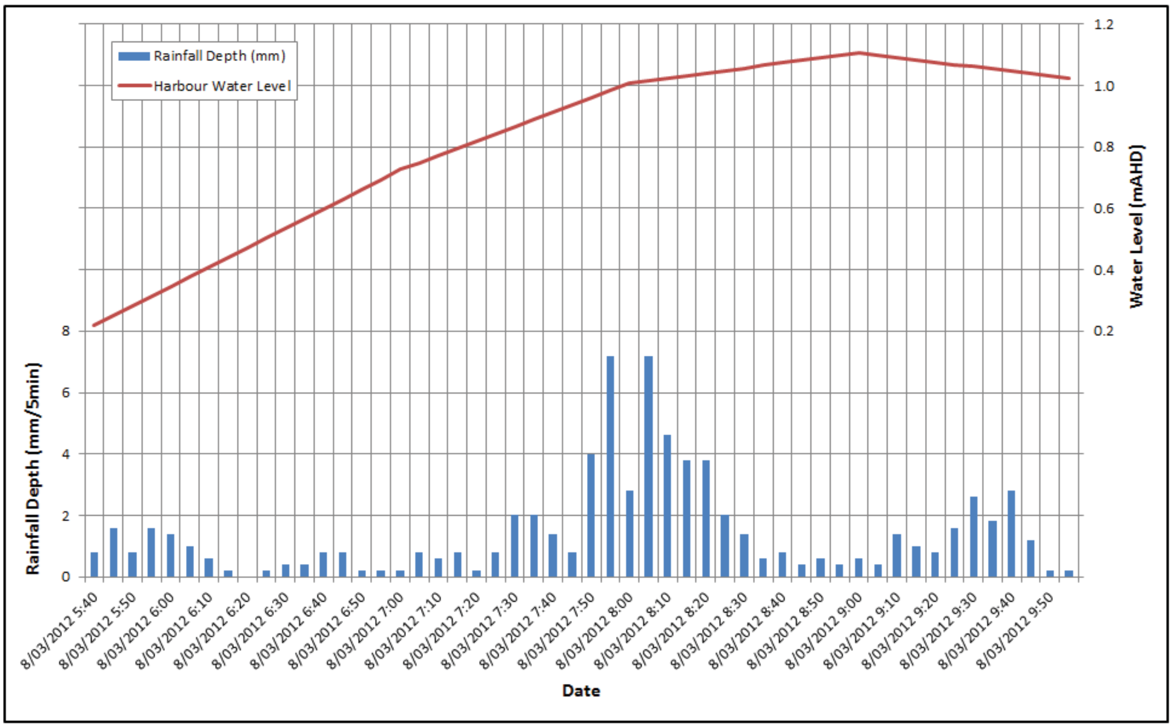


Figure 5-7 Recorded rainfall and harbour water level – 8 March 2012

5.6.2 Observed and Simulated Flood Behaviour

Results of modelling at the key locations reported by the community consultation respondents are discussed in the following sections.

5.6.2.1 Hickson Road, Walsh Bay

A longer term resident (9 years) reported flooding in a basement garage on Hickson Road. The road is further reported to be flooded after intense storms. Figure 5-9 shows the flooding in the area. As shown, the street is flooded above kerb level which would provide the opportunity for flows to enter basement levels through driveways or other road level entrances. This modelled level of road inundation provides support to the observations from the resident.

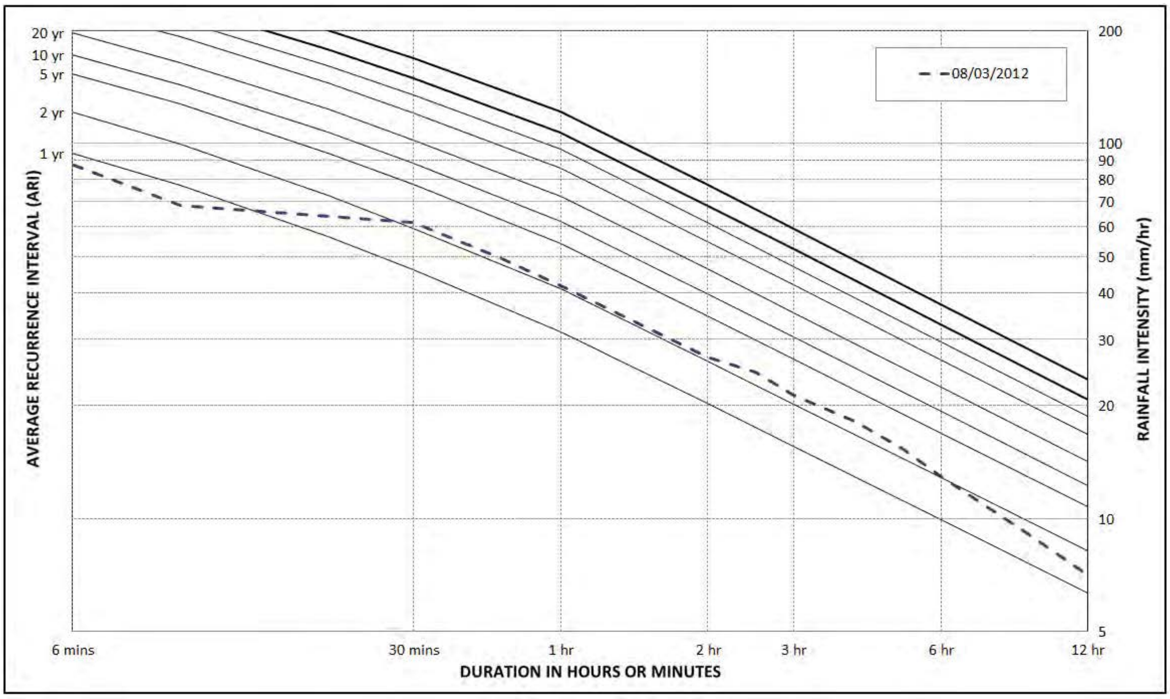


Figure 5-8 Comparison of 8 March 2012 rainfall with IFD relationships

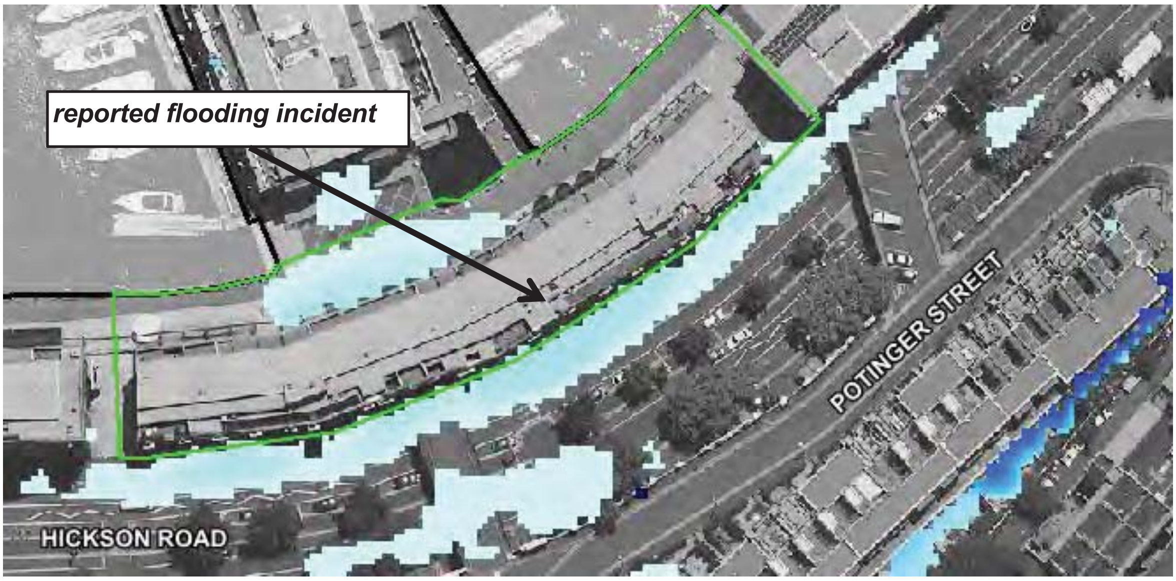


Figure 5-9 Flooding reports on Hickson Road, Walsh Bay

5.6.2.2 Gloucester Street, The Rocks

A resident on Harrington Street reported that regular flooding occurs at the low point on Gloucester Street. The low point on Gloucester Street is not effectively drained and the standing water which remains after rainfall events seeps into the basement storage below. The same resident reported that the footpath on the western side of Cumberland Street (near the intersection with Essex Street) has standing water after every rainfall event. Figure 5-10 shows results of flooding in the area near Gloucester Street.

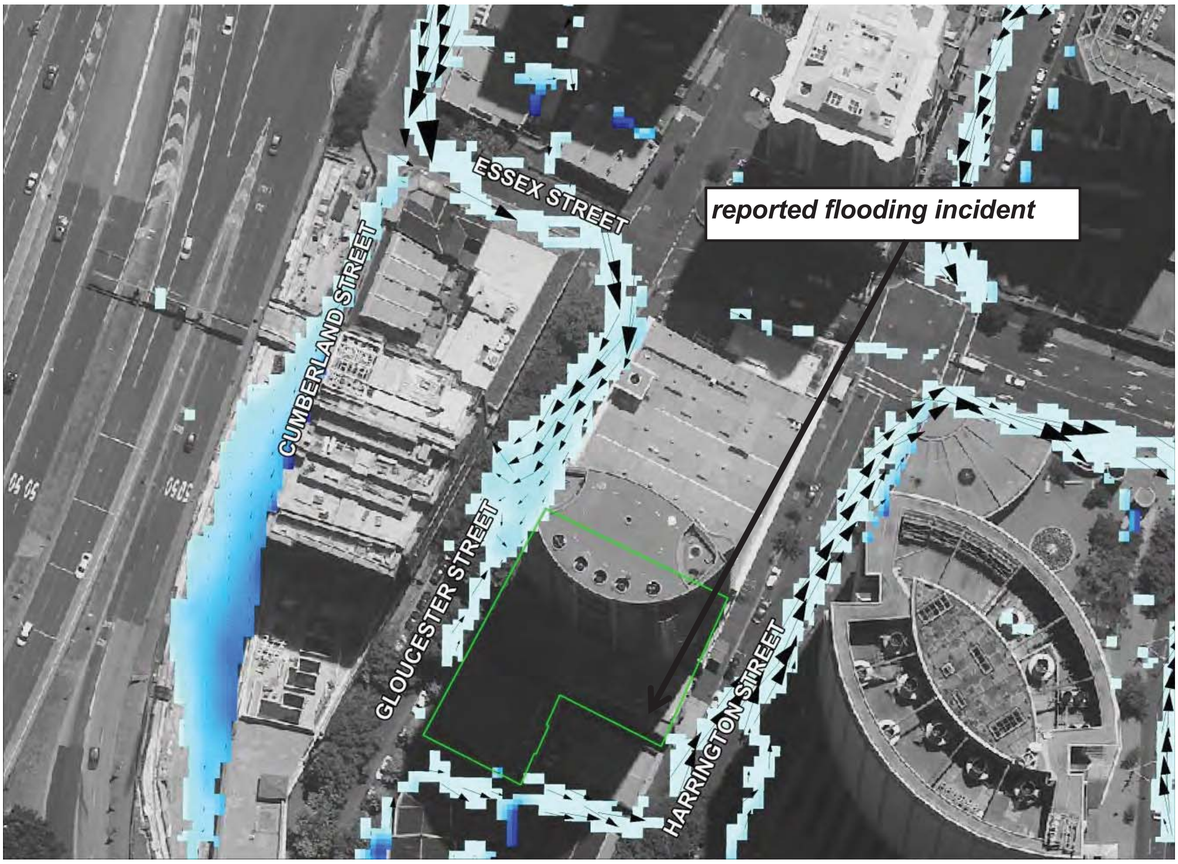


Figure 5-10 Flooding reports on Gloucester Street, The Rocks

The results presented in Figure 5-10 demonstrate that the model is simulating the observed flooding behaviour on Gloucester Street and at the corner of Essex Street and Cumberland Street. Overall the model is produces flood behaviour generally consistent with the reports obtained via the community consultation.

