ATTACHMENT D

WOOLLOOMOOLOO CATCHMENT AREA FLOOD STUDY (DRAFT REPORT)

WOOLLOOMOOLOO FLOOD STUDY

DRAFT REPORT

JULY 2013

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WOOLLOOMOOLOO FLOOD STUDY

FINAL DRAFT REPORT

JULY 2013

Project **Woolloomooloo Flood Study**		**Project Number** **112042**
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Date 2 July 2013		**Verified by** TO BE SIGNED FOR FINAL REPORT
Revision	**Description**	**Date**
1	Draft Report	25 February 2013
2	Second Draft Report	7 June 2013
3	Final Draft Report	2 July 2013

WOOLLOOMOOLOO FLOOD STUDY

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LIST OF ACRONYMS

AHD	Australian Height Datum
ARI	Average Recurrence Interval
ALS	Airborne Laser Scanning
BOM	Bureau of Meteorology
GIS	Geographic Information System
CSIRO	Commonwealth Scientific and Industrial Research Organisation
IFD	Intensity, Frequency and Duration of Rainfall

LGA	Local Government Area
m	metre
m^3/s	cubic metres per second
PMF	Probable Maximum Flood
TUFLOW	one-dimensional (1D) and two-dimensional (2D) flood and tide simulation software program (hydraulic computer model)
1D	One dimensional hydraulic computer model
2D	Two dimensional hydraulic computer model

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FOREWORD

The NSW State Government's Flood Policy provides a framework to ensure the sustainable use of floodplain environments. The Policy is specifically structured to provide solutions to existing flooding problems in rural and urban areas. In addition, the Policy provides a means of ensuring that any new development is compatible with the flood hazard and does not create additional flooding problems in other areas.

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

The Policy provides for technical and financial support by the Government through four sequential stages:

1. ***Flood Study***
   - Determine the nature and extent of the flood problem.
2. ***Floodplain Risk Management Study***
   - Evaluates management options for the floodplain in respect of both existing and proposed development.
3. ***Floodplain Risk Management Plan***
   - Involves formal adoption by Council of a plan of management for the floodplain.
4. ***Implementation of the 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.

The Woolloomooloo Flood Study constitutes the first stage under the program and aims to define the existing flood issue in regard to flood hazard and to provide a suitable basis for the provision of flood planning levels within the study area as well as for an ensuing Floodplain Risk Management Study and Plan.

EXECUTIVE SUMMARY

The Woolloomooloo catchment area within the City of Sydney local government area includes the suburbs of Potts Point, Darlinghurst, Sydney, Surry Hills and Woolloomooloo (Figure 1). The catchment is drained by a series of pits (inlets), pipes and overland flow-paths into Woolloomooloo Bay. Ownership of drainage assets is divided between Sydney Water and the City of Sydney, with the former tending to own the larger "trunk" assets.

The key purpose of this Flood Study is to define existing flood liability and develop a suitable model that can be used as the basis for a future Floodplain Risk Management Study and Plan for the study area, and to assist the City of Sydney and Sydney Water Corporation to undertake flood-related planning decisions for existing and future developments. Previous hydraulic modelling of the study area was limited in extent, did not systematically incorporate overland flow and did not provide design flood level estimates for the catchment.

The primary objectives of the study are:

- to provide a basis for ongoing flood risk management and preparation of the Floodplain Risk Management Study and Plan;
- to determine design flood levels and velocities over the full range of flooding up to and including the PMF from storm runoff in the study area;
- to assess the preliminary hydraulic categories and undertake provisional hazard mapping;
- to provide a model that can establish the effects of future development on flood behaviour, including the impact of any mitigation works such as pipe upgrades and the like; and
- to assess the sensitivity of flood behaviour to potential climate change effects such as increases in rainfall intensities and sea level rise.

This report details the results and findings of the Study. The key elements include:

- a summary of available flood related data;
- details on the build and verification of the hydrologic and hydraulic models;
- sensitivity analysis of the model results to variation of input parameters;
- potential implications of climate change predictions with regard to sea level rise and rainfall intensity increase;
- the definition of design flood behaviour for existing catchment conditions;
- a flood damages assessment.

A glossary of flood related terms is provided in Appendix A.

FLOODING HISTORY

In examining the flooding history it must be noted that the drainage characteristics of this catchment have been significantly altered as a result of urbanisation over the past 100 years. This includes construction of rail, road and drainage infrastructure that have had significant impacts on drainage behaviour. In recent times construction of the Eastern Suburbs railway line to Bondi Junction and the Eastern Distributor road network have been major factors.

There have been many instances of flooding in the past with 8-9th November 1984, 5th August 1986 and 10th April 1998 being the most significant recent storm events recorded as causing extensive flooding throughout the catchment. However flood issues, in Victoria Street for example, seem to occur on an annual to bi-annual basis and includes over floor inundation.

OUTCOMES

The hydrological and hydraulic modelling undertaken for this study has defined flood behaviour for the 2 year, 5 year, 10 year, 20 year, 50 year and 100 year ARI design floods, as well as the Probable Maximum Flood (PMF). Due to the limited available data for calibration and significant changes to the catchment in recent history, a limited calibration and verification of the models to historic data was undertaken. Sensitivity analyses were undertaken to assess the influences of modelling assumptions on key outputs, and the potential impacts of future climate change. Provisional hazard mapping has been completed for the 10 year, 20 year and 100 year and PMF events. Hydraulic category mapping has been completed for the 100 year ARI event.

The design flood modelling indicates that significant flood depths may occur in a number of locations such as Stream Street, Busby’s Lane, Crown Street, Palmer Street, Cowper Wharf Road and Bourke Street and existing flood behaviour at these “hot spots” has been examined. Flooding within Victoria Road has also been investigated due to the frequency of flooding and recent resident complaints.

1. INTRODUCTION

1.1. Background

The Woolloomooloo catchment within the City of Sydney local government area (LGA) includes the suburbs of Potts Point, Darlinghurst, Sydney, Surry Hills and Woolloomooloo (Figure 1). The catchment is drained by a series of pits (inlets), pipes and overland flowpaths into Woolloomooloo Bay. Ownership of drainage assets is divided between Sydney Water and the City of Sydney, with the former tending to own the larger "trunk" assets.

Continued development likely to occur in the catchment means it is important that appropriate tools and information to assess flood risks are available to City of Sydney and Sydney Water for planning purposes. For this reason this Flood Study has been commissioned by City of Sydney (CoS) and Sydney Water Corporation (SWC). The study considers flooding in the Woolloomooloo catchment from a combination of local storm runoff as well as storm surge mechanisms within Woolloomooloo Bay.

1.2. Objectives

The key objective of this Flood Study is to define existing flood liability and develop a suitable model that can be used as the basis for a future Floodplain Risk Management Study and Plan for the study area (Figure 2), and to assist CoS and SWC to undertake flood-related planning decisions for existing and future developments. Previous hydraulic modelling of the study area was limited in extent, did not systematically incorporate overland flow and did not provide flood level estimates for the catchment.

The primary objectives of the study are:

- to provide a basis for ongoing flood risk management and preparation of the Floodplain Risk Management Study and Plan;
- to determine design flood levels and velocities over the full range of flooding up to and including the PMF from storm runoff in the study area;
- to assess the preliminary hydraulic categories and undertaken provisional hazard mapping;
- to provide a model that can establish the effects of future development on flood behaviour, including the impact of any mitigation works such as pipe upgrades and the like; and
- to assess the sensitivity of flood behaviour to potential climate change effects such as increases in rainfall intensities and sea level rise.

This report details the results and findings of the Study. The key elements include:

- a summary of available flood related data;
- details on the build and verification of the hydrologic and hydraulic models;
- sensitivity analysis of the model results to variation of input parameters;
- potential implications of climate change predictions with regard to sea level rise and rainfall intensity increase;

- the definition of design flood behaviour for existing catchment conditions;
- a flood damages assessment.

A glossary of flood related terms is provided in Appendix A

2. BACKGROUND

2.1. Catchment Description

The Woolloomooloo catchment is located in the CoS LGA and includes the suburbs of Potts Point, Darlinghurst, Sydney, Surry Hills and Woolloomooloo. The catchment is fully developed and consists of medium to high-density housing and commercial development with some large open spaces that include Hyde Park, Sandringham Gardens, Fragrance Garden, The Domain Park, the Royal Botanic Gardens, Daffodil Park and a number of other smaller parks.

The catchment covers an area of approximately 160 hectares all of it draining to SWC's major trunk drainage systems (known as SWC 30) taking flows from the upper regions of the catchment to Sydney Harbour at Woolloomooloo Bay. Drainage of the catchment occurs via pits, pipes and overland flowpaths (mainly roads). Ownership of the pipe system is mixed with larger pipes in the catchment (also known as the trunk drainage system) owned by SWC. The trunk drainage system is linked to Council's local drainage system consisting of covered channels, in-ground pipes, culverts and kerb inlet pits. Further information on the drainage system is presented in Section 3.2.

The topography of the catchment is steep with the greatest relief occurring at the top of the catchment which begins at Oxford Street at elevations of around 55 mAHD. At several locations in the catchment there are sharp drops including adjacent to Victoria Street where the elevation can drop by up to 20 metres towards Brougham Street. Generally the upper catchment areas have grades of approximately 2% to 4%. Grades reduce to approximately 1% north of William Street and closer to Woolloomooloo Bay, north of Harmer and Best Streets, the ground surface slope is closer to 0.5%.

2.2. Flooding History

In examining the flooding history it must be noted that the drainage characteristics of the catchment have been significantly altered as a result of urbanisation over the past 100 years. This includes construction of rail, road and drainage infrastructure that are likely to have had significant impacts on drainage behaviour. In recent times construction of the Eastern Suburbs railway line to Bondi Junction and the Eastern Distributor road network have been major factors.

Frequent flooding including over floor inundation of some businesses and residences occurs in areas of the catchment including along Victoria Street, Stream Street, Crown Street and Dowling Street to the south of the railway viaduct. Flooding in many cases appears to be due to sags (localised depressions in roads) which collect excess overland flow and are unable to be effectively drained by above ground flow paths. In other locations development has impeded natural overland flow paths and this has caused issues. One such example is Victoria Street. Flow, particularly from Orwell Street, used to fall off the cliff (due west) towards Brougham Street but is now diverted down Victoria Street, causing inundation of private properties and representing a significant hazard to pedestrians.

There have been many instances of flooding in the past with 8-9 November 1984, 5 August 1986, 10 April 1998 and 12 February 2010 being some of the most significant storm events recorded as causing extensive flooding throughout the catchment. During the 1980's it was reported that floodwaters were deep enough that cars were floating down Crown Street. However flood issues, in Victoria Street for example, seem to occur on an annual to bi-annual basis. Section 3.5 provides details on a number of these past rainfall events responsible for the above mentioned floods.

Photographs of flooding during the April 2012 event (not a particularly large event) have been provided by a resident along Victoria Street (Photo 1 and Photo 2). A flow path with water depths of approximately 0.3 m in the road reserve/footpath area and velocities of 1 to 1.5 m/s is seen to occur here.

Photo 1: April 2012 – Victoria and Orwell Streets looking North

Photo 2: April 2012 – Victoria and Orwell Streets looking South

2.3. Previous Studies - City Area SWC 30 Capacity Assessment July 1996 (Reference 1)

This report was prepared by SWC and investigated the performance of SWC City Area SWC 30 which includes the Woolloomooloo Bay Subgroup and gives an estimate of the impact of potential urban consolidation on that performance.

The study included detailed land investigations of both the hydraulic capacity of SWC's trunk drainage system as well as future land use potential.

The drainage data used for the study included the SWC trunk drainage system only and the analysis was undertaken using a spreadsheet analysis based on:

- rational method for inflows;
- approximate capacities of pipes based on grade and area;
- approximation of channel capacities using Manning's "n" formula and methods for composite roughness and compound sections; and the
- Hydraulic Grade Line Method.

The hydraulic capacity of the Woolloomooloo Bay catchment is summarised in Table 1 (Table 1-4 in Reference 1). Little hydraulic and hydrologic detail was available for the Domain as analysis for that area was not included in the report. The study is useful for determination of system capacity and locations for trunk drainage upgrades, however as it does not define the overland flood hazard in the catchment, the impact of any trunk drainage improvement is unable to be assessed.

Table 1: Summary of Results from Reference 1

Sub system	System (km)	Percent Rated	Percent Satisfying, ARI of				
			2 yr	5 yr	10 yr	20 yr	100 yr
Domain	0.03	0%					
Sir John Young Cres	0.94	60%	100%	18%	0%	0%	0%
Hospital Road	0.84	100%	100%	100%	100%	100%	36%
Woolloomooloo East	3.99	63%	73%	66%	51%	50%	14%
Woolloomooloo West	8.22	49%	57%	43%	39%	31%	15%
McElhone Street	0.26	69%	46%	62%	62%	62%	9%
Victoria Street	1.95	55%	40%	40%	40%	21%	1%
WOOLLOOMOOLOO BAY	16.23	57%	66%	53%	46%	40%	14%

Catchment performance results indicate that the Sir John Young Crescent and Victoria Street catchments were the most under serviced (re: drainage capacity) and potentially the most at risk of flooding with 0% and 21% of the piped system with a 20 year ARI capacity respectively.

3. AVAILABLE DATA

3.1. Topographic Survey

Airborne Light Detection and Ranging (LiDAR) survey (or known as Airborne Laser Scanning – ALS) of the catchment and its immediate surroundings was provided for the study by CoS and is shown on Figure 3. The data was a combination of data collected in 2007 and 2008 with a 1.3 m average point separation. For hard surfaces these data typically have accuracy in the order of ±0.15m in the vertical direction (to one standard deviation).

When interpreting the above, it should be noted that the accuracy of the ground definition can be adversely affected by the nature and density of vegetation, the presence of steeply varying terrain, the vicinity of buildings and/or underground features such as car-parks. Due to the steep and urbanised nature of the catchment these features affected a significant portion of the catchment (greater than typically expected in this type of study) and assumptions regarding the nature of ground surface elevations were made based on site inspection and user judgement.

3.2. Pit and Pipe Data

The catchment is serviced by a major/minor drainage system. The purpose of the major drainage system is to provide drainage for large floods via roads and overland flowpaths, whereas the minor drainage system drains smaller floods via the pit and pipe system. Property drainage is directed to the Kerb and Gutter system where it is then able to enter the Council owned minor street drainage network. Flow is then routed into the SWC owned and maintained SW30 trunk drainage system draining to Woolloomooloo Bay.

When the capacity of the sub-surface drainage system is exceeded there is the potential for velocities and/or flow depths combining to generate high hazard flood conditions along the overland flowpaths (mainly roads).

CoS and SWC provided an asset database including dimensions and invert elevations for the majority of stormwater conduits within the study area. The datasets (Table 2) were used in conjunction with information from Reference 1 (SWC Capacity Assessment) to aid in model build work.

Table 2: Pit and Pipe Data

Data	File Name	Format	Received	Source
pit asset database	Pits Survey	ArcGIS	6/06/2012	COS
pipe asset database	Pipes_Survey	ArcGIS	19/06/2012	COS
pit asset database	SWC_030_Stormwater_Structure_Location	MapInfo	21/05/2012	SWC
pipe asset database	SWC_030_StormwaterChannel_Centreline	MapInfo	21/05/2012	SWC
pipe asset database	City Area SWC 30 Capacity Assessment	PDF	22/05/2012	SWC

A summary of pit and pipe survey data used within the study is provided in Table 3.

Table 3: Modelled Pipe and Pipe Network

Pit Type	Number	Pipe Diameter (mm)	Number	Total Length (m)
Junctions	990	< 450	1,661	21,321
Kerb or Grate Inlets	1,104	450 - 750	251	4,719
Outlet	38	750 - 1000	96	2,257
TOTAL	2,132	1000 - 2400	121	2,566
		2400 – 3660	38	479
		TOTAL	**2,167**	**31,342**

3.3. Rainfall Data

Table 4 presents a summary of the official rainfall gauges (provided by the Bureau of Meteorology - BoM) located close to or within the catchment. These gauges are operated either by SWC or the BoM. There may also be other private gauges in the area (bowling clubs, schools) but data from these has not been collected as there is no public record of their existence. Of the 45 gauges listed in Table 4 over 58% (26) have now closed. The closest rainfall gauge to the catchment is the Paddington Station and the gauge with the longest record is Observatory Hill. Locations of rainfall stations are shown on Figure 4.

Table 4: Rainfall Stations within a 6km radius of Kings Cross

Station No	Owner	Station	Elevation (mAHD)	Distance from Kings Cross (km)	Date Opened	Date Closed	Type
66139	BOM	Paddington	5	0.0	Jan-1968	Jan-1976	Daily
566041	SWC	Crown Street Reservoir	40	0.8	Feb-1882	Dec-1960	Daily
566032	SWC	Paddington (Composite Site)	45	1.0	Apr-1961		Continuous
566032	SWC	Paddington (Composite Site)	45	1.0	Apr-1961		Daily
566009	SWC	Rushcutters Bay Tennis Club	-	1.3	May-1998		Continuous
566042	SWC	Sydney H.O. Pitt Street	15	1.5	Aug-1949	Feb-1965	Continuous
66015	BOM	Crown Street Reservoir		1.5	Feb-1882	Dec-1960	Daily
66006	BOM	Sydney Botanic Gardens	15	1.9	Jan-1885		Daily
66160	BOM	Centennial Park	38	2.1	Jun-1900		Daily
566011	SWC	Victoria Park @ Camperdown	-	2.4	May-1998		Continuous
66097	BOM	Randwick Bunnerong Road		2.4	Jan-1904	Jan-1924	Daily
66062	BOM	Sydney (Observatory Hill)	39	2.7	??		Continuous
66062	BOM	Sydney (Observatory Hill)	39	2.7	Jul-1858	Aug-1990	Daily
66033	BOM	Alexandria (Henderson Road)	15	2.8	May-1962	Dec-1963	Daily
66033	BOM	Alexandria (Henderson Road)	15	2.8	Apr-1999	Mar-2002	Daily
66073	BOM	Randwick Racecourse	25	2.9	Jan-1937		Daily
566110	SWC	Erskineville Bowling Club	10	3.4	Jun-1993	Feb-2001	Continuous
566010	SWC	Cranbrook School @ Bellevue Hill	-	3.4	May-1998		Continuous
566015	SWC	Alexandria	5	3.5	May-1904	Aug-1989	Daily
66066	BOM	Waverley Shire Council		3.6	Sep-1932	Dec-1964	Daily
66149	BOM	Glebe Point Syd. Water Supply	15	3.6	Jun-1907	Dec-1914	Daily
566099	SWC	Randwick Racecourse	30	3.7	Nov-1991		Continuous
66052	BOM	Randwick Bowling Club	75	3.7	Jan_1888		Daily
566141	SWC	SP0057 Cremorne Point	-	4.0			Continuous
66021	BOM	Erskineville	6	4.0	May-1904	Dec-1973	Daily
	SWC	Gladstone Park Bowling Club	-	4.1	Jan-1901		Continuous
566114	SWC	Waverley Bowling Club	-	4.1	Jan-1995		Continuous
566043	SWC	Randwick (Army)	30	4.3	Dec-1956	Sep-1970	Continuous
566077	SWC	Bondi (Dickson Park)	60	4.4	Dec-1989	Feb-2001	Continuous
566065	SWC	Annandale	20	4.5	Dec-1988		Continuous

Station No	Owner	Station	Elevation (mAHD)	Distance from Kings Cross (km)	Date Opened	Date Closed	Type
66098	BOM	Royal Sydney Golf Club	8	4.5	Mar-1928		Daily
66005	BOM	Bondi Bowling Club	15	4.6	Jul-1939	Dec-1982	Daily
66178	BOM	Birchgrove School	10	4.8	May-1904	Dec-1910	Daily
66075	BOM	Waverton Bowling Club	21	5.1	Dec-1955	Jan-2001	Daily
66187	BOM	Tamarama (Carlisle Street)	30	5.1	Jul-1991	Mar-1999	Daily
66179	BOM	Bronte Surf Club	15	5.2	Jan-1918	Jan-1922	Daily
566130	SWC	Mosman (Reid Park)	-	5.3	Jan-1998	Jun-1998	Continuous
566030	SWC	North Sydney Bowling Club	80	5.5	Apr-1950	Sep-1995	Daily
66007	BOM	Botany No.1 Dam	6	5.5	Jan-1870	Jan-1978	Daily
66067	BOM	Wollstonecraft	53	5.8	Jan-1915	Jan-1975	Daily
66061	BOM	Sydney North Bowling Club	75	5.8	Apr-1950	Dec-1974	Daily
566027	SWC	Mosman (Bradleys Head)	85	5.8	Jun-1904		Continuous
566027	SWC	Mosman (Bradleys Head)	85	5.8	Jun-1904		Daily
566006	BOM	Bondi (Sydney Water)	10	5.9	Jun-1997		Operational
66175	BOM	Schnapper Island	5	5.9	Mar-1932	Dec-1939	Daily

BOM = Bureau of Meteorology
SW = Sydney Water

3.4. Analysis of Daily Read Data

An analysis of daily rainfall data was undertaken to identify and place past storm events in some context. All daily rainfall depths greater than 150 mm recorded at Centennial Park (112 years of record), Botanic Gardens (127 years of record) and Observatory Hill (154 years of record) have been ranked and shown in Table 5.

