WOOLLAHRA MUNICIPAL COUNCIL

ROSE BAY CATCHMENT FLOOD STUDY

FINAL REPORT

SEPTEMBER 2010

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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 existing 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 Rose Bay Catchment Flood Study constitutes the first stage of the management process for the Rose Bay Catchment. WMAwater (formerly trading as Webb, McKeown & Associates) were commissioned by Woollahra Municipal Council to prepare this flood study on behalf of Council's Floodplain Risk Management Committee. Funding for this study was provided from the State Government's Flood Risk Management Program and Woollahra Municipal Council on a 2:1 basis. The following report documents the work undertaken and presents outcomes that define flood behaviour for existing catchment conditions.

EXECUTIVE SUMMARY

The NSW Government's Flood Policy provides for:

- a framework to ensure the sustainable use of floodplain environments,
- solutions to flooding problems,
- a means of ensuring new development is compatible with the flood hazard.

Implementation of the Policy requires a four stage approach, the first of which is preparation of a Flood Study to determine the nature and extent of the flood problem.

The Rose Bay Catchment Flood Study was initiated as a result of flooding of roads and residential areas, most recently in January 1991, January, March and April 1989, November 1984 and August 1988. This report has been prepared by WMAwater (formerly trading as Webb, McKeown & Associates) for Woollahra Municipal Council in 2008.

The specific aims of the Rose Bay Catchment Flood Study are to:

- define flood behaviour in the Rose Bay catchment within the Woollahra Municipal Council local government area (LGA),
- prepare flood hazard and flood extent mapping,
- prepare suitable models of the catchment and floodplain for use in a subsequent Floodplain Risk Management Study and Plan.

Rose Bay has a catchment area of approximately 5.2km^2. The area drains to Sydney Harbour (Figure 1) and includes the suburbs of Bellevue Hill, Rose Bay and parts of Vaucluse within Woollahra Council LGA and Dover Heights and North Bondi suburbs in Waverley Council LGA. The upper catchment comprises of steep slopes with medium density developments with few non-residential developments and little open space. The lower part of the catchment comprises flatter slopes occupied by low to medium residential development and a significant area of open space comprising Woollahra and Royal Sydney golf courses. Stormwater from the upper section is carried within an underground pipe network or when exceeded, along roads and private property. The runoff travels through the lower section via underground pipes, and the main open stormwater channel through Woollahra and Royal Sydney golf courses. Most of the drainage infrastructure was installed in the 1930s.

Hydrologic and hydraulic investigations have been undertaken to determine the response of the drainage system to the 1 year, 2 year, 5 year, 10 year, 20 year, 100 year ARI events, and the Probable Maximum Flood (PMF). The results of these investigations are quantified where the overland flow exceeds approximately 2 m^3/s in the 100 year ARI event. This threshold was adopted by Council to distinguish between major and minor flooding.

The key phases of the Rose Bay Catchment Flood Study that have been undertaken are summarised below:

Review all available data, namely:

- reports, photographs, Council records,
- newsletter and questionnaire response,
- review of Council's database of resident reports,
- review of rainfall data,
- a comprehensive Airborne Laser Scanning (ALS) survey was undertaken in 2006 to obtain ground levels across the entire catchment.

Determine Approach: A DRAINS hydrologic model of the catchment within Woollahra LGA had already been established by Brown Consulting (Reference 1), which simulated pipe flow and overland flow through private property and along roads. A DRAINS model over the Waverley Council LGA was set up as part of Reference 2. A two-dimensional (2D) SOBEK hydraulic model was established in the middle to lower reaches of the Woollahra LGA to convert the upstream flows obtained from both DRAINS models into flood levels and velocities.

Calibration to Historical Flood Levels: Due to the lack of available data a rigorous calibration of the SOBEK model could not be undertaken. However a limited calibration of the SOBEK model to historical flood height data was undertaken. This generally indicated that the SOBEK results were similar to the historical data.

Determination of Design Flood Flows and Levels: Design rainfall data from Woollahra Council and design temporal patterns from Australian Rainfall and Runoff (Reference 3) were obtained and input to the two DRAINS model to determine design inflows. The lower part of the system downstream of New South Head Road is influenced by a combination of flows entering from the Rose Bay catchment and elevated water levels in Rose Bay. These influences were considered in the SOBEK model. Sensitivity analyses were also undertaken of the SOBEK model results. Due to the limited quality and quantity of the calibration data available and in view of the sensitivity analyses, it is estimated that the order of accuracy is up to ±0.3 m for the reach downstream of New South Head Road and ±0.5 m for the reaches upstream. These orders of accuracy are typical of such studies and can only be improved upon with additional observed flood data to refine the model calibration.

Flood Problem Areas: The study has indicated that floodwaters will inundate the Rose Bay shopping precinct and lower Bellevue Hill area in the 1 year ARI and greater events. In the upper parts of the catchment floodwaters will cross roads and enter private properties in an event of this magnitude. This is a significant problem in Bellevue Hill, where in some cases the road level is above the footpath on one side and also the floor level of the adjoining houses. Water can therefore flow down driveways and into private properties and possibly above house floor levels.

Outcomes: The main outcomes of this study are as follows:

- full documentation of the methodology and results,
- preparation of flood contour, hazard and extent maps for the Rose Bay catchment within Woollahra LGA,
- a modelling platform that will form the basis for a subsequent Floodplain Risk Management Study and Plan.

One recommendation of this study is to highlight the importance of collecting and maintaining a database of historical rainfall and flood height data. Whilst both Woollahra Municipal Council and Sydney Water (a review of Waverley Council's records was not undertaken as part of this study) have some records of flooding it is vital that flood height data from any future event is photographed immediately (within 24 hours) of the event. In the upper catchment the magnitude and direction of flow paths should also be accurately recorded.

1. INTRODUCTION

1.1 General

The Rose Bay catchment between Sydney Harbour and the high ridges west of Bondi (Figure 1) is located primarily within the Woollahra Municipal Council LGA, and covers an area of approximately 516 hectares. Approximately 40% (200 hectares) is located within the Waverley Council LGA. The catchment drains the suburbs of Bellevue Hill, Rose Bay and a small portion of Vaucluse within Woollahra LGA and North Bondi and Dover Heights within Waverley LGA.

Flooding problems have been experienced at a number of locations within the Woollahra part of the catchment during periods of heavy rainfall. Woollahra Municipal Council has undertaken to address this issue by preparing a comprehensive Flood Study covering both the middle and lower parts of the catchment. The upper section comprises a pipe and overland flow system along roads whilst the lower section comprises an open channel section through the Woollahra and Royal Sydney golf courses. Floodwaters also discharge from smaller ocean outfalls directly into Rose Bay.

The road drainage systems within the upper catchment of Woollahra LGA comprises a network of underground pipes which were largely installed by Woollahra Municipal Council in the 1930's. The open channel section and larger pipe systems were first constructed around 1895 by the equivalent of what is now Sydney Water with subsequent improvements added between 1926 and 1938. The open channel section is owned and operated by Sydney Water. A detailed survey of the Sydney Water drainage system within Waverley and Woollahra LGAs was undertaken in Reference 4, and is summarised in Section 2.2.1 of this report.

The land usage within the Woollahra LGA is predominantly urban residential development, comprising a mixture of pre-1940 free standing residences and new brick detached buildings, including a number of medium density developments. The non-residential development in the catchment includes several schools, parks (including Cranbrook playing fields and the golf courses), churches and community buildings. There are no significant industrial developments and few major commercial developments. The latter are generally along New and Old South Head Roads.

