ATTACHMENT E

RUSHCUTTERS BAY CATCHMENT FLOOD STUDY (DRAFT REPORT)

RUSHCUTTERS BAY

FLOOD STUDY

DRAFT REPORT

JUNE 2013

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RUSHCUTTERS BAY FLOOD STUDY

FINAL DRAFT REPORT

JUNE 2013

Project **Rushcutters Bay Flood Study**	Project Number **112022**
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RUSHCUTTERS BAY FLOOD STUDY

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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
- 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.

EXECUTIVE SUMMARY

The Rushcutters Bay catchment area within the City of Sydney local government area (LGA) includes the suburbs of Potts Point, Elizabeth Bay, Kings Cross, Darlinghurst, Paddington and Rushcutters Bay (Figure 1). The catchment is drained by a series of Sydney Water pipes, overland flow paths and open channels into Rushcutters Bay.

The key objective of this Flood Study is to develop a suitable hydraulic model that can be used as a basis for a Floodplain Risk Management Plan for the Study area, and to assist City of Sydney to undertake flood-related planning decisions for existing and future developments. Previous hydraulic modelling of the study area was limited in extent, and did not estimate flood levels in the City of Sydney portions of the catchment.

The primary objectives of the study are:

- to determine the flood behaviour including 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 provide a model that can establish the effects of future development on flood behaviour;
- to assess the sensitivity of flood behaviour to potential climate change effects such as increases in rainfall intensities and sea level rise; and
- to assess the hydraulic categories and undertake provisional hazard mapping.

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

- a summary of available flood related data;
- establishment and validation of the hydrologic and hydraulic models;
- sensitivity analysis of the model results to variation of input parameters;
- potential implications of climate change projection;
- the estimation of design flood behaviour for existing catchment conditions; and
- a flood damages assessment.

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

FLOODING HISTORY

Significant catchment development occurred in the latter part of the 19th century. The 1861 census indicated a population of 2,700 which rose to 19,000 by 1890. In that time the number of houses increased from approximately 500 to 3,800. The current catchment population is of the order of 15,000 (Reference 1). Early references clearly identify parts of the lower catchment as low lying and swampy. There was also mention of surface and stormwater problems (flooding and water quality).

The effect of urbanisation on the quantity (and quality) of runoff from the catchment has not been assessed but would have been significant. As the catchment is already heavily urbanised any new developments are unlikely to produce further significant increases in peak flows.

There have been many instances of flooding in the past with 8-9 November 1984, 6 January 1989 and 26 January 1991 being some of the more significant storm events causing extensive flooding throughout the catchment. Section 3.4.1 provides details on a number of these past rainfall events responsible for the above mentioned floods.

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, a limited verification of the models to anecdotal historical information 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 Sims Street, Taylor Street, Sturt Street, Oxford Street, Boundary Street, Barcom Avenue, McLachlan Avenue and Womerah Avenue which is supported by a limited calibration and anecdotal reports of flooding.

1. INTRODUCTION

1.1. Background

The Rushcutters Bay catchment within the City of Sydney local government area (LGA) includes the suburbs of Potts Point, Elizabeth Bay, Kings Cross, Darlinghurst, Paddington and Rushcutters Bay (Figure 1). The catchment is drained by a series of Sydney Water pipes, overland flow paths and open channels into Rushcutters Bay.

The present Flood Study has been commissioned by City of Sydney (CoS), with assistance from the NSW Office of Environment and Heritage (OEH). This study considers flooding in the Rushcutters Bay catchment within the City of Sydney's LGA from local storm runoff and continued development means it is important that appropriate tools and information to assess flood risks are available to City of Sydney for planning future development in the area.

1.2. Objectives

The key objective of this Flood Study is to develop a suitable hydraulic model that can be used as a basis for a Floodplain Risk Management Plan for the Study area (Figure 2), and to assist City of Sydney to undertake flood-related planning decisions for existing and future developments. Previous hydraulic modelling of the study area was limited in extent, and did not estimate flood levels in the City of Sydney portions of the catchment.