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Table 5: Daily Rainfall greater than 150 mm

Centennial Park (66160)		
Records since 1900		
Rank	Date	Rainfall (mm)
1	28/03/1942	302
2	06/08/1986	236
3	03/02/1990	222
4	12/08/1975	221
5	13/10/1975	205
6	31/01/1938	201
7	30/04/1988	193
8	10/02/1956	192
9	23/01/1933	189
10	09/02/1958	185
11	11/10/1975	184
12	07/07/1931	177
13	09/04/1945	177
14	07/08/1998	162
15	17/05/1943	159
16	04/02/1990	156
17	10/07/1957	155
18	14/11/1969	155
19	01/05/1955	154
20	09/02/1992	151
21	28/07/2008	150
22	13/01/2011	150

Botanic Gardens (66006)		
Records since 1885		
Rank	Date	Rainfall (mm)
1	06/08/1986	340
2	28/03/1942	277
3	09/02/1992	264
4	09/11/1984	248
5	03/02/1990	238
6	01/05/1988	230
7	02/05/1953	226
8	11/03/1975	217
9	01/05/1955	193
10	11/02/1956	191
11	13/01/2011	186
12	07/07/1931	181
13	08/01/1973	174
14	28/05/1989	171
15	19/05/1998	159
16	05/02/2002	158
17	31/01/1938	158
18	09/02/1958	155
19	10/02/1992	155
20	10/01/1949	150
21	22/08/1971	150

Observatory Hill (66062)		
Records since 1858		
Rank	Date	Rainfall (mm)
1	06/08/1986	328
2	28/03/1942	281
3	03/02/1990	244
4	09/11/1984	235
5	25/02/1973	226
6	28/05/1989	212
7	11/03/1975	198
8	07/07/1931	198
9	10/02/1956	192
10	06/02/1978	191
11	29/04/1960	191
12	17/01/1988	191
13	09/02/1992	190
14	01/05/1955	188
15	13/01/2011	180
16	08/01/1973	169
17	03/04/1961	168
18	12/01/1918	166
19	09/03/1913	166
20	11/04/1998	165
21	06/04/1982	165
22	06/04/1984	164
23	24/03/1984	164
24	13/10/2002	162
25	17/02/1968	157
26	06/05/1998	154
27	23/01/1955	152
28	11/06/1991	151

The main points regarding these data are:

- March 1942 and August 1986 were the largest daily events recorded at all gauges. Both events recorded similar rainfall depths at all three gauges. February 1990 was in the top 5 rank for all gauges, again showing very similar rainfall depths at each gauge;
- February 1992 showed a significant difference between the three gauges (151 mm, 253 mm and 190 mm);
- Apart from March 1942 the top 4 ranked daily events occurred from 1975 onwards; and
- March 1975 showed similar depths at three gauges (184 mm, 217 mm and 198 mm).

3.5. Analysis of Pluviometer Data

Pluviometers continuously record rainfall and as such can identify the magnitude and extent of the peak rainfall bursts that cause flooding. These records are therefore much more valuable than daily rainfall gauges but as they have only been installed for approximately the last 30 years they cannot be used to describe prior events. Table 6 lists the maximum storm intensities for the four largest recent rainfall events from both the pluviometers and the daily read gauges.

Table 6: Maximum Recorded Storm Depths (in mm)

Station Location	5 Nov 1984		8/9 Nov 1984		6 Jan 1989		26 Jan 1991	
	30 min	60 min	30 min	60 min	30 min	60 min	30 min	60 min
Paddington	36	52	54	91	53	56	52	53
Observatory Hill	20	32	90	119	42	42	60	65

Station Location	5 Nov 1984	8 Nov 1984 (1)	9 Nov 1984 (1)	6 Jan 1989	26 Jan 1991
Royal Botanic Gardens	-	37	248	49	59
Observatory Hill	121	44	234	47	65
Paddington	108	71	208	63	54

Notes: (1) November 1984 event consisted of two separate rainfall bursts (between 6:00am and 10:00am and 9:00pm and midnight). Both produced flooding but the second burst was more intense. One possible reason why there are so few recorded flood levels is that the second burst occurred at night and thus few would have been outside to view the flood extent or record levels.

The above data indicate that for January 1989, March 1989 and January 1991 the peak 30 minute rainfall comprised the majority of the daily rainfall. However, for November 1984 the 30 minute peak was part of a much larger rainfall event. The August 1986 event, although one of the largest on record for daily rainfall did not have high intensity peak burst rainfall which is more likely to cause flooding within the Woolloomooloo catchment.

Storm intensities and durations recorded at the Paddington pluviometer for all the major storm events are given in Table 7.

Table 7: Paddington Pluviometer Storm Intensities (mm/h)

Duration	**6 min**	**10 min**	**20 min**	**30 min**	**60 min**	**120 min**
12 Aug 1983	175	156	106	84	48	28
(approx. ARI)	*(10)*	*(20)*	*(10)*	*(10)*	*(5)*	*(2)*
5 Nov 1984	120	108	84	72	52	39
(approx. ARI)	*(2)*	*(2)*	*(5)*	*(5)*	*(5)*	*(10)*
8-9 Nov 1984	125	123	114	108	91	74
(approx. ARI)	*(2)*	*(5)*	*(10)*	*(25)*	*(75)*	*(>100)*
6 Jan 1989	215	195	155	108	56	30
(approx. ARI)	*(50)*	*(50)*	*(50)*	*(25)*	*(5)*	*(5)*
9 Mar 1989	140	138	114	85	54	28
(approx. ARI)	*(5)*	*(10)*	*(15)*	*(10)*	*(5)*	*(2)*
21 Apr 1989	140	120	78	54	29	14
(approx. ARI)	*(5)*	*(5)*	*(2)*	*(2)*	*(1)*	*(1)*
26 Jan 1991	190	162	138	103	53	27
(approx. ARI)	*(20)*	*(2)*	*(40)*	*(20)*	*(5)*	*(2)*

One of the more recent flood events occurred on 12 February 2010. The event occurred at approximately 11:00pm at night and was characterised by a short intense burst of rainfall (mostly over a 30 minute period), causing property inundation in many areas of the catchment.

3.5.1. Design Rainfall Data

Design rainfall depths and temporal patters for various storm durations in the study area were obtained from Australian Rainfall and Runoff 1987 (ARR87 – Reference 2), for events up to and including the 100 Year ARI event. Probable Maximum Precipitation estimates were derived according to BoM guidelines (Reference 3). A summary of the design rainfall depths is provided in Table 8 and a comparison of the design rainfall Intensity-Frequency Duration (IFD) data and significant historic storms in the catchment is shown on Figure 5.

Table 8: Rainfall Intensity-Frequency Duration Data

Duration	Design rainfall Intensity (mm/hr)						
	1 Year	2 Year	5 Year	10 Year	20 Year	50 Year	100 Year
5 minute	103	132	166	186	211	245	271
10 minute	79.2	101	129	145	165	193	213
20 minute	58.1	74.9	96.6	109	126	148	164
30 minute	47.4	61.2	79.6	90.4	104	123	137
1 hour	32.0	41.5	54.5	62.2	72.2	85.4	95.5
2 hour	20.7	26.9	35.5	40.5	47.1	55.7	62.4
3 hour	15.9	20.6	27.1	31.0	36.0	42.6	47.6
6 hour	10.0	13.0	17.0	19.4	22.5	26.6	29.7
12 hour	6.40	8.28	10.8	12.3	14.3	16.8	18.8
24 hour	4.15	5.36	7.00	7.96	9.22	10.9	12.2
48 hour	2.65	3.43	4.49	5.10	5.92	6.99	7.82
72 hour	1.97	2.55	3.33	3.78	4.39	5.18	5.79

3.6. Historical Flood Information

A data search was carried out to identify the dates and magnitudes of historical floods. The search concentrated on the period since approximately 1970 as data prior to this date would generally be of insufficient quality and quantity for model calibration (due to a lack of rainfall resolution). Unfortunately there were no stream height gauges in the catchment or any other means of reliably determining the level of past flood events so the following sources were used:

- Sydney Water database,
- questionnaire issued in November 2012,
- local residents.

For storms in urban areas flooding occurs quickly and as such it is difficult to collect and identify flood marks. Also many changes have occurred in the catchment that make historical flood marks less useful than they otherwise might be. The 1986 and 1984 storms are close to the largest rainfall events on record and the 1986 event led to a number of peak water levels being observed, mainly in the lower parts of the catchment (where high volume events are problematic). More recent information for flood events occurring from 2007 to 2012 was collected as part of this study and includes the February 2010 event.

Significant changes to the topography and built form in the catchment means that flood events earlier than 2000 are not useful for calibration. The February 2010 event is the only event useful for model calibration. Given the limited data for calibration, model verification relies upon comparisons of specific yield (peak flow per unit area) with similar studies in proximity of the catchment.

Descriptions of historical flood information are provided in Table 9 and locations of recorded flooding are shown in Figure 9.

Table 9: Historical Flood Information

Location	Description	Flood Event	Level (mAHD)	Source
4 Yurong Street	Water entered properties adjacent to intersection	19/4/1950	-	SWC
60-70 William Street	Water in sag	9/4/1988 to 10/4/1988	-	SWC
60-72 Sir John Young Crescent	Flood level on driveway	5/8/1986	3.96	SWC
24 Crown Street	Property flooded above floor level	5/8/1986	4.04	SWC
10 Bourke Street	Property flooded above floor level	5/8/1986	2.06	SWC
12 Bourke Street	Property flooded above floor level	5/8/1986	2.00	SWC
123 Victoria Street	Road Flooded	12/02/2010	30.20	CC
Between 2 - 34 Crown Street	Road Flooded	regularly	4.2	CC
137A Victoria Street	Above Floor Inundation	14/6/2007 to 16/6/2007	-	CC
	Road Flooded		30.5	CC
Corner of Bossley Terrace and Crown Street	Road Flooding leading to property inundation	26/02/2008	3.9	CC
		12/02/2010	3.9	CC
		30/05/2011	3.9	CC
		8/03/2012	4.0	CC
		17/04/2012	4.3	CC

Note: "CC" refers to flood information obtained during the community consultation process outlined in Section 3.7.

3.7. Community Consultation

In collaboration with CoS, a questionnaire and newsletter were distributed to residents and owners of property within the study area by post, describing the role of the Flood Study in the floodplain risk management process, and requesting records of historical flooding. A total of 537 surveys were distributed with reply paid envelopes, and 38 responses were received (a return rate of 7%) which is typical for such work.

The information requested in the survey included details about length of residency in the catchment, descriptions of any experiences of flooding, and evidence of flood heights or extents such as photographs of flood marks.

The occasions when respondents recalled being affected by flooding are summarised in Table 10. The most frequently recalled flood related to the February 2010 storm, although other events were also mentioned by a number of respondents.

Table 10: Summary of Reported Incidences of Flooding

Flood Event	Total Reponses	House Flooded (above floor)	Other Buildings Flooded (above floor)	Other Descriptions of Flooding
April 1998	2	2	0	0
February 2001	4	1	0	3
June 2007	2	1	0	1
February 2008	1	0	1	0
February 2010	5	2	1	2
May 2011	2	1	1	0
July 2011	1	0	0	1
March 2012	1	0	1	0
April 2012	1	0	1	0
October 2012	1	0	0	1

A summary of responses from the Community Consultation process is shown on Figure 6, with locations of flooding shown on Figure 7. A number of flood photographs of flooding within the catchment are shown on Figure 8.

CROWN STREET

Residents near the intersection of Crown Street and Bossley Terrace have reported regular flooding issues which have been exacerbated since the roundabout on Sir John Young Crescent was resurfaced, thereby redirecting additional floodwaters into the Crown Street low point. Blockage is mentioned as a regular occurrence with cars parked in front of inlet pits causing or exacerbating this issue.

DOWLING STREET

Complaints of minor flooding within Dowling Street have led to private construction of a small (150mm) pipe joining the CoS kerb and gutter system on Dowling Street through the property to Judge Street.

VICTORIA STREET

Residents within Victoria Street experience frequent flooding both in relation to the upper and lower level residences, with flood marks indicating depths of greater than 1 m in April 2012 at the front door of the lower residence. Flood photos, videos and flood marks were made available to Council and WMAwater showing indicative depths and velocities down Victoria Street during the event. A business along Victoria Street has also reported regular flooding and property inundation with flooding reported approximately every year. The property owner has since installed flood barriers to avoid further flood damage.

The flood experiences described in the survey responses generally related to smaller and more frequent flooding which mostly cause ponding of stormwater in roadways or gardens, although instances of above floor flooding in both residential and non-residential properties were also reported. February 2010 and April 1998 were the storms with the most records of above floor inundation of residential property with two properties inundated in each event.

A copy of the questionnaire and newsletter is provided in Appendix B.

4. STUDY METHODOLOGY

4.1. Approach

The approach adopted in flood studies to determine design flood levels largely depends upon the objectives of the study and the quantity and quality of the data (survey, flood, rainfall, flow etc). High quality survey datasets were available for this study, which enabled a detailed topographic model of the catchment to be established. However the historical data (such as rainfall, stream-flows and flood mark data) were relatively limited. A diagrammatic representation of the flood study process is shown below.

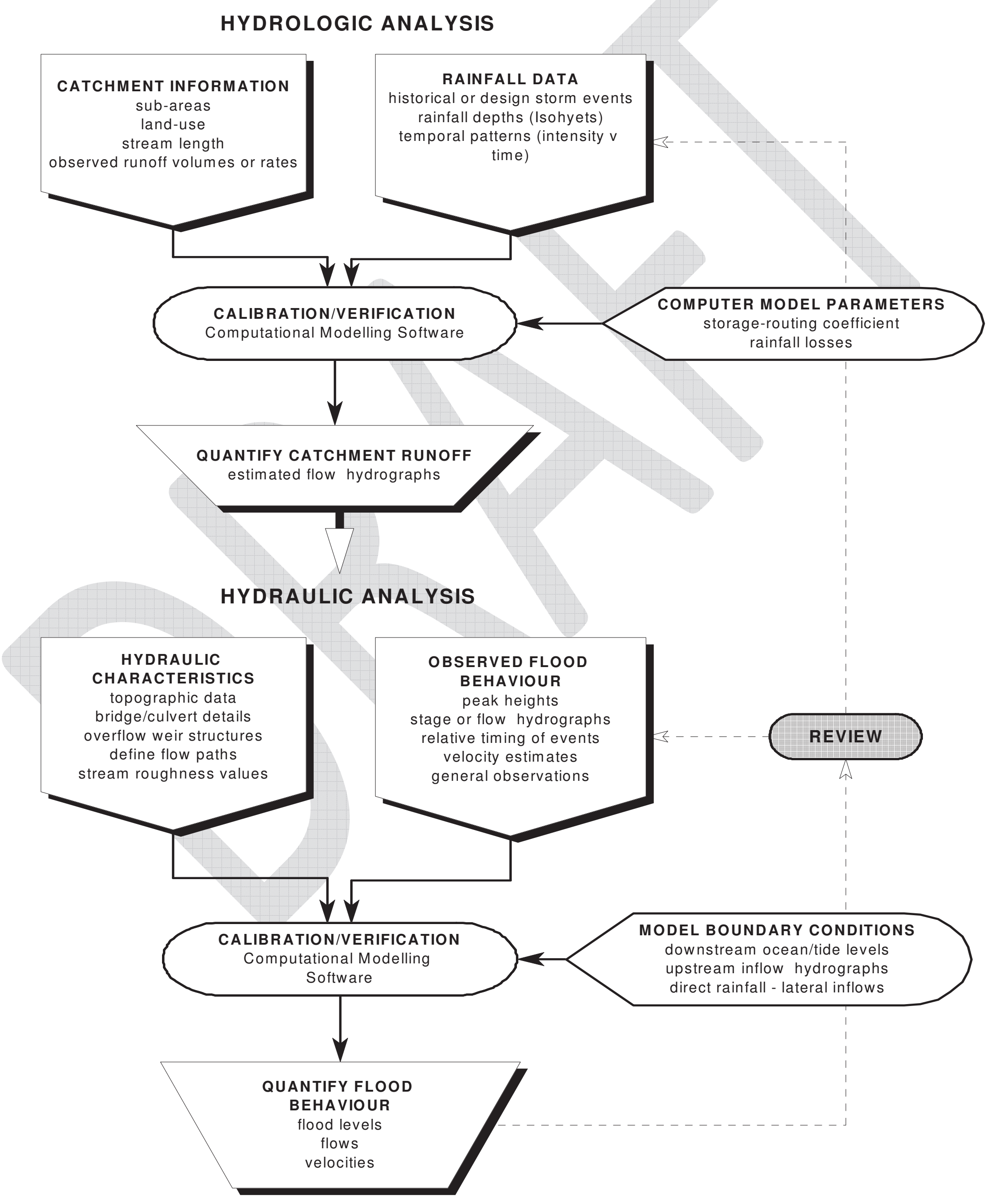


Diagram 1 Flood Study Process

The estimation of flood behaviour in a catchment is undertaken as a two-stage process, consisting of:

1. hydrologic modelling to convert rainfall estimates to overland flow and stream runoff; and
2. hydraulic modelling to estimate overland flow distributions, flood levels and velocities.

When historical flood data is available it can be used to allow calibration of the models, and increase confidence in the estimates. The calibration process is undertaken by altering model input parameters to match the reproduction of observed catchment flooding. Recorded rainfall and stream-flow data area are required for calibration of the hydrologic model, while historic records of flood levels, velocities and inundation extents can be used for the calibration of hydraulic model parameters.

There are no stream-flow records in the catchment, so the use of a flood frequency approach for the estimation of design floods or independent calibration of the hydrologic model is not possible.

Flood estimation in urban catchments generally presents challenges for the integration of the hydrologic and hydraulic modelling approaches, which have been treated as two distinct tasks as part of traditional flood modelling methodologies. As the main output of a hydrologic model is the flow at the outlet of a catchment or sub-catchment, it is generally used to estimate inflows from catchment areas upstream of an area of interest, and the approach does not lend itself well to estimating flood inundation in mid- to upper-catchment areas, as required for this study. The aim of identifying the full extent of flood inundation can therefore be complicated by the separation of hydrologic and hydraulic processes into separate models, and these processes are increasingly being combined in a single modelling approach.

In view of the above, the broad approach adopted for this study was to use a widely utilised and well-regarded hydrologic model to conceptually model the rainfall concentration phase (including runoff from roof drainage systems, gutters, etc.). The hydrologic model used design rainfall patterns specified in Reference 2, and the runoff hydrographs were then used in a hydraulic model to estimate flood depths, velocities and hazard in the study area.

The sub-catchments in the hydrologic model were kept small (less than a typical residential block) such that the overland flow behaviour for the study was generally defined by the hydraulic model. This joint modelling approach was checked, where possible, against observed historical flood levels and observed flooding behaviour. Additionally, the estimated flows at various points in the catchment were validated against previous studies and alternative methods.

4.2. Hydrologic Model

DRAINS (Reference 4) is a hydrologic/hydraulic model that can simulate the full storm hydrograph and is capable of describing the flow behaviour of a catchment and pipe system for real storm events, as well as statistically based design storms. It is designed for analysing urban or partly urban catchments where artificial drainage elements have been installed.

The DRAINS model is broadly characterised by the following features:

- the hydrological component is based on the theory applied in the ILSAX model which has seen wide usage and acceptance in Australia,
- its application of the hydraulic grade line method for hydraulic analysis throughout the drainage system,
- the graphical display of network connections and results.

DRAINS generates a full hydrograph of surface flows arriving at each pit and routes these through the pipe network or overland, combining them where appropriate. Consequently, it avoids the "partial area" problems of the Rational Method and additionally it can model detention basins (unsteady flow rather than steady state).

Runoff hydrographs for each sub-catchment area are calculated using the time area method and the conveyance of flow through the drainage system is then modelled using unsteady flow calculations. This provides improved prediction of hydraulic behaviour, consistency in design, and greater freedom in selecting pipe slopes. It requires more complicated design procedures, since pipe capacity is influenced by upstream and downstream conditions.

4.3. Hydraulic Model

The availability of high quality LIDAR/ALS data means that the study area is suitable for two-dimensional (2D) hydraulic modelling. Various 2D software packages are available (SOBEK, TUFLOW, Mike FLOOD) and the TUFLOW package (Reference 5) was adopted as it is widely used in Australia and WMAwater have extensive experience in the use of the TUFLOW model.

The Woolloomooloo study area consists of a wide range of developments, with residential, commercial and open space areas. Overland flood behaviour in the catchment is generally two-dimensional, with flooding along road reserves and areas prone to ponding. For this catchment, the study objectives require accurate representation of the overland flow system including kerbs and gutters and defined drainage controls.

The 2D model is capable of dynamically simulating complex overland flow regimes and interactions with sub-surface drainage systems. It is especially applicable to the hydraulic analysis of flooding in urban areas which is typically characterised by short-duration events and a combination of underground piped and overland flow behaviour.

For the hydraulic analysis of complex overland flow paths (such as the present study area where overland flow occurs between and around buildings), an integrated 1D/2D model such as TUFLOW provides several key advantages when compared to a 1D only model. For example, a 2D approach can:

- provide localised detail of any topographic and /or structural features that may influence flood behaviour;
- better facilitate the identification of the potential overland flow paths and flood problem areas;
- dynamically model the interaction between hydraulic structures such as culverts and complex overland flowpaths; and
- inherently represent the available flood storage within the 2D model geometry.

Importantly, a 2D hydraulic model can better define the spatial variations in flood behaviour across the study area. Information such as flow velocity, flood levels and hydraulic hazard can be readily mapped across the model extent. This information can then be easily integrated into a GIS based environment enabling the outcomes to be readily incorporated into Council's planning activities. The model developed for the present study provides a flexible modelling platform to properly assess the impacts of any overland flow management strategies within the floodplain (as part of the ongoing floodplain management process).

In TUFLOW the ground topography is represented as a uniformly-spaced grid with a ground elevation and a Manning's "n" roughness value assigned to each grid cell. The grid cell size is determined as a balance between the model result definition required and the computer run time (which is largely determined by the total number of grid cells).

4.4. Design Flood Modelling

Following validation of the hydrologic model against previous studies with similar catchment characteristics and alternative calculation methods, the following steps were undertaken:

- a limited calibration was undertaken to the February 2010 event with comparisons of reported flooding to design flood levels;
- design outflows for localised sub-catchments were obtained from the DRAINS hydrologic model and applied as inflows to the TUFLOW model;
- sensitivity analysis was undertaken to assess the relative effect of changing various TUFLOW modelling parameters.

5. HYDROLOGIC MODELLING

5.1. Sub-catchments

A hydrological model of the study catchment was established using the DRAINS software package (Reference 4). Sub-catchment areas were delineated based on ALS survey and making the assumptions that:

- properties generally drain to streets or inlet pits; and
- flow in streets is along gutters and uni-directional.