The main catchment outlet into Sydney Harbour at Rose Bay is via the Sydney Water open channel, which runs in a general north-westerly direction from Old South Head Road. There are several smaller piped outfalls as well as many informal overland flow paths. The floodplain of the Sydney Water channel is largely contained within Woollahra and Royal Sydney golf courses and associated open space areas. Upstream of Woollahra golf course the main channel is covered, travelling under Old South Head Road to North Bondi. The portion of the Rose Bay catchment in the Waverley LGA (approximately 200ha), can be divided into two sub-catchments, North Bondi and Dover Heights (Figure 1).

The North Bondi sub-catchment between the North Bondi cliffs and Old South Head Road is largely a natural depression. This is drained by a system of pipes and box culverts operated by Sydney Water (Reference 4), which discharges into the main stormwater channel at Owen Street travelling under Old South Head Road. This sub-catchment, which includes most of the suburb of North Bondi, has an area of 66ha.

The other sub-catchment in Waverley LGA, includes the majority of Dover Heights and lies east of Old South Head Road and north of Onslow Street discharging into the Woollahra LGA at Abermarle Avenue. This sub-catchment has an area of 133ha.

These two sub-catchments in the Waverley LGA are not part of the study area for this flood study, and hence the flooding problems in these areas have not been examined. However, the inflows from these areas across Old South Head Road are included in the hydraulic modelling.

1.2 Objectives

Woollahra Municipal Council engaged WMAwater (formerly trading as Webb McKeown & Associates) to undertake the Rose Bay Catchment Flood Study utilising current technology and data. The information and results obtained from the study are to provide a firm basis for the development of targeted stormwater management strategies, and to develop a subsequent Floodplain Risk Management Study and Plan.

The study was developed in order to meet the primary objective of defining the flood behaviour (1 year, 2 year, 5 year, 10 year, 20 year, 100 year ARI design storms and the Probable Maximum Flood) in the Rose Bay catchment by

- identifying major overland flow paths (greater than 2 m^3/s in the 100 year ARI event) from the established DRAINS model (References 1 and 2),
- using a hydraulic modelling to determine flood levels, flows and velocities for these overland flow paths.

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

- a summary of available historical flood related data,
- calibration of the hydraulic model,
- definition of the design flood behaviour for existing conditions through the analysis and interpretation of model results.

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

2. BACKGROUND

2.1 Catchment Description

As noted previously, the entire Rose Bay catchment has been developed for mostly residential or commercial purposes with the only areas of open space used as parks and golf courses. In terms of local drainage, the roads in the urban parts of the catchment have been formed with kerbs and gutters draining to an underground pipe system. In the Bellevue Hill sub-catchment runoff discharges to the open channel system within Woollahra and Royal Sydney golf courses. The open channel system consists of a concrete section from the outlet at Rose Bay to approximately 600 m upstream where the Woollahra golf course has two weirs placed across the channel. Upstream of this the channel has grassy banks. There is no open channel system within the Rose Bay sub--catchment.

The Rose Bay catchment area (shown on Figure 1) comprises a total of 516 ha which can be subdivided into the following sub-areas:

- Bellevue Hill - 209ha and Rose Bay/Vaucluse - 108ha within Woollahra LGA,
- North Bondi - 133ha and Dover Heights - 66ha within Waverley LGA.

The topography of the catchment originally consisted of a mix of sandstone ridges and large sand dunes, extending between Bondi Beach and Rose Bay. These sandstone ridges, common throughout much of metropolitan Sydney occur on the eastern side of the catchment. The Bellevue Hill area is underlain by sandstone bedrock. The lower portions of the catchment includes former sand dunes levelled in the 1920s for development. Some of the urbanisation occurred prior to the installation of road drainage systems in the 1900s, and hence many buildings were constructed on overland flow paths. This creates a significant drainage/flooding problem, especially in the vicinity of the Rose Bay shopping area on New South Head Road.

The Bellevue Hill area, west of the golf courses, rises steeply from O'Sullivan Road. This area varies from small to large detached residences and medium to large high rise residential units. This area is largely impervious, either paved or situated on bare sandstone or a thin layer of sandy soil. This report is concerned with flooding under existing catchment conditions and the effect of urbanisation on the quantity (and quality) of runoff from the catchment had not been assessed but is likely to have been significant.

The development mix within the Waverley LGA is different to the Woollahra LGA part of the catchment and generally comprises single detached and semi-detached dwellings located on sandy soils. There is very little commercial development. Some medium density residential units exist around Kent Road and Marion Street.

Reference 4 calculated the catchment land use shown in Table 1 for the Bellevue Hill and North Bondi areas, but did not include Dover Heights or Rose Bay-Vaucluse sub-catchments as these were not part of their study area.

Table 1: Land Uses within the Bellevue Hill/North Bondi Sub-catchments

	Sub-catchment		Total
	North Bondi	Bellevue Hill	
Residential (%)	98	64	77
Commercial (%)	1.5	0.5	1
Reserves and Golf Courses (%)	0.5	35.5	22
Total Area (ha)	**133**	**206**	**339**

Note: Data taken from Reference 4.

2.2 Drainage System

2.2.1 Open Channel

Table 2 provides an overview of the key characteristics of the open channel drainage system downstream of Old South Head Road. The open channel system is owned and administered by Sydney Water and exits through 4.08 m by 2.15 m twin box culverts under New South Head Road to Rose Bay.

Table 2: Open Channel Dimensions

Location * (Sydney Water Designation)	Chainage (m)	Dimensions (m) (width x height)	Description	Average Upstream Slope	Invert Level (mAHD)
A	0	4.08 X 2.15	Twin Box Section	1 in 183	0.12
B	33	8.42 x 2.12	Concrete Channel	1 in 4760	0.30
	38	4.25 x 1.30	Concrete Channel		
C	271	4.50 x 1.83	Concrete Masonry Channel	1 in 73	0.35
	278	5.95 x 1.72	Masonry Channel	1 in 380	0.45
F	524	5.70 x 1.2	Masonry Channel	Horizontal	1.10
	532	4.40 x 1.26	Masonry Channel		
G	556	4.30 x 1.22 (channel)	Small Weir		1.09 *(base of weir)*
H	590	1.70 x 0.79 (gate aperture)	Large Gated Weir		2.59 *(base of weir)*
	590	6.5 x 0.80	Open Earth Channel	1 in 440	2.20 approx.
	690	7.6 x 1.46	Open Earth Channel		2.27 approx.
	750	5.9 x 0.97	Open Earth Channel		2.60 approx.
J	963	2.35 x 1.08	Box Section	1 in 132	3.05
L	1176	2.35 x 1.52	Box Section	1 in 400	
M	1200	2.64 x 1.68	Box Section	1 in 400	

* Refer Figure 1. Taken from Reference 4.

2.2.2 Piped Drainage

Table 3 provides a summary of the piped network system within the Woollahra LGA DRAINS model. Photographs 1 to 10 show some features of the drainage system immediately upstream of the open channel.