5.7 Historical Accounts of Flooding from TROVE database review

Section 2.4 presents results of a review of newspaper articles for further insight into key historic flood events and flood behaviour within the City Area catchment. The database details were restricted to flooding events prior to approximately 1950. Catchment conditions, including stormwater drainage infrastructure and extent of development, are likely to be significantly different now compared with conditions at the time of these historical records which limits the validity of using these details for model calibration. However, these historic details can be useful to verify that flooding occurs in the reported locations, thus validating the modelling tool developed for this study. A comparison of the reported flood mechanisms has been made with modelled conditions of the 8 March 2012 event.

In the City Area catchment the key accounts of flooding are as follows:

- Circular Quay flooded to depth of 1-4 feet (April 1949, March 1914)
- Pitt Street Flooded (1877, 1878, 1912, 1913, 1938 and 1949)

- Main flow path has been identified as Market Street, Elizabeth Street and Park Street from Hyde Park (October 1877, August 1878, June 1949)

Flooding behaviour predicted by the model in the vicinity of Circular Quay is shown in Figure 5-11. Historic accounts of flooding report that flooding has previously occurred to depths of 1- 4 ft in this general area. The modelling shows that this location is susceptible to flooding. Upstream overland flows, mainly from Pitt Street, flow rapidly in a northern direction towards Circular Quay and Sydney Harbour. Alfred Street is relatively flat and upstream flows spread out at this location before flowing under the Cahill Expressway to Sydney Harbour. For the March 2012, January 1991 and November 1984 calibration events, the modelled depths at Alfred Street range from very shallow depths to 0.9m. This supports the historic reports of this area being flood prone.

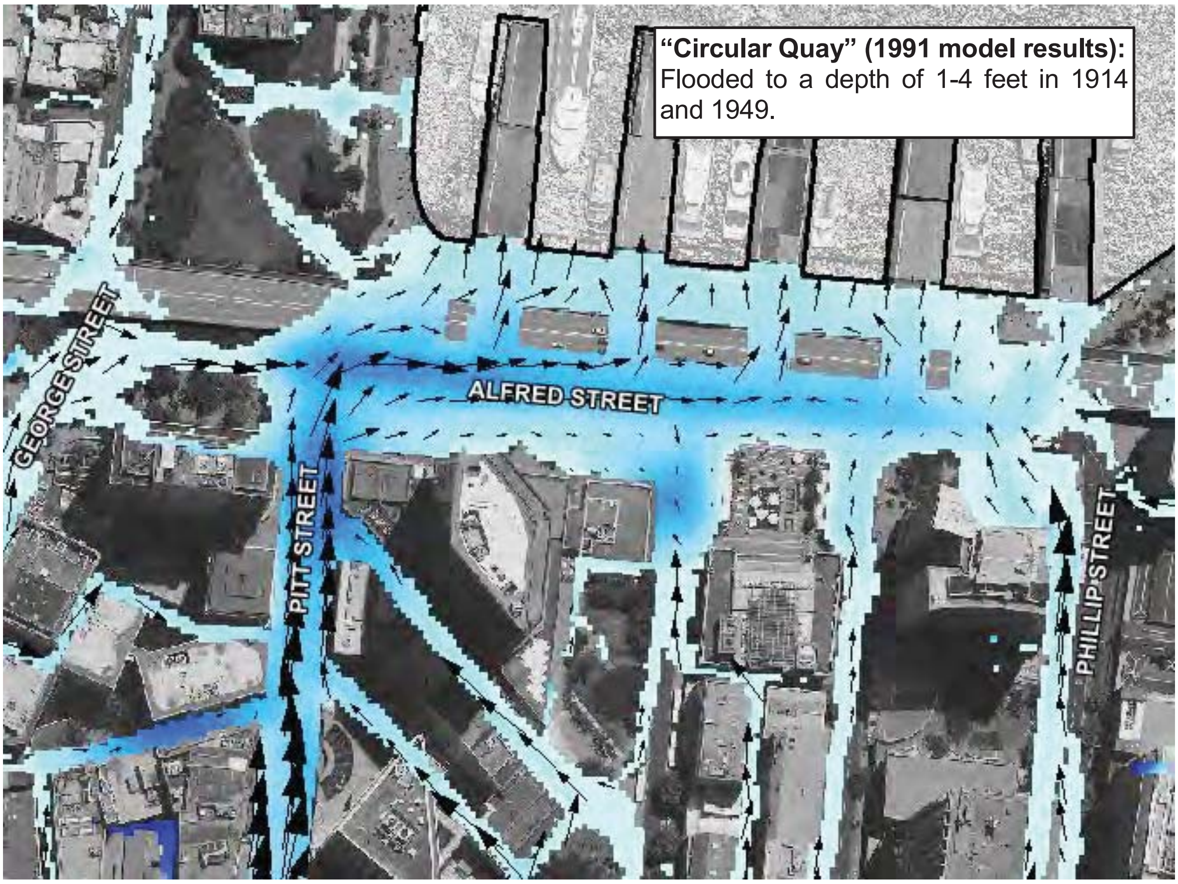


Figure 5-11 Historic flooding reports at Circular Quay.

Pitt Street has a long history of flooding incidents. A descriptive passage from an evening news broadcast on 1 August 1878 sets the standard for the flood potential:

"In less than a quarter of an hour from the commencement of what we call nothing less else than a deluge, a boat might have been pulled along Pitt Street from Market Street to King Street, and in King Street from Pitt Street to George Street"

Historic accounts of flooding refer to storms in 1877, 1878, 1912, 1913, 1938 and 1949. Further reports of flooding were noted for the November 1984 event where water reached a depth of at least 300 mm which exceeded the kerb level and flooded adjacent shops.

Figure 5-12 supports the historic accounts of Pitt Street functioning as an overland flow path. Figure 5-12 further shows that Pitt Street flows are generated from flows along Market Street and Park Street which convey Hyde Park run-off.

Figure 5-12 Historic flooding reports on Pitt Street and from Hyde Park

Due to the anecdotal nature of the newspaper flood reports and the fact that the reported flood events occurred over 130 years ago, these flood observations could not be strictly used as a calibration data set. Replication of the general flow behaviour however has proven valuable in validating the model schematisation.

5.8 Historical Accounts of Flooding from SWC Records

As presented in Section 2.3 SWC has an extensive database of historic flood reports. Reports of flooding prior to 1983 were not considered as calibration events since the catchment conditions which resulted in the flooding are unknown. However, these historic details can be useful to verify that flooding occurs in the reported locations, thus validating the modelling tool developed for this study. A comparison of the reported flood mechanisms has been made against those modelled by the 8 March 2012 event.

Figure 5-13 and Figure 5-14 shows the SWC flooding reports which weren't included as part of the model calibration. It is noted that the location of these flooding reports are approximate, since the address references often refer to buildings which no longer exist.