The DRAINS hydrologic runoff-routing model was used to determine hydraulic model inflows for the local sub-catchments within the study area. The catchment layout for the DRAINS model is shown on Figure 10.

5.2. Key Model Parameters

5.3. Impervious Areas

Runoff from connected impervious surfaces such as roads, gutters, roofs or concrete aprons occurs significantly faster than from natural surfaces, resulting in a faster concentration of flow at the bottom of a catchment, and increased peak flow in some situations. It is therefore necessary to estimate the proportion of a catchment area that is covered by such surfaces.

For each sub-catchment the proportion of pervious (grassed and landscaped), impervious (paved) and supplementary areas (paved not directly connected to pipe system) were determined from field and aerial photographic inspections and summarised in Table 11.

Table 11: Summary of Catchment Imperviousness values used in DRAINS

Area	Area (ha)	%
Paved Area	120	75
Grassed Area	32	20
Supplementary	8	5
TOTAL	160	100

5.4. Rainfall Losses

Methods for modelling the proportion of rainfall that is “lost” to infiltration are outlined in AR&R (Reference 2). The methods are of varying complexity, with the more complex options only suitable if sufficient data are available (such as detailed soil properties). An industry accepted method used for design flood estimation is the Horton Infiltration loss model used within DRAINS software.

Losses from a paved or impervious area are considered to comprise only an initial loss (an amount sufficient to wet the pavement and fill minor surface depressions). Losses from grassed areas are comprised of an initial loss and a continuing loss. The continuing loss was calculated from infiltration curves based on work by Horton in the 1930's which decreases as the storm duration progresses and is determined using the estimated representative soil type and antecedent moisture condition.

It was assumed that the soil in the catchment has a slow infiltration rate potential and the antecedent moisture condition was considered to be rather wet. The latter was justified by the fact that the peak rainfall burst can typically occur within a longer rainfall event that has a duration lasting days. The adopted parameters are summarised in Table 12.

Table 12: Adopted Hydrologic Loss Parameters

RAINFALL LOSSES	
Paved Area Depression Storage (Initial Loss)	1.0 mm
Grassed Area Depression Storage (Initial Loss)	5.0 mm
SOIL TYPE	3
Slow infiltration rates. This parameter, in conjunction with the AMC, determines the continuing loss	
ANTECENDENT MOISTURE CONDITIONS	3
Description	Rather wet
Total Rainfall in 5 Days Preceding the Storm	12.5 to 25mm

5.5. Time of Concentration

The surface runoff from each sub-area contributing to a pit has a particular *time of concentration*. This is defined as the time it takes for runoff from the upper part of a sub-area to start contributing as inflow to the pit. It is mainly related to the flow path distance, slope and surface type over which the runoff has to travel.

The time of concentration was defined as the sum of:

- constant property flow times plus gutter flow times, and
- overland flow time based on the Kinematic wave equation.

The flow time was defined using a flow length based on the sub-catchment slope and the size and shape of the contributing catchment. The relationship was developed based on a catchment of similar characteristics within the Sydney region and is generally suitable for application in the present investigation.

Time of concentration can have a significant bearing upon the accumulated peak flows achieved further downstream, sensitivity to these assumptions were assessed in Section 9.

5.6. Verification of Methodology

Ideally hydrologic models are calibrated and validated against observed stream flow information; however for the study area no such data is available. Thus verification is undertaken in which results from the current study are compared with similar studies in adjacent catchments and specific and general expectations of catchment flooding behaviour.

Flow results from the Kensington – Centennial Park Flood Study, June 2011 (Reference 6) and the Rushcutters Bay Flood Study, October 2007 (Reference 7) were compared to those used in the current study for individual sub-catchments.

To remove the effects that differences in catchment delineation can have on peak discharge the specific yield of a number of sub-catchments were determined. Specific yield is calculated by dividing the peak discharge by the area of the upstream catchment. This removes the obvious effects that differences in sub-catchment size have on peak discharge. Table 13 provides the model comparisons for 3 random sub-catchments from each model.

Table 13: Comparison of 20 and 100 Year ARI DRAINS results with References 6 and 7.

Model	Catchment Name	Area (ha)	Impervious %	20 Year ARI		100 Year ARI	
				Peak Discharge (m^3/s)	Specific Yield ($m^3/s/ha$)	Peak Discharge (m^3/s)	Specific Yield ($m^3/s/ha$)
Current Study	VIC037	0.8	92	0.4	0.6	0.3	0.6
Current Study	WEST059	0.5	92	0.3	0.6	0.3	0.7
Current Study	WEST004	1.4	94	0.6	0.4	0.8	0.5
Reference 6	F-G	3.3	95	1.8	0.5	2.3	0.7
Reference 6	E1-E2	2.3	80	1.0	0.5	1.3	0.6
Reference 6	AN2Det	3.5	83	1.6	0.5	2.1	0.6
Reference 7	aP24AA2	14.7	90	8.2	0.6	10.1	0.7
Reference 7	aP7Z7	0.4	90	0.2	0.6	0.3	0.7
Reference 7	aP3A1	2.7	90	1.5	0.5	1.9	0.7

Discrepancies between the compared specific yields can be attributed to a number of reasons such as the variance of loss parameters, differences in land use and difference in the applied routing method (peak flow also correlates to catchment area, but not linearly).

Specific yield for the 100 year ARI event in the current study was found to vary from 0.5 to 0.7 m^3/s per hectare and averaging at 0.7 m^3/s per hectare. The range of values is largely dependent on land use with more urbanised sub-catchments producing higher specific yields.

It was found that the flows produced by the different models are comparable and thus the hydrologic method employed in the current study is considered robust and adequately representative of flood conditions. Additionally sensitivity testing is carried out on design model runs although this work will herein be limited to the sensitivity testing of the overall modelling system and this is reported upon in Section 9.

6. HYDRAULIC MODELLING

6.1. Model Extents

A hydraulic model was established for the study using the TUFLOW package (Reference 5). The model covers the entire study area and extends to Woolloomooloo Bay. The model extent is indicated on Figure 11.

6.2. Terrain Model

A computational grid cell size of 2 m by 2 m was adopted, as it provides an appropriate balance between providing sufficient detail for roads and overland flow paths, while still resulting in workable computational run-times. The model grid was established by sampling from a triangulation of filtered ground points from the LiDAR/ALS dataset. The grid size is the smallest possible grid that can be used given that cell sides and centres are defined (essentially a 1 m by 1 m grid) and data is fundamentally informed by data points separated by approximately 1.3 m spacing at best.

Permanent buildings and other significant structures likely to act as significant flow obstructions were incorporated into the terrain model. These features were identified from the available aerial photography and modelled as impermeable obstructions to the flood flow (i.e. they were removed from the model grid).

As mentioned in Section 3.1 due to the urban nature and often steep gradients in the catchment, the LiDAR dataset was often not sufficient to define ground surface elevations for the hydraulic model. Locations for which LiDAR data was unavailable included:

- The Domain sports fields;
- sections of the Eastern Distributor;
- the northern end of Victoria Street;
- ground levels above underground features, e.g. car parking or tunnels; and
- areas of steep relief.

In poorly defined areas where the terrain consists of road reserve, ground surface levels were informed by site inspection, surrounding LiDAR data and general continuity of road slope and section shape.

The Domain sports fields were assumed to have a constant draining slope of 1% towards the swale on the south-eastern edge seen in Photo 3 and Photo 4. Site survey of the swale depth and width was undertaken and this information was included in the hydraulic model.

Photo 3: The Domain sports fields next to Sir John Young Crescent

Photo 4: Swale on the south-eastern boundary of the fields.

Sections of the Eastern Distributor from the Art Gallery Road tunnel to Wilson Street were not available in the LiDAR dataset and assumptions about the road surface slope were based on surrounding LiDAR survey and visual inspection. These areas can be seen in Figure 3 and Photo 5 and Photo 6.

Photo 5: Looking north from the Wilson Street footbridge towards Sir John Young Crescent and the Eastern Distributor

Photo 6: Cowper Wharf Road underpass below the Eastern Distributor

Grantham Lane at the northern-most and downstream end of Victoria Street did not have LiDAR data available, possibly due to the steep terrain adjacent to the road and pathway. A 1% grade was assumed from the location of available data until the low point near the lanes intersection with Grantham Street and St Neot Avenue.

Locations where steep relief has affected LiDAR ground survey have been addressed separately in the following section.

6.3. Steep Relief

There are areas of very steep relief throughout the catchment. These can be problematic for the 2D model and cause 2D instabilities. As a result, where abrupt transitions in topography occur these locations have been included in the hydraulic model as 1D broad crested weirs. The weir crests have been determined from LiDAR and site inspection.

Examples of locations where weir flow has been assumed are shown in Photo 7 to Photo 10.

Photo 7: Forbes Street stairs onto William Street

Photo 8: Hills Stairs from Victoria Street

Photo 9: Victoria Street wall downstream of McElhone Stairs

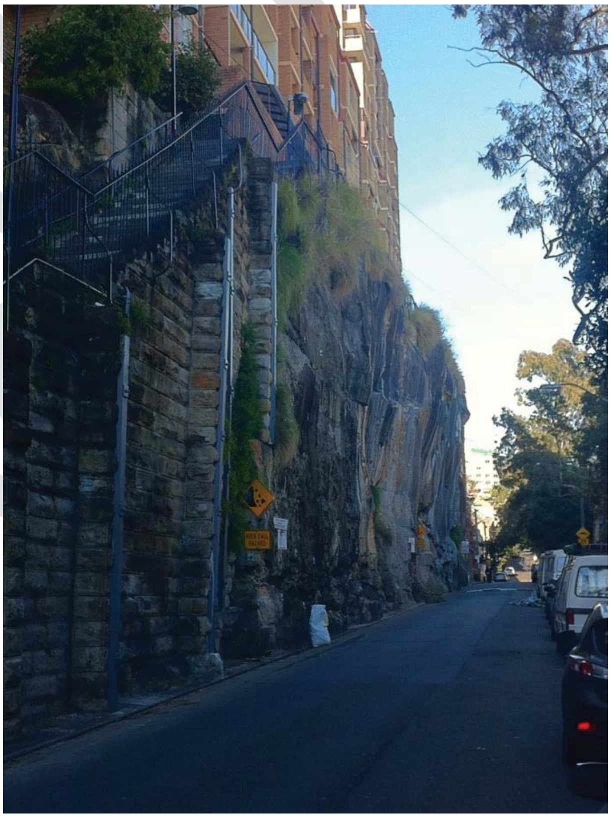


Photo 10: Vertical drop from Victoria Street properties to Brougham Street

6.4. Fencing and Obstructions

In areas where significant overland flow interacted with obstructions/fencing the resolution of refinement in TUFLOW was enhanced. For critical areas, site survey was undertaken to determine wall height and extent. For example the divider between Palmer Street and the Eastern Distributor (Photo 11) was surveyed to determine whether ponding of floodwater in the Palmer Street low point is able to spill onto the Eastern Distributor.

Photo 11: Divider between Palmer Street and the Eastern Distributor

Where fencing is adjacent to areas of steep relief, they have been included as broad crested weirs as discussed in Section 6.3. A large number of these are present in the study area.

6.5. Boundary Conditions

The model schematisation is illustrated on Figure 11, including the location of the sub-catchment inflow boundary conditions. In addition to runoff from the catchment, downstream areas can also be influenced by high water levels in Woolloomooloo Bay i.e. tidal influences may occur in conjunction with rainfall events. Consideration must therefore be given to the possibility of coincident flooding from both catchment runoff and backwater effects from Woolloomooloo Bay.

A full joint probability analysis to consider the interaction of these two mechanisms is beyond the scope of the present study. It is accepted practice to estimate design flood levels in these situations using a 'peak envelope' approach that adopts the highest of the predicted levels from the two mechanisms. NSW government guidelines (Reference 8) specify recommended approaches for setting the tailwater at an ocean level boundary for flood risk assessment. A table of design tailwater scenarios is given in Table 14 with design ocean levels from Reference 9.

Table 14 – Adopted Co-incidence of Ocean and Rainfall Events

OCEAN Event		DESIGN EVENT (ARI)	RAINFALL Event	
Peak Design Ocean Level (m AHD)	Co incident Design Rainfall Event (ARI)		Co incident Design Ocean Event (ARI)	Co incident Design Ocean Level (m AHD)
1.45	100 year	**PMF**	100 year	1.43
1.43	20 year	**100 year**	20 year	1.40
1.42	20 year	**50 year**	20 year	1.40
1.40	20 year	**20 year**	20 year	1.40
1.20	10 year	**10 year**	10 year	1.20
1.20	5 year	**5 year**	5 year	1.20
1.20	2 year	**2 year**	2 year	1.20

For ocean level events smaller than a 20 year ARI event, the relevant design flows are used in conjunction with a level of 1.2 mAHD, slightly higher than the Highest Astronomical Tide within Sydney Harbour.

A sensitivity analysis of the relative impacts of assuming different tailwater conditions due to climate change is presented in Section 9.3.

6.6. Hydraulic Roughness

The adopted roughness values (Table 15) are consistent with typical values in the literature (References 2) and previous experience with modelling similar catchment conditions. The sensitivity of model results to changes the roughness values is discussed in Section 9.

Table 15 - Mannings 'n' values

Surface Type	Manning's "n" value
Very short grass or sparse vegetation	0.035
General overland areas, gardens, roadside verges, low density residential lots etc. (default)	0.045
Medium density vegetation	0.060
Heavy vegetation	0.100
Roads, paved surfaces	0.025
Concrete pipes	0.013

Culvert Type	Manning's "n" value
Concrete pipes	0.013
Clay Pipes	0.025
Brick	0.014
PVC	0.011

6.7. Blockage Assumptions

Blockage of hydraulic structures is an important issue in the design and management of drainage systems. Blockage is produced by a range of different processes and can reduce the capacity of drainage systems by partially or completely closing the drainage structure.

Inlet pits are critical parts of drainage systems, and collect the runoff from the streets and other parts of the urban catchment and convey these to the piped underground system. Stormwater inlets are especially prone to blockage and temporary blockage may occur during a storm due to a range of issues, all materials that appear on the road can end up in the pit inlets; the most common blockage material is leaves and other small vegetation as well as general litter. Other obstructions include parked cars or trucks.

CoS has a pit maintenance program which aims to service approximately 12,000 pits throughout Council's LGA. Maintenance of an individual pit may only occur once every 6 to 12 months, or after a major storm event or resident complaint. As such it is impossible to accurately estimate the degree of blockage during a storm and for this reason a conservative approach has been applied.

Blockage to inlet pits was applied as per the Queensland Urban Drainage Manual (Reference 10) and Project 11 of the AR&R revision project (Table 16). All pipes have been included in the hydraulic model with no blockage as it is important to consider minor stormwater as well as major flooding events due to frequent flooding of properties in the catchment.

Table 16 – Theoretical capacity of inlet pits based on blockage assumptions

Sag Inlet Pit	
Kerb Inlet	80%
Grated Inlet	50%
Combination	grate assumed 100% blocked
On-Grade Inlet Pit	
Kerb Inlet	80%
Grated Inlet	60%
Combination	90%

The sensitivity of the catchment's drainage response to blockage assumptions within the sub-surface drainage network is discussed Section 9.

7. CALIBRATION

7.1. Overview

The Woolloomooloo catchment has experienced a number of large changes throughout its recent history. These include installation of large trunk drainage culverts in 1987 extending from Palmer Street to Woolloomooloo Bay and the recent construction of the Eastern Distributor in 1997, which has altered the catchment response significantly.

Historic flood levels near the trapped low point in Crown Street north of Cathedral Street are affected by the construction of the Eastern Distributor to the east, changes to Sir John Young Crescent and recent construction works (currently being undertaken in 2012) at a site within Crown Street, which used to be a car park prior to 1995.

Construction of the SWC Western Main Drain In 1987 has also increased drainage capacity in the lower reaches of the catchment and will have an effect on all locations with recorded flood levels.

The Eastern Distributor was completed in 1997 and overland flow which would have otherwise contributed to flooding within the most downstream areas of the catchment such as the Bourke Street low point are now routed through the Cowper Wharf underpass. Photo 12 shows the Cahill Expressway in 1978 prior to construction of the Eastern Distributor, with aerial photography taken in June 1983 shown in Photo 13. Photo 14 shows the Cahill Expressway and Eastern Distributor in October 2012 with the Eastern Distributor raised significantly above previous road levels.

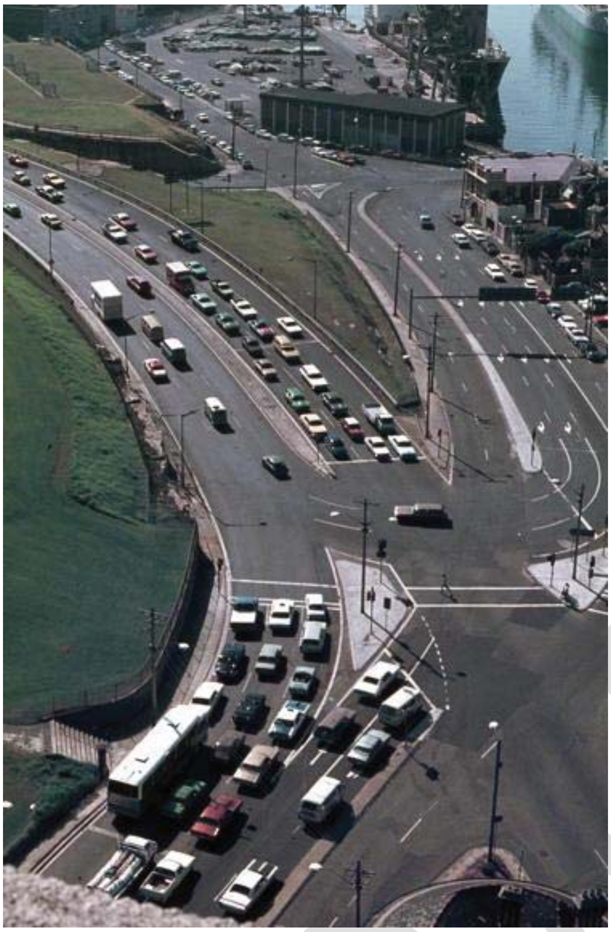


Photo 12: 1978 with Bourke Street seen top at right and The Domain on the left.

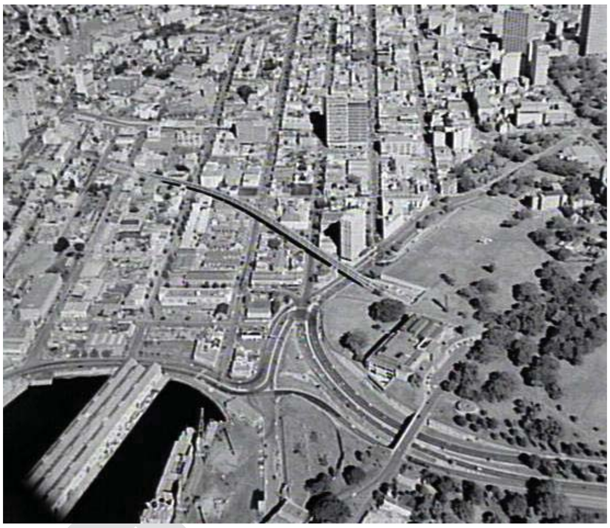


Photo 13: June 1983 Aerial photo showing Woolloomooloo Bay, Cahill Expressway

Photo 14: September 2012 looking north towards Eastern Distributor

Given that many of the historic flood levels recorded in the catchment were surveyed prior to 1987 and the number of changes to the catchment since that time, the historical data prior to the year 2000 (Section 3.6) are of little value for use in calibration.

As a result of catchment changes, very limited calibration data is available and what calibration is available will need to be supplemented with model verification.

7.2. Calibration – 12 February 2010 Event

The February 2010 rainfall event had a recurrence interval of approximately 20 years and consisted of short burst rainfall over a 30 minute period, typical of that required to cause flooding within the Woolloomooloo catchment. Two flood marks were recorded for the event along with anecdotal information.

The flood event occurred at between 11:00pm and 12:00am on 12/13 February 2010. Given the event occurred at night, there were no photographs of flooding and levels recorded were based upon water marks and mud marks the next morning. A comparison of modelled peak flood levels for the 12/13 February 2010 event against recorded levels is made in Table 17 and on Figure 12.

Table 17 –12 February 2010 Flood Levels – Modelled vs Recorded

Location	Date	Observed Level (mAHD)	Modelled Level (mAHD)
Crown Street	regularly	4.2	4.4
Cathedral Street	12/2/2010	3.9	4.3
Victoria Street	12/2/2010	30.5	30.5

Table 17 indicates a good match between the model and observed data. The Victoria Street match is perfect, the Crown Street match very good and the Cathedral Street match relatively poor. However the exact location of the observed flood peak is unknown and the area it is attributed to experiences a strong flood gradient.

Overall there was a lack of observed data, however where that data does exist, it tends to confirm the suitability of the modelling system.

Flood levels taken at Crown Street and Cathedral Street are affected by flooding in the Crown Street low point. In order for excess water to exit the low point it must pass through Bossley Terrace which has a crest elevation of 3.8 mAHD.

The timing of the flood event means there is some uncertainty with regards to recorded flood levels. Model sensitivity to the width of the overland flow path through Bossley Terrace, hydrologic flows and assumptions regarding the construction site on Sir John Young Crescent were investigated and it was found that the representation of the crest elevation and width of the overland flow path along Bossley Terrace had the most significant effect on flood levels within the Crown Street low point.

7.3. Model Verification

Given the limited calibration data, verification of modelled results was necessary. Recorded flood levels in Table 18 have been assessed and compared against design flood levels.

