7. HYDRAULIC MODELLING

7.1. Terrain Model

A computational grid cell size of 2 m by 2 m was adopted, as it provided an appropriate balance between providing sufficient detail for roads and overland flow paths, while still resulting in practicable computational run-times. The model grid was established by sampling from a triangulation of filtered ground points from the LiDAR dataset.

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).

7.2. Boundary Conditions

The model schematisation is illustrated on Figure 11, including the location of the stormwater pits and pipes. In addition to runoff from the catchment, the reach of the open channel downstream of Glenmore Road can also be influenced by backwater effects from high water level in Rushcutters Bay. These two distinct mechanisms produce flooding in Rushcutters Bay as well as in the open channel but may not result from the same storm. Under some circumstances it can be expected that tidal influences will occur in conjunction with rainfall events. Consideration must therefore be given to accounting for the join probability of coincident flooding from both catchment runoff and backwater effects from Rushcutters Bay.

A full joint probability analysis is beyond the scope of the present study, and research into this issue for the east coast of Australia has not yet led to a comprehensive approach for modelling the combined mechanisms. 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 10) specify approaches for setting the tailwater at an ocean level boundary for flood risk assessment. The guideline provides three approaches to the development of appropriate tailwater levels for open entrances, for consideration in flood risk assessments. The first two approaches involve a fixed and dynamic boundary condition with a maximum level of 2.6 mAHD. The third requires a site specific assessment, which is recommended where the first 2 options are considered too conservative. The Consideration of Sea Level Rise in Flood and Coastal Risk Assessment paper presented at the NSW Floodplain Management Authorities Conference (McLuckie et al, 2011) states:

> *"Where the* [2.6 mAHD] *fixed approach is likely to be too conservative for the resultant decision, either the dynamic ocean boundary provided in the guideline or one specifically developed for the location and the associated conditions should be used to assess flood behaviour. Studies undertaken under the State's Floodplain*

> *Management Program are not to use the conservative fixed ocean boundary condition unless specifically agreed to by DECCW."*

It was therefore considered appropriate to determine a site specific ocean water level boundary condition for this study. Rushcutters Bay is in a highly sheltered portion of Sydney Harbour. The large size of Sydney Harbour significantly reduces the potential for wave setup to increase harbour water levels (as there is enough depth at the entrance for ocean wave inflows to flow back out through the entrance).

As a result of the estuary size and the protected location of Rushcutters Bat, the influence of ocean level components such as wave action and associated potential for wave setup are significantly reduced. These effects have a relatively short duration and are more important for smaller coastal catchments with an exposed entrance. Therefore for this study the wave setup was assumed to be negligible. For Rushcutters Bay, the principal components to be considered in setting tailwater levels are tides and barometric effects (storm surge).

The annual high astronomical tide (due to gravitational effects of celestial bodies) on the NSW coast is around 1.1 mAHD to 1.2 mAHD. The highest recorded tide at Fort Denison in Sydney Harbour is 1.5 mAHD, which included barometric effects (storm surge) from a low pressure cell, and the 1% AEP level at Fort Denison is 1.45 mAHD.

A table of design tailwater scenarios adopted for this study is given in Table 14 with design ocean levels taken from Reference 11.

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.

Along the LGA boundary, which coincides with Nield Avenue and the Sydney Water open channel, design flood levels from Reference 2 were adopted as a boundary condition. Results from Reference 2 were unavailable for the 2 year ARI event and therefore a 5 year ARI downstream boundary condition was adopted for this event.

For historic events, sensitivity analyses of boundary conditions were undertaken with the following scenarios shown in Table 15. It was found that the tailwater boundaries had very little impact on results. This is because even the low-lying reclaimed areas of the catchment are generally above 2 m, which is above the range of adopted tailwater levels.

Table 15 – Boundary Condition Scenarios for Historic Rainfall Events

Scenario	Weigall Tailwater	Ocean Level (mAHD)
1	5 year	0.0
2	5 year	1.0
3	100 year	0.0
4	100 year	1.0

A sensitivity analysis of the relative impacts of assuming different tailwater conditions due to climate change is presented in Section 10.3.

7.3. Hydraulic Roughness

The adopted roughness values are consistent with typical values in the literature (References 6, 12, and 13) and previous experience with modelling similar catchment conditions. The sensitivity of model results to changes the roughness values is discussed in Section 10.

Table 16 - 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

7.4. 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 may occur naturally on the road can end up in the pit inlets; the most common material is leaves and other small vegetation as well as general litter. Other obstructions include parked cars or trucks. Blockage was applied to inlet pits rather than pipes for this study.

It is impossible to accurately estimate the degree of blockage during a storm and for this reason a conservative approach has been applied which generally assume trunk drainage pipes of diameter smaller than 450 mm do not convey flow in the TUFLOW modelling. In some locations the trunk drainage system had no direct connection to inlet pits and under these circumstances Council pipes smaller than 450mm linking inlet pits to the trunk drainage system assumed to be clear of blockage in order to more accurately model the trunk drainage system capacity. Pipes smaller than 450mm in diameter were also included in the modelling where they represented the only means of drainage from an areas (such as a trapped low point).

Blockage to inlet pits was applied as per the Queensland Urban Drainage Manual (Reference 14) and Project 11 of the AR&R revision project (Table 17).

Table 17 – 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 of assumptions within the underground drainage network is assessed in Section 10.

8. MODEL CALIBRATION

8.1. Overview

It is preferable to test the performance of the hydrological/hydraulic models against observed flood behaviour from past events within the catchment. The assumed model parameters can be adjusted so that the modelled behaviour best represents the historical patterns of flooding. The process of adjusting model parameters to best reproduce observed flood behaviour is known as model calibration. Usually, the models are calibrated to a single flood event for which there is sufficient flood data available (e.g. peak-flood levels, observations regarding flowpaths or flood extents etc). The performance of the calibrated model can then be tested by simulating other historical floods and comparing the ability of the calibrated models to reproduce the observed behaviour. This process is known as model validation.