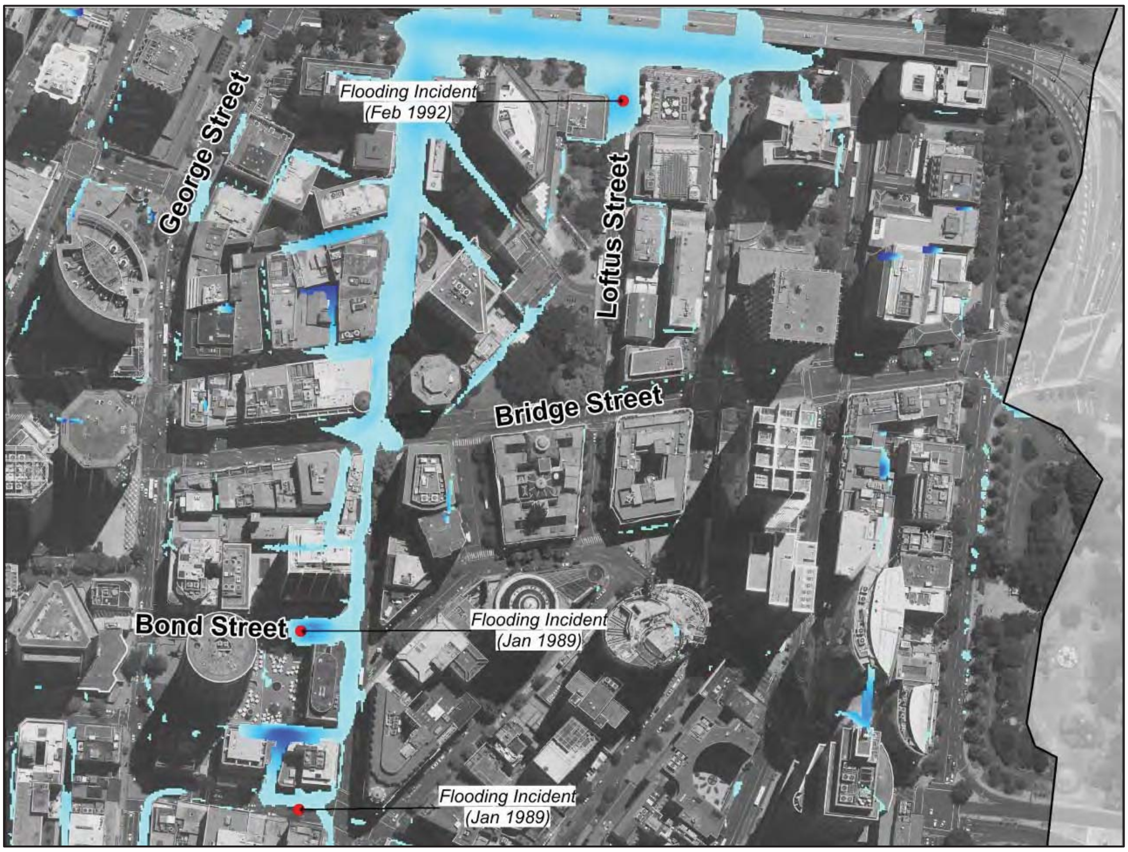


Figure 5-13 SWC Historic flooding reports in Haymarket area

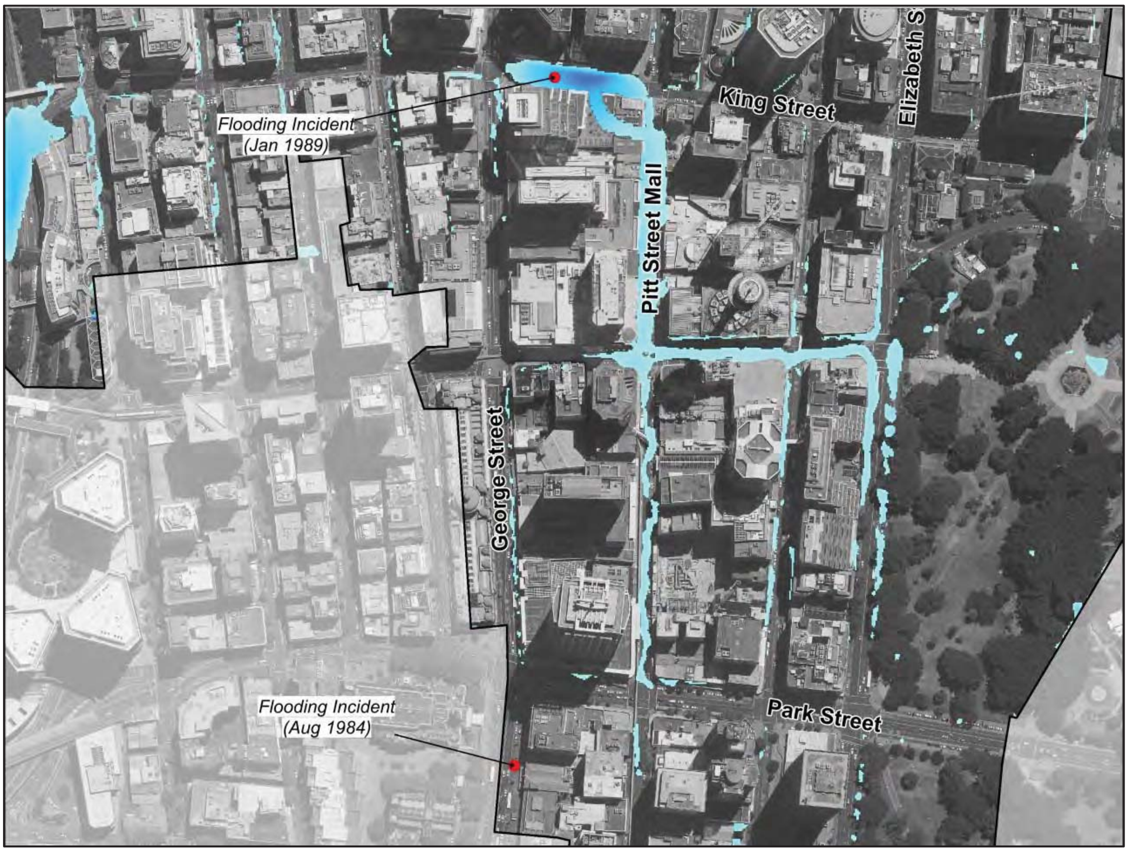


Figure 5-14 SWC Historic Flooding reports in Ultimo Area

As presented in Figure 5-13 and Figure 5-14, the historic reports of flooding consistently affect the same locations. Further, current catchment flood modelling shows flooding still occurs at the historic locations.

Loftus Lane flooding was previously presented in the January 1991 calibration event. Flooding at this location was additionally reported to have occurred in January 1992 which resulted in street flooding.

The car park entrance in Bond Street was overtopped for the January 1989 event. This flooding mechanism had previously been reported for the January 1991 calibration event.

Hunter Street reported flooding in January 1989 resulting in a car park entrance being overtopped.

The King Street low point between George and Pitt Streets has numerous reports of flooding. January 1989 recorded another event which resulted in flooding at this location. For the 1989 event, the car park entrance in the low point was not overtopped.

In August 1984 it was reported that Town Hall Station and Sydney Square Arcade was inundated. Town Hall Station is on the divide between the Darling Harbour and City Area catchments and therefore flooding (without contributing factors such as a blockage event) is unlikely. Sydney Square Arcade couldn't be identified, therefore this report of flooding wasn't able to be used for verification.

At all locations, with the exception of the Town Hall Station flooding report, modelled flooding is shown to typically represent the observed flood behaviour.

5.9 Catchment Flow Verification

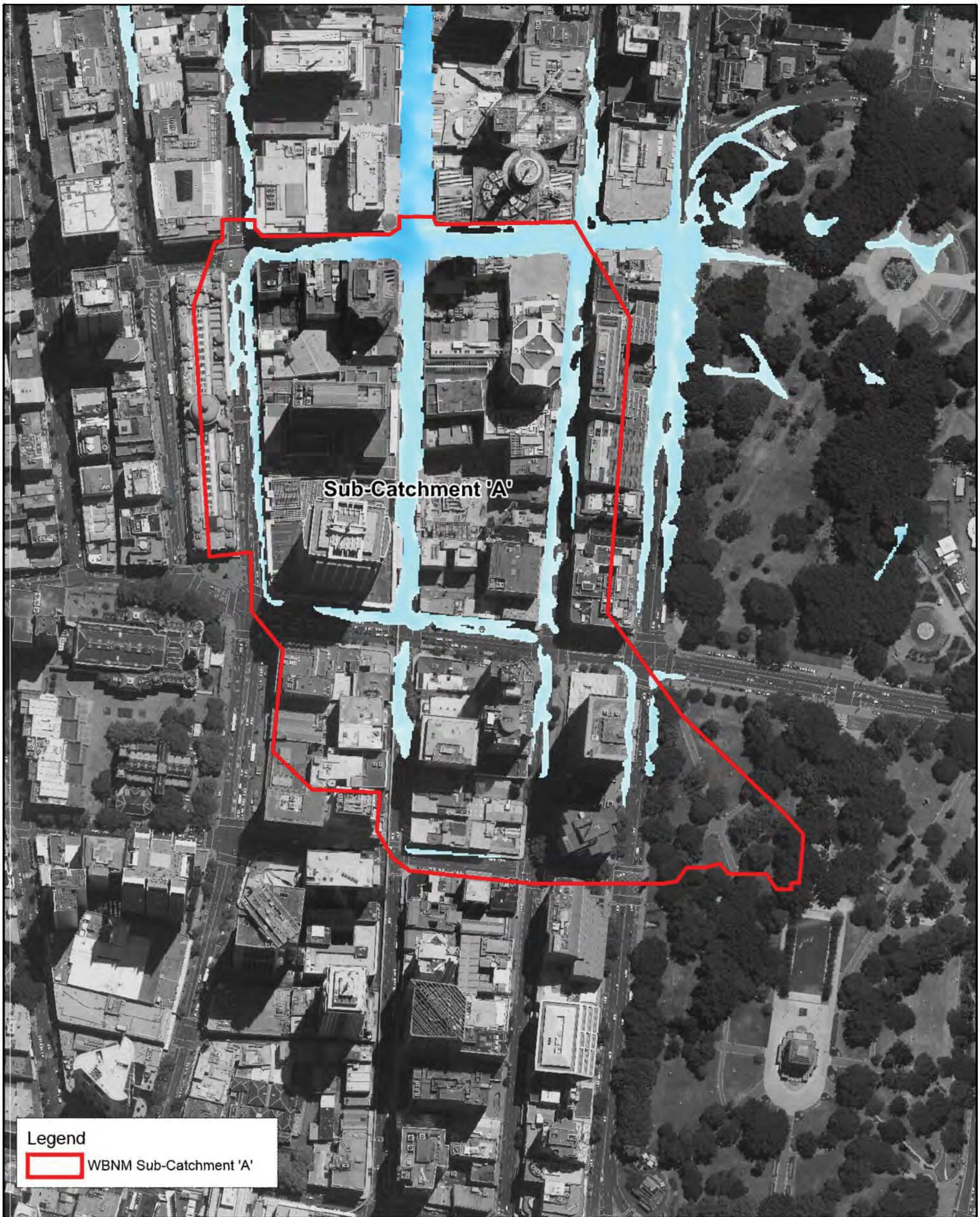
Verification of the adopted "direct-rainfall" approach for modelling the catchment hydrology has been achieved by undertaking additional hydrological modelling of selected sub-catchments within the overall study area using alternate modelling methods.

The verification approach involved setting up a WBNM model for a sub-catchment, as shown in Figure 5-15.

5.9.1 Watershed Bound Network Model (WBNM)

WBNM is a runoff-routing hydrological model used to represent catchment rainfall-runoff relationships. WBNM has been developed and tested using Australian catchments in the states of NSW, Queensland, Victoria and South Australia. WBNM models are developed on the basis of a catchment divided into a number of sub-areas based on the stream network. This allows hydrographs to be calculated at various points within the catchment, and the spatial variability of rainfall and rainfall losses to be modelled. WBNM separates overland flow routing from channel routing, allowing changes to either or both of these processes, for example in urbanising catchments.

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



Title:

City Area
Sub-Catchment for Catchment Flow Verification

Figure: 5-15

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5.9.2 Flow Verification Results

The WBNM model has been schematised using recommended parameters to represent the subject sub-catchments.

Modelling using both WBNM and the TUFLOW model developed for this study has been undertaken for the following design rainfall events:

- 10% AEP, 90 minute duration storm; and
- 1% AEP, 90 minute duration storm.

Comparisons between the calculated catchment discharge and the cumulative volume are given in Figure 5-16. The figure show that the flow generated by TUFLOW correlates well with the WBNM estimates. The following observations can be made:

- The timing of the rising limbs of the hydrographs compare favourably;
- The timing of the peaks and troughs in the hydrographs shape compare favourably;
- TUFLOW produces a slightly more 'peaky' catchment response with marginally higher peak flows; and
- WBNM produces a higher cumulative volume of runoff.