Table 18 – Comparison of Recorded Flood Levels against Design Flood Levels

Location	Date	Observed Level (mAHD)	Modelled Flood Level (mAHD)			
			2Y ARI	10Y ARI	20Y ARI	100Y ARI
Bourke Street	5/8/1986	2.1	1.5	1.7	2.1	2.3
Bourke Street	5/8/1986	2.0	1.5	1.7	2.1	2.3
Sir John Young Crescent	5/8/1986	4.0	4.1	4.3	4.4	4.8
Crown Street	5/8/1986	4.0	4.1	4.3	4.4	4.8
Crown Street	Regularly	4.2	4.1	4.3	4.4	4.8
Cathedral Street	12/2/2010	3.9	4.1	4.3	4.4	4.7
Victoria Street	14/6/2007	30.7	30.6	30.7	30.7	30.7

Victoria Street	12/2/2010	30.5	30.5	30.5	30.6	30.6

The location at which the flood level at Sir John Young Crescent for the 1986 event was surveyed was uncertain and therefore an accurate comparison to modelled results was unable to be made. In general flood levels taken during the 1986 event are not comparable to current day conditions due to catchment changes.

Flood levels along Victoria Street were found to have little variation between events of different frequency of occurrence with 100 Year ARI flooding only causing marginally higher flood levels than that of a 2 Year ARI event. Modelled results compare well to observed flood behaviour and therefore results within this area of the catchment are considered robust.

Modelled flood levels near the Crown Street low point were generally found to be higher compared to recorded levels. However, as discussed previously there was some uncertainty in the underlying data.

8. DESIGN FLOOD MODELLING

8.1. Critical Duration

To determine the critical storm duration for various parts of the catchment, modelling of the 100 year ARI event was undertaken for a range of design storm durations from 15 minutes to 12 hours, using temporal patterns from Reference 2. An envelope of the model results was created, and the storm duration producing the maximum flood depth was determined for each grid point within the study area.

It was found that the 60, 90 and 120 minute storms were critical for the majority of the catchment, with downstream areas near Bourke Road and Palmer Street having a critical duration of 60 minutes. The peak flood depths produced for these storm events were generally found to be within ±0.02 m throughout the catchment, with levels varying by ±0.02 near the Palmer Street depression and by ±0.01 m along Victoria Street. Given the small differences in peak flood levels, the 60 minute duration was taken to be the critical storm duration.

For the PMF event the critical duration was found to be 15 minutes for the upper areas of the catchment, with the 30 minute duration event critical for areas downstream of Cathedral Street. Flood levels vary by up to 0.2 m in areas where the 15 minute event is critical, whereas in the lower areas of the catchment where the 30 minute event dominates flood levels vary by 0.07 m between the two events. Due to these differences, a peak envelope of the 15 minute and 30 minute event was used to define the PMF flood extent.

8.2. Overview of Results

Design results are influenced by both rainfall driven events and ocean tailwater levels. For design events greater than 20 year ARI the adopted tailwater level generally reduces the pipe capacity within the study are due to backwater effects. Details of boundary condition assumptions with regards to ocean tailwater levels may be found in Section 6.5.

The results from this study are provided in the following forms:

- Peak flood depths and levels on Figure 13 to Figure 19,
- Provisional flood hazard on Figure 20 to Figure 23,
- Preliminary hydraulic categorisation on Figure 24 to Figure 27.

Results have been provided to Council in digital format compatible with Council's Geographic Information System (GIS).

8.3. Results at Key Locations

The results at key locations for peak flows, levels and depths are shown on Table 19 and Table 20 (refer to Figure 11 for locations).

Table 19 – Peak Flows (m^3/s) at Key Locations

ID	Location	Name	Type	2y ARI	5y ARI	10y ARI	20y ARI	50y ARI	100y ARI	PMF
1	Wiliam Street D/S Stream Street	WilliamParal	Overland	0.0	0.0	0.0	0.1	6.2	8.7	55.5
		pRS_015	Piped	0.0	0.0	0.0	0.0	0.0	0.1	0.1
		pWestMD_036	Piped	3.9	4.3	4.5	5.0	3.3	3.3	3.3
2	Crown Street D/S Cathedral Street	CrownSt_03	Overland	1.0	1.9	2.5	3.2	6.9	8.4	14.1
		pCrown_008	Piped	0.2	0.2	0.2	0.2	0.1	0.1	0.1
3	The Domain flow into Cahill Expressway	Domain_Out_01	Overland	0.0	0.0	0.0	0.1	0.1	0.1	0.3
		pDRAP15584B	Piped	0.3	0.5	0.6	0.7	0.9	1.0	1.6
		pDRAP15585	Piped	0.3	0.5	0.6	0.8	1.0	1.1	1.9
		pHR_011	Piped	0.5	0.6	0.7	0.8	0.9	0.9	1.4
4	Cowper Wharf Road D/S Eastern Distributor	Cowper01	Overland	0.4	0.9	1.3	2.1	3.1	3.7	23.0
		pHR_001	Piped	0.5	0.6	0.7	0.7	0.7	0.8	1.0
		pSJY_001	Piped	1.8	1.9	2.0	2.1	1.6	1.6	1.8
5	Bourke Street	Bourke	Overland	0.4	0.9	1.3	2.0	2.2	2.4	4.4
		pWestMD_001A	Piped	3.3	4.6	5.4	6.5	5.1	5.2	5.8
		pWestMD_001B	Piped	3.4	5.0	5.9	6.6	5.1	5.2	5.8
6	Forbes Street	Forbes	Overland	0.0	0.0	0.0	0.3	1.1	1.2	10.7
		pEastMC_004	Piped	3.3	4.0	4.3	4.4	3.3	3.4	4.0
		pDRAP13622	Piped	0.0	0.1	0.1	0.2	0.8	0.8	0.9
7	Dowling Street	Dowling_01	Overland	0.5	0.9	1.2	1.7	2.2	2.6	5.5
		pDRAP13611E	Piped	0.8	0.8	0.9	0.9	0.7	0.7	0.9
8	Victoria Street	Vic_01A	Overland	0.2	0.3	0.4	0.5	0.6	0.8	4.9
		pVic_022	Piped	0.2	0.2	0.2	0.2	0.2	0.2	0.2
9	Butlers Stairs	Butlers_W	Overland	0.0	0.0	0.0	0.0	0.0	0.0	1.2
10	Orwell Street	Orwell_001	Overland	0.4	0.6	0.7	1.0	1.4	1.5	5.7
		pDRAP14217	Piped	0.0	0.0	0.0	0.0	0.0	0.0	0.1
		pDRAP14216A	Piped	0.1	0.1	0.1	0.1	0.1	0.1	0.2
11	Hughes Street	HughesSt02	Overland.	0.3	0.3	0.4	0.5	0.5	0.6	3.4
12	Victoria Street	Vc001	Overland	0.7	1.1	1.3	1.4	1.6	1.8	6.3
		pDRAP14879A	Piped	0.3	0.3	0.3	0.3	0.3	0.3	0.3
13	Victoria Street	Vc002	Overland	0.6	1.4	1.7	2.1	2.5	2.8	10.9
		pVic_017	Piped	0.2	0.2	0.2	0.2	0.2	0.2	0.2
		pDRAP14877A	Piped	0.6	0.6	0.6	0.6	0.5	0.5	0.6
14	Victoria Street U/S McElhone Stairs	Vic_004	Overland	0.7	1.5	1.9	2.3	2.8	3.1	12.6
		pVic_016	Piped	0.2	0.2	0.2	0.2	0.2	0.2	0.2
		pDRAP14269	Piped	0.6	0.6	0.6	0.7	0.6	0.6	0.6

Table 20 – Peak Flood Levels (mAHD) and Depths (m) at Key Locations

ID	Location	2 year ARI		5 year ARI		10 year ARI		20 year ARI		50 year ARI		100 year ARI		PMF	
		Level	Depth	Level	Depth	Level	Depth	Level	Depth	Level	Depth	Level	Depth	Level	Depth
1	Francis Street	16.8	0.2	17.0	0.4	17.1	0.5	17.2	0.5	17.2	0.6	17.3	0.6	17.5	0.9
2	Francis Lane	15.3	0.4	15.9	1.1	16.4	1.6	16.5	1.7	16.7	1.9	16.7	1.9	17.2	2.3
3	Yurong Lane	10.7	0.8	11.8	1.9	12.3	2.4	12.9	3.0	13.2	3.3	13.3	3.4	14.1	4.2
4	Busby Lane	7.0	0.9	7.1	1.0	7.1	1.0	7.2	1.0	7.4	1.2	7.4	1.3	8.3	2.1
5	Crown Street	4.1	0.5	4.2	0.6	4.3	0.7	4.4	0.8	4.7	1.1	4.7	1.2	5.6	2.0
6	Palmer Street	2.5	0.4	2.7	0.5	2.7	0.6	2.8	0.7	3.4	1.2	3.4	1.3	3.8	1.7
7	Cowper Wharf Road underpass	2.7	0.4	2.8	0.5	2.8	0.6	2.9	0.6	2.9	0.7	3.0	0.7	3.5	1.3
8	Bourke Street	1.5	0.1	1.6	0.2	1.7	0.3	2.1	0.7	2.3	0.9	2.3	0.9	2.8	1.4
9	The Domain	19.1	0.2	19.2	0.3	19.2	0.3	19.2	0.4	19.3	0.4	19.3	0.4	20.2	1.3
10	Victoria Street	30.5	0.2	30.5	0.2	30.6	0.3	30.6	0.3	30.7	0.4	30.7	0.4	31.1	0.8

8.4. Provisional Flood Hazard and Preliminary Hydraulic Categorisation

Maps of provisional hydraulic hazard are presented on Figure 20 and Figure 23. Hazard categories were determined in accordance with Appendix L of the NSW Floodplain Development Manual (Reference 11).

Preliminary hydraulic categorisations for the 10, 20, 100 year ARI and PMF events are provided on Figure 24 to Figure 27. There is no technical definition of hydraulic categorisation that would be suitable for all catchments, and different approaches are used by different consultants and authorities, based on the specific features of the study catchment in question.

For this study, hydraulic categories were defined using the approach adopted in Howells et al (Reference 12) and the following criteria were applied:

- Floodway is defined as areas where:
  - the peak value of velocity multiplied by depth (V x D) > 0.25 m^2/s **AND** peak velocity > 0.25 m/s, **OR**
  - peak velocity > 1.0 m/s **AND** peak depth > 0.15m

  The remainder of the floodplain is either Flood Storage or Flood Fringe,
- Flood Storage comprises areas outside the Floodway where peak depth is > 0.5 m; and
- Flood Fringe comprises areas outside the Floodway where peak depth is < 0.5 m.

8.5. Preliminary Flood ERP Classification of Communities

The Floodplain Development Manual, 2005 (Reference 11) requires flood studies to address the management of continuing flood risk to both existing and future development areas. As continuing flood risk varies across the floodplain so does the type and scale of emergency response problem and therefore the information necessary for effective Emergency Response Planning (ERP). Classification provides an indication of the vulnerability of the community in flood emergency response and identifies the type and scale of information needed by the SES to assist in emergency response planning (ERP).
action can be taken prior to the flood.

Table 21: Response Required for Different Flood ERP Classifications

Classification	Response Required		
	Resupply	Rescue/Medivac	Evacuation
High Flood Island	Yes	Possibly	Possibly
Low Flood Island	No	Yes	Yes
Area with Rising Road Access	No	Possibly	Yes
Areas with Overland Escape Routes	No	Possibly	Yes
Low Trapped Perimeter	No	Yes	Yes
High Trapped Perimeter	Yes	Possibly	Possibly
Indirectly Affected Areas	Possibly	Possibly	Possibly

Table 21 (taken from Reference 13) provides an indication of the response required for areas with different classifications. However, these may vary depending on local flood characteristics and resultant flood behaviour i.e. in flash flooding or overland flood areas. The criteria for classification of floodplain communities outlined in Reference 13 are generally more applicable to riverine flooding where significant flood warning time is available and emergency response.

In urban areas like the Woolloomooloo catchment, flash flooding from local catchment and overland flow will generally occur as a direct response to intense rainfall without significant warning. At most (if not all) flood affected properties in the catchment, remaining inside the home or building is likely to present less risk to life than attempting to drive or wade through floodwaters, as flow velocities and depths are likely to be greater in the roadway.

ERP Classification for the Woolloomooloo catchment is shown on Figure 28. Areas near the Stream Street low point have been classified as low flood island due to the very high depths in the road in more frequent events. Other areas have been classified as high flood island as they are only isolated in PMF flooding.

9. SENSITIVITY ANALYSIS

9.1. Overview

Due to lack of historical data suitable for undertaking a thorough model calibration, a number of assumptions have been made for the selection of the design approach/parameters, primarily relying on default parameter values or values used in similar (and proximate) studies. The following sensitivity analyses were undertaken for the 100y ARI event to establish the variation in design flood level that may occur if different assumptions were made:

- Routing Lag: The hydrologic routing length values were adjusted by ± 20% for all sub-catchments;
- Manning's "n": The roughness values were increased and decreased by 20% within areas of overland flow;
- Inflows / Climate Change: Sensitivity to rainfall/runoff estimates was assessed by increasing the rainfall intensity by 10%, and
- Pipe Blockage: Sensitivity of blocking all pipes by 50% was considered.

9.2. Results of Sensitivity Analyses

Table 23 and Table 22 provide a summary of peak flood level and flow changes at various locations for the sensitivity scenarios. Overall results were shown to be relatively insensitive to routing, roughness and blockage with results tending to be within ± 0.2 m which can generally be accommodated within the freeboard (typically 0.5 m) applied to the 100 year ARI results to determine the Flood Planning Levels.

The sensitivity testing thus provides confidence that as long as the model emulates ground conditions and hydraulic structures, within a range of typical values for parameters, the model will produce accurate and reliable design flood levels.

Table 22 – Results of Sensitivity Analyses – 100 Year ARI Event Depths (m)

ID	Location	100 Year ARI Peak Flood Depth (m)	Decrease in routing by 20%	Increase in routing by 20%	Roughness decreased by 20%	Roughness increased by 20%	Increase in rainfall by 10%	Pipe Blockage 50%
			Difference with 100 Year ARI base case (m)					
1	Francis Street	0.6	-	-	-	-	0.02	-0.02
2	Francis Lane	1.9	-	-	-0.02	0.02	0.03	-
3	Yurong Lane	3.4	-	-	-	-	0.06	0.02
4	Busby Lane	1.3	-	-	-	-	0.07	0.02
5	Crown Street	1.2	-	-	-	-	0.07	0.02
6	Palmer Street	1.3	-	-	-	-0.02	0.04	0.04
7	Cowper Wharf Road underpass	0.7	-	-	0.14	-	0.03	0.04
8	Bourke Street	0.9	-	-	-	-	0.03	0.03
9	The Domain	0.4	-	-	-	-	0.03	0.07
10	Victoria Street	0.4	-	-	-	-	0.02	-

Table 23 – Results of Sensitivity Analyses – 100 Year ARI Event Flows (m^3/s)

ID	Location	Name	Type	100 Year ARI Peak Flood Flow (m^3/s)	Decrease in routing by 20%	Increase in routing by 20%	Roughness decreased by 20%	Roughness increased by 20%	Increase in rainfall by 10%	Pipe Blockage 50%
					Difference with 100 Year ARI base case (m^3/s)					
1	Wiliam Street D/S Stream Street	WilliamParal	Overland	8.7	0.07 (1%)	-0.10 (-1%)	0.19 (2%)	-0.27 (-3%)	2.37 (27%)	0.88 (10%)
		pRS_015	Piped	0.1	0.00 (3%)	0.00 (-4%)	0.00 (-1%)	0.00 (0%)	0.03 (28%)	-0.04 (-41%)
		pWestMD_036	Piped	3.3	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	-0.33 (-10%)
2	Crown Street D/S Cathedral Street	CrownSt_03	Overland	8.4	0.04 (1%)	-0.06 (-1%)	-0.24 (-3%)	0.05 (1%)	1.12 (13%)	0.36 (4%)
		pCrown_008	Piped	0.1	0.00 (-1%)	0.00 (1%)	-0.01 (-4%)	0.01 (4%)	0.00 (-1%)	-0.08 (-55%)
3	The Domain flow into Cahill Expressway	Domain_Out_01	Overland	0.1	-0.02 (-19%)	-0.01 (-15%)	0.01 (13%)	-0.02 (-20%)	0.04 (41%)	0.00 (0%)
		pDRAP15584B	Piped	1.0	0.02 (2%)	-0.03 (-3%)	0.00 (0%)	0.01 (1%)	0.10 (10%)	-0.32 (-32%)
		pDRAP15585	Piped	1.1	0.02 (2%)	-0.03 (-3%)	-0.01 (-1%)	0.01 (1%)	0.13 (11%)	-0.33 (-30%)
		pHR_011	Piped	0.9	0.01 (1%)	-0.01 (-1%)	-0.07 (-7%)	0.04 (5%)	0.06 (6%)	-0.28 (-30%

ID	Location	Name	Type	100 Year ARI Peak Flood Flow (m^3/s)	Decrease in routing by 20%	Increase in routing by 20%	Roughness decreased by 20%	Roughness increased by 20%	Increase in rainfall by 10%	Pipe Blockage 50%
					Difference with 100 Year ARI base case (m^3/s)					
4	Cowper Wharf Road	Cowper01	Overland	3.7	0.09 (2%)	-0.06 (-2%)	0.16 (4%)	-0.15 (-4%)	0.67 (18%)	0.86 (23%)
	D/S Eastern Distributor	pHR_001	Piped	0.8	0.01 (1%)	-0.01 (-1%)	-0.05 (-7%)	0.04 (5%)	0.05 (6%)	-0.30 (-37%)
		pSJY_001	Piped	1.6	0.00 (0%)	0.00 (0%)	0.01 (0%)	-0.02 (-1%)	0.03 (2%)	-0.87 (-54%)
5	Bourke Street	Bourke	Overland	2.4	0.06 (3%)	-0.11 (-5%)	-0.02 (-1%)	-0.07 (-3%)	0.18 (7%)	0.00 (0%)
		pWestMD_001A	Piped	5.2	0.00 (0%)	0.00 (0%)	0.00 (0%)	-0.01 (0%)	0.06 (1%)	-0.24 (-5%)
		pWestMD_001B	Piped	5.2	0.00 (0%)	0.00 (0%)	0.00 (0%)	-0.01 (0%)	0.07 (1%)	-1.18 (-23%)
6	Forbes Street	Forbes	Overland	1.2	0.00 (0%)	0.01 (0%)	0.08 (6%)	-0.06 (5%)	0.31 (25%)	0.06 (5%)
		pEastMC_004	Piped	3.4	0.00 (0%)	0.00 (0%)	-0.01 (0%)	0.02 (1%)	0.08 (2%)	-0.56 (-17%)
		pDRAP13622	Piped	0.8	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	-0.43 (-55%)
7	Dowling Street	Dowling_01	Overland	2.6	0.00 (0%)	-0.01 (0%)	0.17 (7%)	-0.05 (-2%)	0.40 (15%)	0.32 (12%)
		pDRAP13611E	Piped	0.7	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.01 (2%)	-0.20 (-28%)
8	Victoria Street	Vic_01A	Overland	0.8	0.01 (1%)	-0.01 (-1%)	0.02 (2%)	-0.02 (-3%)	0.09 (12%)	0.01 (1%)
		pVic_022	Piped	0.2	0.00 (0%)	0.00 (0%)	0.00 (1%)	0.00 (1%)	0.00 (0%)	-0.11 (-58%)
9	Butlers Stairs	Butlers_W	Overland	0.0	0.00 (10%)	0.00 (-14%)	-0.01 (-62%)	0.01 (67%)	0.03 (124%)	0.01 (38%)
10	Orwell Street	Orwell_001	Overland	1.5	0.01 (1%)	-0.03 (-2%)	0.13 (9%)	-0.01 (-1%)	0.22 (15%)	0.04 (3%)
		pDRAP14217	Piped	0.0	0.00 (0%)	0.00 (0%)	0.00 (-7%)	0.00 (7%)	0.00 (11%)	0.01 (52%)
		pDRAP14216A	Piped	0.1	0.00 (0%)	0.00 (0%)	0.00 (-1%)	0.00 (1%)	0.00 (1%)	-0.04 (-39%)
11	Hughes Street	HughesSt02	Overland.	0.6	0.00 (0%)	-0.01 (-2%)	0.02 (4%)	0.00 (0%)	0.04 (7%)	-0.01 (-1%)
12	Victoria Street	Vc001	Overland	1.8	0.02 (1%)	-0.02 (-1%)	0.08 (5%)	-0.11 (-6%)	0.12 (7%)	0.03 (2%)
		pDRAP14879A	Piped	0.3	0.00 (0%)	0.00 (0%)	0.00 (1%)	0.00 (0%)	0.00 (1%)	-0.15 (53%)
13	Victoria Street	Vc002	Overland	2.8	0.01 (0%)	-0.08 (-3%)	0.16 (6%)	-0.17 (-6%)	0.26 (9%)	0.18 (6%)
		pVic_017	Piped	0.2	0.00 (0%)	0.00 (0%)	0.00 (-1%)	0.00 (1%)	0.00 (0%)	-0.11(-56%)
		pDRAP14877A	Piped	0.5	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	-0.31 (-58%)
14	Victoria Street	Vic_004	Overland	3.1	0.09 (3%)	0.04 (1%)	0.16 (5%)	-0.09 (-3%)	0.43 (14%)	0.36 (11%)
	U/S McElhone Stairs	pVic_016	Piped	0.2	0.00 (0%)	0.00 (0%)	0.00 (-1%)	0.00 (1%)	0.00 (0%	-0.11 (-56%)
		pDRAP14269	Piped	0.6	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (1%)	0.00 (0%)	-0.34 (-56%)

9.3. Climate Change

9.3.1. Rainfall Increase

The Bureau of Meteorology has indicated that there is no intention at present to revise design rainfalls to take account of potential climate change, as the implications of temperature changes on extreme rainfall intensities are presently unclear, and there is no certainty that the changes would in fact increase design rainfalls for major flood producing storms. There is some recent literature by CSIRO that suggests extreme rainfalls may increase by up to 30% in parts of NSW (in other places the projected increases are much less or even a similar magnitude decrease); however this information is not of sufficient accuracy for use as yet (Reference 14).

Any change in design flood rainfall intensities will increase the frequency, depth and extent of inundation across the catchment. It has also been suggested that the cyclone belt may move further southwards. The possible impacts of this on design rainfalls cannot be ascertained at this time as little is known about the mechanisms that determine the movement of cyclones under existing conditions.

