

ATTACHMENT B

**WOOLLOOMOOLOO CATCHMENT FLOOD
STUDY (DRAFT REPORT)**



WOOLLOOMOOLOO FLOOD STUDY

DRAFT REPORT



JUNE 2013



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WOOLLOOMOOLOO FLOOD STUDY

FINAL DRAFT REPORT

JUNE 2013

Project Woolloomooloo Flood Study		Project Number 112042
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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 and hydraulic category mapping has been completed for the 10 year, 20 year and 100 year ARI and PMF events.

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 area 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

DRAFT

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 $\pm 0.15\text{m}$ 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/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.

Table 5: Daily Rainfall greater than 150 mm

Centennial Park (66160)			Botanic Gardens (66006)			Observatory Hill (66062)		
Records since 1900			Records since 1885			Records since 1858		
Rank	Date	Rainfall (mm)	Rank	Date	Rainfall (mm)	Rank	Date	Rainfall (mm)
1	28-Mar-42	302	1	06-Aug-86	340	1	06-Aug-86	328
2	06-Aug-86	236	2	28-Mar-42	277	2	28-Mar-42	281
3	03-Feb-90	222	3	09-Feb-92	264	3	03-Feb-90	244
4	12-Aug-75	221	4	09-Nov-84	248	4	09-Nov-84	235
5	13-Oct-75	205	5	03-Feb-90	238	5	25-Feb-73	226
6	31-Jan-38	201	6	01-May-88	230	6	28-May-89	212
7	30-Apr-88	193	7	02-May-53	226	7	11-Mar-75	198
8	10-Feb-56	192	8	11-Mar-75	217	8	07-Jul-31	198
9	23-Jan-33	189	9	01-May-55	193	9	10-Feb-56	192
10	09-Feb-58	185	10	11-Feb-56	191	10	06-Feb-78	191
11	11-Mar-75	184	11	13-Jan-11	186	11	29-Apr-60	191
12	07-Jul-31	177	12	07-Jul-31	181	12	17-Jan-88	191
13	09-Apr-45	177	13	08-Jan-73	174	13	09-Feb-92	190
14	07-Aug-98	162	14	28-May-89	171	14	01-May-55	188
15	17-May-43	159	15	19-May-98	159	15	13-Jan-11	180
16	04-Feb-90	156	16	05-Feb-02	158	16	08-Jan-73	169
17	10-Jul-57	155	17	31-Jan-38	158	17	03-Apr-61	168
18	14-Nov-69	155	18	09-Feb-58	155	18	12-Jan-18	166
19	01-May-55	154	19	10-Feb-92	155	19	09-Mar-13	166
20	09-Feb-92	151	20	10-Jan-49	150	20	11-Apr-98	165
21	28-Jul-08	150	21	22-Aug-71	150	21	06-Apr-82	165
22	13-Jan-11	150				22	06-Apr-84	164
						23	24-Mar-84	164
						24	13-Oct-02	162
						25	17-Feb-68	157
						26	06-May-98	154
						27	23-Jan-55	152
						28	11-Jun-91	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
<i>(approx. ARI)</i>	(10)	(20)	(10)	(10)	(5)	(2)
5 Nov 1984	120	108	84	72	52	39
<i>(approx. ARI)</i>	(2)	(2)	(5)	(5)	(5)	(10)
8-9 Nov 1984	125	123	114	108	91	74
<i>(approx. ARI)</i>	(2)	(5)	(10)	(25)	(75)	(>100)
6 Jan 1989	215	195	155	108	56	30
<i>(approx. ARI)</i>	(50)	(50)	(50)	(25)	(5)	(5)
9 Mar 1989	140	138	114	85	54	28
<i>(approx. ARI)</i>	(5)	(10)	(15)	(10)	(5)	(2)
21 Apr 1989	140	120	78	54	29	14
<i>(approx. ARI)</i>	(5)	(5)	(2)	(2)	(1)	(1)
26 Jan 1991	190	162	138	103	53	27
<i>(approx. ARI)</i>	(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 patterns 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.

Misgivings about large changes in the catchment mean that flood events earlier than 2000 are not useful for calibration and this leaves only the February 2010 event 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 catchment, 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.

DRAFT

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.