Table 3: Pit and Pipe Drainage Network (taken from Reference 1)

PITS - BELLEVUE HILL SUB-CATCHMENT					
Sag Pits		**OnGrade Pits**		**Others**	
0.9 m lintel	7	0.9 m lintel	115	Outlet	1
1.2 m lintel	4	1.2 m lintel	64	Node	78
1.8 m lintel	13	1.8 m lintel	97		
2.4 m lintel	4	2.4 m lintel	48		
Grate only	1	3.0 m lintel	4		
SA1 (Type 2) - 1% longitudinal grade	8	Grate only	42		
		Kerb inlet 0.85 m lintel 1% crossfall	1		
		SA1 (Type 2) - 1% longitudinal grade	141		
		Unrestricted entry	1		
		SA2 (Type 5) - 1% longitudinal grade	3		
TOTAL	**37**	**TOTAL**	**516**	**TOTAL**	**79**

PITS - ROSE BAY SUB-CATCHMENT					
Sag Pits		**OnGrade Pits**		**Others**	
0.9 m lintel	4	0.9 m lintel	50	Node	26
1.2 m lintel	2	1.2 m lintel	31		
1.8 m lintel	5	1.8 m lintel	63		
2.4 m lintel	1	2.4 m lintel	23		
3.0 m lintel	2	3.0 m lintel	4		
Grated pit 0.9 m x 0.45 m	1	Grate only	18		
SA1 (Type 2) - 1% longitudinal grade	1	Grated Inlet Pit	13		
		Grated pit 0.9 m x 0.45 m	5		
		SA1 (Type 2) - 1% longitudinal grade	131		
TOTAL	**16**	**TOTAL**	**338**	**TOTAL**	**26**

Pipe Diameter (mm)	**Bellevue Hill Sub-catchment**	**Rose Bay Sub-catchment**
<300	21	25
300	186	111
375	136	80
450	120	57
525	39	14
600	50	25
675	1	0
750	39	16
825	5	0
900	7	1
1050	0	10
1200	19	0
1350	0	3
1500	0	12
1800	0	8
Box Culverts	0	3
TOTAL	**623**	**365**

Photo 1: Open channel at Manion Avenue looking upstream

Photo 2: Open channel at Manion Avenue looking upstream

Photo 3: Open channel at Manion Avenue looking downstream

Photo 4: Footpath and carport below level of road at Latimer Road

Photo 5: New South Head Road at Rose Bay looking west

Photo 6: Worth Arcade draining ponding on New South Head Road, Rose Bay

Photo 7: Worth Arcade looking south towards Rose Bay shopping area

Photo 8: Stormwater outlet at Rose Bay

Photo 9: Mudflats and seawall at Rose Bay looking west

Photo 10: Stormwater outlet at end of Caledonia Road

2.3 Previous Studies

A summary of previous investigations undertaken in the study area is provided in the following sections.

2.3.1 Woollahra Drains Modelling, November 2006 (Reference 1)

This study undertook DRAINS hydrologic modelling over a major part of the Woollahra LGA. Four separate DRAINS models were created incorporating Council's piped stormwater drainage network details in order to provide information on likely flooding problems. The Rose Bay Catchment area is covered by two of these models, a Bellevue Hill model which incorporates the open channel system and a Vaucluse model which includes Rose Bay.

The methodology for that assessment was broadly as follows:

a) obtain pit, pipe and ground level data from Council,
b) undertake site inspections,
c) develop base-case DRAINS models (Version 2006.19),
d) provide preliminary results and seek comments from Council,
e) revise models and provide output as GIS layers.

The soil type 3 and antecedent moisture condition 3 were adopted throughout with design rainfalls from Council's website. Blocking factors were set to 0.5 for sag pits and 0.0 for ongrade pits. Generally the Hornsby pit capacity data set were used to model kerb inlets with single grates. Relationships were created for other inlet structures (refer Table 3).

2.3.2 Rose Bay SWC Catchment Management Study 1991 (Reference 4)

This study was undertaken as an overall investigation of stormwater drainage and water pollution issues in the catchment connected to the Sydney Water open channel. The full length of the open channel and pipe systems controlled by Sydney Water, Woollahra and Waverley Municipal Councils was included.

A large percentage of the report detailed water quality issues which are not relevant for this Flood Study. A comprehensive questionnaire survey was undertaken (7,000 sent out) and the results have been reproduced in this present study (Section 3.3.2) as they are still relevant.

An ILSAX hydrological model and a SWMM hydraulic model were developed, and from these results, a cost-benefit analysis was undertaken to assess measures to reduce flooding. The main recommendations from this report (relating to stormwater drainage) were to provide new and duplicate pipe systems in the North Bondi sub-catchment which is outside the study area of this study. New pits within the Bellevue Hill area were also recommended.

2.4 Causes of Flooding

Flooding within the Rose Bay catchment may occur as a result of a combination of factors including:

- An elevated water level in Sydney Harbour (Rose Bay) due to a high tide and/or storm surge.
- Elevated water levels within the open channel section of the Rose Bay catchment and along roads and through private property as a result of intense rain over the Rose Bay catchment. The water level in the channel and elsewhere may also be affected by constrictions (e.g. culverts, blockages, fences, buildings).
- Local runoff over a small area accumulating (ponding) in low spots. Generally this occurs in areas which are relatively flat with limited potential for drainage. This type of flooding may be exacerbated by inadequate or blocked local drainage provisions and restricted overland flow paths.

These factors may occur in isolation or in combination with each other. Generally the peak water level in Rose Bay occurs as a result of ocean influences (tides, storm surge), this may or may not occur in conjunction with intense flood producing rainfall over the Rose Bay catchment (this combination did not occur in all previous flood events in the 1980's and 1990's). The last major oceanic induced event in Sydney Harbour (Rose Bay) was in May 1974 (where the level reached approximately 1.5 mAHD).

The peak levels in the Rose Bay catchment are typically the result of short duration storms of up to two hours duration. In contrast, the peak levels in Sydney Harbour (Rose Bay) would typically result from longer duration meteorological influences of say 24 hours or longer. Thus flooding in the Rose Bay catchment and in Sydney Harbour (Rose Bay) itself can be independent events which do not necessarily result from the same period of oceanic and meteorologic conditions.

3. DATA

The first stage in the investigation of flooding matters is to establish the nature, size and frequency of the problem. On large river systems such as the Hawkesbury River there are generally stream height and historical records dating back to the early 1900's, or in some cases even further. However, in small urban catchments such as Rose Bay there are no stream gauges or official historical records available. A picture of flooding must therefore be obtained from an examination of rainfall records and local knowledge. For this reason, a comprehensive data collection exercise was undertaken.

3.1 Historical Rainfall

No detailed review of historical rainfall data was undertaken as part of References 1 or 2. Therefore a brief summary of the information collected for the Rushcutters Bay Flood Study (Reference 5) is outlined below.

3.1.1 Summary of Pluviometer Data from Reference 5

Pluviometer records (continuous record of rainfalls) provide a more detailed description of temporal variations in rainfall than daily (24 hourly) records. Table 4 lists the maximum storm intensities for the four largest recent rainfall events from the available pluviometers and daily read gauges.

Table 4: November 1984, January 1989, March 1989 and January 1994 Maximum Recorded Storm Depths (in mm)

Station Location	9 Nov 1984		6 Jan 1989		9 March 1989		26 Jan 1991	
	20 min	30 min	20 min	30 min	20 min	30 min	20 min	30 min
Paddington	38	54	52	54	38	43	46	52
Observatory Hill*	57	80	42	44	24	30	44	58
Vaucluse	43	50	39	43	19	24	23	24

Station Location	24 hour totals to 0900 hrs				
	8 Nov 1984 (3)	9 Nov 1984 (3)	6 Jan 1989	9 Mar 1989	26 Jan 1991
Royal Botanic Gardens	37	248	49	39	59
Rose Bay	-	(1)	85	40	53
Observatory Hill	44	234	47	35 (2)	65
Paddington	71	166	56	50	54

Notes:

* approximate depths

(1) Gauge washed away in flood.
(2) Accumulated total over a four day period.
(3) The 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 the most 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.