The primary objectives of the study are:

- to determine the flood behaviour including design flood levels and velocities over the full range of flooding up to and including the PMF;
- to provide a model that can establish the effects of flood behaviour of future development;
- to assess the sensitivity of flood behaviour to potential climate change effects such as increases in rainfall intensities and sea level rise; and
- to assess the hydraulic categories and undertake provisional hazard mapping.

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

- a summary of available flood related data;
- establishment and validation of the hydrologic and hydraulic models;
- sensitivity analysis of the model results to variation of input parameters;
- potential implications of climate change projection;
- the estimation of design flood behaviour for existing catchment conditions; and
- a flood damages assessment.

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

2. BACKGROUND

2.1. Catchment Description

The Rushcutters Bay catchment is located in the suburbs of Potts Point, Elizabeth Bay, Kings Cross, Darlinghurst, Paddington and Rushcutters Bay. The region lies within the City of Sydney Local Government Area (LGA) and has been extensively developed for urban usage.

The land usage within the study area is predominantly urban residential development, comprising a mixture of pre-1900 terrace buildings (mostly south of William Street) and new high-rise apartment buildings, including several medium- and high-density developments (mostly north of William Street). The non-residential development in the catchment includes several schools, parks (including the Rushcutters Bay Park and Weigall Sportsgrounds), churches and community buildings including St Vincents Hospital. There are no major industrial developments, and commercial developments are primarily concentrated in the upper catchment areas around Oxford Street and Kings Cross. There are some larger commercial sites such as car dealerships/workshops in the lower part of the catchment near Weigall Sportsgrounds.

The catchment covers an area of approximately 92 hectares draining to Sydney Water's major trunk drainage systems to route flows from the upper regions of the catchment. The area drains into Sydney Harbour at Rushcutters Bay via the Sydney Water open channel, which generally runs in a north-westerly direction between the Weigall and White City sports complexes. The channel floodplain is largely contained within a series of parks and open spaces. 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 3.3.

The topography of the catchment is steep with the greatest relief occurring at the top of the catchment along Oxford Street at elevations of 65 mAHD which slopes north-east at grades of approximately 5% to 10%. The downstream end of the study area is also the flattest part of the catchment, comprising reclaimed lands within Rushcutters Bay Park, which has a relatively gentle ground gradient of 1%.

2.1.1. Flooding History

Significant catchment development occurred in the latter part of the 19th century, alongside a major increase in the broader Sydney population between 1860 and 1890. The current catchment population is of the order of 15,000 (Reference 1). Early references clearly identify parts of the lower catchment as low lying and swampy. There was also mention of surface and stormwater problems (flooding and water quality).

The effect of urbanisation on the quantity (and quality) of runoff from the catchment has not been assessed but would have been significant. As the catchment is already heavily urbanised any new developments are unlikely to produce further significant increases in peak flows.

There have been many instances of flooding in the past with 8-9 November 1984, 6 January 1989 and 26 January 1991 being some of the more significant storm events causing extensive flooding throughout the catchment. Section 3.4.1 provides details on the rainfall events responsible for the above mentioned floods.

2.2. Previous Studies

2.2.1. Rushcutters Bay SWC No. 84 Catchment Management Study

The Rushcutters Bay SWC No. 84 Catchment Management Study, 1991 (Reference 1) was undertaken as an overall investigation of stormwater drainage and water pollution issues in the catchment. The full length of the open channel and piped system controlled by Sydney Water, Woollahra and the City of Sydney Councils was examined.

A large part of the report covered water quality issues not relevant to this Flood Study. However the study included a comprehensive questionnaire survey (8,900 sent out), the results of which have been reproduced in this study (Section 3.8) as they are still relevant.

An ILSAX hydrological model and HEC-2 hydraulic model were developed and based on the results a cost-benefit analysis was undertaken to assess measures to reduce flooding. The main recommendations from the report (relating to stormwater drainage) were to provide new and duplicate pipe systems. The study found many of the pipes in the catchment had a 1 in 1 year ARI capacity.

2.2.2. Rushcutters Bay Catchment Flood Study

This report (Reference 2) was prepared for Woollahra Municipal Council by WMAwater and examines flooding issues for the portion of the Rushcutters Bay catchment within the Woollahra LGA.