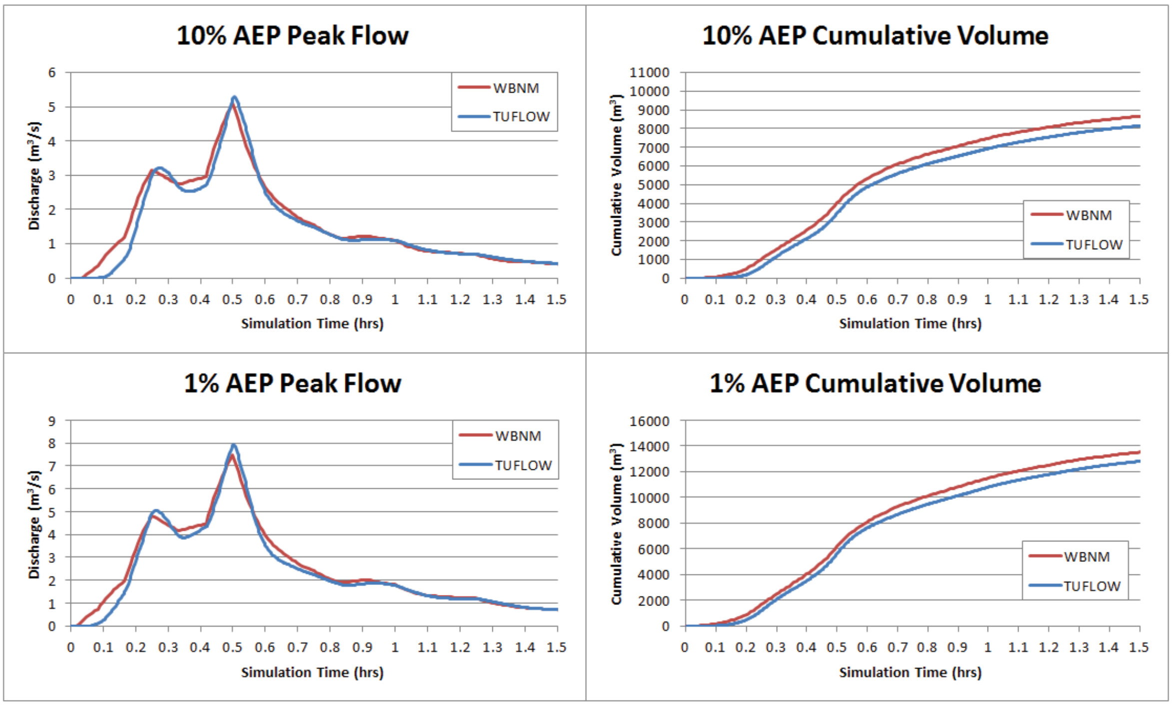

Figure 5-16 Catchment flow verification for sub-catchment 'A' (12.5ha area)

WBNM has been verified against empirical data and can therefore be relied upon to provide a reasonable estimate of the expected runoff for these sub-catchments. However, WBNM is a lumped catchment approach and does not represent all the physical features within the catchment which are being modelled in the TUFLOW model (e.g. steep, paved overland flow paths), which may explain some of the differences in the calculated hydrograph shapes.

The differences in cumulative volume can be attributed to the residual volume of water in the TUFLOW model (water trapped in storage) throughout the simulation. Once this residual volume has been taken into account, the difference between the total volume calculated between the two methods is less than 2%.

The good correlation demonstrated between the two modelling methods indicates that the modelling methodology adopted for the City Area Flood Study provides a reasonable basis to assess overall flood behaviour.

5.10 Model Parameters Adopted for Design Event Modelling

The values for the Manning's '*n*' roughness and rainfall infiltration losses developed for the defined land use categories (refer to Figure 2-4) determined through the model calibration and validation process and adopted for design event modelling are shown in Table 5-2.

Table 5-2 Adopted TUFLOW model parameters

Land Use Category	Manning's '*n*'	Fraction Impervious	Initial Loss (mm)	Pervious Area Infiltration Loss (mm/h)
Roads	0.02	100%	1.0	0.0
Buildings	N/A	100%	1.0	0.0
Public Recreation	0.05	10%	10.0	2.5
Metro Centre	0.04	90%	1.0	2.5
Rail Corridor	0.04	10%	1.0	2.5
General Residential	0.04	90%	1.0	2.5
Mixed Use	0.04	90%	1.0	2.5
Commercial Core	0.04	90%	1.0	2.5

5.11 Summary of Model Verification

Every effort has been made to fully utilise the limited historic accounts of flooding. In the absence of surveyed flood level records, anecdotal accounts of flood behaviour have been sourced from Sydney Water records and community consultation undertaken for this study. For all verification events, the model has demonstrated an ability to reasonably simulate observed flood behaviour as described by anecdotal reports.

To strengthen the verification process, historical accounts of flooding (some of which occurred over 60 years ago) have also been obtained. The general flood mechanisms described are well represented by the model.

Flows from TUFLOW have been compared to flows generated by WBNM. WBNM is a hydrological model which uses empirical relationships determined from Australian catchments. The peak flows and volume match well with the WBNM estimates.

Fully utilising the available information available, the developed model is demonstrated to be a suitable tool for design flood estimation.

6 DESIGN FLOOD CONDITIONS

Design floods are estimated floods used for planning and floodplain management investigations. They are based on having a probability of occurrence specified as either:

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

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

Table 6-1 Design flood terminology

ARI[1]	AEP[2]	Comments
500 years	0.2%	An estimated flood or combination of floods which represent the worst case scenario with a 0.2% probability of occurring in any given year.
100 years	1%	As for the 0.2% AEP flood but with a 1% probability.
50 years	2%	As for the 0.2% AEP flood but with a 2% probability.
20 years	5%	As for the 0.2% AEP flood but with a 5% probability.
10 years	10%	As for the 0.2% AEP flood but with a 10% probability.
5 years	18%	As for the 0.2% AEP flood but with a 18% probability.
2 years	39%	As for the 0.2% AEP flood but with a 39% probability.
PMF[3]		An estimated flood or combination of floods which represents the Probable Maximum Flood event possible.

1 Average Recurrence Interval (years)

2 Annual Exceedance Probability (%)

3 Probable Maximum Flood

The design events simulated include the PMF event, 0.2% 1%, 2%, 5%, 10%, 18% and 39% AEP events for catchment derived flooding and the 1 year ARI Sydney Harbour water level for ocean/tidal derived flooding. The 1% AEP flood is generally used as a reference flood for land use planning and control.

In determining the design floods it is necessary to take into account the critical storm duration of the catchment. Small catchments are more prone to flooding during short duration storms while for large catchments longer durations will be critical. For example, considering the relatively small size of the study area catchments, they are potentially prone to higher flooding from intense storms extending over a few hours rather than a couple of days.

6.1 Design Rainfall

Design rainfall parameters have been derived using standard procedures defined in *Australian Rainfall and Runoff – A Guide to Flood Estimation* (AR&R) (Pilgrim, DH, 2001) which are based on statistical analysis of recorded rainfall data across Australia. The derivation of location specific design rainfall parameters (e.g. rainfall depth and temporal pattern) for the City Area catchment is presented herein.

6.1.1 Rainfall Depths

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

The Probable Maximum Precipitation (PMP) is used in deriving the Probable Maximum Flood (PMF) event. The theoretical definition of the PMP is “the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of year” (Pilgrim, DH, 2001). The ARI of a PMP/PMF event ranges between 10^4 and 10^7 years. The PMP has been estimated using the Generalised Short Duration Method (GSDM) derived by the Bureau of Meteorology. The method is appropriate for durations up to 6 hours and considered suitable for small catchments in the Sydney region.

A range of storm durations from 15 minutes to 9 hours were modelled in order to identify the critical storm duration for design event flooding in the catchment. Table 6-2 shows the average design rainfall intensities based on AR&R adopted for the modelled events.

Table 6-2 Rainfall intensities for design events (mm/h)

Duration	2 YR ARI	5 YR ARI	10% AEP	5% AEP	2% AEP	1% AEP	0.2% AEP	PMP
15 min	83	108	122	140	164	182	222	640
25 min	66	85	97	112	132	148	180	n/a
30 min	60	78	89	103	122	136	166	480
45 min	48	63	72	84	99	111	136	400
1.00 h	41	53	61	71	84	95	116	350
1.50 h	32	42	48	56	66	74	91	300
2.0 h	26	35	40	46	55	62	76	265
2.5 h	23	30	35	40	48	53	n/a	232
3.0 h	20	27	31	36	42	47	58	213
4.0 h	n/a	n/a	n/a	n/a	n/a	n/a	n/a	183
4.5 h	16	20	23	27	32	36	44	n/a
5.0 h	n/a	n/a	n/a	n/a	n/a	n/a	n/a	160
6.0 h	13	17	19	22	26	30	36	142
9.0 h	10	13	15	17	20	23	28	n/a

The areal reduction factor takes into account the unlikelihood that larger catchments will experience rainfall of the same design intensity over the entire area. Due to the relatively small size of the catchment and adopting a conservative approach, an aerial reduction factor was not applied in this study.

6.1.2 Temporal Patterns

The IFD data presented in Table 6-2 provides for the average intensity that occurs over a given storm duration. Temporal patterns are required to define what percentage of the total rainfall depth occurs over a given time interval throughout the storm duration.

For frequent, large and rare design flood events including the 20% to 0.5% AEP events, design temporal rainfall patterns from AR&R (Pilgrim, DH, 2001) for temporal zone 1 have been adopted. For the PMF event, the temporal pattern as provided in BOM (2003) was used.

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

6.1.3 Rainfall Losses

The rainfall losses utilised in calibration modelling (refer to Section 5.10) have been adopted for all design event modelling, excluding the PMF event, with the adopted values shown in Table 5-2. The PMF event modelling has adopted losses are as per AR&R recommendations (Pilgrim, DH, 2001) with an initial loss of 0mm and a continuing loss of 1mm/h.

The applied losses are varied across the hydraulic model extent based on the land use surface type as illustrated in Figure 4-3. As outlined in Section 4, the land use surface types were identified based on aerial photography and GIS data supplied by Council.

6.1.4 Critical Storm Duration

A series of model runs were carried out in order to identify the critical storm duration for the City Area catchment. Standard durations from the 15-minute to the 9-hour events were simulated utilising the design temporal patterns from AR&R (Pilgrim, DH, 2001).

No single critical storm duration was found for the study area, but rather, the critical duration varies across the catchment. Some regions of the catchment are affected more by the total volume produced in a given rainfall event, particularly in trapped low points. The variation in critical storm duration is discussed further in Section 7.1.2.