3.1.2 November 1984

The 8th-9th November 1984 storm was a significant rainfall event across the Sydney and Wollongong region. Table 5 (taken from Reference 5) shows that this storm had an approximate ARI of 100 years across several locations in Sydney. It consisted of two bursts with the latter the most intense period and flooding was reported throughout the catchment.

Table 5: ARI Estimates of the 8th November 1984 Rainfall

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

3.2 Rose Bay Water Level Data

Water level variations in Rose Bay will impact on flood levels in the lower parts of the open channel system. The variations are largely as a function of astronomic tides but may also be influenced by:

- wind set up and the increased barometric effect,
- wave set up,
- wave runup,
- the Greenhouse Effect (Climate Change).

The adopted design water levels (taken from Reference 6) in Sydney Harbour at Fort Denison are given in Table 6.

Table 6: Adopted Design Water Levels at Fort Denison

ARI (year)	Water Level (mAHD)
20	1.38
50	1.42
100	1.45
Events >100y ARI	Not known but assumed as 1.50

However, these elevated water levels are unlikely to occur in conjunction with a flood over the Rose Bay catchment which is generated by a short duration (less than 2 hours) rainfall event. The coincidence of rainfall and ocean level events has been assessed in many similar studies, including Reference 5. The approach of using a static water level of 1.0 mAHD in conjunction with flooding in the local catchment was adopted for this present study. This level approximates to a tide that is only exceeded a few times in a year.

3.3 Historical Flood Information

3.3.1 Overview

A data search was carried out to identify the dates and magnitudes of historical floods. The search concentrated on the period since approximately 1980 as it was considered that data prior to this date would generally be of insufficient quality and quantity for model calibration. Unfortunately there is no stream height gauges in the catchment or other means of reliably determining the level of past flood events. Reliance must therefore be made on the following:

- Woollahra Municipal Council records,
- Sydney Water database,
- previous reports,
- questionnaire issued in June 2007 as part of this study,
- local newspapers,
- local residents.

3.3.2 Reference 4

Reference 4 undertook a review of all available flood information for the Bellevue Hill and North Bondi catchments including flood depths, types of flooding and locations, and dates of flooding.

For Reference 4 some 7000 questionnaires were distributed with approximately 2% returned. A summary of the key responses are provided in Table 7.

Table 7: Questionnaire Results (Reference 4)

Item	Yes Response
Ever experienced flooding?	77%
Nature of flooding?	
• Above house floor	19%
• Under house	10%
• In yard	32%
• In street	37%

Most respondents agreed that November 1984 was the worst flood they had encountered. The list of dates of flooding in Reference 4 included no events prior to the 1980s. However it is unrealistic to assume that there were no prior flood events. For example, $10^{th}/11^{th}$ March 1975 produced significant flooding throughout the Sydney and Wollongong region and produced a significant daily total (over 200 mm at Centennial Park and Botanic Gardens). Reference 7 reported rainfall depths at Sydney Observatory Hill for the 1, 2 and 3 hour durations equal to or in excess of the 100 year ARI design rainfall. Though there appears to be no reports of flooding in the Rose Bay catchment for this event.

Reference 4 also provides a summary of the flooding problems within the Bellevue Hill sub-catchment. The majority of these locations are east of Old South Head Road, in the North Bondi (Waverley LGA) sub-catchment which is not within the study area of this current assessment.

There has also been works implemented following the recommendations made in Reference 4, hence some of the flooding problems identified in the areas below may now be alleviated.

- the low lying flat areas around Plumer and O'Sullivan Roads due to water ponding,
- the weirs in the Woollahra Golf Course obstructing flows,
- along Balfour Road and Powell Road due to large overflows,
- isolated flooding problems in the upper catchment in streets such as Latimer Road, due to overland flows in gutters discharging onto footpaths.

Collected historical flood levels from Reference 4 are shown in Table 8 with the locations shown on Figure 2.

Table 8: Historical Flood Levels (mAHD)

Location	House No.	Storm Date				
		Nov 84	**Jan 89**	**Mar 89**	**Dec 90**	**Jan 91**
Bellevue Hill Sub-catchment:						
Balfour Rd	49				AF	
	72	BF	BF			
	75	Street				
	104				Yard	
Latimer Rd	22	AF in 1988 storm				
	55	Yard in 1988 storm				
Marion Av	8	Street		Always in heavy rain		
	12			Street	Street	
	18				Yard	
	20	Street				
	22	Street	Street	Street	Street	
O'Sullivan Rd	63	Street		Always in heavy rain		
Plumer Rd	20	Yard/Street		Always in heavy rain		
Salisbury Rd	60				AF	
	74	AF				

Key:
AF = above floor
BF = below floor
Yard = flooding in yard
Street = flooding over road

The limited flood history that is available does suggest significant flood problems have occurred in the past.

3.3.3 Reference 1

The results from the DRAINS model outputs analysed in Reference 1 suggest that problems may exist in the following areas within the Bellevue Hill subcatchment:

- 11 and 13 Bundarra Road and 8, 10 and 12 Blaxland Road,
- 19, 21 and 23 Bunyula Road and 58 and 60 Boronia Road,
- 49 and 51 Boronia Road and 177 and 179 O'Sullivan Road,

- 63 and 65 Victoria Road,
- 2 Beresford Crescent and 50, 52 and 56 Beresford Road,
- 24, 26, 19 and 21 Balfour Street,
- 7 Aston Gardens,
- 9 Cranbrook Lane and 13, 15 and 17-19 Cranbrook Road,
- Cranbrook School.

Within the Rose Bay subcatchments problems may exist at:
- 482, 484-486 and 488-492 Old South Head Road,
- properties along Spencer Street,
- 34, 36, 51, 53 and 55 Dover Road,
- 56, 58, 71 and 73a Wilberforce Avenue,
- about half of the Rose Bay Shopping Centre, particularly at the intersection of Newcastle Street and New South Head Road.

3.3.4 Newspaper Reports of November 1984 Event

The November 1984 storms occurred over several days and caused widespread damage across Sydney, hence generating a large amount of media interest. Reports in the Sydney Morning Herald (10/11/1989) and The Sun (16/11/1989) indicate that Rose Bay was one of the worst affected suburbs. Photographs 11 to 14 show the extent of the damage.

Events described in the articles include:

- A ‘wave’ of water ran down Newcastle Street and Wilberforce Avenue to the shops at New South Head Road, where water smashed shop windows and stacked cars on top of each other (shown in Photo 11).

- This water then went through Percival Park, ‘tearing great gashes in the soil’, shown in Photo 13.

- Eight shops in the Rose Bay shopping centre were damaged, the worst being opposite Newcastle Street on New South Head Road. Water was reported as 1.7 m deep inside one of these shops, and 1.5 m deep in another.

- A mudslide was caused by a burst pipe on the playing field at Scots College, shown in Photo 12 sending mud down the gully to Cranbrook Road, and filling houses and cars with sand (Photo 14).

- Where the two flow paths of Newcastle Street and Wilberforce Avenue met, 2 m high waves were created.