Flood discharges and levels were determined for the Rushcutters Bay catchment using the DRAINS and TUFLOW computer models. At the downstream end of the model, a tailwater level of 1.0 mAHD was adopted after consideration of historic tidal records in Sydney Harbour at Fort Denison.

The study indicates that floodwaters inundate Trumper Park and the White City tennis complex in 5 year ARI and greater events. The yards of many private properties adjoining the open channel would also be inundated.

3. AVAILABLE DATA

3.1. Topographic Survey

Airborne Light Detection and Ranging (LiDAR) survey of the catchment and its immediate surroundings was provided for the study by City of Sydney and is shown on Figure 3. The data was a combination of data collected in 2007 and 2008 with a 1.3m average point separation. For hard flat surfaces these data typically have accuracy in the order of:

- ±0.15m in the vertical direction (to one standard deviation); and
- ±0.25m in the horizontal 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 and/or the presence of steeply varying terrain.

3.2. Open Channel

An open channel system within the Rushcutters Bay catchment is located downstream of Glenmore Road. The system is owned and administered by Sydney Water. In the past parts of the drainage system acted as a combined stormwater and sewerage system. However Sydney Water has undertaken works to largely separate these systems.

The open channel is at the very downstream of the Rushcutters Bay study area and design flow conditions within the channel have been established in Reference 2. Additional details of the channel may be found in Reference 2.

3.3. Pit and Pipe Data

The catchment is serviced by a major/minor drainage 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. At the bottom of the catchment, flow is routed into the Sydney Water Corporation (SWC) owned and maintained trunk drainage system that crosses under New South Head Road and drains to Rushcutters Bay.

When the capacity of the drainage system is exceeded, flow occurs along road reserves and other overland flow paths, with the potential for velocities and/or flow depths combining to generate high hazard flood conditions in some locations. For the catchment branch south of William Street, the main drainage paths in the road network include Victoria Street, Barcom Avenue, West Street, Womerah Avenue, McLachlan Avenue and Neild Avenue. North of William Street, the main flow paths include Bayswater Road, Roslyn Street/Gardens, and Waratah Street.

City of Sydney provided an asset database including dimensions and invert elevations for the majority of stormwater conduits within the study area. The following datasets were used to define stormwater infrastructure in modelling for this study:

- pipe asset database "WMA_DataSupply.gdb: Pipes_Survey" (received 16/03/2012);
- pit asset database "WMA_DataSupply.gdb: Pits_Survey" (received 16/03/2012);
- pit and pipe data from Reference 2.

A summary of pit and pipe survey data used within the study is provided in Table 1.

Table 1: Modelled Pipe and Pipe Network

Pit Type	Number
Outlet	4
Kerb or Grate Inlets	357
Junctions	379

Pipe Diameter (mm)	Number	Total Length (m)
< 450	552	8260
450 - 750	122	2580
750 - 1000	29	900
1000 - 2400	52	1730
> 2400	13	580

3.4. Rainfall

3.4.1. Historical Rainfall

Table 2 presents a summary of the official rainfall gauges (provided by the Bureau of Meteorology located close to or within the catchment. These gauges are operated either by Sydney Water (SW) or the Bureau of Meteorology (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 2 over 58% (26) have now closed. The gauge with the longest record is Observatory Hill, operating from 1858 to the present. The closest pluviometer gauge to the study area catchment is Paddington, which has been in operation from 1968. Locations of rainfall stations are shown on Figure 4.