Projected increases to evaporation are also an important consideration because increased evaporation would lead to generally dryer catchment conditions, resulting in lower runoff from rainfall. Mean annual rainfall is projected to decrease, which will also result in generally dryer catchment conditions. The influence of dry catchment conditions on river runoff is observable in climate variability using the Indian Pacific Oscillation (IPO) index (Reference 15). Although mean daily rainfall intensity is not observed to differ significantly between IPO phases, runoff is significantly reduced during periods with fewer rain days. Although given high levels of urbanisation of the study catchment, any such impact will be minimal.

The combination of uncertainty about projected changes in rainfall and evaporation makes it extremely difficult to predict with confidence the likely changes to peak flows for large flood events within the Woolloomooloo catchment under warmer climate scenarios.

In light of this uncertainty, the NSW State Government advice (Reference 14) recommends sensitivity analysis on flood modelling should be undertaken to develop an understanding of the effect of various levels of change in the hydrologic regime on the project at hand. Specifically, it is suggested that increases of 10%, 20% and 30% to rainfall intensity be considered.

9.3.2. Sea Level Rise

In October 2009 the NSW Government issued its Policy Statement on Sea Level Rise (Reference 16) which states"

"Over the period 1870-2001, global sea levels rose by 20 cm, with a current global average rate of increase approximately twice the historical average. Sea levels are expected to continue rising throughout the twenty-first century and there is no scientific evidence to suggest that sea levels will stop rising beyond 2100 or that current trends will be reversed.

Sea level rise is an incremental process and will have medium to long-term impacts. The best national and international projections of sea level rise along the NSW coast are for a rise relative to 1990 mean sea levels of 40 cm by 2050 and 90 cm by 2100. However, the 4th Intergovernmental Panel on Climate Change in 2007 also acknowledged that higher rates of sea level rise are possible";

In August 2010, the former NSW Department of Environment, Climate Change and Water issued the:

- Flood Risk Management Guide (Reference 8): Incorporating sea level rise benchmarks in flood risk assessments.

In addition an accompanying document *Derivation of the NSW Government's sea level rise planning benchmarks* provided technical details on how the sea level rise assessment was undertaken.

Although there are some minor variations in the sea levels predicted in these studies, policies, and guides, they all agree on an ocean level rise on the NSW coast of around 0.9 metre by the year 2100 relative to 1990 levels.

The previous guideline, the NSW Sea Level Rise Policy Statement (2010) (Reference 16) and associated guides, indicated a metre sea level rise by the year 2100 and a 0.4 metre rise by the year 2050. It should be noted that climate change and the associated rise in sea levels will continue beyond 2100. Recent changes have NSW State Government endorsement of sea level rise predictions. Unless specific Councils adopt an alternative policy, predicted sea level rises as per NSW 2010 will continue to be used.

9.3.3. Results

The effect of increasing the design rainfalls by 10%, 20% and 30% has been evaluated for the 100 year ARI event; resulting in a relatively significant impact on peak flood levels in the study area. Generally speaking, each incremental 10% increase in flow results in a 0.1 m to 0.2 m increase in peak flood levels at most of the locations analysed.

The 100 year ARI event with a rainfall increase of 30% is approximately equivalent to a 500 year ARI event in present day conditions and an impact on flood levels particularly in flow paths/storage areas is not unexpected.

Sea level rise scenarios have very little impact on flood levels within the catchment except for within Bourke Street where a 0.9 m sea level increase by 2100 will increase peak flood levels by 0.1m.

Table 24 and Table 25 show the change in peak flows and flood levels due to the effect of climate change induced rainfall increases and sea level rise.

Table 24 – Results of Climate Change Analyses – 100 Year ARI Event Depths (m)

ID	Location	100 Year ARI Peak Flood Flow (m^3/s)	Rainfall Increase 10%	Rainfall Increase 20%	Rainfall Increase 30%	2050 Sea Level +0.4 m	2100 Sea Level +0.9 m
			Difference with 100 Year ARI Base Case (m^3/s)				
1	Francis Street	0.6	0.02	0.03	0.04	-	-
2	Francis Lane	1.9	0.03	0.06	0.08	-	-
3	Yurong Lane	3.4	0.06	0.12	0.17	-	-
4	Busby Lane	1.3	0.07	0.12	0.19	-	-
5	Sir John Young Crescent	1.2	0.07	0.12	0.17	-	-
6	Palmer Street	1.3	0.04	0.07	0.11	-	0.02
7	Cowper Wharf Road underpass	0.7	0.03	0.07	0.10	-	-
8	Bourke Street	0.9	0.03	0.06	0.09	0.05	0.13
9	The Domain	0.4	0.03	0.06	0.09	-	-
10	Victoria Street	0.4	0.02	0.05	0.07	-	-

Table 25 – Results of Climate Change Analyses – 100 Year ARI Event Flows (m^3/s)

ID	Location	Name	Type	100 Year ARI Peak Flood Flow (m^3/s)	Rainfall Increase 10%	Rainfall Increase 20%	Rainfall Increase 30%	2050 Sea Level +0.4 m	2100 Sea Level +0.9 m
					Difference with 100 Year ARI Base Case (m)				
1	Wiliam Street D/S Stream Street	WilliamParal	Overland	8.7	2.37 (27%)	5.06 (58%)	7.64 (88%)	0.01 (0%)	0.00 (0%)
		pRS_015	Piped	0.1	0.03 (28%)	0.03 (30%)	0.03 (28%)	0.00 (0%)	0.00 (0%)
		pWestMD_036	Piped	3.3	0.00 (0%)	0.00 (0%)	0.01 (0%)	0.00 (0%)	0.00 (0%)
2	Crown Street D/S Cathedral Street	CrownSt_03	Overland	8.4	1.12 (13%)	2.14 (26%)	2.90 (35%)	0.01 (0%)	0.01 (0%)
		pCrown_008	Piped	0.1	0.00 (-1%)	0.00 (-1%)	0.00 (-1%)	0.00 (0%)	0.00 (-3%)
3	The Domain flow into Cahill Expressway	Domain_Out_01	Overland	0.1	0.04 (41%)	0.01 (13%)	0.03 (36%)	0.00 (0%)	0.00 (0%)
		pDRAP15584B	Piped	1.0	0.10 (10%)	0.19 (19%)	0.27 (27%)	0.00 (0%)	0.00 (0%)
		pDRAP15585	Piped	1.1	0.13 (11%)	0.23 (20%)	0.33 (29%)	0.00 (0%)	0.00 (0%)
		pHR_011	Piped	0.9	0.06 (6%)	0.11 (12%)	0.15 (16%)	0.00 (0%)	0.00 (0%)
4	Cowper Wharf Road D/S Eastern Distributor	Cowper01	Overland	3.7	0.67 (18%)	1.36 (37%)	2.09 (57%)	0.06 (2%)	0.33 (9%)
		pHR_001	Piped	0.8	0.05 (6%)	0.10 (12%)	0.14 (17%)	0.00 (0%)	0.00 (0%)
		pSJY_001	Piped	1.6	0.03 (2%)	0.06 (4%)	0.08 (5%)	-0.19 (-12%)	-0.47 (-30%)
5	Bourke Street	Bourke	Overland	2.4	0.18 (7%)	0.36 (15%)	0.53 (22%)	-0.81 (-34%)	-2.39 (-100%)
		pWestMD_001A	Piped	5.2	0.06 (1%)	0.12 (2%)	0.16 (3%)	-0.79 (-15%)	-2.07 (-40%)
		pWestMD_001B	Piped	5.2	0.07 (1%)	0.13 (3%)	0.18 (4%)	-0.87 (-17%)	-2.30 (-44%)
6	Forbes Street	Forbes	Overland	1.2	0.31 (25%)	0.76 (61%)	1.25 (101%)	0.46 (37%)	2.14 (173%)
		pEastMC_004	Piped	3.4	0.08 (2%)	0.15 (5%)	0.21 (6%)	-0.57 (-17%)	-1.45 (173%)
		pDRAP13622	Piped	0.8	0.00 (0%)	0.00 (0%)	0.00 (0%)	-0.23 (-29%)	-0.49 (-62%)
7	Dowling Street	Dowling_01	Overland	2.6	0.40 (15%)	0.76 (29%)	1.02 (39%)	-0.05 (-2%)	-2.50 (-96%)
		pDRAP13611E	Piped	0.7	0.01 (2%)	0.03 (4%)	0.04 (6%)	-0.12 (-16%)	-0.32 (-44%)

ID	Location	Name	Type	100 Year ARI Peak Flood	Rainfall Increase 10%	Rainfall Increase 20%	Rainfall Increase 30%	2050 Sea Level +0.4 m	2100 Sea Level +0.9 m
8	Victoria Street	Vic_01A	Overland	0.8	0.09 (12%)	0.28 (38%)	0.39 (52%)	0.00 (0%)	0.00 (0%)
		pVic_022	Piped	0.2	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)
9	Butlers Stairs	Butlers_W	Overland	0.0	0.03 (124%)	0.06 (290%)	0.09 (433%)	0.00 (0%)	0.00 (0%)
10	Orwell Street	Orwell_001	Overland	1.5	0.22 (15%)	0.37 (25%)	0.55 (37%)	0.04 (3%)	-0.01 (0%)
		pDRAP14217	Piped	0.0	0.00 (11%)	0.01 (19%)	0.01 (30%)	0.00 (0%)	0.00 (0%)
		pDRAP14216A	Piped	0.1	0.00 (1%)	0.00 (2%)	0.00 (3%)	0.00 (0%)	0.00 (0%)
11	Hughes Street	HughesSt02	Overland.	0.6	0.04 (7%)	0.14 (23%)	0.22 (36%)	-0.01 (0%)	0.00 (0%)
12	Victoria Street	Vc001	Overland	1.8	0.12 (7%)	0.25 (14%)	0.38 (21%)	0.00 (0%)	0.00 (0%)
		pDRAP14879A	Piped	0.3	0.00 (1%)	0.00 (1%)	0.00 (1%)	0.00 (0%)	0.00 (0%)
13	Victoria Street	Vc002	Overland	2.8	0.26 (9%)	0.54 (19%)	0.88 (31%)	-0.03 (-1%)	-0.05 (-2%)
		pVic_017	Piped	0.2	0.00 (0%)	0.00 (1%)	0.01 (2%)	0.00 (0%)	0.00 (0%)
		pDRAP14877A	Piped	0.5	0.00 (0%)	0.00 (1%)	0.00 (0%)	0.00 (0%)	0.00 (0%)
14	Victoria Street U/S McElhone Stairs	Vic_004	Overland	3.1	0.43 (14%)	0.72 (23%)	1.10 (35%)	0.01 (0%)	0.07 (2%)
		pVic_016	Piped	0.2	0.00 (0%)	0.00 (1%)	0.00 (2%)	0.00 (0%)	0.00 (0%)
		pDRAP14269	Piped	0.6	0.00 (1%)	0.00 (1%)	0.00 (0%)	0.00 (1%)	0.00 (0%)

10. DAMAGES ASSESSMENT

The cost of flood damages and the extent of the disruption to the community depend upon many factors including:

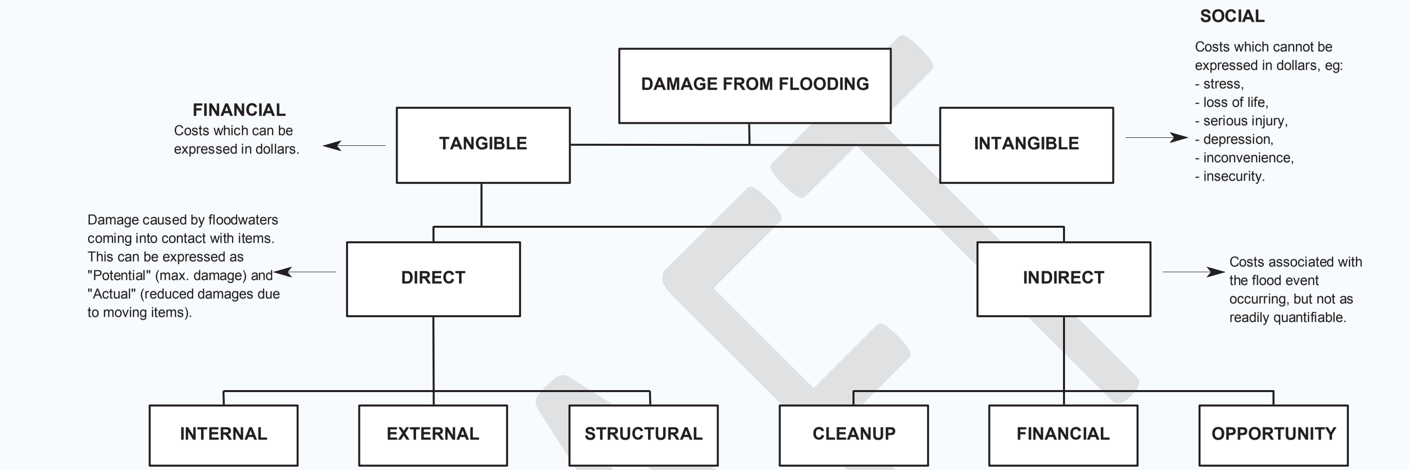
- the magnitude (depth, velocity and duration) of the flood,
- land usage and susceptibility to damage,
- awareness of the community to flooding,
- effective warning time,
- the availability of an evacuation plan or damage minimisation program,
- physical factors such as failure of services (pits and pipes), flood borne debris, sedimentation, and
- the types of asset and infrastructure affected.

The estimation of flood damages tends to focus on the physical impact of damages on the human environment but there is also a need to consider the ecological cost and benefits associated with flooding. Flood damages can be defined as being tangible or intangible. Intangible damages are those to which a monetary value cannot easily be attributed. Types of flood damages are shown on Table 26.

While the total likely damages in a given flood are useful to get a “feel” for the magnitude of the flood problem, it is of little value for absolute economic evaluation. When considering the economic effectiveness of a proposed mitigation measure, the key question is what are the total damages prevented over the life of the measure? This is a function not only of the high damages which occur in large floods but also of the lesser but more frequent damages which occur in small floods.

The standard way of expressing flood damages is in terms of average annual damages (AAD). AAD represents the equivalent average damages that would be experienced by the community on an annual basis, by taking into the account the probability of a flood occurrence. By this means, the smaller floods, which occur more frequently, are given a greater weighting than the rare catastrophic floods.

Table 26 – Breakdown of Flood Damages Categories



	INTERNAL	EXTERNAL	STRUCTURAL	CLEANUP	FINANCIAL	OPPORTUNITY
RESIDENTIAL	Contents of Buildings: Clothes, Carpets, Furniture, Valuables, Fittings, Appliances	External Items: Vehicles, Laundries, Caravans, Sheds, Tools, Gardens, Fences	Physical Damage to Buildings: Gyprock, Cupboards, Scour of Footings, Houses becoming buoyant (floating off footings)	Clean Carpets, Walls, Clothes; Re-instate Furniture; Remove Mud and Debris	Loss of wages, Living costs (temporary accomodation and food), Time to repair/replace damaged items	Not Applicable
RURAL	Contents of Buildings: Clothes, Carpets, Furniture, Valuables, Fittings, Appliances	External Items: Vehicles, Sheds (stables/barns), Machinery, Tools, Fences, Feed storage, Saddles, Crops &/or Stock, Irrigation Systems	Physical Damage to Structures: Damage to Homestead, Sheds, Access tracks, Protection levees	Clean Homestead and Out-buildings; Remove Debris; Dispose of affected crops &/or stock	Loss of Farm Production and Income, Re-instatement of Pastures, Supplementary feeding of stock (by hand or outside agistment), Stock movement/ transport, Living costs (temporary accomodation and food)	Sowing or harvesting of Crops, Sale of Stock (at depreciated value or dependent on market influences)
COMMERCIAL	Contents of Buildings: Products, Stock, Fittings, Tools, Machinery, Raw Materials	External Items: Vehicles, Machinery, Display, Raw Materials/Stockpiles, Fences	Physical Damage to Buildings	Dispose of damaged products, stock, materials; Cleaning and Re-instatement	Loss of Productivity and Income, Bank Interest Charges	Loss of existing &/or Potential Trade
PUBLIC AUTHORITIES	Contents of Public Buildings and Facilities	Public Property and Facilities: Parks, Signs, Machinery, Equipment	Physical Damage to Infrastructure: Electricity, Water, Telephone, Gas, Road & Rail Transport Links	Remove Mud & Debris from Facilities, Public & Private Property Repairs (temporary & permanent)	Disruption of Services, Community Service Relief Grants	Provision of Public Service

A flood damages assessment was undertaken for existing development for overland flooding within the Woolloomooloo catchment. This was based on a detailed floor level survey which was undertaken for properties considered flood liable. The study area contains a total of 2844 cadastral lots of which 241 were surveyed or approximately 8% of the study area. Only properties which have surveyed floor levels have been included in the flood damages assessment.

A number of properties within the study area have below ground floors or basement car parking. In the case of below ground floors it was assumed that 50% would be inhabited and the maximum depth of flooding would be 1m. For basement car parking, if water could access the car park damages were assumed to be $10,000 (assumed 50% have a car at a cost of $20,000 per car park).

Damages to public structures have not been assessed. A summary of flood damages for the catchment is provided in Table 27 and Table 28 and with the building floors inundated shown on Figure 29.

Table 27 – Summary of Flood Damages

Design Flood Event	Residential Properties Flooded Above Floor Level	Commercial Properties Flooded Above Floor Level	Total Properties Flooded Above Floor Level
2 Year ARI	35	16	51
5 Year ARI	56	21	77
10 Year ARI	58	29	87
20 Year ARI	77	40	117
50 Year ARI	105	51	156
100 Year ARI	106	54	160
PMF	142	65	207

Note: * Excludes all damages to public assets

Table 28 – Summary of Flood Damages

Design Flood Event	Residential Properties Tangible Flood Damages	Commercial Properties Tangible Flood Damages	Total Tangible Flood Damages*
2 Year ARI	$ 2,330,000	$ 621,000	$ 2,950,000
5 Year ARI	$ 3,090,000	$ 746,000	$ 3,840,000
10 Year ARI	$ 3,550,000	$ 890,000	$ 4,440,000
20 Year ARI	$ 4,420,000	$ 1,140,000	$ 5,580,000
50 Year ARI	$ 5,800,000	$ 2,390,000	$ 8,190,000
100 Year ARI	$ 6,410,000	$ 3,000,000	$ 9,410,000
PMF	$ 9,480,000	$ 7,070,000	$ 16,600,000
	Average Annual Damages		$ 2,840,000

Note: * Excludes all damages to public assets

Data was provided in terms of cadastral lots and in many cases there were a number of properties within each cadastral lot. For an individual building floor levels may vary, with multiple levels, and only the lowest floor level was surveyed. Nevertheless the damages provide the best indicative assessment of the annual cost of flooding to residents.

10.1. Discussion

Overall 160 buildings were flooded over floor level in the 100 year ARI event, approximately 6% of properties in the study area. Further work during the Floodplain Risk Management Study (FRMS) will address these flood liable properties. It may be that a recommendation be made as part of the subsequent FRMS that some buildings be altered (raised or limited works) in order to reduce overall flood risk in the catchment.

STREAM STREET AREA

Flooding within the Printers Lane and Seale Lane low point appear to be affected frequently with above flood flooding identified in the 2 year ARI event. Properties near the Stream Street hot spot in Stanley Lane are also affected.

CROWN STREET AREA

Properties in this area are mixed residential and commercial. Of these residential buildings most of the buildings were not flooded until a 5 year ARI event.

BOURKE STREET AREA

Flood affectation of properties in the lower Woolloomooloo catchment area near Bourke and Forbes Streets is fairly infrequent with the majority of properties unaffected by flooding above floor level until the PMF event.

One property along Bourke Street is affected by above floor flooding in a 10 year ARI event and further nine properties are flood affected in a 20 year ARI event. Along Forbes Street there are two properties affected by flooding above floor level in a 2 year ARI event.

On the eastern end of Bland Street near its intersection with Dowling Street four properties are affected above floor level in flood events larger than 5 Year ARI.

VICTORIA STREET AREA

Properties along Victoria Street are flood affected in events as frequent as the 2 year ARI including several below street level.

11. DISCUSSION

11.1. Flooding Hot Spots

Historically flooding problems occur throughout the catchment, with seven instances of reported above floor flooding (as documented in Section 3.6). Some of the areas where flooding is problematic are described herein as “hotspots” and are discussed in some detail.

11.1.1. Stream Street

Stream Street, as the name suggests, is along a natural depression and was once a major overland flow-path within the Woolloomooloo catchment. With the construction of William Street and buildings along Yurong Lane, this flow path is effectively blocked and water ponds which has historically caused above floor flooding to nearby properties.

Flooding Behaviour

The contributing catchment area is approximately 23 ha. The main culvert draining through Stream Street is the SWC’s Western Main Drain (910 mm x 1370 mm under William Street) which ultimately drains to Woolloomooloo Bay. Two branches of the CoS pipes drain through Stream Street along Stanley Lane and Yurong Lane connecting to the Western Main Drain (details of pipe sizes shown on Figure 30).

The low point shown on Figure 30 receives overland flow from William Street, Riley Street, Stanley Lane and Yurong Lane. Downstream, William Street acts as a weir with the lowest road crest level at 12.7 mAHD. During flood events equal to or greater than 20 Year ARI peak flood levels within the Stream Street low point exceed the crest level of William Street and excess flows are conveyed overland via Riley Street to the northern part of the catchment.

Table 29 lists peak design flood levels and depths within Stream Street and Yurong Lane and Table 30 lists peak flows for the locations marked on Figure 30.