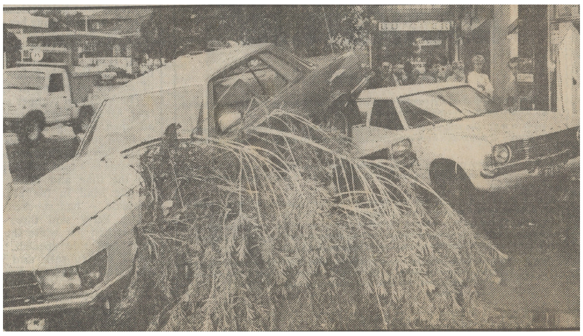


Photo 11: Cars piled on top of each other, New South Head Road (source - SMH, 10/11/1989)

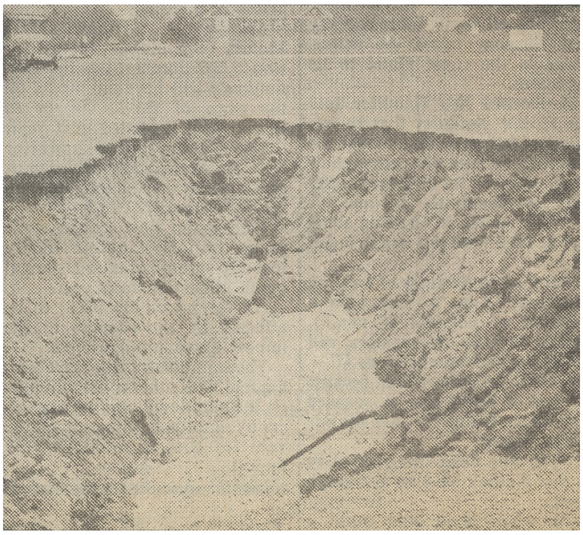


Photo 12: A burst stormwater pipe causing a mudslide at Scots College (source - SMH, 10/11/1989)

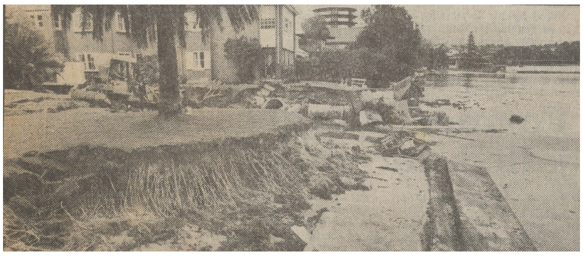


Photo 13: Flow coming from Rose Bay shopping area damages park and foreshore (source - SMH, 10/11/1989)

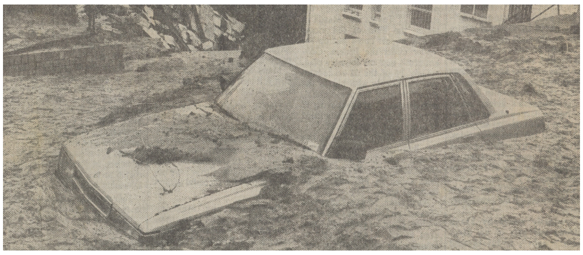


Photo 14: Sand from mudslide fills car (source - SMH, 10/11/1989)

3.3.5 Information from Council Archives

A search was carried out of Woollahra Municipal Council archives for documents relevant to flooding in the catchment. The relevant properties, dates of flooding and description of events are listed in Table 9. Some of the dates are events already mentioned previously (such as 6/1/1989, 8/11/1984 and 26/1/1991). Other dates are typically from local flooding caused by inadequate household or street drainage and may not have occurred in conjunction with significant catchment flooding (this being the main focus of this present study).

Table 9: Flood Related Data from Council Documents

Address	Date	Description
Beresford Road	06/01/1989	Water entered properties from Beresford Road, moved through No. 75 and 77 Beresford Road and then into No. 86 Balfour Road.
49 Boronia Road	02/03/1981	Flooding of property, retaining wall collapsed into property. This resulted from water ponding against the retaining wall due to the reverse fall of the footpath.
	01/09/2002	Runoff from street entered property - went down pathway, into backyard.
51 Boronia Road	November 1984	Rubble from road dumped in backyard.
	26/01/1991	Flooding at property.
	01/09/2002	Runoff from street entered property - went down pathway, into backyard.
11 Bundarra Road	08/01/1973	Flooding 3 mm - 19 mm in house (area received 152 mm rain in 2 hours). Flow went over the concrete driveway across the footpath, through the gate and down the pathway to the front entrance door.
	09/04/1973	Water entered property though not as extensive as 8/01/73.
	01/05/1973	Flow entered property, into house (area received 25 mm of rain in 20 mins).
13 Bundarra Road	09/04/1973	Overflow from footpath entered property.
Dover Road	06/01/1989	Water half way across nature strips outside houses No's 49 - 63.
	November 1984	Number of houses on west side of this section of Dover Road were flooded from short duration, heavy storm.
51 Dover Road	June 1986	Water ponding in front of No's 51, 53 and 55 Dover Road, perhaps aggravated by the camber of the road itself.
	06/05/1986	Faint water marks on the brick wall at the fence alignment of No. 51. These marks were located approximately 60 mm above the back of the concrete footpath. Water flowed into property under roller door and into the building. Interviews with other residents living in the vicinity of the subject property (No's 55 and 32) indicated that at the peak of the flood, water completely covered the road. Dover Road is on a flat grade with gutter grates no greater than 0.5% grade which may contribute to the flooding problem.
72 Salisbury Road	2001	Front footpath had lifted and was diverting street water into property. During heavy storms water flows into property.
45 Salisbury Road	1986	Water from gutter flow finds its way across the driveway at No. 47. This has resulted from a kerb height that has been reduced consecutively by pavement re-seals.

The above record provides minimal information on the November 1984 event which caused extensive damage throughout the catchment.

3.4 Results from July 2007 Resident Questionnaire

A total of 3146 questionnaires were sent out, of which 328 (10%) were returned. The results are shown on Figure 3. The main outcome of the survey was the relatively low level of response and the absence of detailed flood height data. Figure 3 shows that many residents have only recently moved into the area, and thus would not have experienced the significant floods of November 1984 and the early 1990s. The location of the respondents to the various questions are provided on figures in Appendix B.

3.5 ALS Survey

The Airborne Laser Scanning (ALS) data was provided to Council under separate cover and used for establishing the 2D hydraulic model. This survey was flown in December 2005 and comprised ground levels at approximately 1 m to 2 m intervals. These data have a vertical accuracy of the order of ±0.15 m. The ALS levels are shown on Figure 4.