Table 2: Rainfall Stations with a 6km Radius of Paddington Gauge

Station No.	Owner	Station	Elevation (mAHD)	Distance from Paddington (km)	Date Opened	Date Closed	Type
66139	BOM	Paddington	5	0.0	Jan-1968	Jan-1976	Daily
566041	SW	Crown Street Reservoir	40	0.8	Feb-1882	Dec-1960	Daily
566032	SW	Paddington (Composite Site)	45	1.0	Apr-1961		Continuous
566032	SW	Paddington (Composite Site)	45	1.0	Apr-1961		Daily
566009	SW	Rushcutters Bay Tennis Club	-	1.3	May-1998		Continuous
566042	SW	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	SW	Victoria Park @ Camperdown	-	2.4	May-1998		Continuous

Station No.	Owner	Station	Elevation (mAHD)	Distance from Paddington (km)	Date Opened	Date Closed	Type
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	SW	Erskineville Bowling Club	10	3.4	Jun-1993	Feb-2001	Continuous
566010	SW	Cranbrook School @ Bellevue	-	3.4	May-1998		Continuous
566015	SW	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	SW	Randwick Racecourse	30	3.7	Nov-1991		Continuous
66052	BOM	Randwick Bowling Club	75	3.7	Jan_1888		Daily
566141	SW	SP0057 Cremorne Point	-	4.0			Continuous
66021	BOM	Erskineville	6	4.0	May-1904	Dec-1973	Daily
	SW	Gladstone Park Bowling Club	-	4.1	Jan-1901		Continuous
566114	SW	Waverley Bowling Club	-	4.1	Jan-1995		Continuous
566043	SW	Randwick (Army)	30	4.3	Dec-1956	Sep-1970	Continuous
566077	SW	Bondi (Dickson Park)	60	4.4	Dec-1989	Feb-2001	Continuous
566065	SW	Annandale	20	4.5	Dec-1988		Continuous
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	SW	Mosman (Reid Park)	-	5.3	Jan-1998	Jun-1998	Continuous
566030	SW	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	SW	Mosman (Bradleys Head)	85	5.8	Jun-1904		Continuous
566027	SW	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

3.5. Analysis of Daily Read Data

Table 3: Daily Rainfall greater than 150 mm

Centennial Park		
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

Randwick Bowling Club (66052)		
Records since Jan 1888		
Rank	Date	Rainfall (mm)
1	06/08/1986	297
2	29/10/1959	265
3	28/03/1942	243
4	03/02/1990	225
5	10/02/1956	213
6	31/01/1938/	213
7	11/03/1975	201
8	17/01/1988	178
9	12/10/1902	178
10	28/04/1966	177
11	04/02/1990	175
12	19/11/1900	164
13	09/02/1992	162
14	28/07/1908	161
15	09/02/1958	158
16	29/05/1906	155
17	30/08/1963	152
18	27/04/1901	150

Randwick Racecourse (66073)		
Records since Jan 1937		
Rank	Date	Rainfall (mm)
1	10/02/1992	294
2	20/11/1961	270
3	30/10/1959	267
4	06/08/1986	263
5	11/03/1975	261
6	14/05/1962	258
7	10/02/1958	256
8	05/02/1990	248
9	03/02/1990	244
10	09/11/1984	240
11	20/03/1978	237
12	06/11/1984	223
13	28/03/1942	213
14	31/01/1938	211
15	10/02/1956	195
16	30/04/1988	175
17	30/08/1963	174
18	07/08/1967	171
19	10/01/1949	170
20	14/11/1969	160
21	05/02/2002	157
22	16/06/1952	156
23	04/03/1977	155
24	03/05/1948	154
25	04/04/1988	152
26	28/04/1966	151
27	05/03/1979	151

For the purposes of this study, 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), Randwick Bowling Club (124 years of record) and Randwick Racecourse (75 years of record) have been ranked and shown in Table 3.

The main points regarding these data are:

- February 1990 was in the top 10 for all gauges, showing very similar rainfalls at each gauge (between 220 and 245 mm);
- August 1986 looks like the most significant widespread daily rainfall event;
- March 1942 and August 1986 were the largest daily events recorded for the Centennial Park and Randwick Bowling Club gauges with approximately 300 mm. Randwick

Racecourse also recorded high rainfall for these days, although some spatial variation is shown;

- February 1992 showed a significant difference between the three gauges (151 mm, 162 mm and 294 mm). Analysis of the Botanic Gardens and Observatory Hill gauges show rainfalls of 264 mm and 190 mm for this day, implying a wide spatial range of rainfall depths;
- Data for the November 1984 event, which was known to produce flooding in the study area, is available at the Randwick Racecourse gauge and the Paddington gauge where it ranked 10th for total daily rainfall.