To calibrate/validate the models requires a sufficient amount of flood data within the model extent. There is no stream gauge within the catchment and therefore it is not possible to conduct a thorough calibration of modelled flows to observed data. The largest flood events known to have occurred within the catchment occurred on 8-9th November 1984, 6 January 1989 and 26 January 1991. For these major events, there is limited flood height data, and only anecdotal or approximate depths were available. As a result the hydrologic and hydraulic models were validated against observed flood behaviour and limited emphasis was placed on tuning the models to exactly match depths.

When flooding occurs within the catchment in future, it is recommended that Council undertake to collect any available information (rainfall data, flood heights etc) as soon as practicable after the event.

8.2. Validation Results

The modelled results for the historical events were compared to observed flood behaviour and depth information documented in Reference 1 and additional observations were collected as part of the Community Consultation process. A comparison of this data against the model results for 8-9th November 1984, 6th January 1989 and 26th January 1991 is provided in Table 18 and Figure 12, Figure 13 and Figure 14.

Table 18 – Comparison of Historic Flood Data to Modelled Results

Location	Flood Event	Description	Observed		Modelled		Difference (m)
			Level (mAHD)	Depth (m)	Level (mAHD)	Depth (m)	
Taylor Street Low Point	Nov 1984	Depth in road	-	1.3	47.1	0.5	-0.8
Sturt Street Low Point	Nov 1984	Depth in road	-	1.6	46.6	1.8	0.2
Oxford Street (East)	Jan 1989	Depth above footpath	-	1.0	63.9	0.9	-0.1
Taylor Street Low Point	Jan 1989	Depth in road	-	< 1.3	47.2	0.6	-0.7
Sturt Street Low Point	Jan 1989	Depth in road	-	< 1.6	46.6	1.8	0.2
Boundary Street	Jan 1989	Flow through property	-	0.15	-	-	-
Boundary and Liverpool St	Jan 1989	Street Flooding	-	0.5	21.5	0.5	0.0
Neild Ave Low Point	Jan 1989	Properties Flooded	-	0.5	6.0	0.5	0.0
Intersection of Neild Ave and New South Head Rd	Jan 1989	Southern Carriageway Inundated	-	0.4	5.0	0.5	0.1
Waratah Street Low Point	Jan 1989	Depth in Road	-	0.5	2.5	0.4	-0.1
Oxford Street (West)	Jan 1991	Depth above adjacent footpath	-	0.45	46.4	0.4	-0.05
Oxford Street (West)	Jan 1991	Depth above adjacent footpath	-	0.45	46.4	0.5	0.05
Oxford Street (West)	Jan 1991	Depth above Adjacent footpath	-	0.45	46.4	0.4	-0.05
Oxford Street (East)	Jan 1991	Depth above footpath	-	1.0	63.8	0.8	-0.2
Taylor Street Low Point	Jan 1991	Depth in road	-	1.3	47.2	0.5	-0.8
Taylor Street Low Point	Jan 1991	Overtopped front fence	> 47.4	-	47.2	0.4	-0.2
Sturt Street Low Point	Jan 1991	Depth in road	-	1.6	46.6	1.8	0.2
Intersection of Neild Ave and New South Head Rd	Jan 1991	Southern Carriageway Inundated	-	0.4	5.0	0.4	0.0

In the January 1991 event, water overtopped the 0.5 m high front fence near the Taylor Street low point and at the rear of the property lapped at floor level. This information was converted to an approximate height in mAHD based on surrounding LiDAR data.

Properties within Sims, Taylor and Sturt Streets have experienced substantial road flooding in the past with reported depths of greater than 1 m. The lowest available flow-path from Taylor Street to Sturt Street is through a property along Taylor Street. Photo 1 shows the existing fence with a gap underneath, however it is not known whether the same fence was in place in historic events. Given the difference in peak flood depths between Taylor Street and Sturt Street low points, it is quite likely that the flow-path through Taylor Street was historically more blocked (by fences/gates for example) than under current conditions, which would have increased flood levels within Taylor Street.

Photo 1: Flow path from Taylor Street to Sturt Street

Property flooding at Boundary Street was observed in January 1989. Reference 1 states that the flooding is likely a local runoff problem and that flows along the adjacent path routed through the property from the rear and into Boundary Street. Survey information within this area is not sufficiently defined in order for the hydraulic model to be able to replicate this flow path and as such modelled results do not match observed flooding at this location.

Recorded flood levels were also compared against design flood levels (in Table 19), to provide some perspective as to whether the modelled range of design flood levels was consistent with observed historical variability. Recorded flood levels near the Weigall Sportsground open channel have not been included as part of this assessment as downstream flood levels have been adopted from Reference 2.

Table 19 – Comparison of Historic Flood Data to Design Results

Location	Flood Event	Observed Depth (m)	Modelled Flood Depth (mAHD)			
			2Y ARI	10Y ARI	20Y ARI	100Y ARI
Oxford Street (West)	Jan 1989	1.0	0.5	0.8	0.9	1.1
Oxford Street (East)	Mar 1977	0.15	0.3	0.4	0.4	0.4
Oxford Street (East)	Jan 1991	0.45	0.3	0.4	0.4	0.4
Oxford Street (East)	Mar 1977	0.15	0.4	0.5	0.5	0.5
Oxford Street (East)	Jan 1991	0.45	0.4	0.5	0.5	0.5