4. APPROACH ADOPTED

4.1 General

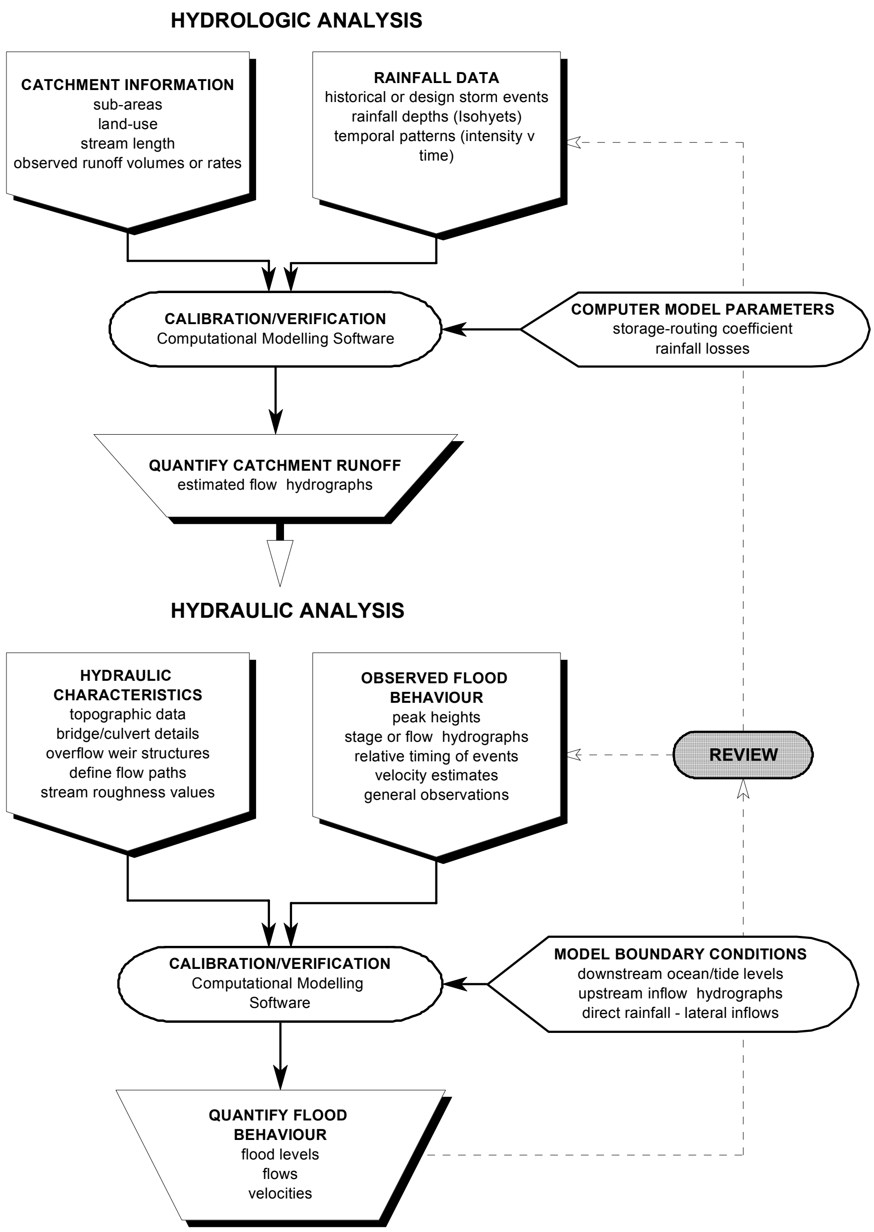
A diagrammatic representation of the Flood Study process is shown in Diagram 1. The urbanised nature of the study area with its mix of pervious and impervious surfaces, and existing piped and overland flow drainage systems has created a complex hydrologic and hydraulic flow regime. An existing hydrologic model (DRAINS - References 1 and 2) was used to create flow boundary conditions for input to a 1D-2D SOBEK unsteady flow hydraulic model.

The SOBEK model extents were determined where overland flows were greater than 2 m^3/s in the 100y ARI event. In upper parts of the catchment, streets were modelled as 1D reaches as this provides a more accurate definition of the topography. A 2D grid was established elsewhere, with a 10 m grid within the golf courses and a 2 m grid within the remaining areas.

The SOBEK hydraulic model was used to assess stormwater overland flows, through streets, the stormwater channel, and across the floodplain. The model included open channel details, ALS ground height data and inflows from the two DRAINS models (References 1 and 2). The model extent is shown on Figure 4.

To ensure confidence in the results, the SOBEK model requires calibration and verification against observed historical events. In an urban drainage situation, such as the Rose Bay catchment, rarely are sufficient historical flood data available to permit either a flood frequency approach or a rigorous calibration of hydrologic and hydraulic models using a rainfall and runoff approach. With the limited amount of flood height data available and given the lack of any stream gaugings, the model calibration process focussed on reproducing recorded peak November 1984 flood levels in the Rose Bay shopping precinct with the SOBEK hydraulic model. The calibrated SOBEK hydraulic model was then used to quantify the design flood behaviour for a range of design storm events up to and including the Probable Maximum Flood (PMF).

Diagram 1: Flood Study Process



4.2 SOBEK

The SOBEK modelling package includes a finite difference numerical model for the solution of the depth averaged shallow water flow equations in two dimensions. The SOBEK software is produced by Delft Hydraulics (Reference 8) and has been widely used for a range of similar projects both internationally and within Australia. The model is capable of dynamically simulating complex overland flow regimes. 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 supercritical and sub-critical flow behaviour.

For the hydraulic analysis of overland flow paths, such as those identified in the present study on Figure 4, a two-dimensional (2D) model such as SOBEK provides several key advantages when compared to a traditional one-dimensional (1D) model. For example, in comparison to a 1D approach, a 2D model 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,
- inherently represent the available floodplain 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 in detail across the model extent. This information can then be easily integrated into a GIS based environment enabling the outcomes to be incorporated into Council's planning activities. Furthermore, the SOBEK software provides a more flexible modelling platform to properly assess the impacts of any overland flow management strategies in the proposed floodplain risk management study.

The main disadvantage of the 2D approach is that model run times increase significantly from a few minutes for a 1D simulation to several hours for a 2D simulation.

In the Rose Bay catchment, streets in the upper parts of the catchment were deemed to be better represented using 1D sections rather than a 2D grid, because of the steep and narrow nature of the flow paths (Figure 4). SOBEK allows for 1D reaches to be coupled to 2D grids.

4.3 DRAINS Model

As noted previously two DRAINS models were established. Reference 1 developed a DRAINS model for the Rose Bay/Vaucluse subcatchment and another for Bellevue Hill. These two models were combined together in this study for ease of use. Reference 4 created two DRAINS models for the Dover Heights and the North Bondi subcatchments. Again for ease of use these two Waverley LGA models were combined for ease of use. The Waverley and Woollahra DRAINS models could not be combined as a single catchment model for use in the study as they adopted slightly different catchment parameters. Thus if they were combined the results from one LGA would be different to those provided in the references.

Figures 5a and 5b show the pit and pipe DRAINS model network taken from Reference 1 (Rose Bay and Bellevue Hill sub-catchments). Figures 6a and 6b show the resulting peak overland flows for the 100y ARI and PMF events from these models. It should be noted that the inflows to the Woollahra LGA from the Waverley LGA DRAINS models are also shown.

5. HYDRAULIC MODELLING

5.1 General

Given the objectives of the study, the availability of ALS data and the nature of the flat terrain at the downstream limit of the catchment, coupled with steep roads in the upper part of the catchment, a 1D-2D overland flow hydraulic model was assumed to provide the most effective assessment of flood behaviour. The 1D-2D overland model was established using the SOBEK software package (Reference 8), which is widely used in Australia and internationally.

5.2 Methodology of SOBEK Model

A 10 m and a 2 m 2D grid was generated from the ALS data. The ALS ground surface within the SOBEK model extent is shown on Figure 4. The boundary conditions were defined as:

- Overland flows entering the model extent from the DRAINS models were defined as line boundaries.
- 1D reaches upstream of the 2D model were connected to the 2D component by a 1D-2D boundary.
- Surface pit sub-catchments located within the 2D model extent were defined as point sources. This assumed that the inlet pits contained within the 2D model extent were not capable of any more flow, but were also not surcharging (i.e. the sub-surface drainage system was at capacity). This assumption was necessary for the interaction between the DRAINS and SOBEK models.
- Pipe flows entering the SOBEK model extent from DRAINS were included as nodes with lateral flows.

SOBEK allows the open stormwater channel to be modelled as a 1D component and this is coupled with a 2D overland receiving component. At a specified distance along the channel, a calculation point solves the momentum and continuity equations for both the 1D channel and overland flows.

The SOBEK model also included pipes/culverts of 600 mm diameter or greater. Pipes smaller than this were excluded as it was considered that the flow in these pipes is a small percentage of the total and the flow carried is likely to be significantly reduced due to blockage in the pipes or inlet restrictions (vehicles parked, debris). Thus the overland flow and peak flood levels in these reaches are likely to be slightly overestimated.

The major box culvert structure over the channel at New South Head Road was modelled as an orifice and a culvert. This is to simulate both the entry losses and friction losses along the culvert.