6.2 Design Ocean Boundary

The 2010 NSW Government document entitled “Flood Risk Management Guide – incorporating sea level rise benchmarks in flood risk assessments” recommends that the local catchment 1% AEP flood should be run in conjunction with a 5% ARI tailwater condition. It further recommends that the inverse scenario be run to confirm that the dominant flooding mechanism is not from downstream water levels. If the flooding from the downstream water is demonstrated to produce peak flood conditions in parts of the catchment, an envelope of both scenarios must be used to define the extent of the 1% AEP flood.

Modelling undertaken has confirmed that in all City Area catchment locations the 1% AEP local catchment flood with a 5% AEP tailwater generates higher flood levels than the 5% AEP flood with a 1% AEP tailwater. Because the local catchment flood dominates the tailwater flood, an envelope does not need to be developed when producing design flood results.

The 2008 NSW Government document entitled “Fort Denison: Sea Level Rise Vulnerability Study” presents the Sydney Harbour design still water levels, which are shown in Table 2-3. There is little variation in harbour water levels for different frequencies, specifically, the 1% AEP harbour water level is only 0.06 m higher than the 5% AEP flood level. This also explains why the 1% AEP local catchment flood with a 5% AEP tailwater is always dominant for the subject catchment.

The 2010 NSW Government document entitled “Flood Risk Management Guide – incorporating sea level rise benchmarks in flood risk assessments” does not give guidance for the combination of annual exceedance probabilities of the local catchment flood and tailwater conditions for design events other than the 1% AEP flood.

Based on other NSW flood studies, the proposed combination of local catchment floods with tailwater scenarios is presented in Table 6-3.

Due to the small variations in Sydney Harbour water levels for differing frequencies, the inverse combinations are not required to be simulated. The small variation in Sydney Harbour water levels for differing frequencies also means that design flood levels are not sensitive to the local flood and tailwater combinations chosen.

Table 6-3 Local catchment flood/tailwater combinations

Design Event	Local Catchment Flood	Tailwater#
2 year ARI	2 year ARI	1 year ARI
5 year ARI	5 year ARI	2 year ARI
10% AEP (10 year ARI)	10% AEP (10 year ARI)	2 year ARI
5% AEP (20 year ARI)	5% AEP (20 year ARI)	5 year ARI
2% AEP (50 year ARI)	2% AEP (50 year ARI)	10% AEP (10 year ARI)
1% AEP (100 year ARI)	1% AEP (100 year ARI)	5% AEP (20 year ARI)
0.2% AEP (500 year ARI)	0.2% AEP (500 year ARI)	1% AEP (100 year ARI)
PMF	PMF	1% AEP (100 year ARI)

modelled as static/constant peak water level.

6.3 Pit Inlet Blockages

Based on community consultation feedback for frequent events and the Sydney Development Control Plan (DCP), different pit blockages were adopted based on the magnitude of the storm. The following pit blockages were used for design event modelling:

5 year ARI and more frequent

- Kerb inlets (on-grade) pits are assumed to be 20% blocked; and
- Sag pits are assumed to be 50% blocked.

Rarer than the 5 year ARI

- Kerb inlets (on-grade) pits are assumed to be 50% blocked; and
- Sag pits are assumed to be 100% blocked.

6.4 Modelled Design Events

6.4.1 Catchment Derived Flood Events

A range of design events were defined to model the behaviour of catchment derived flooding within the City Area catchment including the 2 year ARI, 5 year ARI, 10% AEP, 5% AEP, 2% AEP, 1% AEP, 0.2% AEP and PMF events. The catchment derived flood events were based on the following:

- Design rainfall parameters derived from standard procedures defined in AR&R (Pilgrim, DH, 2001);
- Static Harbour water boundary as presented in Table 6-3; and
- Blockage of drainage infrastructure as detailed in Section 6.3.

6.4.2 Tidal Inundation

Limited tidal inundation has been investigated based on the 1 year ARI Sydney Harbour water level (1.24 m AHD) (see Appendix A, Figure A- 36).

7 DESIGN FLOOD RESULTS

A range of design flood events were modelled, the results of which are presented and discussed below. The simulated design events included the 2 year ARI, 5 year ARI, 10% AEP, 5% AEP, 2% AEP, 1% AEP, 0.2% AEP and PMF events for catchment derived flooding and the 1 year ARI Harbour level for the tidal inundation mapping.

A range of design event storm durations have been simulated for each event. The design results presented in the remainder of the report represent the maximum values across all durations (peak envelope) for each design event simulated.

A series of design flood maps are provided in Appendix A. Supplementary to mapped results output, tabular results of peak flood behaviour have been provided for all design events in Table 7-1 and Table 7-2. The locations of flooding behaviour reported in Table 7-1 and Table 7-2 are shown in Figure 7-1 and Figure 7-2, respectively.

Table 7-1 Peak design flood levels

Location#	2yr ARI	5yr ARI	10% AEP	5% AEP	2% AEP	1% AEP	0.2% AEP	PMF
H01	18.59	18.68	18.71	18.77	18.82	18.86	18.94	19.49
H02	16.95	17.18	17.28	17.33	17.37	17.41	17.47	17.87
H03	14.81	14.86	14.94	15.00	15.05	15.10	15.19	15.75
H04	9.48	9.53	9.58	9.64	9.70	9.73	9.82	10.48
H05	5.09	5.24	5.41	5.48	5.54	5.59	5.71	6.47
H06	2.50	2.62	2.71	2.76	2.81	2.85	2.91	3.20
H07	15.49	15.54	15.60	15.63	15.65	15.68	15.72	16.02
H08	23.23	23.26	23.27	23.28	23.30	23.31	23.34	23.59
H09	2.41	2.50	2.59	2.65	2.69	2.72	2.77	2.94
H10	21.04	21.08	21.10	21.12	21.13	21.16	21.23	21.51
H11	11.02	11.04	11.06	11.08	11.09	11.10	11.11	11.24
H12	2.61	2.63	2.65	2.68	2.71	2.74	2.77	2.81
H13	2.51	2.55	2.56	2.58	2.59	2.61	2.64	2.89
H14	2.47	2.49	2.54	2.57	2.59	2.60	2.63	2.78

Refer to Figure 7-1 for the reporting locations

Table 7-2 Peak design flood flows – pipe (P) and overland (Q)

Location#	2yr ARI	5yr ARI	10% AEP	5% AEP	2% AEP	1% AEP	0.2% AEP	PMF
Q01	0.9	1.3	1.6	2.0	2.1	2.4	3.0	8.0
Q02	1.6	2.8	3.5	4.4	5.2	6.2	8.6	28.7
Q03	1.7	3.9	4.8	6.7	8.2	9.8	13.4	47.0
Q04	1.0	3.2	9.2	13.0	16.7	20.7	29.1	101.7
Q05	2.9	6.5	11.2	15.8	20.4	25.1	35.1	120.5
Q06	0.6	4.4	10.0	14.9	20.1	25.4	36.7	134.0
Q07	0.8	1.3	2.0	2.8	3.1	3.5	5.2	11.2
P01	3.6	3.9	4.1	4.0	4.1	4.2	4.2	4.4
P02	1.0	1.3	1.4	1.4	1.5	1.5	1.5	1.7
P03	1.4	1.8	2.0	2.1	2.2	2.2	2.5	2.7
P04	0.6	0.9	0.7	0.7	0.8	0.8	0.9	1.5
P05	0.7	0.9	0.9	1.0	1.1	1.2	1.4	2.0
P06	4.9	5.0	4.9	5.0	5.0	4.9	5.0	5.1
P07	5.1	5.5	5.6	5.7	5.8	5.9	6.1	6.8
P08	3.8	4.1	3.3	3.4	3.5	3.6	3.9	4.7

Refer to Figure 7-2 for the reporting locations

Title:

City Area Result Locations
Level Recording - Points and Profile

Figure: 7-1

Rev: -

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

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Title:

City Area Result Locations
Flow Recording - Overland and Pipe Flow

Figure: 7-2

Rev: -

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7.1 Peak Flood Conditions

7.1.1 Flooding Behaviour

7.1.1.1 Overview

Section 2.1 provides a general overview of the layout of the drainage network infrastructure and major flow paths. The trunk drainage network across the study area is comprised of predominantly pipe reaches. Overland flow routes are generally confined to the road network which is typical of urban environments, but even more pronounced in the Sydney City Area catchment.

Pitt Street forms the primary overland flow path that drains the majority of the City Area catchment. The top of the Pitt Street catchment is bounded by Hyde Park to the east, Liverpool Street to the south and York Street to the west. Runoff from the catchment extremities drains quickly to the primary overland flow path along Pitt Street downstream to Circular Quay (i.e. in a northerly direction).

Figure 7-3 shows the peak flood level profile along Pitt Street (for the location of profile see Figure 7-1). These flood levels show that the upstream portion of Pitt Street (chainage 600m; southern end) is not as sensitive to the event exceedance probability as the lower parts of the catchment (chainage 1200m; northern end). From the 2 year ARI to the 1% AEP, flood levels at Martin Place only increase by 0.2 m compared with 0.4 m lower downstream at Alfred Street where the catchment has a lower slope and is conveying greater flow. The modelling shows that water ponds in the Alfred Street area immediately adjacent to Circular Quay.

As presented in Section 4.3, significant drainage infrastructure exists along the alignment of this flow path, specifically:

- The Tank Stream which is aligned between George and Pitt Streets and is represented as Pipe P08 in Figure 7-2: and
- Pipe P07 (refer to Figure 7-2) which runs in a direction towards Sydney Opera House before discharging into Sydney Harbour.

Modelling results show that both of these drainage systems are flowing approximately at capacity for the 2 year ARI event (see Table 7-2).