Location	Flood Event	Observed Depth (m)	Modelled Flood Depth (mAHD)			
			2Y ARI	10Y ARI	20Y ARI	100Y ARI
Oxford Street (East)	Jan 1991	0.45	0.4	0.4	0.4	0.5
Sims Street Low Point	Feb 2012	0.6	0.5	0.7	0.8	0.9
Sims Street Low Point	Feb 2010	0.6	0.5	0.7	0.8	0.9
Taylor Street Low Point	Nov 1984	1.3	0.4	0.5	0.6	0.6
Taylor Street Low Point	Jan 1989	< 1.3	0.4	0.5	0.6	0.6
Taylor Street Low Point	Jan 1991	1.3	0.4	0.5	0.6	0.6
Taylor Street Low Point	-	0.15	0.1	0.1	0.1	0.2
Taylor Street Low Point	Jan 1991	> 0.6	0.3	0.4	0.5	0.5
Sturt Street Low Point	Nov 1984	1.6	1.6	1.8	1.8	1.8
Sturt Street Low Point	Jan 1989	< 1.6	1.6	1.8	1.8	1.8
Sturt Street Low Point	Jan 1991	1.6	1.6	1.8	1.8	1.8
Boundary Street	Jan 1989	0.15	-	-	-	-
Boundary Street	-	0.9	-	-	-	-
Barcom Avenue	June 2007	0.15	0.2	0.2	0.2	0.2
Barcom Avenue	April 1998	0.5	0.9	0.9	0.9	0.9
Boundary and Liverpool St	Jan 1989	0.5	0.3	0.4	0.5	0.6
Intersection of Womerah Ave and Liverpool St	-	0.15	0.1	0.1	0.2	0.2
McLachlan Avenue	Aug 1983	0.2	0.7	0.8	0.9	0.9
Neild Ave Low Point	Jan 1989	0.5	0.4	0.5	0.5	0.6
Intersection of Neild Ave and New South Head Rd	Aug 1983	0.45	0.3	0.4	0.5	0.5
Intersection of Neild Ave and New South Head Rd	Jan 1989	0.4	0.3	0.4	0.5	0.5
Intersection of Neild Ave and New South Head Rd	Jan 1991	0.4	0.3	0.4	0.5	0.5
Waratah St Low Point	Jan 1989	0.5	0.3	0.4	0.4	0.5

Given the lack of surveyed flood levels and the general paucity of detailed data the modelled results correspond reasonably well with anecdotal flooding observations and general catchment flow behaviour.

9. DESIGN FLOOD MODELLING

9.1. Critical Duration

To determine the critical storm duration for various parts of the catchment, modelling of the 100 Year ARI event was undertaken for a range of design storm durations from 15 minutes to 12 hours, using temporal patterns from Reference 6. An envelope of the model results was created, and the storm duration producing the maximum flood depth was determined for each grid point within the study area.

The critical duration within the catchment varies. A significant portion of the catchment has a critical duration of 30 minutes, including along the majority of Barcom Avenue where flood levels vary by ±0.05 m for the range of durations. Along Boundary Street and McLachlan Avenue the critical duration was found to be 120 minutes, with flood levels varying by ±0.05 m generally. Along Victoria Street where the critical duration was found to be 60 minutes, with levels varying by up to 0.1 m for other durations. The difference between peak flood levels between the 60 minute and 120 minute duration event however was found to be less than ±0.02m. The 120 minute duration was assessed as the critical storm duration for the catchment generally, as even in upper catchment areas the flood levels were only slightly lower (within 0.05 m) than shorter durations.

9.2. Overview of Results

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

- Peak flood level profiles on Figure 15 to Figure 17,
- Peak flood depths and levels on Figure 18 to Figure 24,
- Provisional flood hazard on Figure 25 to Figure 28,
- Preliminary hydraulic categorisation on Figure 29 to Figure 32.

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

9.3. Results at Key Locations

The results at key locations for peak flood flows, velocities, levels and depths are shown on Table 20 and Table 21 (refer to Figure 11 for locations).

Table 20 – Peak Flows (m^3/s) at Key Locations

ID	Location	Name	Type	2y ARI	5y ARI	10y ARI	20y ARI	50y ARI	100y ARI	PMF
1	Victoria Street U/S St Vincents Hospital	RB028	Overland	0.5	0.7	1.2	2.4	3.3	4.2	20.3
2	Barcom Street near Oxford St	RB027	Overland	0.0	0.0	0.0	0.0	0.1	0.1	2.6
		DRAP10737	Piped	0.9	1.2	1.2	1.2	1.3	1.4	2.0
		DRAP10760	Piped	0.5	0.6	0.7	0.7	0.7	0.6	1.0
5	Hopewell Street Near Oxford St	RB018	Overland	0.5	0.9	1.1	1.4	1.7	2.1	12.2
		DRAP11186	Piped	0.1	0.2	0.2	0.2	0.2	0.2	0.4
6	Boundary Street below Burton St	RB042	Overland	3.3	5.4	6.8	8.5	10.2	12.6	53.3
		DRAP10836B	Piped	1.9	2.1	2.1	2.2	2.2	1.6	2.6
7	Womerah Avenue	RB101	Overland	0.2	0.2	0.3	0.3	0.4	0.4	1.2
8	Boundary Street near Dillan St	RB048	Overland	5.4	9.1	11.2	13.8	16.5	19.9	82.6
		DRAP10660B	Piped	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		DRAP10791	Piped	2.5	2.8	2.9	3.1	3.2	2.5	4.0
9	McLachlan Ave (West)	RB099	Overland	3.0	5.1	6.2	7.6	9.0	10.8	39.5
		DRAP10807B	Piped	3.0	3.5	3.6	3.8	3.9	3.3	4.9
10	McLachlan Ave (East)	RB073	Overland	2.4	4.4	5.5	6.8	7.9	9.4	30.1
		DRAP10807D	Piped	3.6	4.0	4.2	4.4	4.5	3.9	5.2
11	Neild Ave D/S of Boundary Street	RB060	Overland	4.6	7.3	9.1	11.2	13.4	16.5	77.9
		DRAP10897	Piped	0.2	0.2	0.2	0.2	0.2	0.2	0.2
		DRAP11062	Piped	0.5	0.5	0.5	0.5	0.6	0.6	0.6
		DRAP11161	Piped	0.4	0.4	0.4	0.5	0.5	0.5	0.5
12	Roslyn Gardens	RB082	Overland	0.4	0.6	0.8	1.0	1.2	1.5	7.8
		DRAP14439A	Piped	0.0	0.1	0.1	0.1	0.2	0.2	0.3