3.6. Analysis of Pluviometer Data

Pluviometer records provide a more detailed description of temporal variations in rainfall for sub-daily durations. Table 4 lists the maximum storm intensities for the four largest recent rainfall events from both the pluviometers and the daily read gauges.

Table 4: Maximum Recorded Storm Depths (in mm)

	5 Nov 1984		8/9 Nov 1984		6 Jan 1989		26 Jan 1991	
Station Location	30 min	60 min	30 min	60 min	30 min	60 min	30 min	60 min
Paddington	36	51	54	91	53	54	52	53
Observatory Hill	20	32	90	119	42	42	60	65
UNSW (Avoca Street)[(1)]	65	112	41	58	-	-	-	-
UNSW (Storey Street) [(1)]	65	90	33	46	-	-	-	-

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

Notes:

(1) From Reference 3.

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, for both the storms investigated.

Storm intensities and durations recorded at the Paddington gauging station for significant historical storm events are given in Table 5.

Table 5: 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)*

Data taken from Reference 2.

3.6.1. November 1984 Storm

The 8-9th November 1984 storm was a significant rainfall event across the Sydney and Wollongong region and is well documented in Reference 4. Table 6 shows that this storm had an approximate 100 Year ARI intensity across several locations in Sydney. The storm was separated into two distinct bursts (6:00am to 10:00am and 9:00pm to midnight). The latter was the most intense period and flooding was reported throughout the catchment, though the actual timing of the flooding is unknown.

Table 6: ARI Estimates of the 8-9th November 1984 Rainfall (From Reference 2)

Station	Rainfall Duration				
	0.5 hour	1 hour	2 hour	3 hour	6 hour
Sydney – Observatory Hill	100y	100y	100y	100y	100y
Mosman	20y	50y	100y	20y	10y
Vaucluse	100y	100y	50y	20y	10y

At the Paddington gauge the 8-9th November 1984 storm had similar intensity of the 30 minute duration as the January 1989 and January 1991 storms. However, anecdotal information indicates that the 8-9th November 1984 event produced greater flooding than other recent events in downstream areas of the catchment. Possibly this is because the event was part of an extended period of rainfall that partially “filled” the lower floodplain areas prior to the peak storm burst.

3.6.2. January 1989 and January 1991 Storms

The 6th January 1989 and 26th January 1991 storm events were both high intensity, short duration events which occurred over the period of an hour. Although not as large as the 8-9th November 1984 storm in terms of volume or longer duration intensity, the 1989 and 1991 storm events had a higher intensity for durations up to the 20 minute burst and caused extensive flooding throughout the catchment. For the most intense 20 minute rainfall burst the 6 January 1989 event had an approximate ARI of 50 years, and the 26 January 1991 event had an ARI of approximately 40 years. For upper catchment areas with short critical durations, these shorter more intense rainfall events are more likely to cause flooding throughout the majority of the study area.

3.7. Design Rainfall Data

Design rainfall depths and temporal patters for various storm durations at the study area were obtained from Australian Rainfall and Runoff 1987 (ARR87), for events up to and including the 100 Year ARI event. Probable Maximum Precipitation estimates were derived according to Bureau of Meteorology (BoM) guidelines (Reference 5). A summary of the design rainfall depths is provided in Table 7 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 7: Rainfall Intensity-Frequency Duration Data

Duration	Design rainfall Intensity (mm/hr)						
	1 Year	2 Years	5 Years	10 Years	20 Years	50 Years	100 Years
5 minute	106	134	168	188	213	247	272
10 minute	80.9	103	131	146	167	194	214
20 minute	59.5	76.5	98.1	111	127	149	165
30 minute	48.5	62.5	80.9	91.7	106	124	138
1 hour	32.7	42.4	55.4	63	73	86.2	96.2
2 hour	21.1	27.3	35.8	40.8	47.4	56	62.6
3 hour	16	20.8	27.3	31.1	36	42.6	47.6
6 hour	10	13	17	19.3	22.4	26.4	29.5
12 hour	6.35	8.21	10.7	12.2	14.1	16.6	18.5
24 hour	4.11	5.31	6.93	7.87	9.1	10.7	12
48 hour	2.64	3.41	4.45	5.06	5.85	6.9	7.69
72 hour	1.96	2.54	3.3	3.74	4.33	5.1	5.69