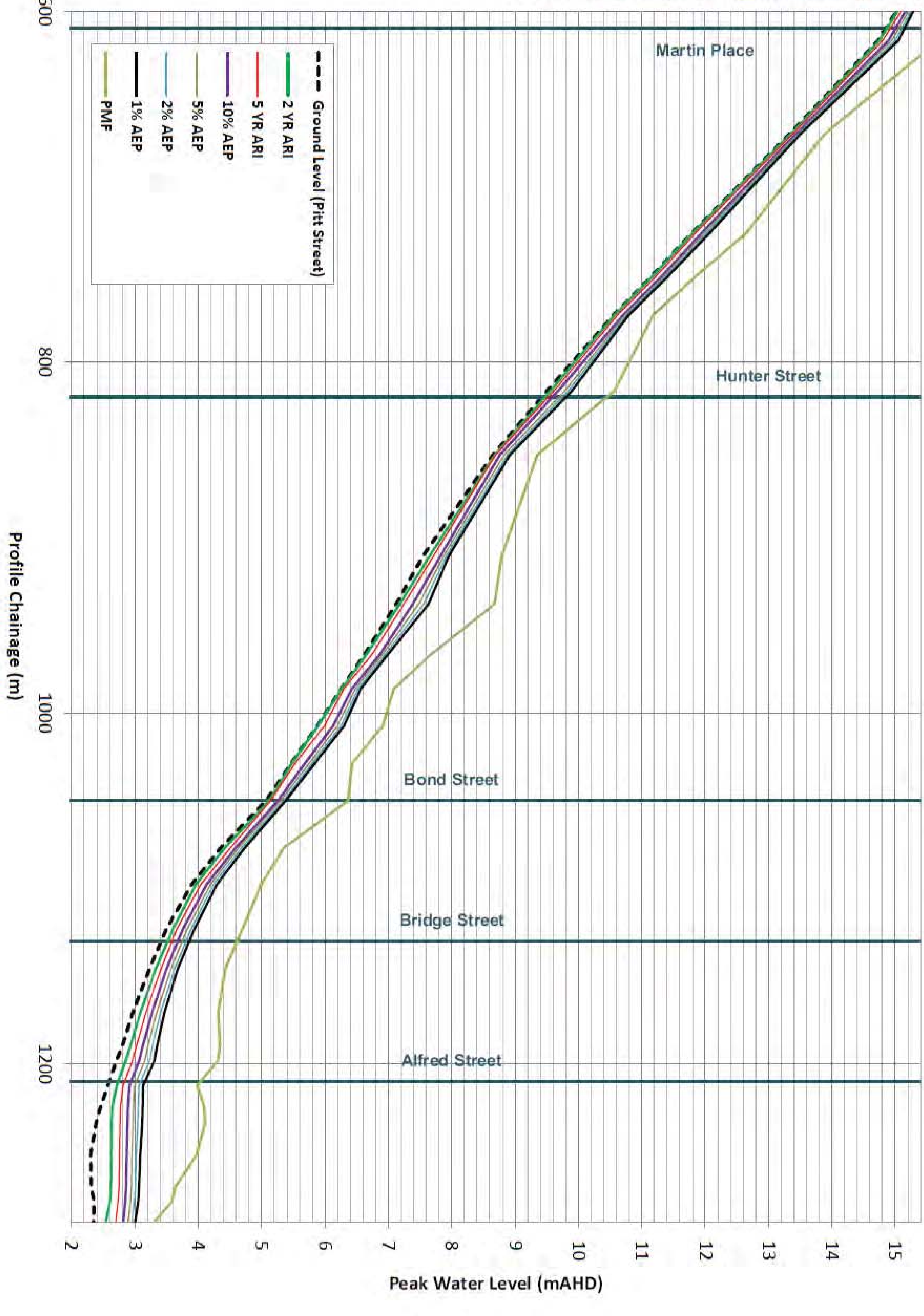
Overland flows in the upper reaches of the Pitt Street overland flow path range from 1.7 m^3/s in the 2 year ARI event to 9.8 m^3/s in the 1% AEP event at Pitt Street Mall (location Q03 in Table 7-2). Lower in the catchment near Bridge Street (location Q04), peak overland flows range from 1.0 m^3/s in the 2 year ARI event to 20.7 m^3/s in the 1% AEP event.

Flooding in the rest of the Sydney City Area catchment is generally a result of concentration of overland flow from localised catchments in trapped low points where limited drainage capacity currently exists.

Peak flood behaviour for design modelling is best interpreted by reviewing the extensive series of design flood mapping figures presented in Appendix A.

FIGURE 7-3

PITT STREET PROFILE - DESIGN EVENT RESULTS



7.1.2 Catchment-Derived Flood Events

As presented in Section 6, a range of durations has been modelled and enveloped for each annual exceedance probability modelled. For complete catchment modelling, it is common for different durations to produce critical flood levels at different locations. Upper catchment reaches or isolated areas with small catchments will likely respond to a shorter duration event. Lower catchment reaches, catchment areas with large upstream detention volumes or large upstream areas will likely respond to longer storms with greater volume. Given a single duration is not appropriate to define critical conditions throughout the catchment, all durations are modelled and the results of each combined to form an envelope grid. This ensures that critical design flood conditions are presented in the mapping across the entire catchment.

Figure 7-4 shows the 1% AEP critical duration assessment for the City Area catchment. As shown, the majority of the catchment is critical for the 90 minutes and 120 minute duration, with localised upper catchment areas and the Walsh Bay area critical for the 25 minute storm duration.

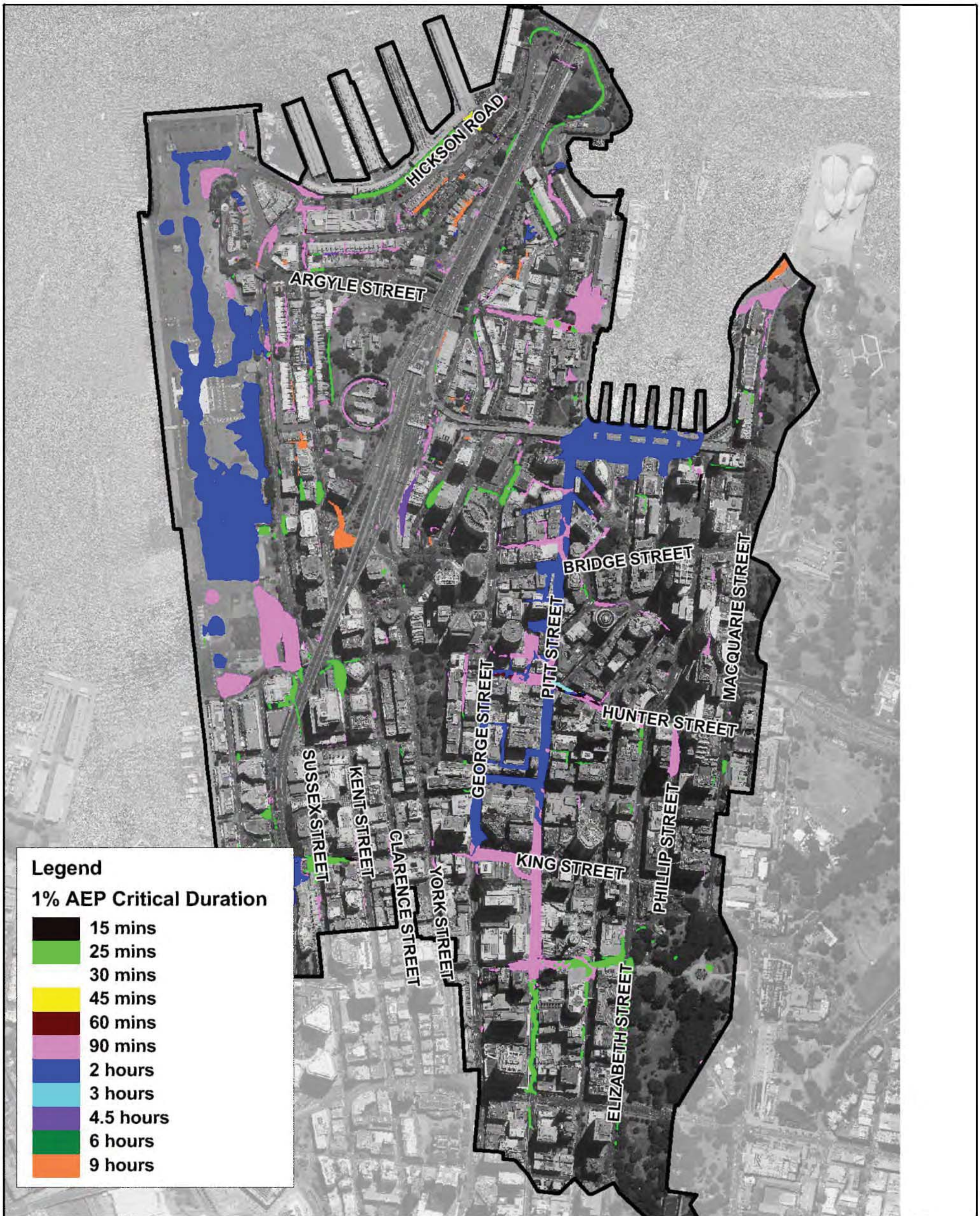
Table 7-3 shows the differences in flood level for individual storm durations compared with the maximum flood level envelope which combines all durations. The single storm duration which most represents the maximum flood levels across the study area is the 90 minute storm. This duration has therefore been selected as the critical duration for the sensitivity analysis and climate change modelling. For all design event modelling however, all storm durations have been modelled to most accurately produce a peak flood envelope.

Table 7-3 Critical duration assessment (peak flood level difference (m) from maximum envelope)

Location#	015min	025min	030min	045min	060min	090min	120min	180min	270min	360min	540min
H01	-0.08	-0.01	-0.02	-0.04	-0.01	+0.00	-0.02	-0.13	-0.18	-0.24	-0.26
H02	-0.07	-0.02	-0.03	-0.04	-0.01	+0.00	+0.00	-0.09	-0.14	-0.20	-0.23
H03	-0.10	-0.03	-0.04	-0.05	-0.01	+0.00	+0.00	-0.11	-0.16	-0.21	-0.25
H04	-0.14	-0.05	-0.05	-0.07	-0.02	+0.00	-0.01	-0.09	-0.14	-0.22	-0.24
H05	-0.17	-0.06	-0.07	-0.06	-0.01	+0.00	+0.00	-0.11	-0.17	-0.24	-0.30
H06	-0.13	-0.05	-0.05	-0.04	-0.01	+0.00	+0.00	-0.07	-0.11	-0.15	-0.19
H07	-0.05	-0.02	-0.02	-0.02	-0.01	+0.00	+0.00	-0.06	-0.09	-0.12	-0.13
H08	-0.02	+0.00	+0.00	-0.01	-0.01	+0.00	-0.01	-0.04	-0.05	-0.07	-0.08
H09	-0.08	-0.04	-0.05	-0.05	-0.01	+0.00	-0.02	-0.06	-0.08	-0.14	-0.20
H10	-0.03	+0.00	-0.01	-0.03	-0.01	-0.01	-0.01	-0.07	-0.09	-0.12	-0.14
H11	-0.01	+0.00	+0.00	-0.01	+0.00	+0.00	-0.01	-0.04	-0.06	-0.07	-0.08
H12	-0.05	-0.01	-0.02	-0.01	+0.00	+0.00	+0.00	-0.08	-0.11	-0.14	-0.15
H13	-0.01	+0.00	-0.01	-0.02	-0.01	+0.00	-0.01	-0.06	-0.07	-0.10	-0.11
H14	-0.08	-0.04	-0.03	-0.02	-0.01	-0.01	+0.00	-0.03	-0.03	-0.04	-0.05

Refer to Figure 7-1 for the reporting locations

The design flood results, as presented in a flood mapping series in Appendix A, are the maximum condition for all of the modelled durations. For each of the simulated design events, a map of peak flood level, depth and velocity is presented covering the study area.