Table 21 – Peak flood levels (m AHD) and depths (m) at key locations for all design events

ID	Location	2 year ARI		5 year ARI		10 year ARI		20 year ARI		50 year ARI		100 year ARI		PMF	
		Level	Depth	Level	Depth	Level	Depth	Level	Depth	Level	Depth	Level	Depth	Level	Depth
1	Sims Street	49.0	0.6	49.2	0.8	49.2	0.8	49.3	0.9	49.4	1.0	49.5	1.1	49.7	1.4
2	Oxford Street (West)	63.5	0.4	63.7	0.6	63.8	0.7	63.9	0.8	64.0	0.9	64.1	1.0	64.7	1.7
3	Victoria Street	61.8	1.4	62.2	1.7	62.2	1.7	62.2	1.7	62.2	1.7	62.2	1.8	62.6	2.2
4	Taylor Street	47.0	0.3	47.1	0.4	47.1	0.4	47.2	0.5	47.2	0.5	47.2	0.5	48.2	1.5
5	Sturt Street	46.4	1.4	46.5	1.6	46.6	1.6	46.6	1.6	46.6	1.7	46.7	1.7	47.1	2.2
6	Victoria St adjacent St Vincents Hospital	43.9	0.4	44.1	0.5	44.3	0.7	44.6	1.1	44.8	1.2	44.9	1.3	45.4	1.8
7	Boundary Street	12.8	0.4	12.8	0.5	12.8	0.5	12.9	0.5	12.9	0.6	13.0	0.6	13.7	1.4
8	McLachlan Ave	6.2	0.5	6.3	0.6	6.3	0.7	6.4	0.7	6.4	0.8	6.5	0.8	7.0	1.4
9	Neild Ave and New South Head Rd	4.8	0.2	4.9	0.2	4.9	0.2	4.9	0.3	5.0	0.3	5.0	0.3	5.3	0.7
10	Kellett Place	33.0	0.7	33.1	0.7	33.1	0.7	33.2	0.8	33.2	0.8	33.2	0.8	33.6	1.3
11	Waratah Street	2.3	0.3	2.4	0.3	2.4	0.4	2.5	0.4	2.5	0.5	2.5	0.5	2.8	0.8

9.4. Provisional Flood Hazard and Preliminary True Hazard

Maps of provisional hydraulic hazard are presented on Figure 25 (10 Year ARI) to Figure 28 (PMF). Hazard categories were determined in accordance with Appendix L of the NSW Floodplain Development Manual (Reference 15).

The provisional hazards were reviewed in this study to consider other factors such as rate of rise of floodwaters, duration, threat to life, danger and difficulty in evacuating people and possessions and the potential for damage, social disruption and loss of production. These factors and related comments are given in Table 22.

Table 22: Weightings for Assessment of True Hazard

Criteria	Weight (1)	Comment
Rate of Rise of Floodwaters	High	The rate of rise in the creek channels and onset of overland flow along roads would be very rapid, which would not allow time for residents to prepare.
Duration of Flooding	Low	The duration for local catchment flooding will generally be less than around 6 hours, resulting in inconvenience to affected residents but not generally a significant increase in hazard.
Effective Flood Access	High	Roads within the catchment will generally be inundated prior to property inundation, which may restrict vehicular access during a flood.
Size of the Flood	Moderate	The hazard can change significantly at some locations with the magnitude of the flood, particularly in the residential areas near Sims, Taylor and Sturt Streets and along Oxford Street. However, these higher hazard areas are generally captured by mapping a range of events using the provisional hazard criteria.
Effective Warning and Evacuation Times	High	There is very little, if any, warning time. During the day residents will be aware of the heavy rain but at night (if asleep) residential and non-residential building floors may be inundated with no prior warning.
Additional Concerns such as Bank Erosion, Debris, Wind Wave Action	Low	The main concern would be debris blocking culverts or bridges. This is considered to have a high probability of occurrence and will significantly increase the hazard. There is also the possibility of vehicles being swept into the main channels (as occurred in Newcastle in June 2007) causing blockage. However design modelling for this study includes significant blockage and the provisional hazard classification therefore includes this factor. Wind wave action is unlikely to be an issue but waves from traffic may be, due to the proximity of flood prone properties to main traffic routes.
Evacuation Difficulties	Low	Given the quick response of the catchment evacuation is not considered to be necessary (it is safer to remain than to cross fast flowing floodwaters) except in a few instances and therefore was not given significant weight for assessing true hazard.
Flood Awareness of the Community	Low	The flood awareness of the community is quite high due to the frequency of recent flood events. As a result of this awareness of problem flood areas, this factor is assigned a low weight in assessing true flood hazard.
Depth and Velocity of Floodwaters	High	In areas of overland flow roads are subject to fast flowing water. There is always a risk of a car or pedestrian being swept into flood waters. However this factor is largely included in the provisional hydraulic hazard calculation metrics.

Note: (1) Relative weighting in assessing the preliminary true hazard.