3.8. 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. Unfortunately there were no stream height gauges in the catchment. The following sources were used:

- Woollahra Municipal Council records,

- Sydney Water database,
- previous reports,
- questionnaire issued in November 2012,
- follow-up conversations with local residents.

A summary of flood events is listed in Table 8, with descriptions of historical flood information provided in Table 9 and locations of recorded flooding shown on Figure 9.

Table 8: Historical Floods

Event	Depth estimate	Qualitative description	Total
18 February 1959	2	0	2
19 November 1961	1	0	1
December 1970	0	1	1
1 March 1975	0	1	1
1 March 1977	1	0	1
4 March 1977	2	0	2
1 November 1979	0	1	1
1 February 1980	0	1	1
1 February 1981	0	1	1
12 August 1983	2	0	2
8 November 1984	2	1	3
March 1989	0	1	1
April 1989	0	1	1
6 January 1989	11	0	12
26 January 1991	7	0	7
9 April 1998	1	2	3
Unknown	2	1	3

Table 9: Historical Flood Information

ID	Location	Description	Flood Event	Observed Depth (m)	Comments	Source
1	Oxford Street (East)	Above floor inundation	January 1989	1.0	Depth observed above footpath level	Reference 1
			March 1989	-		Reference 1
			April 1989	-		Reference 1
			January 1991	-		Reference 1
2	Taylor Street low point	Properties adjacent to low point flooded	1984	1.3	Depth observed in the road	Reference 1
			January 1989	<1.3	Flooding marginally less than 1984 and January 1991 events	Reference 1
			January 1991	1.3	Depth observed in the road	Reference 1
3	Sturt Street low point	Properties adjacent to low point flooded	1984	1.6	Depth observed in the road	Reference 1
			January 1989	<1.6	Flooding marginally less than 1984 and January 1991 events	Reference 1
			January 1991	1.6	Depth observed in the road	Reference 1
4	Taylor Street	Property flooded	26 January 1991	-	Overtopped 0.5 m high fence at front of property peak at floor level at rear of property	Reference 1
5	Oxford Street (West)	Property flooded	4 March 1977	0.15	Flooding at depth above footpath	SWC database
			January 1991	0.45	Water up to 0.45 m above adjacent footpath to No. 84	Reference 1
6	Oxford Street (West)	Property flooded	4 March 1977	0.15	Flooding at depth above footpath	SWC database
			January 1991	0.45	*as for previous*	Reference 1

ID	Location	Description	Flood Event	Observed Depth (m)	Comments	Source
7	Oxford Street (West)	Property flooded	January 1991	0.45	*as for previous*	Reference 1
8	St Vincents Hospital	Building flooded	December 1970	-	Caused by drainage backwater. Since then the Hospital has isolated its drainage system from the main line.	SWC database
		Basement flooded	January 1989	-		Reference 1
9	Boundary Street	Property flooded	January 1989	0.15	flows along adjacent path routing through the property	Reference 1
10	Boundary and Liverpool Street	Severe street flooding	6 January 1989	0.5	Depth/velocity such that 16 cars were washed 100 m down the street	Reference 1
11	Intersection of Womerah Avenue and Liverpool Street	Eastern footpath flooded	-	0.15	Caused by street litter and park cars	Reference 1
12	Corner of Boundary Street and McLachlan Avenue	Above floor inundation	-	-	Above floor inundation of properties adjacent to McLachlan Street eastern low point and extending south for 20 m.	Reference 1
13	Neild Avenue low point	Properties flooded	January 1989	0.5	Flow routed through Neild Avenue properties to west of McLachlan Avenue low point	Reference 1
14	Neild Avenue intersection with New South Head Road	Road flooded	18 February 1959	0.05	depth above coping	Reference 1
			19 November 1961	0.05	depth above coping	Reference 1
			12 August 1983	0.45	depth on road	Reference 1
				1.3	depth above coping	Reference 1
			January 1989	0.4	Southern carriage way inundated	Reference 1