Table 29 – Stream Street Peak Design Flood Levels, Depths and Flows across William Street (m^3/s) (refer Figure 30)

Design Event	Peak Flood Level (mAHD)	Peak Flood Depth (m)	William St Overflow (m^3/s)
2Y ARI	10.7	0.9	0.0
5Y ARI	11.8	2.0	0.0
10Y ARI	12.3	2.5	0.0
20Y ARI	12.9	3.1	0.1
50Y ARI	13.2	3.4	6.2
100Y ARI	13.3	3.5	8.7
PMF	14.1	4.3	55.5

Table 30 – Stream Street Peak Flows (refer Figure 30)

Peak Overland Flow (m^3/s)							
Location	2Y ARI	5Y ARI	10Y ARI	20Y ARI	50Y ARI	100Y ARI	PMF
1	0.4	0.8	1.0	1.7	3.0	3.5	17.9
2	0.0	0.1	0.2	0.4	0.6	0.7	1.5
3	0.3	0.5	0.7	1.2	3.4	4.8	18.5
4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.5
5	0.5	1.0	1.3	1.6	2.2	2.5	13.3
6 (1)	0.0 (-0.4)	0.0 (-0.7)	0.0 (-0.9)	0.0 (-1.2)	0.2 (-1.6)	0.6 (-1.9)	15.7 (-3.9)
7	0.0	0.0	<0.1	0.7	6.0	7.9	33.5
8	0.0	0.0	0.0	0.1	6.2	8.7	55.5

Note (1): In events smaller than or equal to the 20 Year ARI event runoff travel south from William Street through Yurong Street into the low point (denoted by negative values). In events greater than 20 Year ARI peak water levels in the low point are high enough that excess flows from the low point travel north through Yurong Street into William Street.

Peak PipeFlow (m^3/s)									
Location	Size (mm)	Capacity	2Y ARI	5Y ARI	10Y ARI	20Y ARI	50YARI	100Y ARI	PMF
2	1370 x 910 (ovoid)	< 2y ARI	2.6	2.8	2.8	2.8	1.7	1.7	1.8
4	300	2y ARI	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1
5	525	< 2y ARI	0.2	0.2	0.2	0.2	0.2	0.2	0.1
8	1830 x 1220 (ovoid)	2y ARI	3.9	4.3	4.5	5.0	3.3	3.3	3.3

11.1.2. Busby Lane Low Point

Busby Lane is located on the northern side of William Street and branches off from Riley Street, providing access to a number of commercial properties then re-joining Riley Street to the north. Council has indicated flooding issues have occurred in the past.

Flooding Behaviour

Figure 31 shows the trunk drainage and peak design flood depths for the 100 Year ARI event within the lane. Ground elevations are significantly lower than the adjoining Riley Street. Busby Lane has a low point of 7.0 mAHD which is approximately 1.1 m lower than the Riley Street exit and any excess overland flow which cannot be conveyed by the underground drainage system will pond.

Table 31 lists the peak flood levels and depths in the low point and Table 32 lists peak flows for the locations marked on Figure 31.

Table 31 – Busby Lane Peak Design Flood Levels and Depths (refer Figure 31)

Design Event	Level (mAHD)	Depth (m)
2Y ARI	7.0	1.0
5Y ARI	7.1	1.1
10Y ARI	7.1	1.1
20Y ARI	7.2	1.2
50Y ARI	7.4	1.4
100Y ARI	7.4	1.4
PMF	8.3	2.3

Table 32 – Busby Lane Peak Flows (refer Figure 31)

Peak Overland Flow (m^3/s)							
Location	2Y ARI	5Y ARI	10Y ARI	20Y ARI	50Y ARI	100Y ARI	PMF
3	<0.1	<0.1	<0.1	0.1	0.5	0.5	3.8
4	0.0	0.2	0.3	0.4	0.9	1.0	3.8

Peak Pipe Flow (m^3/s)									
Location	Size (mm)	Capacity	2Y ARI	5Y ARI	10Y ARI	20Y ARI	50YARI	100Y ARI	PMF
1	1830 x 1220 (ovoid)	20y ARI	0.5	0.5	0.5	0.1	0.3	0.3	0.3
2	450	< 2y ARI	4.3	4.7	4.9	5.6	4.1	4.1	4.3
5	1830 x 1220 (ovoid)	20y ARI	4.6	5.0	5.2	5.3	4.1	4.1	4.3

11.1.3. Crown Street Low Point

The Crown Street low point is located at the intersection of Crown Street and Bossley Terrace and is adjacent to a site which was previously a car park and is now under development. Overflow from the Crown Street low point continues to the adjacent Palmer Street (see Section 11.1.4).

Flooding Behaviour

Table 33 lists the peak flood levels and depths within Crown Street and Table 34 lists the peak flows for the locations marked on Figure 32.

Table 33 – Crown Street Peak Design Flood Levels and Depths (refer Figure 32)

Design Event	Level (mAHD)	Depth (m)
2Y ARI	4.1	0.5
5Y ARI	4.2	0.6
10Y ARI	4.3	0.7
20Y ARI	4.4	0.8
50Y ARI	4.6	1.1
100Y ARI	4.7	1.1
PMF	5.6	2.0

Table 34 – Crown Street Peak Flows (refer Figure 32)

Peak Overland Flow (m^3/s)							
Location	2Y ARI	5Y ARI	10Y ARI	20Y ARI	50Y ARI	100Y ARI	PMF
1	1.0	1.9	2.5	3.2	6.9	8.4	14.1
2	0.4	0.5	0.7	0.8	1.0	1.2	29.8
3 [(1)]	0.0 (-0.2)	0.0 (-0.4)	0.0 (-0.4)	0.0 (-0.5)	0.3 (-0.5)	1.2 (-0.6)	20.3 (-2.1)
5	<0.1	0.1	0.1	0.6	0.6	1.5	22.0
6	0.0	0.0	0.0	0.0	<0.1	0.2	3.7
7	0.0	0.0	0.0	0.0	<0.1	0.1	4.2
8	1.1	2.1	2.9	3.8	6.8	7.8	19.1
9	1.1	2.1	2.8	3.7	6.6	7.6	18.1

Note [(1)]**:** In events smaller than or equal to the 20 Year ARI event runoff travels south into the low point (denoted by negative values). In events greater than 20 Year ARI peak flow travels north out of the low point.

Peak Pipe Flow (m^3/s)									
Location	Size (mm)	Capacity	2Y ARI	5Y ARI	10Y ARI	20Y ARI	50YARI	100Y ARI	PMF
1	375	< 2y ARI	0.2	0.2	0.2	0.2	0.1	0.1	0.1
3	600	< 2y ARI	0.4	0.3	0.3	0.3	0.3	0.3	0.4
4	1830 x 1220 (ovoid)	< 2y ARI	5.2	5.5	5.6	5.6	4.1	4.1	4.2
5	1830 x 1220 (ovoid)	< 2y ARI	5.3	5.6	5.7	5.8	4.6	4.6	4.2

Overland flow enters the low point from Cathedral Street to the south and Sir John Young Crescent from the west and to the north. Excess water is drained via Bossley Terrace and in larger events via Sir John Young Crescent to the north.

11.1.4. Palmer Street Low Point

The Palmer Street low point is located below the Eastern Railway line alongside Palmer Street and the Eastern Distributor (Photo 15). Adjacent properties are primarily commercial and although there is no record of past flooding there is considerable drainage infrastructure at the low point. Many physical changes to the catchment have occurred in the past 20 years which have directly affected drainage from the low point. Firstly in 1987 a twin culvert line was constructed which starts at the low point via a large inlet pit seen in Photo 16. Secondly in 1997 the Eastern Distributor was completed, with wall barriers varying in height from 0.8 ~ 1.3 m adjacent to the low point. Additional inlet capacity was added within Palmer Street as seen in Photo 17 and Photo 18.

Photo 15: Palmer Street Low Point

Photo 16: 4 m by 4 m inlet pit

Photo 17: 7.2m lintel and 7x0.6x1.0 m grated inlets

Photo 18: 4x0.6x1.0 m grated inlets

Flooding Behaviour

Pipe sizes of the trunk drainage system through Palmer Street and the adjacent Sir John Young Crescent are shown on Figure 33. Table 35 lists the peak flows for the locations marked on Figure 33.

Table 35 – Palmer Street Peak Flows (refer Figure 33)

Peak Overland Flow (m^3/s)							
Location	2Y ARI	5Y ARI	10Y ARI	20Y ARI	50Y ARI	100Y ARI	PMF
1	<0.1	0.1	0.2	0.2	1.0	2.2	6.5
2	1.1	2.1	2.8	3.7	6.6	7.6	18.1
3	0.0	0.0	0.0	0.0	0.2	0.6	14.0
4	<0.1	<0.1	<0.1	0.1	0.4	1.0	10.0
5	0.0	0.0	0.0	0.0	3.4	7.2	44.5

Peak Pipe Flow (m^3/s)										
Location	Size (mm)	Capacity	2Y ARI	5Y ARI	10Y ARI	20Y ARI	50YARI	100Y ARI	PMF
1	675	2y ARI	0.3	0.4	0.5	0.6	0.5	0.5	0.7
4	1520 x 2440 (irregular)	10y ARI	4.1	4.6	4.8	4.7	3.5	3.5	3.8
6	2 x 840 x 1830 BC	< 2y ARI	3.8	5.1	5.7	6.3	5.4	5.4	5.6
7	2 x 1520 x 2440 BC	< 2y ARI	1.6	2.3	2.6	2.9	2.8	2.9	3.0

Modelling shows that floodwater enters the low point from Cathedral Street via Palmer Street to the south and from the Crown Street low point (Section 11.1.3) from the west via Bossley Terrace and north via Sir John Young Crescent and through adjacent properties.

During large storm events, water levels in the low point overtop the barrier dividing Palmer Street and the Eastern Distributor and overflows enter the north-bound Eastern distributor tunnel exit. Site survey of the barrier indicated a crest level of 3.1 mAHD. Table 36 lists peak flood levels and depths within the low point and peak flows overtopping the barrier.

Table 36 – Palmer Street Peak Design Flood Levels, Depths and Flows across the Eastern Distributor Barrier (m^3/s) (refer Figure 33)

Design Event	Level (mAHD)	Depth (m)	Barrier Overflow (m^3/s)
2Y ARI	2.4	0.4	0.0
5Y ARI	2.6	0.6	0.0
10Y ARI	2.7	0.7	0.0
20Y ARI	2.8	0.8	0.0
50Y ARI	3.4	1.3	3.4
100Y ARI	3.5	1.4	7.2
PMF	3.8	1.8	44.5

11.1.5. Victoria Street

Victoria Street consists of mainly residential and small commercial properties and is located on the eastern side of the Woolloomooloo catchment. The top of the catchment is located near the intersection of Surrey Street and Victoria Street and the catchment area contributing to pipe flows through Victoria Street is larger than that contributing to overland flow. In recent events, flood waters have been observed to travel through the street at the western side of the street in the gutter at depths between 0.3 to 0.5 m.

Photo 19: Victoria Street looking north from Butlers Stairs.

Photo 20: Examples of flood barriers located at commercial premises on Victoria Street.

Flooding Behaviour

Pipe sizes of the trunk drainage system are shown on Figure 34. Table 37 lists the peak flood flows for the locations marked on Figure 34.

Table 37 – Victoria Street Peak Flows (refer Figure 34)

Peak Overland Flow (m^3/s)							
Location	2Y ARI	5Y ARI	10Y ARI	20Y ARI	50Y ARI	100Y ARI	PMF
1	0.2	0.3	0.4	0.5	0.6	0.8	4.9
2	0.0	<0.1	<0.1	<0.1	<0.1	0.1	2.6
3	0.4	0.6	0.7	1.0	1.4	1.5	5.7
4	0.3	0.3	0.4	0.5	0.5	0.6	3.4
5	0.7	1.1	1.3	1.4	1.6	1.8	6.3
6	0.2	0.3	0.4	0.5	0.7	0.8	3.0
7	0.6	1.4	1.7	2.1	2.5	2.8	10.9

Peak Pipe Flow (m^3/s)									
Location	Size (mm)	Capacity	2Y ARI	5Y ARI	10Y ARI	20Y ARI	50YARI	100Y ARI	PMF
1	450	< 2y ARI	0.2	0.2	0.2	0.2	0.2	0.2	0.2
3 (1)	300	100y ARI	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1
3 (1)	375	100y ARI	0.1	0.1	0.1	0.1	0.1	0.1	0.2
5	450	< 2y ARI	0.2	0.2	0.2	0.2	0.2	0.2	0.2
5	600	< 2y ARI	0.3	0.3	0.3	0.3	0.3	0.3	0.3
6	300	< 2y ARI	0.1	0.1	0.1	0.1	0.1	0.1	0.1
7	450	< 2y ARI	0.2	0.2	0.2	0.2	0.2	0.2	0.2
7	600	< 2y ARI	0.6	0.6	0.6	0.6	0.5	0.5	0.6

Note (1)**:** Limited pit inlet capacity along Orwell Street means that drainage pipes are under-utilised – despite this we still get surcharging occurring at the corner of Orwell and Victoria Streets.

Piped and overland flow from Orwell Street, Hughes Street and Tusculum Lane easement join flows from Victoria Street from the east. The percentage of piped and overland flow contributed to the Victoria Street overland and sub-surface drainage system is described in Table 38.

Table 38 – Victoria Street system flow distribution (m^3/s) (refer Figure 34)

Location	2 Year ARI	20 Year ARI	100 Year ARI
Victoria Street U/S of Orwell Street	0.4	0.7	0.9
Orwell Street	0.5	1.1	1.6
Hughes Street	0.3	0.5	0.6
Tusculum Lane easement	0.3	0.6	0.9
Victoria Street D/S of easement	1.5	2.9	3.6

Sub-surface drainage within Victoria Street reaches full capacity in less than a 2 year ARI event. The largest peak inflow into the Victoria Street system is from Orwell Street. In flood events with a 2 year ARI or greater intensity any additional flows delivered from adjoining streets such as Orwell Street must surcharge at the intersection with Victoria Street, contributing to the existing overland flows and exacerbating flooding issues, albeit downstream of Butlers Stairs and some of the worst affected residences.

Within Orwell Street pit inlet capacity is limited with approximately 50~60% of the 300 mm pipe capacity being used in all design events and approximately 90% of the 375 mm pipe capacity being used in all design events (Location 3 – Figure 34). Given that downstream pipes within Victoria Street are at capacity in a 2 Year ARI event having Orwell Street pipes at full capacity will provide no additional benefit to Victoria Street properties.

At the Victoria Street and Orwell Street intersection the topography naturally grades from east to west and prior to the construction of properties along Victoria Street, a large proportion of overland flow would continue from Orwell Street and flow full due west down to Brougham Street. In existing conditions, water is diverted down Victoria Street via the gutter and footpath causing inundation of properties.

The road surface gradient along Victoria Street varies. From the top of the catchment to approximately half way between Earl Street and Butlers Stairs, the grade is typically 3% and this changes to approximately 1% until just south of the Tusculum Lane easement where the road gradient becomes approximately 4% (Figure 35). Past the Tusculum Lane easement the increase in grade results in reduced peak flood depths and generally lower flood hazard. The low road and pipe grades upstream of the Tusculum Lane easement are part of the reason for the low pipe capacity within this section of Victoria Street.

11.1.6. Cowper Wharf Road underpass

The underpass is below the Eastern Distributor and connects traffic from the Cahill Expressway and Sir John Young Crescent to Cowper Wharf Road and Woolloomooloo Bay.

Pipe sizes of the trunk drainage system are shown on Figure 36. The underpass represents a low point and any excess overland flow which cannot be conveyed by the underground drainage system will pond with depths of up to 0.8 m in the 100 year ARI event. Table 39 lists the peak flood depths within the low point and Table 40 lists peak flows for the locations marked on Figure 36.

Table 39 – Cowper Wharf Road underpass Design Peak Depths (refer Figure 36)

Design Event	Depth (m)
2Y ARI	0.5
5Y ARI	0.6
10Y ARI	0.6
20Y ARI	0.7
50Y ARI	0.7
100Y ARI	0.7
PMF	1.3

Table 40 – Cowper Wharf Road underpass Peak Flows (refer Figure 36)

Peak Overland Flow (m^3/s)							
Location	2Y ARI	5Y ARI	10Y ARI	20Y ARI	50Y ARI	100Y ARI	PMF
1	0.5	1.0	1.2	1.5	2.0	2.1	12.6
2	1.0	1.7	2.0	2.4	3.0	3.7	12.0
3	1.0	2.1	2.7	3.6	4.6	5.4	26.7

Peak Pipe Flow (m^3/s)									
Location	Size (mm)	Capacity	2Y ARI	5Y ARI	10Y ARI	20Y ARI	50YARI	100Y ARI	PMF
1	375	< 2y ARI	0.1	0.1	0.1	0.1	0.1	0.1	0.1
2	750	5y ARI	0.5	0.6	0.7	0.7	0.8	0.8	1.1
3	750	< 2y ARI	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	600	< 2y ARI	0.5	0.6	0.7	0.7	0.7	0.8	1.0

11.1.7. Bourke Street Low Point

Bourke Street and Bland Street consist of a mix of residential and commercial properties and are located at the downstream and northern end of the catchment adjacent to Cowper Wharf Road. Past flooding has been reported within the low point in August 1986 with reported levels of approximately 2.1 mAHD corresponding to depths of approximately 0.5 m in the road.

Flooding Behaviour

A significant portion of catchment flows are routed through Bourke Street which is a result of the conjunction of the Western Main Drain with Bourke Street and Palmer Street SWC trunk drainage systems. Excess overland flow from the Eastern Main Channel system along Forbes Street also contributes to flooding within the low point.

Flooding behaviour within the low point has changed significantly with the construction of the SWC Western Main Drain in 1987 and the Eastern Distributor in 1993 and overland flows which would have otherwise contributed to flooding within the low point are now routed through the Cowper Wharf underpass (see Section 11.1.6).

Pipe sizes of the trunk drainage system are shown on Figure 36. Table 41 lists the peak flood levels and Table 42 lists the peak flood flows for the locations marked on Figure 36.

Table 41 – Bourke Street Design Flood Levels (refer Figure 37)

Design Event	Level (mAHD)	Depth (m)
2Y ARI	1.5	<0.1
5Y ARI	1.6	<0.1
10Y ARI	1.7	0.2
20Y ARI	2.1	0.6
50Y ARI	2.3	0.8
100Y ARI	2.3	0.8
PMF	2.8	1.3

Table 42 – Bourke Street Peak Flows (refer Figure 37)

Peak Overland Flow (m^3/s)							
Location	2Y ARI	5Y ARI	10Y ARI	20Y ARI	50Y ARI	100Y ARI	PMF
1	0.1	0.1	0.2	0.8	1.9	2.3	11.0
2	0.0	0.0	0.0	0.6	1.1	1.2	2.7
3	0.0	0.0	<0.1	0.2	0.5	0.6	2.2
4	0.0	0.0	<0.1	0.3	0.6	0.7	2.2
5	0.0	0.0	0.0	0.0	0.1	0.4	2.2
7	1.0	2.1	2.7	3.6	4.6	5.4	26.7
8	0.0	0.0	0.0	<0.1	2.0	3.4	28.0

Peak Pipe Flow (m^3/s)									
Location	Size (mm)	Capacity	2Y ARI	5Y ARI	10Y ARI	20Y ARI	50YARI	100Y ARI	PMF
1	1520x2440 BC	< 2y ARI	3.8	5.1	5.7	6.3	5.4	5.4	5.6
1	1520x2440 BC	< 2y ARI	2.4	3.3	3.7	3.8	2.8	2.9	3.0
6	1350	< 2y ARI	1.3	1.4	1.4	1.6	1.2	1.2	1.4
7	750	< 2y ARI	0.5	0.6	0.7	0.7	0.7	0.8	1.0
7	600	< 2y ARI	0.3	0.3	0.3	0.3	0.2	0.2	0.2
8	1650 x 2770 BC	< 2y ARI	1.8	1.9	2.0	2.1	1.6	1.6	1.8
8	1660 x 2770 BC	< 2y ARI	3.3	4.6	5.4	6.5	5.1	5.2	5.8
8	1200	< 2y ARI	3.4	5.0	5.9	6.6	5.1	5.2	5.8

12. ACKNOWLEDGEMENTS

This study was carried out by WMAwater and funded by the City of Sydney and Sydney Water Corporation. The assistance of the following in providing data and guidance to the study is gratefully acknowledged:

- City of Sydney;
- Sydney Water Corporation;
- Residents of the City of Sydney within the study area; and
- Bureau of Meteorology.