The Manning's "n" values for each grid cell were estimated from engineering experience and applied to the 2D overland area based on the terrain shown in Table 10.

A major assumption of the hydraulic modelling approach is that the seawall along New South Head Road generally between Wunulla Road and Lyne Park, does not fail during a flood and overland flow can only exit over the top of the wall or at the pedestrian access openings. Thus the seawall acts as a significant barrier to overland flow exiting to Rose Bay.

Table 10: Manning's "n" values within SOBEK

Category	Manning's "n"	Description
1	0.10	Natural bushland, trees.
2	0.02	Streets, paved areas.
3	0.60 (1)	Private property obstructed by fences.
4	0.03	Grassed areas.
5	0.05	Grassed area with obstacles.
6	0.015	Open lined channel.

Note:
(1) The high Manning's "n" value of 0.6 was chosen where fences lay perpendicular to the flow, in order to simulate that water would pond rather than flow in these locations.

5.3 Model Calibration and Verification

Ideally the SOBEK model should be calibrated to one historical event and verified using another historical event. There should also be sufficient historical flood height data (preferably for both historical events) to define the flood gradient within the modelling extent. However as indicated in References 1 and 4 there are very little accurate flood height data available (refer Sections 3.3 and 3.4). Although there is qualitative evidence that flooding has occurred in the past. Whilst flooding has occurred several times along New South Head Road at the Rose Bay shopping precinct the maximum depths have never been accurately recorded.

Thus the only calibration information available are:

- during the November 1984 flood, shop owners in the Rose Bay shopping area reported (SMH, 10/11/1984) that water was approximately 1.5 m to 1.7 m deep at New South Head Road (see Section 3.3.4). Section 3.1.2 suggests that the rainfall for this event approached a 100y ARI event for a 1 to 2 hour duration.

6. DESIGN FLOOD RESULTS

6.1 Overview

There are two basic approaches to determining design flood levels, namely:

- *flood frequency analysis* - based upon a statistical analysis of the flood events, and
- *rainfall and runoff routing* - design rainfalls are processed by hydrologic and hydraulic computer models to produce estimates of design flood behaviour.

The *flood frequency* approach requires a reasonably complete homogeneous record of flood levels and flows over a number of decades to give satisfactory results. No such records were available within the catchment. For this reason a *rainfall and runoff routing* approach using the DRAINS model results was adopted for this study to derive design inflow hydrographs for input to the SOBEK hydraulic model, which determines design flood levels, flows and velocities. This approach reflects current engineering practice and is consistent with the quality and quantity of available data.

6.2 Tailwater Conditions

In addition to runoff from the catchment, the reach of open channel downstream of New South Head Road can also be influenced by backwater effects from high water levels in Sydney Harbour at Rose Bay (Section 3.2). As noted previously, these two distinct mechanisms that produce flooding in the Rose Bay catchment may not result from the same storm. It is acknowledged however that this may not necessarily be the case and that high Sydney Harbour levels may occur in conjunction with rainfall events. Consideration must therefore be given to accounting for the joint probability of coincident flooding from both catchment runoff and backwater effects from Sydney Harbour at Rose Bay.

A full joint probability analysis is beyond the scope of the present study. Traditionally, it is common 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. As the 100 year ARI peak level in Sydney Harbour at Rose Bay due to a high tide/storm surge is largely contained within the stormwater canal downstream of New South Head Road, a single design scenario was adopted. For each design event, the relevant design flows are used in conjunction with a static tailwater level of 1.0 mAHD in Sydney Harbour at Rose Bay. This approach is identical to that adopted in similar such studies elsewhere in Sydney. This simplified approach is considered appropriate given that there is a relatively short transitional zone between the peak levels for the two mechanisms.

A sensitivity analysis of the relative impacts of assuming different tailwater conditions is presented in Section 6.5.

6.3 Blockage Assessment

The role of blockages in exacerbating flood impacts during the August 1998 storm in North Wollongong highlights the importance of considering the implications for blockages in design flood assessment. Whilst most blockages are due to vegetative debris, in an urban environment there is the risk that fences or vehicles may be swept into the channel and cause the same effect (as happened at Newcastle in June 2007).

Based on site inspections, and discussions with Council officers and local residents, the issue of culvert blockages is relevant for the Rose Bay open channel system.

Evidence from the August 1998 North Wollongong storm indicates that there is the potential for culvert openings less than 6 m diagonal width to be blocked during a runoff event. For the Rose Bay open channel this observation would imply that the twin culverts under New South Head Road could be either partially or fully blocked. In all past floods there is no anecdotal or other information to indicate that blockage has occurred at this or any location along the channel.

The twin 4.1 m wide by 2.2 m high box culverts are unlikely to be blocked as upstream is a golf course that is well maintained, with little vegetative or other debris that could cause blockage. Furthermore, any such debris is likely to be “held” upstream of the culverts at the bridges over the channel or where the upstream channel is smaller in size.

To quantify the impacts of potential blockages on design flood behaviour, an unblocked, one culvert blocked and both culverts blocked scenario were simulated for the 20y and 100y ARI events using the SOBEK model. The results are indicated in Table 11.

Table 11: New South Head Road Culvert - Blockage Assessment

Flood Levels (mAHD) upstream at Culverts under New South Head Road			
ARI	**Unblocked**	**50% blockage**	**100% blockage**
100y	2.35	2.73	3.15
20y	2.15	2.41	3.05

As expected, the results indicate that the inclusion of 100% blockage of the culvert (both culverts blocked) under New South Head Road has a significant impact on the peak flood level upstream. However for the design analysis no blockage was assumed, as the culverts are considered unlikely to be blocked for the reasons provided above.

6.4 Design Events

6.4.1 Results

The critical storm duration (produces the highest peak level) was determined to be the 90 minute duration for all design events.

Peak height profiles for the 1, 2, 5, 10, 20 and 100 year ARI events and the PMF are provided on Figure 7. Figures 8 to 14 summarise the results in graphical form. Table 12 lists the peak flood levels at key locations.

Table 12: Key Flood Levels

	Peak Water Level (mAHD)						
	1y ARI	**2y ARI**	**5y ARI**	**10y ARI**	**20y ARI**	**100y ARI**	**PMF**
cnr Powell & Balfour Rds	3.17	3.29	3.37	3.42	3.47	3.56	3.96
culvert u/s of New South Head Rd	1.37	1.60	1.88	2.03	2.15	2.35	3.41
entrance of Royal Sydney Golf Course carpark	2.32	2.33	2.33	2.33	2.33	2.44	3.66
Rose Bay shopping precinct	4.29	4.53	4.72	4.80	4.93	5.11	5.94
cnr Albermarle Ave & Newcastle St	10.02	10.09	10.11	10.12	10.17	10.23	10.35

6.4.2 Comparison with Historical Data

As noted in Section 5.3 the only available historical peak height data was at the Rose Bay shopping precinct. A comparison of the design versus actual flood data recorded in November 1984 is provided in Table 13.

Table 13: Calibration Results

Event	Water Depth (m) Rose Bay Shopping Precinct (assumed to be at 3.5 mAHD)
Recorded November 1984	1.5 to 1.7
100y ARI	1.6
20y ARI	1.4
10y ARI	1.3
5y ARI	1.2

Based on the results in Table 12 the November 1984 event is approximately a 100y ARI event and this approximates the ARI of the rainfall data for that event (Section 3.1.2). Whilst the above is not a rigorous calibration it does indicate that the design flood levels are within the range of levels observed in historical events. When another flood of similar magnitude to November 1984 occurs, it is essential that the model calibration is verified against the available peak flood height data.