For the Rushcutters Bay catchment within the City of Sydney LGA, the factors with high weighting in relation to assessment or true hazard are generally related to the lack of flood warning, and the potential for flooding of access to residential properties prior to above-floor flooding of buildings occurring. In most cases, it is likely that remaining inside the property will present less risk to life than attempting evacuation via flooded routes, as refuge can generally be taken upstairs, or on furniture etc. There may be some properties where remaining inside would present a high risk to life due to very high flood depths, but these properties will generally already be classified as high hazard using provisional hazard criteria.

In general it was found that areas where a high flood hazard would be justified based on consideration of the high weight criteria in Table 22, the area was already designated high hazard as a result of the depth/velocity criteria used to develop the provisional hazard. However, additional information (particularly detailed flood level survey) may warrant revision of the true hazard categories at various properties during the Floodplain Risk Management Study phase.

9.5. Preliminary Hydraulic Categorisation

Preliminary hydraulic categorisations for the 10, 20, 100 year ARI and PMF events are provided on Figure 29 to Figure 32. There is no technical definition of hydraulic categorisation that would be suitable for all catchments, and different approaches are used by different consultants and authorities, based on the specific features of the study catchment in question.

For this study, preliminary hydraulic categories were defined using the approach adopted in Howells et al (Reference 16) and the following criteria were applied:

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

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

9.6. Preliminary Flood ERP Classification of Communities

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

Table 23 (taken from Reference 17) provides an indication of the response required for areas with different classifications. However, these may vary depending on local flood characteristics and resultant flood behaviour i.e. in flash flooding or overland flood areas. The criteria for classification of floodplain communities outlined in Reference 17 are generally more applicable to riverine flooding where significant flood warning time is available and emergency response action can be taken prior to the flood.

Table 23: Response Required for Different Flood ERP Classifications

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

In urban areas like the Rushcutters Bay catchment, flash flooding from local catchment and overland flow will generally occur as a direct response to intense rainfall without significant warning. At most flood affected properties in the catchment, remaining inside the home or building is likely to present less risk to life than attempting to drive or wade through floodwaters, as flow velocities and depths are likely to be greater in the roadway.

Figure 33 shows the preliminary ERP classification within the study area. A large proportion of the study area has been classified as high flood island, due to the reasonably high depths that would occur in road reserves surrounding properties, prior to inundation of the properties themselves.

10. SENSITIVITY ANALYSIS

10.1. Overview

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

- Rainfall Losses: Varying rainfall losses in the hydrologic model were assessed;
- Impervious Percentage: Changed the impervious fraction of each hydrologic sub-catchment by ±20%;
- Manning's "n": The roughness values were increased and decreased by 20% at all locations;
- Inflows / Climate Change: Sensitivity to rainfall/runoff estimates was assessed by increasing the rainfall intensities by 10%, 20% and 30% as recommended under current guidelines. Sea Level Rise scenarios for 2050 and 2100 were considered. Refer to Section 10.3 below for discussion;
- Pipe Blockage: Sensitivity of blocking all pipes by 25% and 50% were considered.

It should be noted that the parameters are not independent and adjustment of one parameter (Manning's "n") would generally require adjustment of other values (such as inflows) in order for the model to produce the same level at a given location.

10.2. Results of Sensitivity Analyses

Table 24 and Table 25 on the following page provide a summary of peak flood level changes at various locations for the sensitivity scenarios. Overall results were shown to be relatively insensitive to routing, roughness and blockage with results tending to be ± 0.05 m which can generally be accommodated within the 0.5 m freeboard applied to the 100 Year ARI results to determine the Flood Planning Levels (FPLs).

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

Table 24 – Results of Sensitivity Analyses – 100 Year ARI Event Flows (m^3/s)

ID	Location	100 Year ARI Peak Flood Flow (m^3/s)	Imperviousness increased by 20%	Imperviousness decreased by 20%	AMC = 1	AMC = 4	Soil = 1	Roughness increased by 20%	Roughness decreased by 20%	Blockage 25%	Blockage 50%
			Difference with 100 Year ARI base case (m^3/s)								
1	Victoria Street U/S St Vincents Hospital	4.2	-0.2	-0.3	-0.1	0.1	0.0	-0.1	0.0	0.4	0.6
2	Barcom Street near Oxford St	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		1.4	0.0	-0.1	-0.1	0.0	0.0	-0.1	0.0	-0.4	-0.7
		0.6	0.0	0.2	0.2	0.0	0.0	0.2	0.0	0.0	0.0
3	Hopewell Street Near Oxford St	2.1	-0.1	-0.1	-0.4	0.0	0.0	-0.1	0.0	0.0	0.0
		0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1
4	Boundary Street below Burton St	12.6	-0.3	-1.0	-1.4	0.3	-0.1	-0.8	0.0	0.0	-0.1
		1.6	0.0	0.7	0.7	0.0	0.0	0.8	0.0	-0.3	-0.6
5	Womerah Avenue	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	Boundary Street near Dillan St	19.9	-0.3	-1.3	-1.4	0.4	-0.1	-1.1	0.0	0.2	0.4
		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		2.5	0.0	0.7	0.7	0.0	0.0	0.8	0.0	-0.5	-1.1
7	McLachlan Ave (West)	10.8	-0.1	-0.6	-0.8	0.2	-0.1	-1.1	0.0	0.1	0.4
		3.3	0.0	0.7	0.7	0.0	0.0	0.8	0.0	-0.6	-1.4
8	McLachlan Ave (East)	9.4	-0.1	-0.5	-0.6	0.1	-0.1	-1.1	0.0	0.2	0.7
		3.9	0.0	0.7	0.6	0.0	0.0	0.8	0.0	-0.7	-1.9
9	Neild Ave D/S of Boundary Street	16.5	-0.4	-0.9	-1.3	0.3	-0.5	-0.2	0.0	0.3	0.7
		0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1
		0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
		0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2
10	Roslyn Gardens	1.5	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1

Note: a dash (-) indicates no significant change

Table 25 – Results of Sensitivity Analyses – 100 Year ARI Event Depths (m)