Title:

Critical Duration Assessment
1% AEP (100 year ARI)

Figure: 7-4

Rev: A

0 250 500m
Approx. Scale

BMT WBM
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Filepath : S:\WATER\PROJECTS\S20022 - Water - Sydney CBD Catchment Flood Study\Drafting\WOR\Figures\FIGURE07-4_CriticalDuration.wor

7.1.3 Tidal Inundation

Limited tidal inundation modelling was undertaken for the 1 year ARI level for Sydney Harbour, which has a level of 1.2 m AHD. This tidal event does not directly pose any flood risk to locations within the study area. It is noted that there is limited sensitivity in Harbour water levels to frequency of design water level. The 1% AEP (100 year ARI) harbour water level is only 0.2 m higher than the 1 year ARI water level (Section 2.2.5, Table 2-3).

7.1.4 Potential Flooding Problem Areas

In simulating the design flood conditions for the Sydney City Area catchment, the following locations have been identified as potential problem areas in relation to flood inundation:

- **Pitt Street**
  As discussed in Section 7.1.1, Pitt Street acts as the primary overland flow path for most of the Sydney City Area catchment. In the 1% AEP event, approximately 20m^3/s is conveyed along Pitt Street at a depth of up to 0.5 m and velocity up to 2.5 m/s. These flooding characteristics represent a significant risk to pedestrians, motorists and property along the majority of Pitt Street within this catchment from Park Street in the south to Alfred Street/Circular Quay in the north.

- **George Street (between King Street and Hunter Street)**
  For a limited length of George Street between King Street and Hunter Street, there is a concentration of overland flow with depths up to 0.3m and velocity up to 2.0 m/s.

- **King Street (between Pitt Street and George Street)**
  A trapped low point exists at this location which is significantly flooded in all design flood events including the 2 year ARI event. Flood levels in the 1% AEP design event are up to 0.5m higher than those in the 2 year ARI event at this location. Responses from the consultation exercise indicated that flooding has occurred at this location in the past.

- **Martin Place (between Pitt Street and George Street)**
  At this location George Street and Pitt Street act as overland flow paths. In the 10% AEP event, water from George Street breaks out and flows through Martin Place to Pitt Street with a velocity of less than 0.5 m/s and a depth of 0.1 m. In the 1% AEP event this flow path has depths up to 0.2 m whilst the velocity remains less than 0.5 m/s.

- **Angel Place**
  Flood depths in the vicinity of Angel Place exceed 1.0m in the 1% AEP design event, resulting in an automatic classification as a high hazard area. Flood depths are up to 0.50m at this location in a 2 year ARI event.

- **Curtin Place**
  A trapped low point exists at this location which is significantly flooded in all design flood events including the 2 year ARI event. Flood levels in the 1% AEP design event are up to 1.0m higher than those in the 2 year ARI event at this location. Responses from the consultation exercise indicated that flooding has occurred at this location in the past.

- **Bond Street**
  A trapped low point exists at this location which is significantly flooded in all design flood events including the 2 year ARI event. Flood levels in the 1% AEP design event are up to 0.5m higher than those in the 2 year ARI event at this location. Responses from the consultation exercise indicated that flooding has occurred at this location in the past. There is an entrance to an underground car park at this location.

- **Phillip Street**
  Flooding occurs at this location for all design events modelled. Whilst the contributing catchment area to this location is relatively small, there is insufficient drainage infrastructure to alleviate flooding. Some water may actually spill into and flood an underground car park, however, such car parks have not been modelled as part of this study.

- **Hickson Road, Walsh Bay**
  Whilst there is a relatively small and localised catchment contributing flow to Hickson Road in the Walsh Bay area, modelling shows that flooding occurs in the 5 year ARI design event (reporting location H13). Furthermore, responses received during the community consultation exercise indicated that flooding has occurred here in the past. At this location the roadway is relatively flat and does not promote efficient drainage. Flooding is relatively shallow with depths less than 0.20m, but these depths may still impede pedestrian and vehicle access and possibly inundate car parks.

7.1.5 Supercritical Flows and Conjugate Depths

As described, sections of the catchment have high velocity flow due to the low hydraulic roughness of the roads which convey the main flow paths and the steepness of the catchment. A catchment of this nature has a tendency to convey supercritical flow which may under-represent the maximum peak water level possible if a hydraulic jump is activated.

For the 1% AEP event, the conjugate depths were calculated for supercritical flow areas. Impact mapping was undertaken to determine the sensitivity of reported model results from the standard depths to the conjugate depths. It was found that conjugate flood levels rarely exceed the standard levels by more than 0.3 m.

Mapping and further discussion of conjugate depth analysis is found in Appendix E.

7.2 Preliminary Hydraulic Categorisation

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

The hydraulic categories as defined in the Floodplain Development Manual are:

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

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

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

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

- Peak flood velocity;

- Peak flood depth;

- Peak velocity-depth product (sometimes referred to as unit discharge);

- Cumulative volume conveyed during the flood event; and

- Combinations of the above.

The definition of hydraulic categories that was considered to best fit the application within the City Area catchment was based on a combination of velocity, velocity-depth product and depth parameters. The adopted hydraulic categorisation is defined in Table 7-4 and is consistent with similar study catchments in the City of Sydney LGA (WMAwater, 2012a and 2012b).

Preliminary hydraulic category mapping for the 1% AEP and PMF design events is included in Appendix A (Figure A- 25 to Figure A- 26). It is also noted that mapping associated with the flood hydraulic categories may be amended in the future, at a local or property scale, subject to appropriate analysis that demonstrates no additional impacts (e.g. if it is to change from floodway to flood storage).

Table 7-4 Provisional hydraulic categories

Hydraulic Category	Definition	Description
Floodway	Velocity * Depth > 0.25 m^2/s AND Velocity > 0.25 m/s OR Velocity > 1.0 m/s.	Areas and flowpaths where a significant portion of floodwaters are conveyed during a flood.
Flood Storage	NOT Floodway AND Depth > 0.2 m	Floodplain areas where floodwaters accumulate before being conveyed downstream. These areas are important for detention and attenuation of flood peaks.
Flood Fringe	NOT Floodway AND Depth < 0.2 m	Areas that are low velocity backwaters within the floodplain. Filling of these areas generally has little consequence to overall flood behaviour.

7.3 Provisional Hazard Categories

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

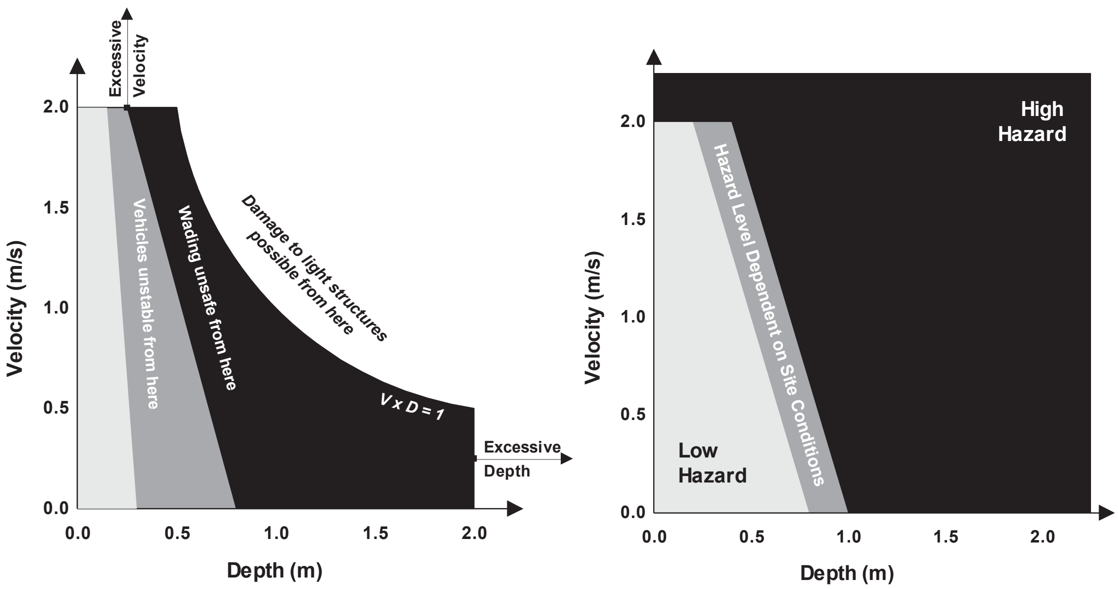
- **High hazard** – possible danger to personal safety; evacuation by trucks is difficult; able-bodied adults would have difficulty in wading to safety; potential for significant structural damage to buildings; and
- **Low hazard** – should it be necessary, trucks could evacuate people and their possessions; able-bodied adults would have little difficulty in wading to safety.

The key factors influencing flood hazard or risk are:

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

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

Figures L1 and L2 in the Floodplain Development Manual (NSW Government, 2005) are used to determine provisional hazard categorisations within flood liable land. These figures are reproduced in Figure 7-5. The provisional hydraulic hazard is included in the mapping series provided in Appendix A for the 10%, 5%, 1% AEP and PMF events (Figure A- 27 to Figure A- 30).



Velocity Depth Relationships **Provisional Hazard Categories**

c:\aac4\n0003\d101.vsd c:\aac4\n0003\d102.vsd

Figure 7-5 Provisional flood hazard categorisation

7.4 Flood Emergency Response Classification

The NSW Government's Floodplain Development Manual (NSW Government, 2005) requires flood studies and subsequent floodplain risk management studies to address the management of continuing flood risk to both existing and future development areas. Continuing flood risk may vary across a floodplain and as such the type and scale of emergency response does also. To assist the state emergency services with emergency response planning floodplain communities may be classified into the following categories (DECC, 2007):

- **High Flood Island** – high ground within a floodplain. Road access may be cut by floodwater creating an island. The flood island includes enough land higher than the limit of flooding to provide refuge.
- **Low Flood Island** – high ground within a floodplain. Road access may be cut by floodwater creating an island. The flood island is lower than the limit of flooding.
- **High Trapped Perimeter** – fringe of the floodplain. Road access may be cut by floodwater. The area includes enough land higher than the limit of flooding to provide refuge.
- **Low Trapped Perimeter** – fringe of the floodplain. Road access may be cut by floodwater. The flood island is lower than the limit of flooding.
- **Areas with Overland Escape Routes** – areas available for continuous evacuation. Access roads may cross low lying flood prone land but evacuation can take place by walking overland to higher ground.
- **Areas with Rising Road Access** – areas available for continuous evacuation. Access roads may rise steadily uphill away from rising floodwaters. Evacuation can take place vehicle and communities cannot be completely isolated before inundation reaches its maximum ;and

- **Indirectly Affected Areas** – areas outside the limit of flooding and therefore will not be inundated or lose road access. They may be indirectly affected as a result of flood damaged infrastructure or due to loss of services.