6.4.3 Hydraulic and Hazard Categorisation

For the purposes of floodplain risk management in NSW the floodplain is divided into one of three Hydraulic categories (floodway, flood storage or flood fringe) and two Hazard categories (Low or High). These terms are defined in Appendix A. Further details of this process are provided in the NSW Government's Floodplain Development Manual (Reference 9). Maps of the categorisation for the 100 year ARI and PMF events are provided on Figures 15 and 16.

The Hydraulic categorisation was determined qualitatively based upon the available hydraulic and survey information together with our knowledge of the Rose Bay catchment and experience in other catchments. The Hazard categorisation was determined quantitatively based upon the available hydraulic and survey information in accordance with the provisional hydraulic hazard categorisation figures provided in Reference 9. As indicated in the NSW Government's Floodplain Development Manual this process of Hazard categorisation is **Provisional** and should be refined at a later date to reflect other factors that influence hazard (such as warning time, flood readiness, rate of rise, duration of flooding, evacuation problems, effective flood access and the type of development).

6.5 Sensitivity Analyses

6.5.1 Model Parameters

Given the lack of reliable historical flood level and streamflow data, only a very limited calibration of the SOBEK model was possible. In view of this, sensitivity analyses were undertaken to determine the impacts of key model parameters on the simulated flood behaviour.

The following sensitivity analyses were carried out for the 100 year ARI event:

- change in tailwater level in Sydney Harbour - Rose Bay,
- ±25% variation in Manning's 'n' value. This parameter reflects the surface friction (a higher "n" the greater the friction and the higher the flood level),
- ±10% and ±20% change in rainfall depth.

The results demonstrate that for a significant flood event, the impacts of assumed tailwater conditions are confined to the very lower reaches of the Rose Bay open channel within the golf course. Model results indicate that even with a relatively high tailwater, the backwater effects do not extend beyond the confines of the golf course or into the Rose Bay shopping precinct. For low tailwater conditions, the results indicate the same. This validates the original design tailwater assumptions (as noted earlier in Section 6.2).

In general, variations in Manning's 'n' roughness values of +/-25% did not result in significant variations in predicted peak flood levels (Appendix C). These results reflect the uncertainty in the modelling (due to the lack of historical data available for calibration) and highlight the potential impacts of assumed bed roughness on predicted flood levels. However, these results are still within the expected accuracy of the hydraulic modelling.

Changes to the design rainfall depth produced minor changes in the predicted flood peaks throughout the model as expected (Appendix C).

6.5.2 Climate Change

The climate change or "Greenhouse" effect has become one of the major environmental concerns over the last 20 years. The term is used to describe the effect of the presence of gases in the atmosphere which allow the sun's rays to penetrate to earth but reduce the amount of incoming energy being back radiated. There is concern that increasing amounts of greenhouse gases resulting from human activity may be raising the average earth surface temperature. As a consequence, this may affect the climate and the sea level. The exact extent of permanent climatic or sea level change can only be established through scientific observation over several decades. Nevertheless, it is prudent to consider the possible range of impacts with regard to flooding in the Rose Bay catchment.

The effect of a change in the sea level on flooding in the Rose Bay catchment will depend on its influence on the adopted flood levels in the Rose Bay catchment. In summary climate change has the potential to alter flood levels in Sydney Harbour - Rose Bay and thus in the lower reaches of the Rose Bay open channel. At this time the full effects have not been accurately quantified. The latest (2007) Intergovernmental Panel on Climate Change (IPCC) information suggests sea level rises of between 0.18 m to 0.59 m by between 2090 and 2100 (estimates ignore ice flow melt). Taking into account ice flow melt and recent CSIRO modelling indicates a possible sea level rise of 0.18 m to 0.91 m by between 2090 and 2100.

Three elevated tailwater levels were simulated for the 100 year ARI event:

- +0.18 m (1.18 mAHD),
- +0.55 m (1.55 mAHD),
- +0.91 m (1.91 mAHD).

The 0.18 m and 0.55 m increase produced only minor increases in flood level upstream and even the 0.91 m increase was still only confined to the golf course and immediately upstream of the outlets north of the Rose Bay shopping precinct.

The effect of climate change on design rainfall increases has not been quantified at this time. The sensitivity analyses indicates the effect of a 10% and 20% increase in design rainfall depths, should this eventuate.

6.6 Comparison of Results with Previous Studies

The only previous study which has documented design flood levels is the Rose Bay SWC Catchment Management Study (Reference 4). Though the majority of levels were in the Waverley LGA which is not part of the present study area. A comparison of the results is provided in Table 14.

Table 14: Comparison of Design Flood Levels (mAHD)

Location / Event	Reference 4					Current Study				
	5y	**10y**	**20y**	**100y**	**PMF**	**5y**	**10y**	**20y**	**100y**	**PMF**
O'Sullivan Rd/Boronia Rd intersection (south)	15.6	15.6	15.6	15.6	15.7	15.2	15.2	15.2	15.2	15.3
O'Sullivan Rd/Bunyula Rd	10.6	10.6	10.6	10.6	10.8	11.1	11.1	11.1	11.2	11.2
150 m north of Bunyula Rd / O'Sullivan Rd intersection	7.8	7.8	7.8	7.8	8.0	8.5	8.5	8.5	8.5	8.5
250 m north of Bunyula Rd / O'Sullivan Rd intersection	6.9	6.9	7.0	7.1	7.7	6.9	6.9	6.9	7.0	7.0
500 m north of Bunyula Rd / O'Sullivan Rd intersection	6.7	6.8	6.9	7.0	7.3	Not wet	Not wet	Not wet	Not wet	6.2
O'Sullivan Rd / Plumer Rd intersection	3.2	3.2	3.2	3.4	4.1	3.3	3.3	3.3	3.3	3.6
Plumer Rd / Balfour Rd intersection	4.1	4.1	4.2	4.2	4.4	4.3	4.3	4.3	4.3	4.5
120 m north of Plumer Rd / O'Sullivan Rd intersection	2.6	2.6	2.6	2.7	3.8	2.8	2.8	2.8	2.8	3.6

The comparison of levels shown in Table 14 provides little conclusive information. This is largely because the results from Reference 4 were based on limited survey data and thus are not directly comparable to the current results which are based on comprehensive ALS data. What is apparent from both sets of results is the relative little difference between the flood levels for the various design events.

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- residents of the Rose Bay catchment.

8. REFERENCES

1. Woollahra Municipal Council
   Woollahra Drains Modelling
   Draft Report, Brown Consulting, November 2006.

2. Waverley Council
   Stormwater Drainage System Mapping and Modelling
   Civic Design, August 2007.

3. Pilgrim, D H (Editor in Chief)
   Australian Rainfall and Runoff - A Guide to Flood Estimation
   Institution of Engineers, Australia, 1987.

4. Water Board
   Rose Bay SWC Catchment Management Study
   Water Board, 1991.

5. Woollahra Municipal Council
   Rushcutters Bay Flood Study
   Webb, McKeown & Associates Pty Ltd, October 2007.

6. Kogarah Council
   Beverley Park Overland Flow Study
   Lawson and Treloar Pty Ltd, October 2004.

7. Bureau of Meteorology
   Technical Report No. 19 Intense Rainfalls from the Thunderstorms over the Sydney Metropolitan and Illawarra Districts - 10 and 11 March 1975
   J G Armstrong, J R Colquhoun, September 1976.

8. Delft Hydraulics
   SOBEK Reference Guide, V2.09.004.

9. New South Wales Government
   Floodplain Development Manual
   April 2005.