ID	Location	Description	Flood Event	Observed Depth (m)	Comments	Source
			January 1991	0.4		Reference 1
15	Waratah Street low point	Road flooded	January 1989	0.5	Surcharging of street drains and ponding of above to of kerb	Reference 1
16	Bayswater Road	Above floor inundation	-	-	Carpark runoff enters ground level shop car-park	Reference 1
17	Bayswater Road	Property flooded	18 February 1959	0.05	Depth above coping of channel	SWC database
18	Oxford Street	Property flooded	1 March 1975	-	Sydney Water comments indicate "greater than 100 Year ARI storm"	SWC database
20	Taylor Street	Property flooded	1 November 1979	-	Gutter flow by-passes gully in South Dowling Street and drains into sag in front of house due to blockage in gully"	SWC database
			1 February 1980	-		SWC database
			1 February 1981	-		SWC database
21	McLahlan Avenue	Above floor flooding	12 August 1983	0.2	depth above floor through showrooms of Monaco Motors	SWC database
				0.6	Above coping of adjacent channel	SWC database
			26 January 1991	-	Monaco Motors flooded	Reference 1
22	Roylston Street	Above floor inundation	6 January 1989	0.9	Depth above floor with houses and garages flooded and extensive damage to property.	SWC database
23	Roylston Street	Above floor inundation	6 January 1989			SWC database
24	Cecit Street	Above floor inundation	6 January 1989			SWC database
25	Barcom Avenue	Above floor inundation	9 April 1998	0.5	Depth above back gate, adjacent Boundary road. Lower floor flooded	SWC database
26	Barcom Avenue	Above floor inundation	9 April 1998	-	Back yard and lower floor flooded	SWC database
27	Barcom Avenue			-		SWC database

ID	Location	Description	Flood Event	Observed Depth (m)	Comments	Source
28	Corner of Greens Street and Oxford Street	Road flooded	1 March 1977	0.5	depth above footpath	CoS Database
			4 March 1977	0.5		CoS Database
29	City East Mail Centre	Above floor inundation	8 November 1984	-	Lower rooms flooded	CoS Database
30	Sims St	Road flooded	19 February 2012	0.6	Occurred at rear of Taylor Street properties	Community Consultation
31	Taylor St Low Point	Property Inundation - Above Floor Level	19 February 2012	0.05	Property flooded from Sims Street through to Taylor Street	Community Consultation
32	Taylor St Low Point	Road Flooding	Regularly	0.15	Occurs on Taylor Street	Community Consultation
33	Boundary Street	Property Inundation - Backyard	-	0.9	Inundation occurred in back yard and moved to front of property.	Community Consultation
34	Barcom Ave	Road Flooded	14 to 16 June 2007	0.15	Approximate height above footpath	Community Consultation
35	Sims St	Road Flooding	12 February 2010	0.6	Occurred at bend in road	Community Consultation
36	McLachlan Ave	Above Floor Inundation	-	0.15	Flooding above floor level on ground level and on below ground levels	Community Consultation

4. COMMUNITY CONSULTATION

In collaboration with Council, 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 792 surveys were distributed with reply paid envelopes, and 36 responses were received (a return rate of 5%).

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 June 2007 storm, although other events were also mentioned by a significant number of respondents. A summary of responses received is shown on Figure 6 and Figure 7.

Table 10: Summary of Reported Incidents of Flooding

Flood Event	Total Reponses	House Flooded (above floor)	Other Buildings Flooded (above floor)	Other Descriptions of Flooding
January 1989	1	0	0	1
February 1993	1	0	0	1
April 1998	1	0	0	1
February 2001	1	0	1	1
June 2007	2	0	2	1
February 2009	1	0	0	1
February 2010	1	1	0	1

The flood experiences described in the survey responses generally related to nuisance flooding, such as ponding of stormwater in roadways or gardens, although one instance of above floor flooding was also reported. February 2010 was the only storm with reported above floor inundation of a residential property. Photographs showing flooding in Victoria Street Paddington from 1989 are shown on Figure 8.