The flood emergency response classification is included in the mapping series provided in Appendix A for the full range of design events simulated (Figure A- 37 to Figure A- 43).

7.5 Conclusion

The TUFLOW hydraulic model has been applied to derive design flood conditions within the City Area catchment using the design rainfall and tidal conditions described in Section 6. The design events considered in this study include the 2 year ARI, 5 year ARI, 10% AEP (10-year ARI), 5% AEP (20-year ARI), 2% AEP (50-year ARI), 1% AEP (100-year ARI), 0.2% AEP (500-year ARI) and Probable Maximum Flood (PMF) events. The model results for the design events considered have been presented in a detailed flood mapping series for the catchment. The flood data presented includes design flood inundation, peak flood water levels and peak flood depths.

Provisional flood hazard categorisation in accordance with Figure L2 of the NSW Floodplain Development Manual (2005) has been mapped for the 10% AEP, 5% AEP 1% AEP and the PMF events, in addition to the hydraulic categories (floodway, flood fringe and flood storage) for all modelled design events.

The flood inundation extents derived from the hydraulic modelling are shown in Appendix A.

8 SENSITIVITY ANALYSIS

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

- Hydraulic roughness;
- Blockage of the stormwater drainage system;
- Change in rainfall losses; and
- Changed tailwater level.

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

As outlined in Section 7 the critical duration varies across the catchment. For the purpose of sensitivity testing the 1% AEP, 90-minute duration, design storm event has been used as the design base case.

8.1 Hydraulic Roughness

Sensitivity tests on the hydraulic roughness (Manning's 'n') were undertaken separately for the 1D stormwater network and for the 2D overland flow paths. Whilst adopted design parameters are within typical ranges, the inherent variability/uncertainty in hydraulic roughness warrants consideration of the relative impact on adopted design flood conditions. The potential uncertainty in selected parameter choice is different between sub-surface conduits which has much firmer guidance in literature versus overland flow paths which could feasible have greater variation.

Sensitivity analysis for the TUFLOW 2D overland flow path Manning's '*n*' values was assessed by applying a 50% increase and a 50% decrease in the adopted values for the baseline design conditions. Sensitivity analysis for the 1D sub-surface pipe network was assessed by applying a 20% increase and a 20% decrease in the adopted values for the baseline design conditions.

The results of the sensitivity tests on hydraulic roughness are summarised in Table 8-1 for the reporting locations indicated in Figure 7-1 and Figure 7-2.

With regard to the TUFLOW 2D overland flow path hydraulic roughness, the model simulations show minor change (generally <0.05 m) in peak flood level for the variation in roughness values. It should be noted that the reduction in hydraulic roughness does not always reduce flood levels and conversely an increase in hydraulic roughness does not always increase peak flood levels which can be attributed to the timing of flows at the confluences of difference flow paths. Of particular interest is Pitt Street which is the main flow path for the catchment, where changes in simulated peak flood levels are less than 0.10 m.

Variation of the hydraulic roughness of the pipe network results in changes to peak flood levels of less than or equal to 0.02 m. In the scenario where pipe roughness is increased, the pipe has a reduced capacity and more flow is conveyed via overland flow paths. In the scenario where the pipe roughness is reduced, the pipe is able to convey a higher flow reducing overland flows and overland flood levels.

Table 8-1 Changes in peak flood levels (m) for Manning's '*n*' sensitivity tests

Location	+ 50% Manning's '*n*' (2D Domain)	- 50% Manning's '*n*' (2D Domain)	+ 20% Manning's '*n*' (1D Domain)	- 20% Manning's '*n*' (1D Domain)
H01	-0.02	+0.09	+0.01	-0.01
H02	+0.01	+0.01	+0.00	+0.00
H03	+0.02	-0.07	+0.01	-0.01
H04	-0.05	+0.12	+0.02	-0.02
H05	+0.03	+0.01	+0.01	-0.01
H06	+0.02	-0.03	+0.01	-0.01
H07	+0.03	-0.09	+0.00	+0.00
H08	+0.01	+0.00	+0.00	+0.00
H09	-0.01	-0.01	+0.01	-0.01
H10	-0.02	+0.02	+0.01	-0.01
H11	+0.01	-0.03	+0.00	+0.00
H12	+0.00	+0.00	+0.01	-0.02
H13	+0.01	-0.01	+0.00	+0.00
H14	+0.01	-0.02	+0.00	+0.00

8.2 Stormwater Drainage Blockage

Structure blockages have the potential to substantially increase the magnitude and extent of property inundation through local increases in water level, redistribution of flows on the floodplain, and activation of additional flow paths. As outlined in Section 6, different pit blockages were considered for different magnitude storms, summarised as follows:

- 5 year ARI and more frequent: Grade Blockage 20%, Sag Blockage 50%
- Rarer than the 5 year ARI: Grade Blockage 50%, Sag Blockage 100%

Pit inlet blockage sensitivity was therefore separately assessed for 5 year ARI design event and also the 1% AEP design event. The blockage scenarios modelled are shown below:

- 5 year ARI: Grade Blockage 50%, Sag Blockage 100%
- 1% AEP: Grade Blockage 100%, Sag Blockage 100%.

The results of the sensitivity tests on blockages are summarised in Table 8-2 for the reporting locations indicated in Figure 7-1.

For the 5 year ARI event, if the level of pit blockage was used, the modelled peak water level would increase typically by less than 0.05 m. A higher sensitivity is exhibited in isolated trapped low points which are more reliant on the drainage network.

For the 1% AEP event, blockage sensitivity analysis assumes a very extreme scenario where no water is allowed into the stormwater system via on-grade or sag pits. Peak water levels for this scenario typically increase by less than 0.1 m though increase higher in isolated locations. Given the extreme sensitivity analysis scenario and the limit of sensitivity analysis modelled confidence can be relied upon the 1% AEP design results used to derive the Flood Planning Level.

Table 8-2 Changes in flood levels for pit inlet blockage sensitivity Tests

Location	5yr ARI Blockage - Grade 50%, Sag 100%	1% AEP Blockage - Grade 100%, Sag 100%
H01	-0.01	+0.10
H02	+0.06	+0.08
H03	+0.04	+0.13
H04	+0.00	+0.10
H05	+0.08	+0.15
H06	+0.04	+0.11
H07	+0.04	+0.05
H08	+0.00	+0.01
H09	+0.03	+0.09
H10	+0.00	+0.25
H11	+0.01	+0.04
H12	+0.00	+0.03
H13	+0.00	+0.16
H14	+0.03	+0.04

8.3 Rainfall Losses

Sensitivity analysis has been undertaken for rainfall losses by assessing both a 50% increase and decrease in rainfall losses (initial loss and infiltration). The fraction impervious parameter was not adjusted. The results of the sensitivity tests on rainfall losses are summarised in Table 8-3 for the reporting locations indicated in Figure 7-1.

The change in flood levels from rainfall loss changes is typically less than 0.01 m. The limited sensitivity to rainfall losses is due to the highly impervious nature of the catchment, whereby there is little opportunity for rainfall infiltration which translates to a negligible change in the amount of rainfall lost via pervious surfaces. Accordingly for the base case condition, losses are already relatively low across the catchment given the extent of impervious areas.

Table 8-3 Changes in peak flood levels (m) for rainfall loss sensitivity tests

Location	+ 50% Rainfall Losses	- 50% Rainfall Losses
H01	+0.00	+0.00
H02	+0.00	+0.00
H03	+0.00	+0.00
H04	+0.00	+0.01
H05	-0.01	+0.01
H06	-0.01	+0.00
H07	+0.00	+0.00
H08	+0.00	+0.00
H09	-0.01	+0.01
H10	+0.00	+0.00
H11	+0.00	+0.00
H12	+0.00	+0.00
H13	+0.00	+0.00
H14	+0.00	+0.00

8.4 Tailwater Level

Sensitivity analysis has been undertaken for tailwater by assessing both a 0.5m increase and decrease in the Harbour water level. The results of the sensitivity tests on tailwater are summarised in Table 8-4 for the reporting locations indicated in Figure 7-1.

Changes in flood levels from tailwater changes are limited indicating little sensitivity to tailwater assumptions.

Table 8-4 Changes in peak flood levels (m) for tailwater sensitivity tests

Location	+ 0.5m Tailwater	- 0.5m Tailwater
H01	+0.00	+0.00
H02	+0.00	+0.00
H03	+0.00	+0.00
H04	+0.00	+0.00
H05	+0.00	+0.00
H06	+0.01	+0.00
H07	+0.00	+0.00
H08	+0.00	+0.00
H09	+0.01	-0.02
H10	+0.00	+0.00
H11	+0.00	+0.00
H12	+0.02	-0.01
H13	+0.01	+0.00
H14	+0.00	+0.00

8.5 Conclusion

A series of sensitivity tests have been undertaken on the modelled flood behaviour of the Sydney CBD catchment. The tests provide a basis for determining the relative sensitivity of modelling results to adopted parameter values. The parameters assessed include:

- Hydraulic roughness;
- Stormwater drainage blockage;
- Design rainfall losses; and
- Tailwater level.

Results were shown to be generally insensitive to the values adopted for deriving the design flood levels and extents for the tailwater, hydraulic roughness and rainfall losses tests, with the magnitude changes in flood level less than 0.10m.

The stormwater drainage blockage sensitivity tests represent an extreme scenario whereby there is 100% blockage applied to the drainage network, effectively eliminating all sub-surface drainage. The 100% blockage scenario indicates that flood levels may increase by up to 0.25m in the 1% AEP design event. This could be considered to be contained within the 0.50m freeboard (if adopted) applied to the 1% AEP results to determine the Flood Planning Levels (FPL).

9 CLIMATE CHANGE ANALYSIS

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

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

It was agreed between Council and BMT WBM that the sea level rise benchmarks from the 2009 NSW Sea level Rise Policy Statement be adopted based on the conclusion that it was the best available information at the time of preparation of this report.

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

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

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

Key elements of future climate change (e.g. sea level rise, rainfall intensity) have been incorporated into the assessment of future flooding conditions in the City Area catchment for consideration in the ongoing floodplain risk management.

9.1 Potential Climate Change Impacts

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

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