ID	Location	100 Year ARI Peak Flood Depth (m)	Imperviousness increased by 20%	Imperviousness decreased by 20%	AMC = 1	AMC = 4	Soil = 1	Roughness increased by 20%	Roughness decreased by 20%	Blockage 25%	Blockage 50%
			Difference with 100 Year ARI base case (m)								
1	Sims Street	1.1	-	-	-	-	-	-	-	-	0.02
2	Oxford Street (West)	1.0	-0.03	-0.04	-0.02	-	-	-	-	0.13	0.22
3	Victoria Street	1.8	-	-	-	-	-	-	-	-0.01	-0.03
4	Taylor Street	0.5	-	-	-	-	-	-	-	0.02	0.04
5	Sturt Street	1.7	-	-	-	-	-	-	-	0.01	0.03
6	Victoria St adjacent St Vincents Hospital	1.3	-0.02	-0.03	-	-	-	-	-	0.05	0.09
7	Boundary Street	0.6	-	-0.02	-0.02	-	-	0.04	-	-	-
8	McLachlan Ave	0.8	-	-0.02	-0.02	-	-	-	-	-	0.03
9	Neild Ave and New South Head Rd	0.3	-	-	-	-	-	-	-	-	0.02
10	Kellett Place	0.8	-	-	-	-	-	-	-	-	-
11	Waratah Street	0.5	-	-	-	-	-	-	-	0.03	0.05

Note: a dash (-) indicates no significant change

10.3. Climate Change

10.3.1. Rainfall Increase

The Bureau of Meteorology has indicated that there is no intention at present to revise design rainfalls to take account of the potential climate change, as the implications of temperature changes on extreme rainfall intensities are presently unclear, and there is no certainty that the changes would in fact increase design rainfalls for major flood producing storms. There is some recent literature by CSIRO that suggests extreme rainfalls may increase by up to 30% in parts of NSW (in other places the projected increases are much less or even decrease); however this information is not of sufficient accuracy for use as yet (Reference 18).

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

Projected increases to evaporation are also an important consideration because increased evaporation would lead to generally dryer catchment conditions, resulting in lower runoff from rainfall. Mean annual rainfall is projected to decrease, which will also result in generally dryer catchment conditions. The influence of dry catchment conditions on river runoff is observable in climate variability using the Indian Pacific Oscillation (IPO) index (Reference 19). Although mean daily rainfall intensity is not observed to differ significantly between IPO phases, runoff is significantly reduced during periods with fewer rain days.

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

In light of this uncertainty, the NSW State Government advice (Reference 18) recommends sensitivity analysis on flood modelling should be undertaken to develop an understanding of the effect of various levels of change in the hydrologic regime on the project at hand. Specifically, it is suggested that increases of 10%, 20% and 30% to rainfall intensity be considered.

10.3.2. Sea Level Rise

In October 2009 the NSW Government issued its Policy Statement on Sea Level Rise (Reference 20) which states"

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

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

In August 2010, the former NSW Department of Environment, Climate Change and Water issued the Flood Risk Management Guide (Reference 10) – *Incorporating sea level rise benchmarks in flood risk assessments*. In addition an accompanying document *Derivation of the NSW Government's sea level rise planning benchmarks* provided technical details on how the sea level rise assessment was undertaken.

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

The previous guideline, the NSW Sea Level Rise Policy Statement (2009) (Reference 20) and associated guides, indicated a 0.9 metre sea level rise by the year 2100 and a 0.4 metre rise by the year 2050. It should be noted that climate change and the associated rise in sea levels will continue beyond 2100. Recent changes have taken away NSW State Government endorsement of sea level rise predictions. Unless Council adopts something else, a 0.9 metre sea level rise by the year 2100 and a 0.4 metre rise by the year 2050 will continue to be used.

10.3.3. Results

The effect of increasing the design rainfalls by 10%, 20% and 30% has been evaluated for the 100 year ARI event, resulting in a relatively insignificant impact on peak flood levels in the study area. Generally speaking, each incremental 10% increase in flow results in a 0.05 m increase in peak flood levels at most of the locations analysed. A 30% increase in rainfalls would therefore not exceed the typical freeboard for most residential properties.

The 100 year ARI event with a rainfall increase of 30% is approximately equivalent to a 500 year ARI event in present day conditions. In flow paths and trapped low points, flood levels were typically found to increase by 0.05 to 0.20 m.

Sea level rise scenarios have very little impact on flood levels within the catchment with a 0.9 m sea level increase by 2100 only increasing downstream flood levels within the Waratah Street low point adjacent to Rushcutters Bay Park by 0.05 m.

Table 26 and Table 27 show the change in peak flows and flood levels due to the effect of climate change induced rainfall increases and sea level rise.

Table 26 – Results of Climate Change Analyses – 100 Year ARI Event Flows (m^3/s)