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Figures

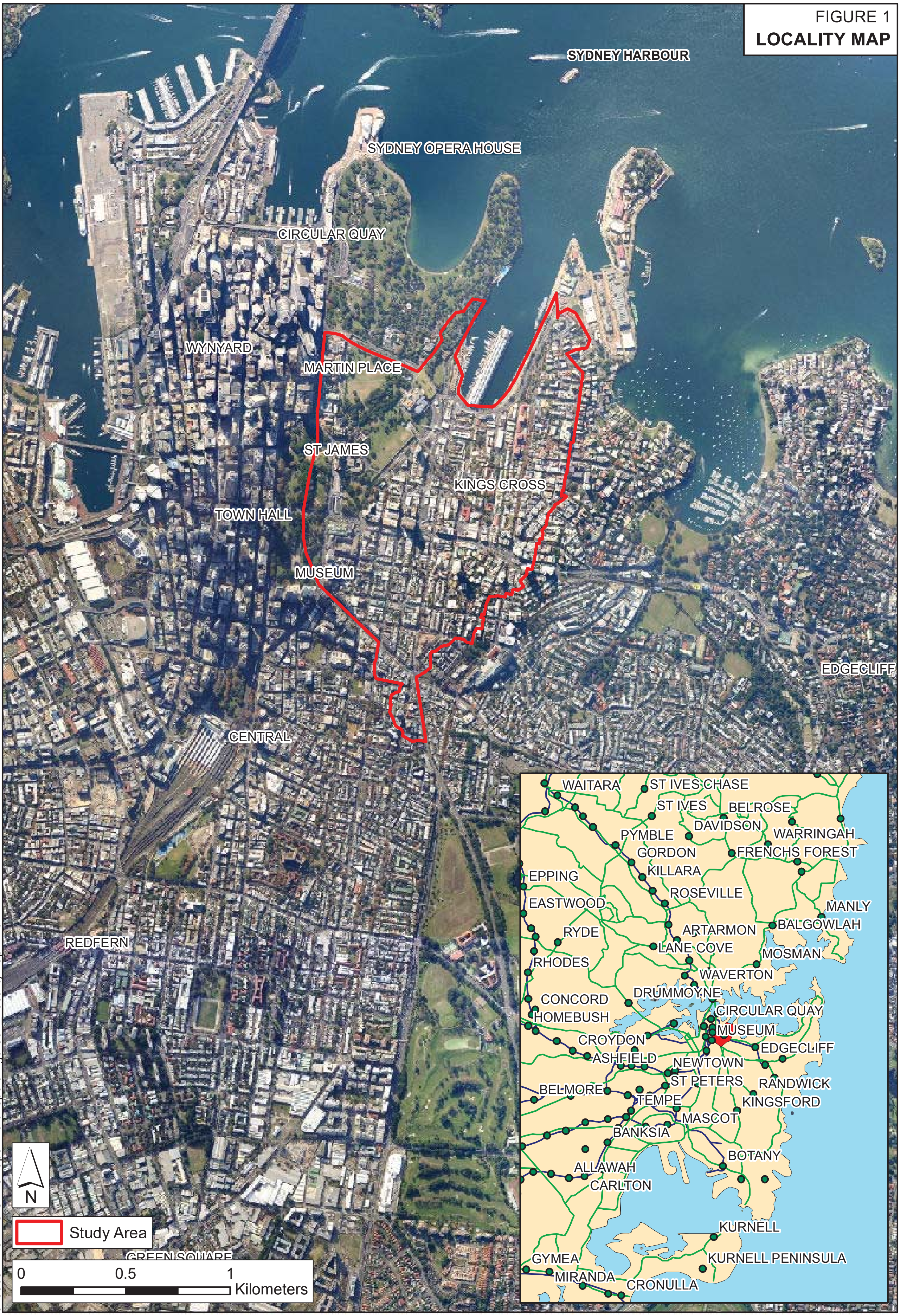

FIGURE 1
LOCALITY MAP

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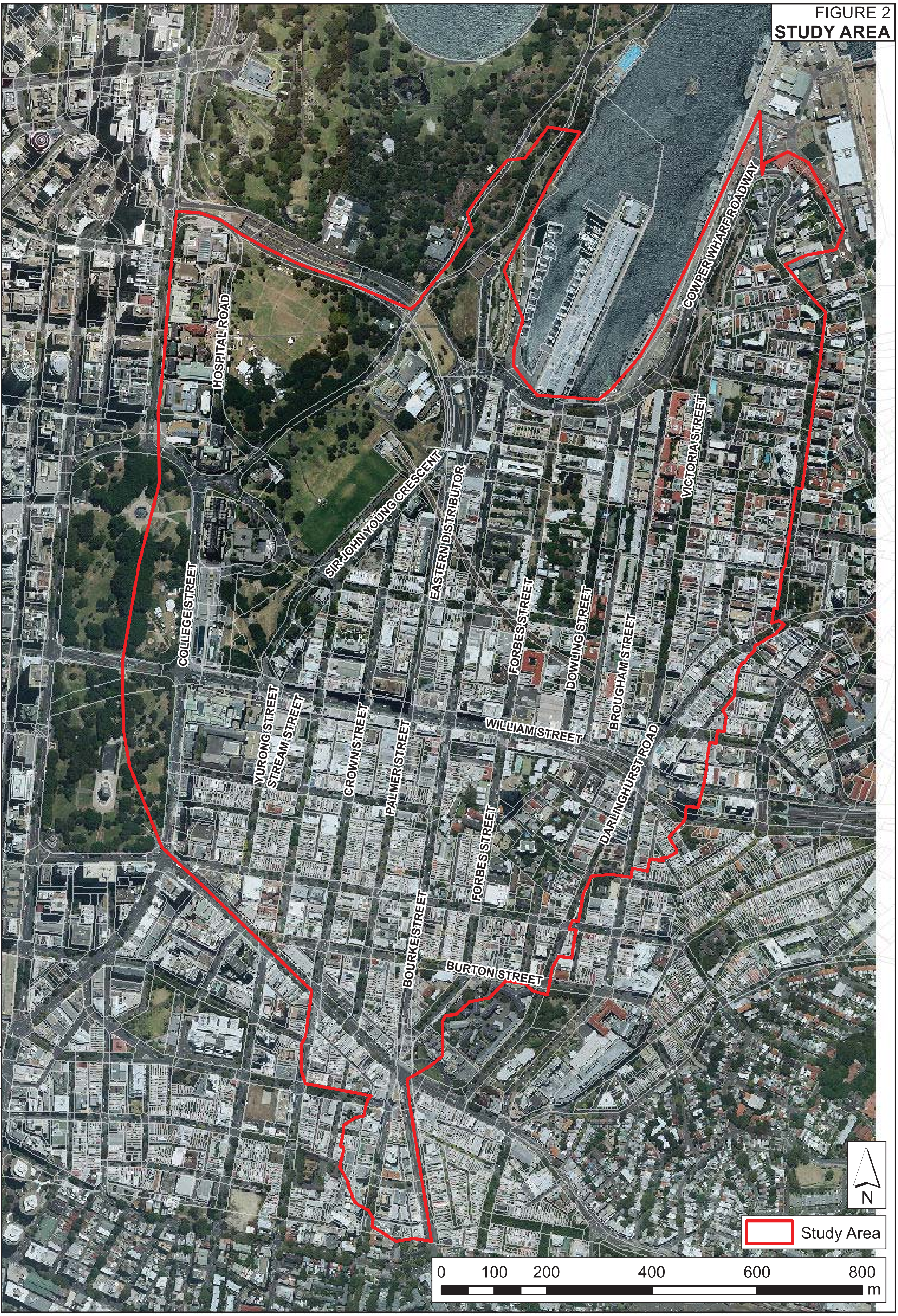
FIGURE 2
STUDY AREA



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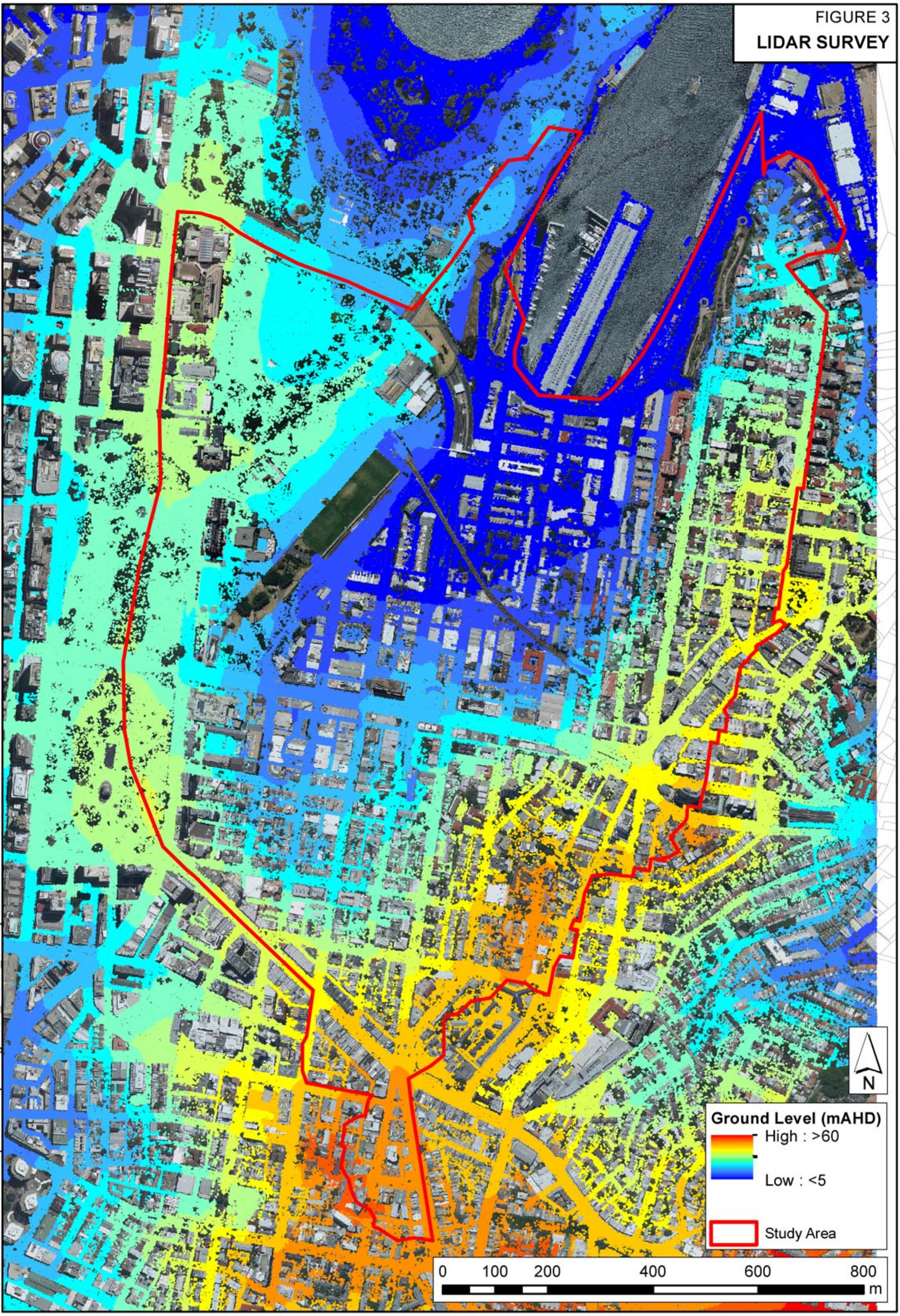
FIGURE 3
LIDAR SURVEY
N
Ground Level (mAHD)
High : >60
Low : <5
Study Area
0
100
200
400
600
800
m
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FIGURE 4
RAINFALL GAUGES

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FIGURE 5

IFD DATA AND RAINFALL COMPARISON
PADDINGTON GAUGE

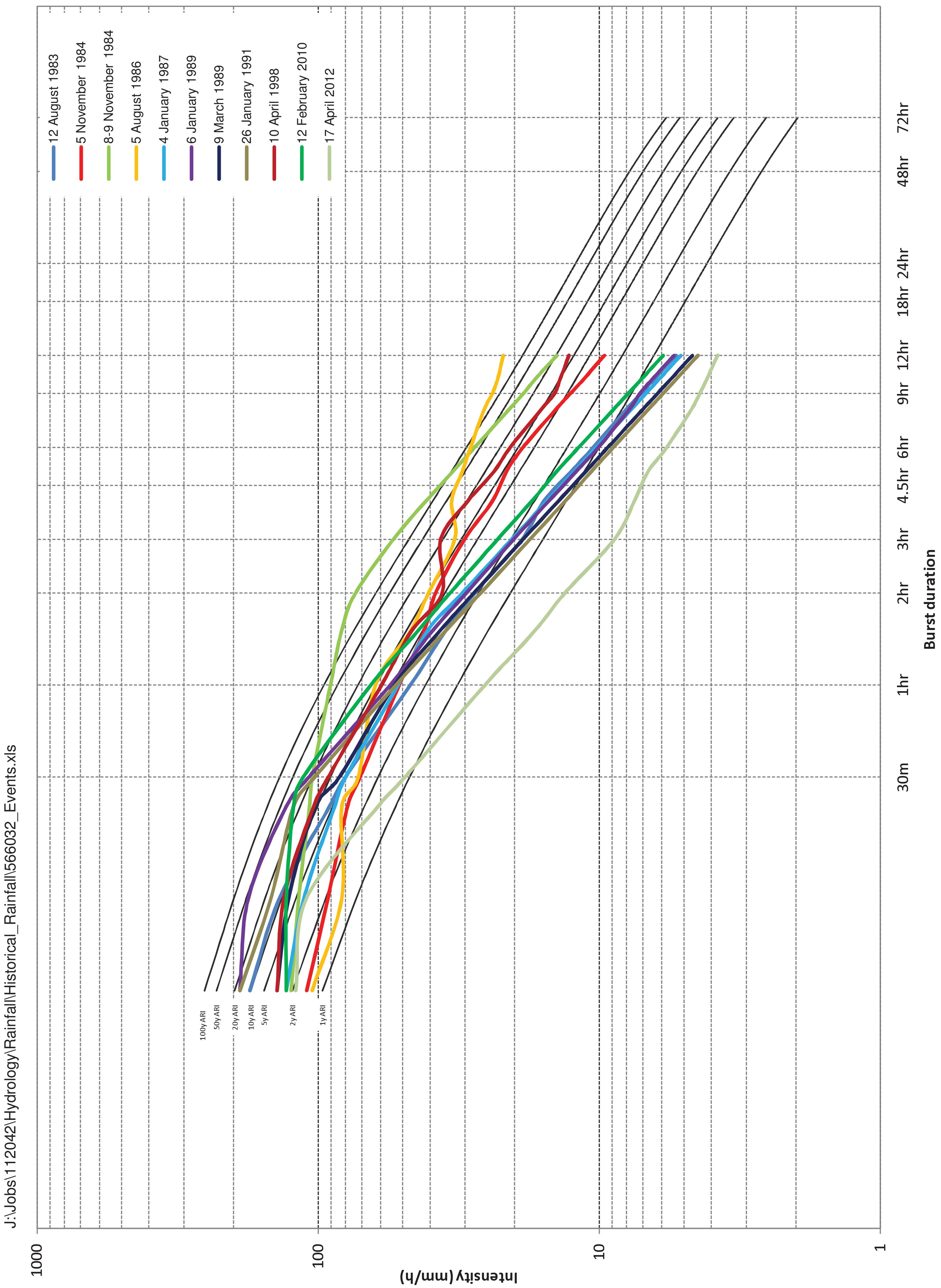
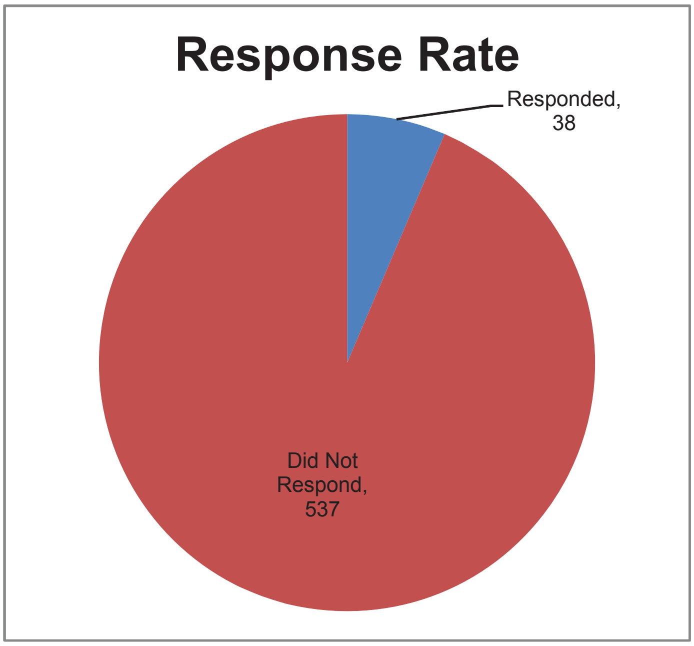
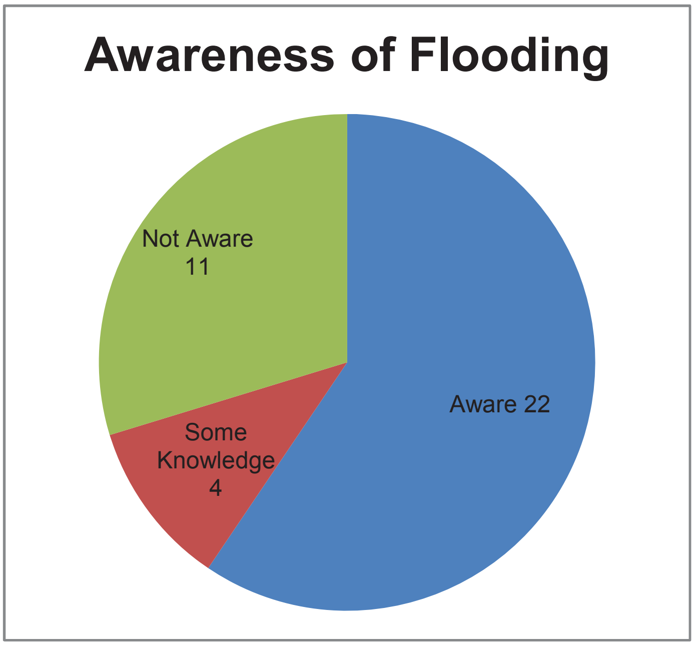
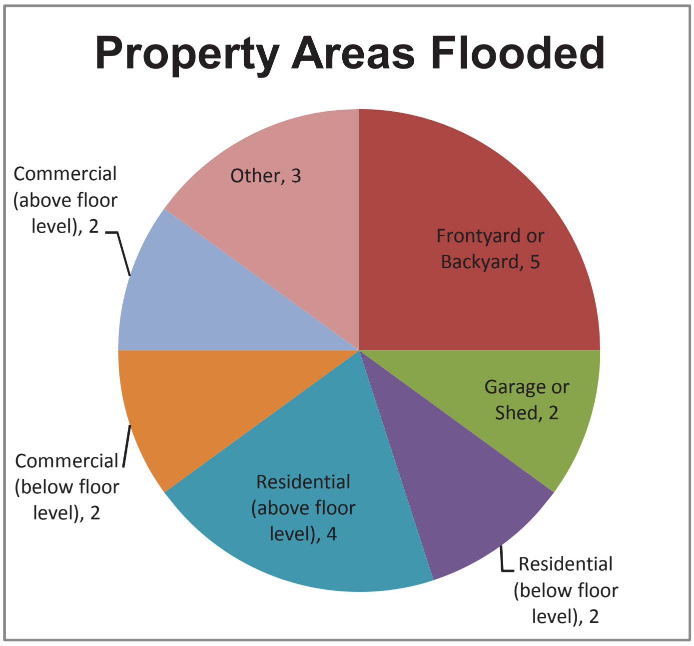
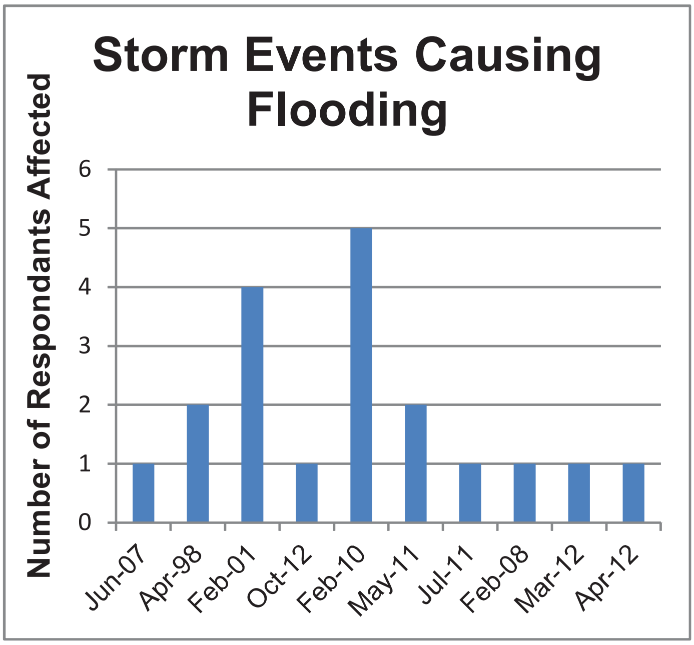