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

5. STUDY METHODOLOGY

5.1. General 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 hydrologic data (such as rainfall patterns and stream-flows) were relatively limited.

The estimation of flood behaviour in a catchment is often conducted 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 improve the reproduction of observed catchment flooding. Recorded rainfall and stream-flow data area 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 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 joint 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 6, 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 calibrated against observed historical flood levels.

Additionally, the estimated flows at various points in the catchment were validated against previous studies and alternative methods.

5.2. Hydrologic Model

DRAINS 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 pipe and open channels is calculated using unsteady flow hydraulics. Open channel flow uses the simpler Hydraulic Grade Line method. 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.

It should be noted that the version of DRAINS used in this study is not a true unsteady flow model as it does not account for the attenuation effects of routing through temporary floodplain storage in overland areas (down streets or in yards).

5.3. Hydraulic Model

The availability of high quality LiDAR 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 7) was adopted as it is widely used in Australia and was considered most suitable for use in this study.

The Rushcutters Bay study area consists of a wide range of development, 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 (e.g. Taylor Street). For this catchment, the study objectives required 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 flow-paths, 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).

5.4. 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:

- design runoff hydrographs 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 modelling parameters; and
- design floods were modelled in TUFLOW using parameters selected to provide a sensible match between design flood levels and available recorded peak flood levels from historical events.

6. HYDROLOGIC MODELLING

6.1. Sub-catchments

A hydrological model of the study catchment was established using the DRAINS software package (Reference 8).

Sub-catchment areas were delineated based on LiDAR 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 model is shown on Figure 10.

6.2. Key Model Parameters

6.3. 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. The adopted values are summarised in Table 11.

Table 11: Summary of Catchment Imperviousness values used in DRAINS

Area	Area (ha)	%
Paved Area	67.5	74
Grassed Area	19.4	21
Supplementary	4.6	5
TOTAL	91.5	100

6.4. Rainfall Losses

Methods for modelling the proportion of rainfall that is “lost” to infiltration are outlined in AR&R. 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 has been assumed that the soil in the catchment has a moderate infiltration rate potential and the antecedent moisture condition was considered to be rather wet. The latter was justified by the fact that for many historical storms in the catchment, the peak rainfall burst typically occurs within a longer event that possibly has a duration of a few 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
Moderate infiltration rates and moderately well drained. This parameter, in conjunction with the Antecedent Moisture Condition, determines the continuing loss (defined by Horton's infiltration equation).	
ANTECENDENT MOISTURE CONDITIONS	3
Description	Rather Wet
Total Rainfall in 5 Days Preceding the Storm	12.5 to 25 mm

6.5. 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 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 was assessed in Section 10.

6.6. Validation of Methodology

Ideally hydrologic models are calibrated and validated against observed stream flow information; however for the study area no such data was available. Thus verification is undertaken in which results from the current study were 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 3) and the Rushcutters Bay Flood Study, October 2007 (Reference 2) were compared to those used in the current study for individual sub-catchments.

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 3 and 2

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	RB049	4.6	76	1.9	0.4	2.5	0.5
Current Study	RB048	0.7	92	0.3	0.5	0.4	0.6
Current Study	RB003	3.3	92	1.5	0.5	1.9	0.6
Reference 3	F-G	3.3	95	1.8	0.5	2.3	0.7
Reference 3	E1-E2	2.3	80	1.0	0.5	1.3	0.6
Reference 3	AN2Det	3.5	83	1.6	0.5	2.1	0.6
Reference 2	aP24AA2	14.7	90	8.2	0.6	10.1	0.7
Reference 2	aP7Z7	0.4	90	0.2	0.6	0.3	0.7
Reference 2	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 in 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 0.6 m^3/s per hectare and averaging at 0.6 m^3/s per hectare. The range of values is largely dependent on land use with more urbanised sub-catchments producing higher specific yields.
The results are comparable for the studies considered.