ID	Location	100 Year ARI Peak Flood Flow (m^3/s)	Rainfall Increase 10%	Rainfall Increase 20%	Rainfall Increase 30%	Sea Level Rise 2050	Sea Level Rise 2100
			Difference with 100 Year ARI Base Case (m^3/s)				
1	Victoria Street U/S St Vincents Hospital	4.2	0.6	1.1	1.7	0.0	0.0
2	Barcom Street near Oxford St	0.1	0.0	0.0	0.1	0.0	0.0
		1.4	0.0	0.1	0.1	0.0	0.0
		0.6	0.0	0.0	0.1	0.0	0.0
3	Hopewell Street Near Oxford St	2.1	0.3	0.6	0.9	0.0	0.0
		0.2	0.0	0.0	0.0	0.0	0.0
4	Boundary Street below Burton St	12.6	1.5	3.0	4.5	0.0	0.0
		1.6	0.0	0.1	0.2	0.0	0.0
5	Womerah Avenue	0.4	0.0	0.1	0.1	0.0	0.0
6	Boundary Street near Dillan St	19.9	2.4	4.8	7.2	0.0	0.1
		0.0	0.0	0.0	0.0	0.0	0.0
		2.5	0.1	0.2	0.2	0.0	0.0
7	McLachlan Ave (West)	10.8	1.2	2.4	3.5	0.0	0.0
		3.3	0.1	0.2	0.3	0.0	0.0
8	McLachlan Ave (East)	9.4	0.9	1.7	2.6	0.0	0.0
		3.9	0.1	0.2	0.3	0.0	0.0
9	Neild Ave D/S of Boundary Street	16.5	2.4	4.6	6.9	0.0	0.0
		0.2	0.0	0.0	0.0	0.0	0.0
		0.6	0.0	0.0	0.0	0.0	0.0
		0.5	0.0	0.0	0.0	0.0	0.0
10	Roslyn Gardens	1.5	0.2	0.5	0.7	0.0	0.0
		0.2	0.0	0.0	0.0	0.0	0.0

Table 27 – Results of Climate Change Analyses – 100 Year ARI Event Depths (m)

ID	Location	100 Year ARI Peak Flood Depth (m)	Rainfall Increase 10%	Rainfall Increase 20%	Rainfall Increase 30%	Sea Level Rise 2050	Sea Level Rise 2100
			Difference with 100 Year ARI Base Case (m)				
1	Sims Street	1.1	0.01	0.03	0.06	-	-
2	Oxford Street (West)	1.0	0.10	0.16	0.21	-	-
3	Victoria Street	1.8	-	-	0.03	-	-
4	Taylor Street	0.9	0.02	0.04	0.05	-	-
5	Sturt Street	0.5	0.03	0.08	0.11	-	-
6	Victoria St adjacent St Vincents Hospital	1.7	0.02	0.05	0.07	-	-
7	Boundary Street	1.3	0.06	0.11	0.15	-	-
8	McLachlan Ave	0.6	0.03	0.06	0.09	-	-
9	Neild Ave and New South Head Rd	0.8	0.03	0.05	0.08	-	-
10	Kellett Place	0.3	0.02	0.04	0.05	-	-
11	Waratah Street	0.8	0.03	0.05	0.07	-	-
12	Sims Street	0.5	0.02	0.04	0.06	-	-

11. DAMAGES ASSESSMENT

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

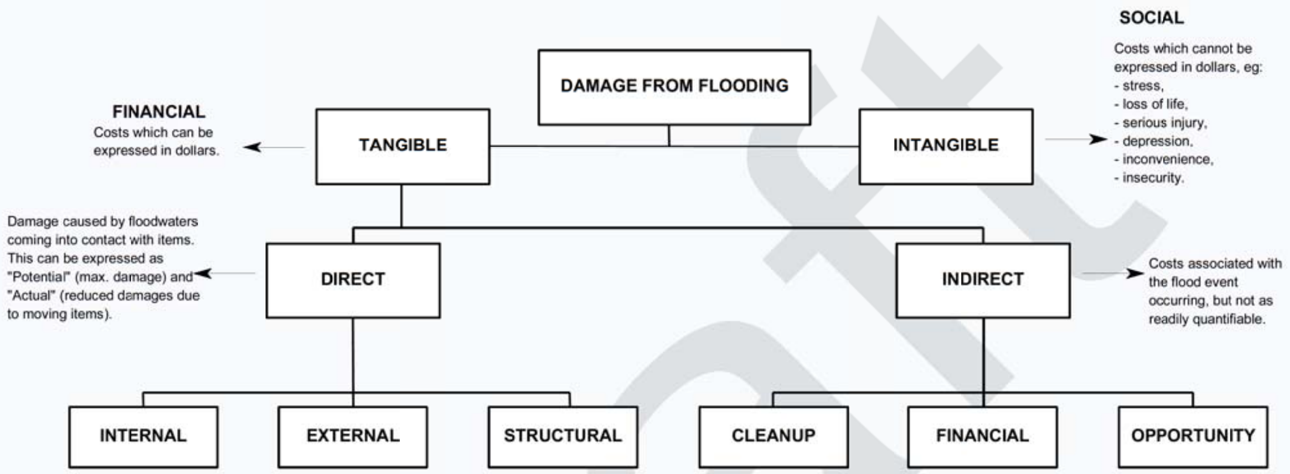
- the magnitude (depth, velocity and duration) of the flood,
- land usage and susceptibility to damage,
- awareness of the community to flooding,
- effective warning time,
- the availability of an evacuation plan or damage minimisation program,
- physical factors such as failure of services (pits and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

The estimation of flood damages tends to focus on the physical impact of damages on the human environment but there is also a need to consider the ecological cost and benefits associated with flooding. Flood damages can be defined as being tangible or intangible. Tangible damages are those to which a monetary value cannot easily be attributed. Types of flood damages are shown on Table 28.

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

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

Table 28 – Breakdown of Flood Damages Categories



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

A flood damages assessment was undertaken for existing development for overland flooding within the Rushcutters Bay catchment. This was based on a detailed floor level survey which was undertaken for 138 properties (613 properties are flood affected in the PMF event). Only properties which have surveyed floor levels have been included in the flood damages assessment.

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

Damages to public structures have not been assessed. A summary of flood damages for the catchment is provided in Table 29 and Table 30 and with the building floors inundated shown on Figure 34.