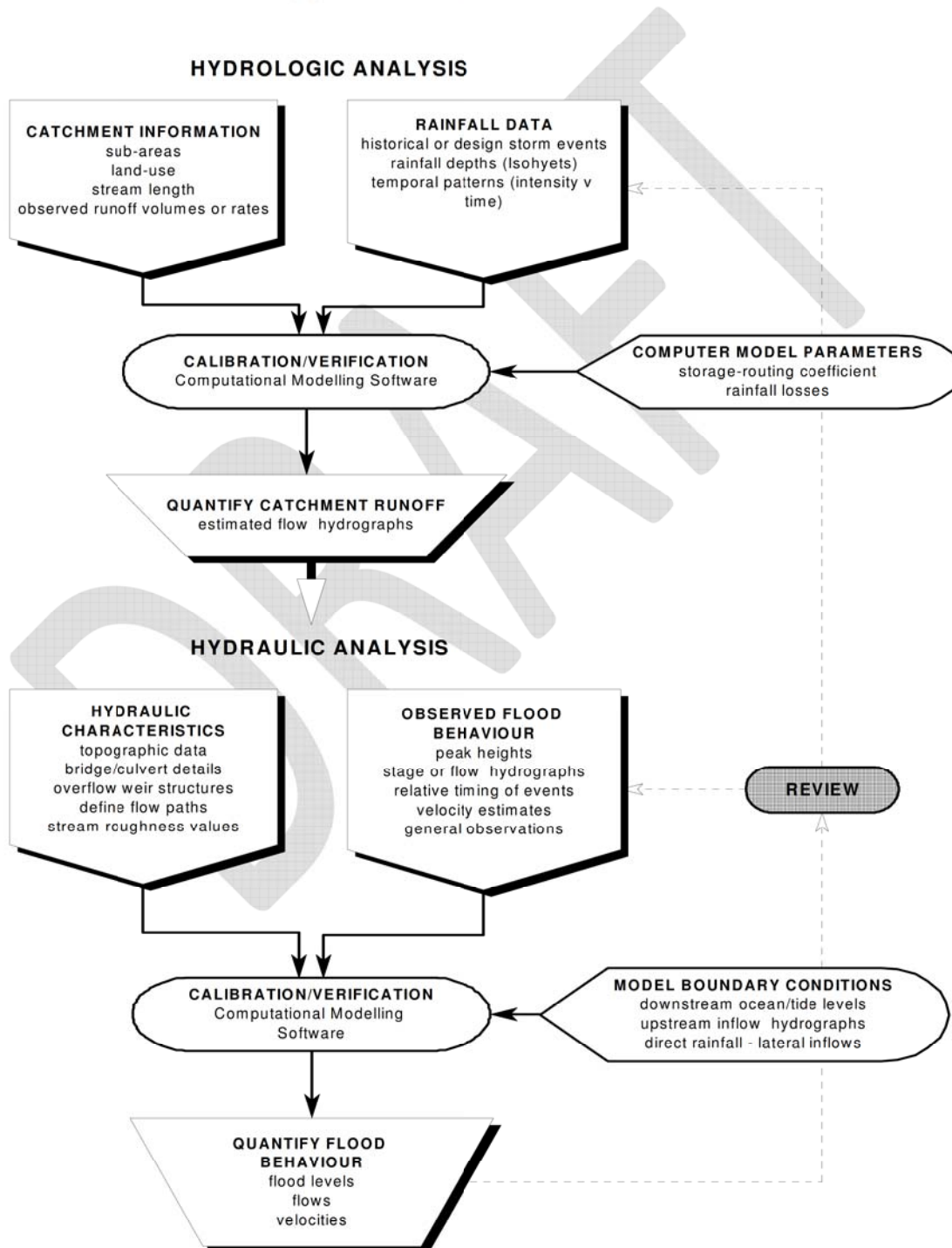


Diagram 1 Flood Study Process

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 area available they 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	
ANTECEDENT 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 m³/s per hectare and averaging at 0.7 m³/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

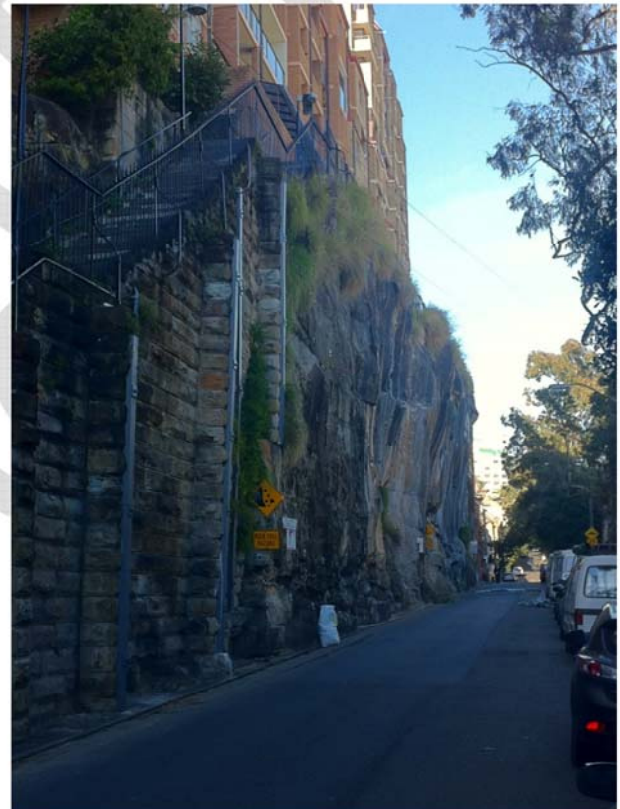


Photo 10: Vertical drop from Victoria Street properties to Brougham Street

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, trucks or general litter.

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.