FIGURE 6
RESULTS OF QUESTIONNAIRE









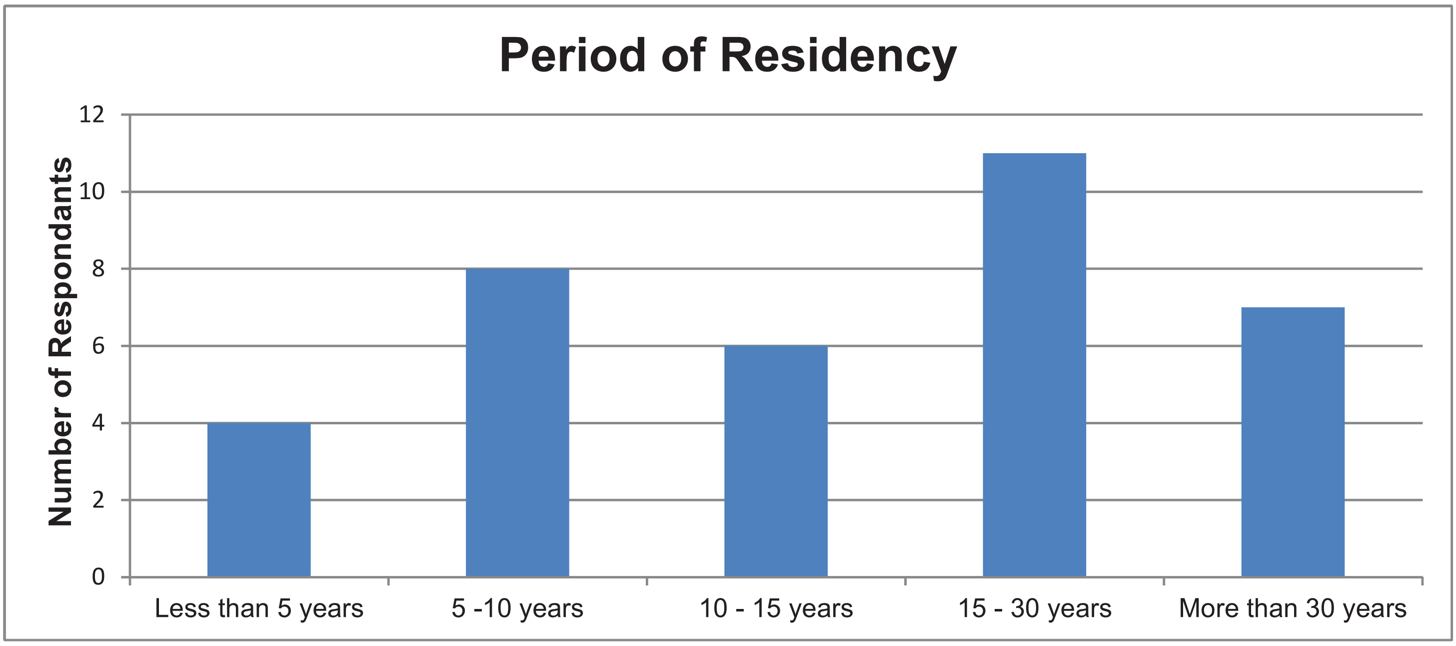


FIGURE 7

REPORTED STORMS & DEPTHS - WOOLLOOMOOLOO

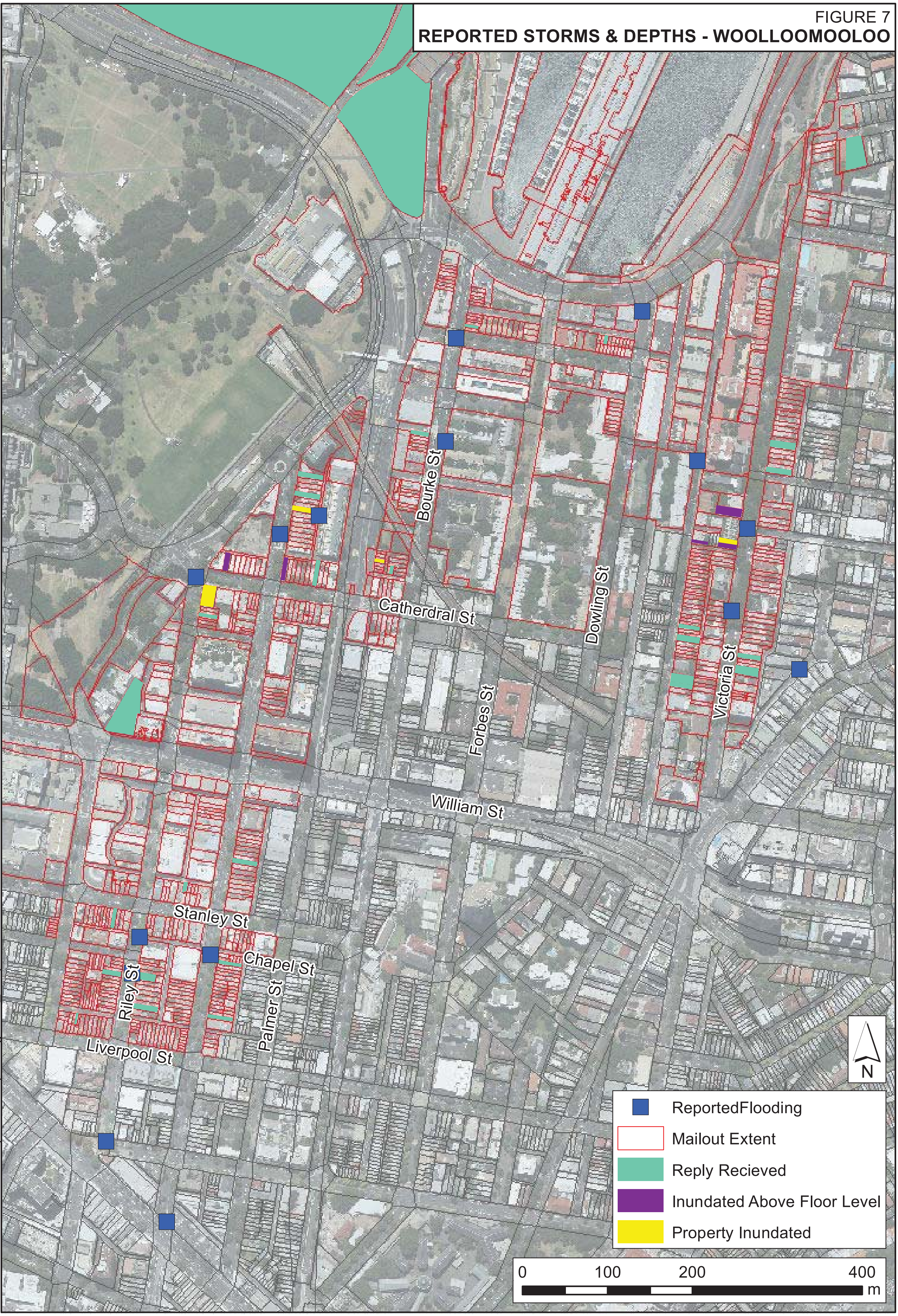


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FIGURE 8A

FLOODING & ELEVATION MARKS
CROWN STREET LOW POINT

Flooding on the corner of Bossley Terrace & Crown Street, 7:39am, 17 April 2012.

Flooding at Crown Street Low Point, 7:44am, 17 April 2012.

Flood barrier installed at Bossley Terrace, with approximate elevation of barrier height.

Flooding at Crown Street Low Point, Woolloomooloo, 7:50am, 17 April 2012.

Flooding at corner Bossley Terrace and Crown Street, Woolloomooloo. 7:51am, 17 April 2012.

Approximate elevation of regular flooding along front fence near Crown Street Low Point.

FIGURE 8B

FLOODING & ELEVATION MARKS
VICTORIA STREET

Floodmarks at residence entrance on Victoria St, Potts Point

Floodmarks at residence entrance on Victoria St.

Floodgates installed to avoid inundation at Victoria St, with approximate elevation of flooding in February 2010.

Flooding, Victoria St, April 2012.

Flooding, Victoria St, April 2012.

Approximate elevation of flooding on Victoria St during June 2007 storm.

FIGURE 9
HISTORICAL FLOODING

Location	Date	Flood Level (mAHD)	Remarks
Yurong St	19/04/1950		Water entered properties adjacent to intersection.
Bourke St	5/08/1986	2.06	Property flooded above floor level.
Bourke St	5/08/1986	2	Property flooded above floor level
Crown St	5/08/1986	4.04	Property flooded above floor level
Sir John Young Cres	5/08/1986	3.96	Flood level on driveway
William St	9/04/1998	-	Water in sag
Victoria Street	12/02/2010	30.20	Road Flooded
Crown Street	Regularly	4.25	Road Flooded
Victoria Street	14/06/2007	-	Above Floor Inundation
	14/06/2007	31.02	Road Flooded
Corner Bossley Terrace & Crown Street	26/02/2008	3.92	Road Flooding leading to property inundation
	12/02/2010	3.92	
	30/05/2011	3.92	
	8/03/2012	3.97	
	17/04/2012	4.27	

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FIGURE 10
HYDROLOGIC MODEL LAYOUT

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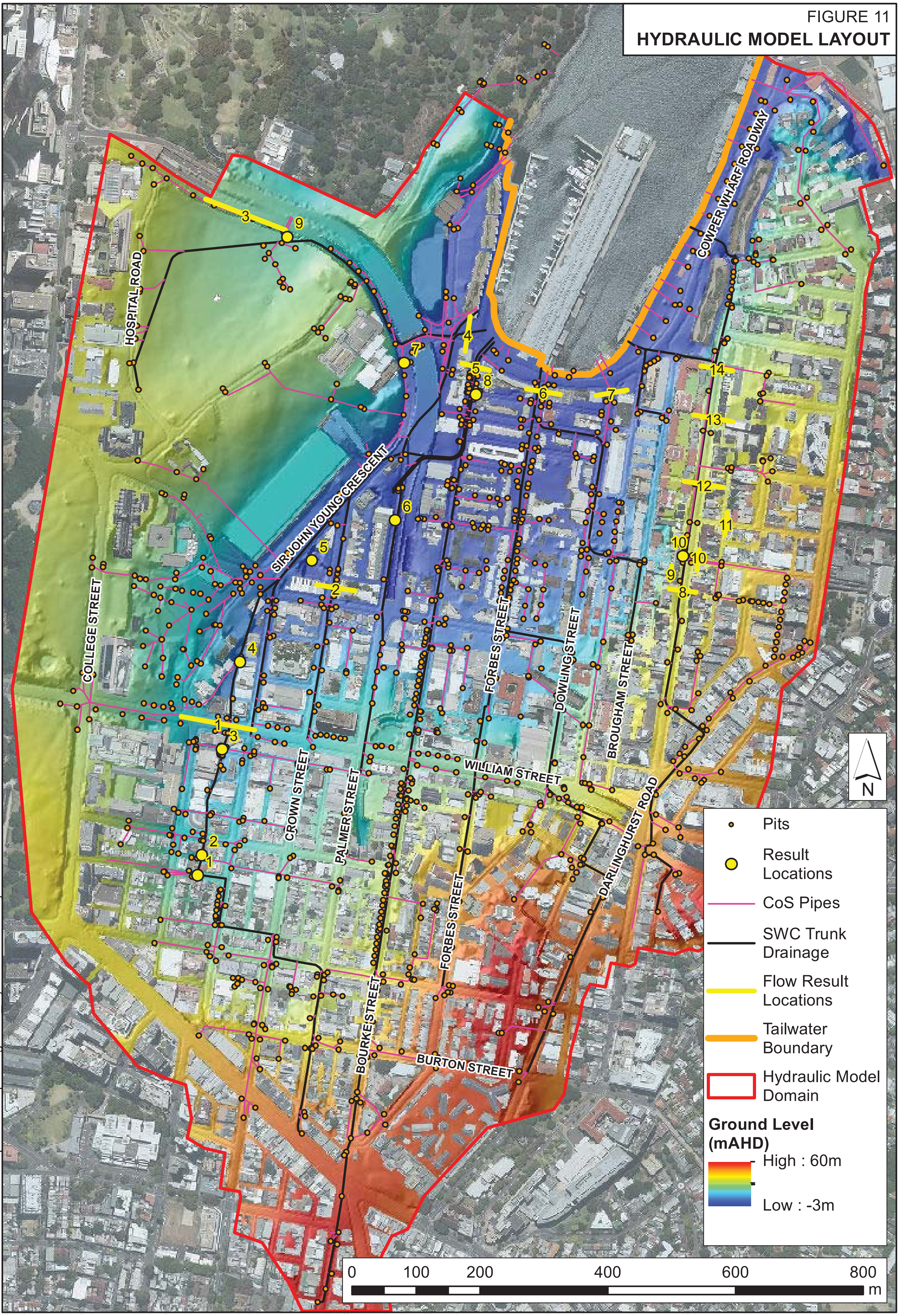

FIGURE 11
HYDRAULIC MODEL LAYOUT

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FIGURE 12
HISTORIC CALIBRATION
12 FEBRUARY 2012

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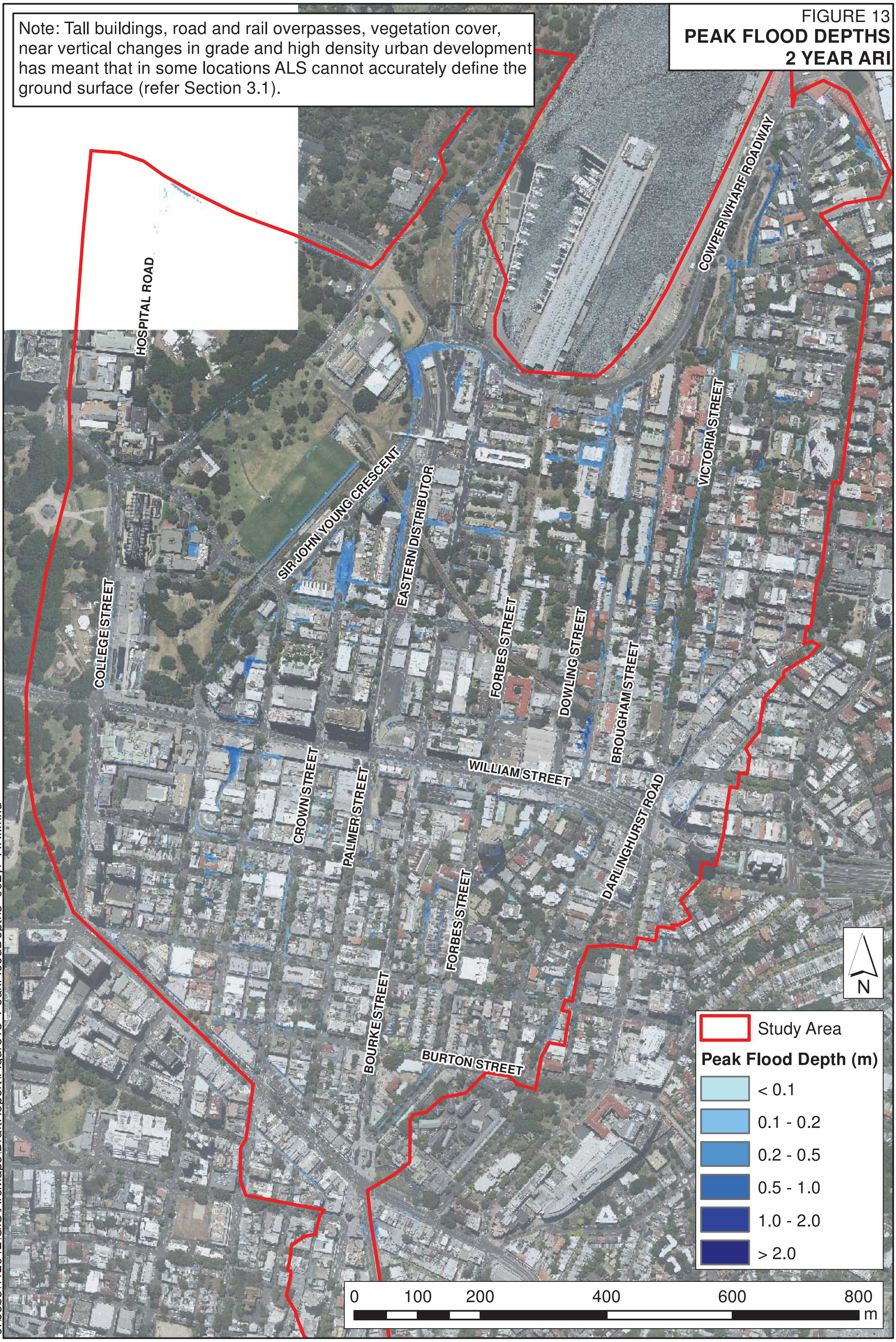

FIGURE 13
PEAK FLOOD DEPTHS
2 YEAR ARI

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FIGURE 14
PEAK FLOOD DEPTHS 5 YEAR ARI

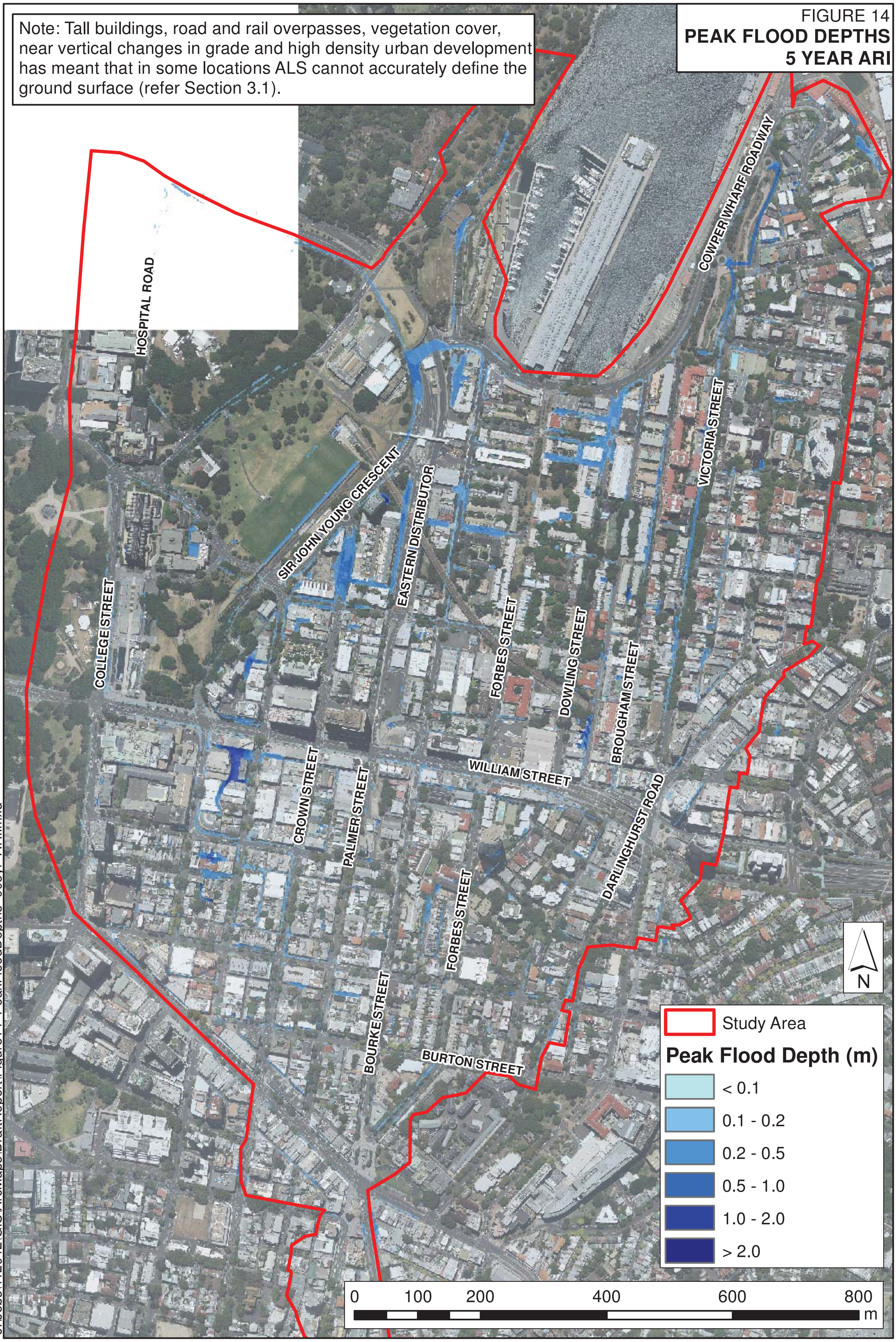

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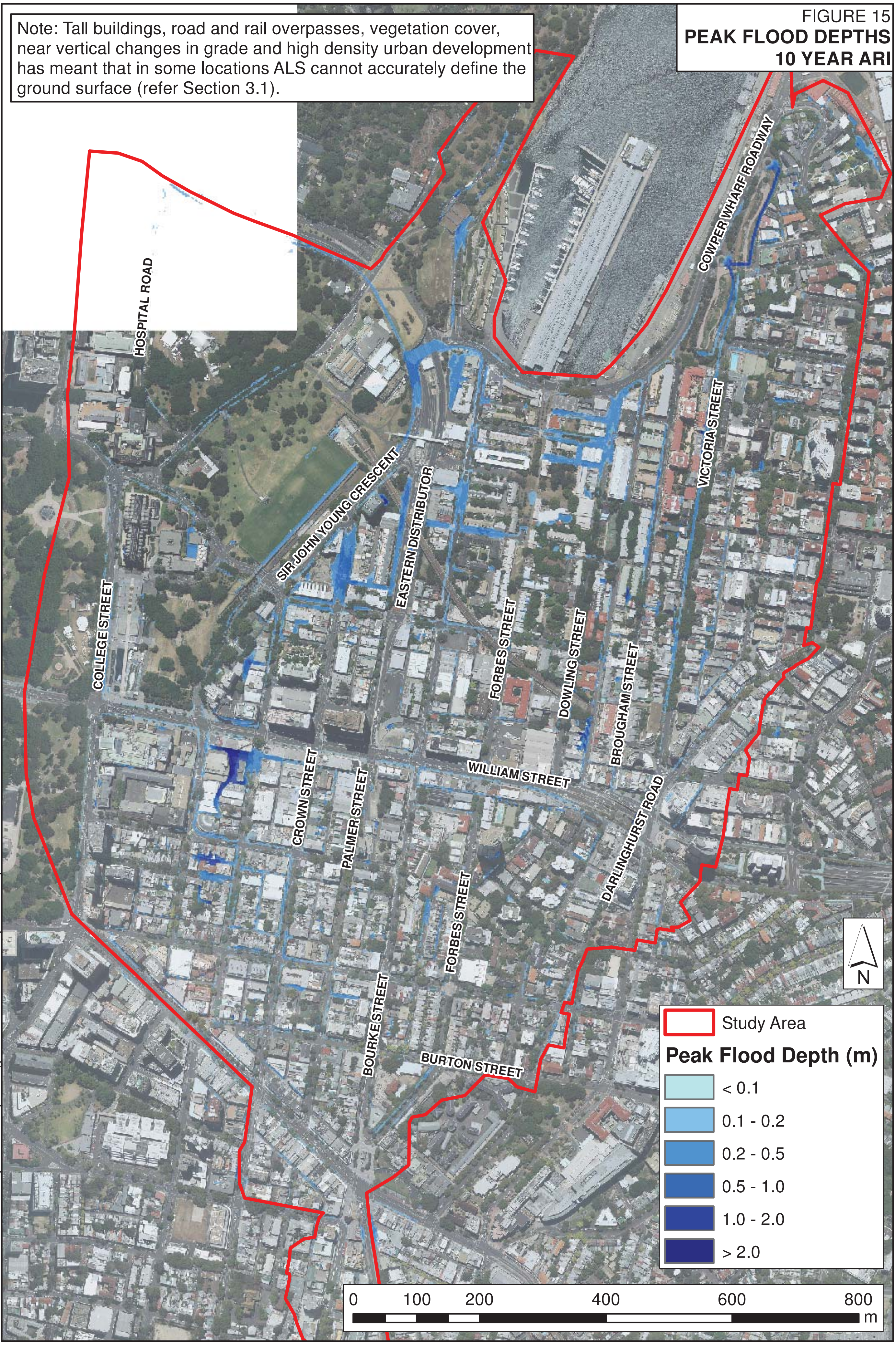
FIGURE 15
PEAK FLOOD DEPTHS 10 YEAR ARI

Note: Tall buildings, road and rail overpasses, vegetation cover, near vertical changes in grade and high density urban development has meant that in some locations ALS cannot accurately define the ground surface (refer Section 3.1).



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