Table 29 – Summary of Properties Flooded Above Floor Level

Design Flood Event	Residential Properties Flooded Above Floor Level	Commercial Properties Flooded Above Floor Level	Total Properties Flooded Above Floor Level
2 Year ARI	20	21	41
5 Year ARI	28	24	52
10 Year ARI	30	25	55
20 Year ARI	32	29	61
50 Year ARI	32	30	62
100 Year ARI	33	31	64
PMF	59	46	105

Note: * Excludes all damages to public assets

Table 30 – Summary of Flood Damages

Design Flood Event	Residential Properties Tangible Flood Damages	Commercial Properties Tangible Flood Damages	Total Tangible Flood Damages*
2 Year ARI	$1,180,000	$1,290,000	$2,470,000
5 Year ARI	$1,480,000	$1,530,000	$3,010,000
10 Year ARI	$1,670,000	$1,680,000	$3,360,000
20 Year ARI	$1,870,000	$1,760,000	$3,630,000
50 Year ARI	$1,940,000	$1,990,000	$3,930,000
100 Year ARI	$2,080,000	$2,250,000	$4,330,000
PMF	$3,780,000	$3,840,000	$7,620,000
Average Annual Damages			$2,150,000

Note: * Excludes all damages to public assets

11.1. Limitations of Flood Damage Assessment in Rushcutters Bay

In most areas the extent of above floor inundation is difficult to accurately assess. The effect of buildings, sheds, fences and other structures can have a significant impact on the direction and depth of floodwaters. Also the exact location and level of all entry points to buildings is unknown.

It should be noted that the number of floors inundated in the smaller events (say up to the 10 year ARI) is probably over estimated compared to what has been observed in past events. It is unlikely that all above floor flooding during past events has been reported, and some properties may have localised features (such as solid brick walls) that prevent above-floor inundation from a certain direction. Additional inaccuracies may result from the estimation of flood levels which ultimately are based on the ALS ground survey (accuracy of approximately 0.2m or more on uneven surfaces).

12. ACKNOWLEDGEMENTS

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- City of Sydney;
- Office of Environment and Heritage;
- Residents of the City of Sydney within the study area; and
- Bureau of Meteorology.

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Figures

FIGURE 1
LOCALITY MAP

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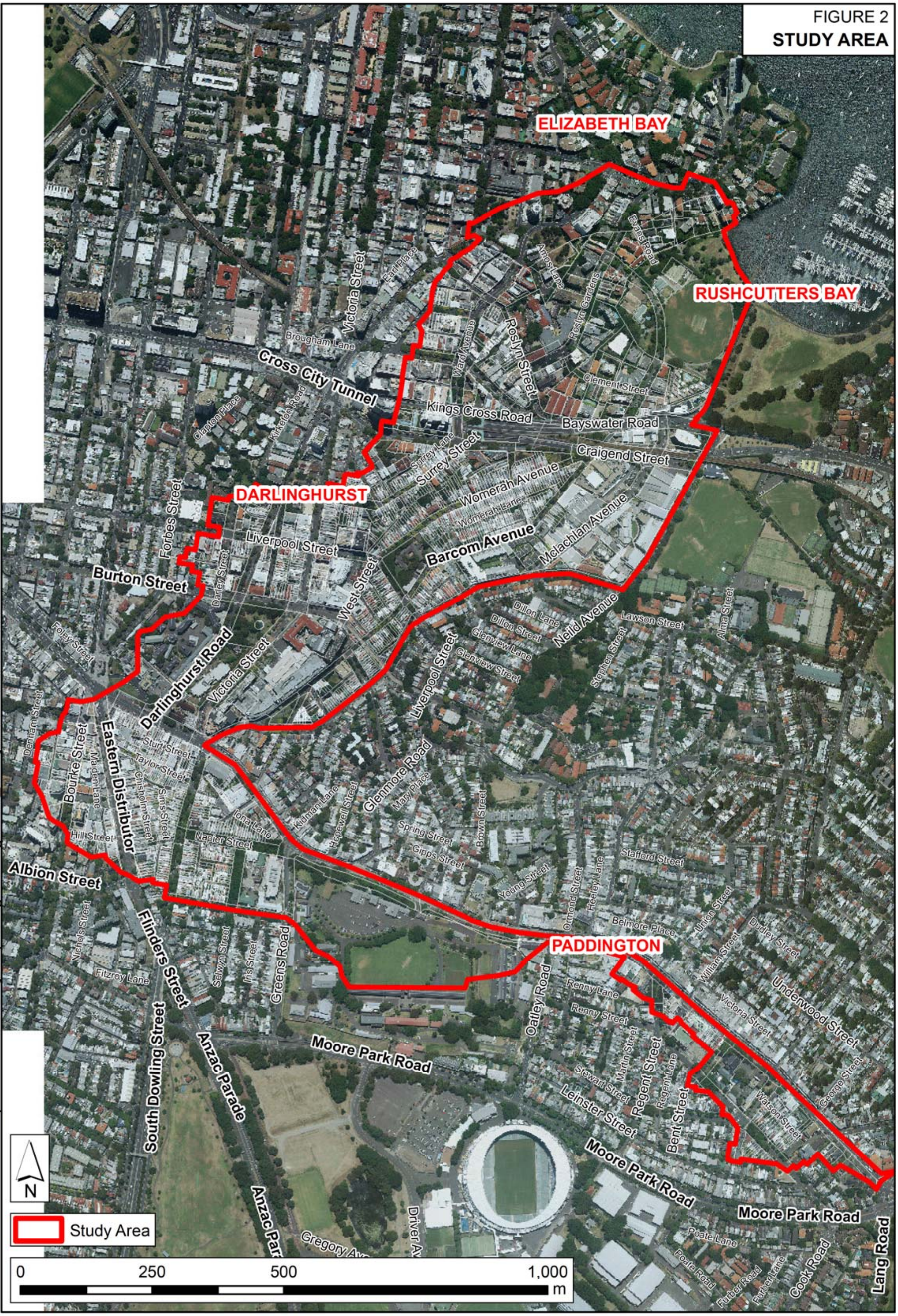
FIGURE 2

STUDY AREA



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