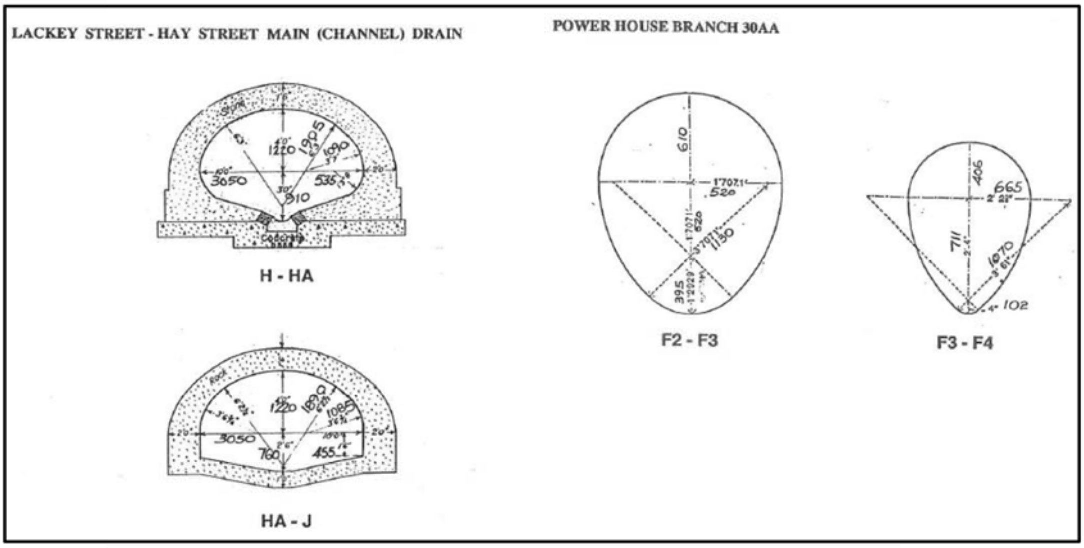


Figure 2-4 Oviform Pipe Examples (SWC, 1996)

Table 2-4 provides a summary of the stormwater infrastructure and Figure 2-5 shows the location of this infrastructure.

Table 2-4 Summary of stormwater infrastructure elements in hydraulic model

Stormwater Infrastructure Type	Number of Elements
Circular	1959
Rectangular	119
Oviform	224
Other*	94
Undefined**	48
TOTAL PIPES	**2444**
Pits	1314
Nodes	651
Connective Nodes***	444
TOTAL NODES/PITS	**2409**

* Not all pipes in Council's GIS database have defined dimensions. These pipes are likely hidden pipes unable to be surveyed. The pipes are classified as "Undefined". Dimensions of these pipes have been assumed based on connected pipe dimensions.

**Small sections of pipes illogically ended or failed to be connected to upstream pits. New pipes have been drawn to connect these stormwater elements. Dimensions of these pipes have been assumed based on connected pipe dimensions. These newly drawn pipes are classified as "Assumed".

*** In order to configure the hydraulic model, nodes were required at all pipe junctions. Nodes manually drawn to satisfy this requirement are referred to as "Connective Nodes".

Title:

City Area Catchment Stormwater Pit/Pipe Dataset

Figure: 2-5

Rev: A

N

0 250 500m

Approx. Scale

BMT WBM

www.bmtwbm.com.au

Filepath : S:\WATER\PROJECTS\S20022 - Water - Sydney CBD Catchment Flood Study\Documents\Figures\

2.3 Sydney Water Corporation Historical Flood Database

Sydney Water Corporation (SWC) maintains a register documenting reports of flooding. The earliest record in this database within the study area is from 1943 and the database is still maintained for current events. The database has very little flood level data (AHD or similar) though can still provide useful information of the locations of flooding hot-spots and the storm events which triggered the reported flooding.

Figure 2-6 shows the locations of all flood reports available for the study area noting also the date of the incident.

The earliest reports of flooding hold diminished value to this current study since the catchment conditions which resulted in the flooding are unknown. Table 2-5 lists the relevant storm events from 1984 up to the most current and list the number of reported locations with flooding for each event. As shown the most recent entry in the flood database is over 20 years old and only has a single flooding report location. The 1983 event has 2 reported locations of flooding available for model result calibration though is over 30 years old.

Table 2-5 Sydney Water flood database for the City Area catchment

Storm Event	Number of Locations with Reported Flooding
22 August 1984	1
5 November 1984	2
8 November 1984	6
6 January 1989	3
26 January 1991	3
9 February 1992	1

Inspection of the Observatory Hill rainfall gauge data showed that the August 1984 and February 1992 events were not recorded.

To gain an appreciation of the significance of the January 1989, January 1991 and 8 November 1984 events, the recorded rainfall depths for various storm durations is compared with the design Intensity-Frequency-Duration (IFD) data for the catchment as shown in Figure 2-7. For a 30 minute duration the January 1989, January 1991 and 8 November 1984 exceeded the 5 year ARI (20% AEP), 20 year ARI (5% AEP) and 500 year ARI (0.02% AEP) respectively.

Title:

SWC Historical Flood Database
City Area Catchment Records

Figure: 2-6

Rev: -

0 250 500m

Approx. Scale

BMT WBM
www.bmtwbm.com.au

Filepath : \S20022 - Water - Sydney CBD Catchment Flood Study\Drafting\WOR\Figures\FIGURE0X-X_SWC_FloodReports.wor

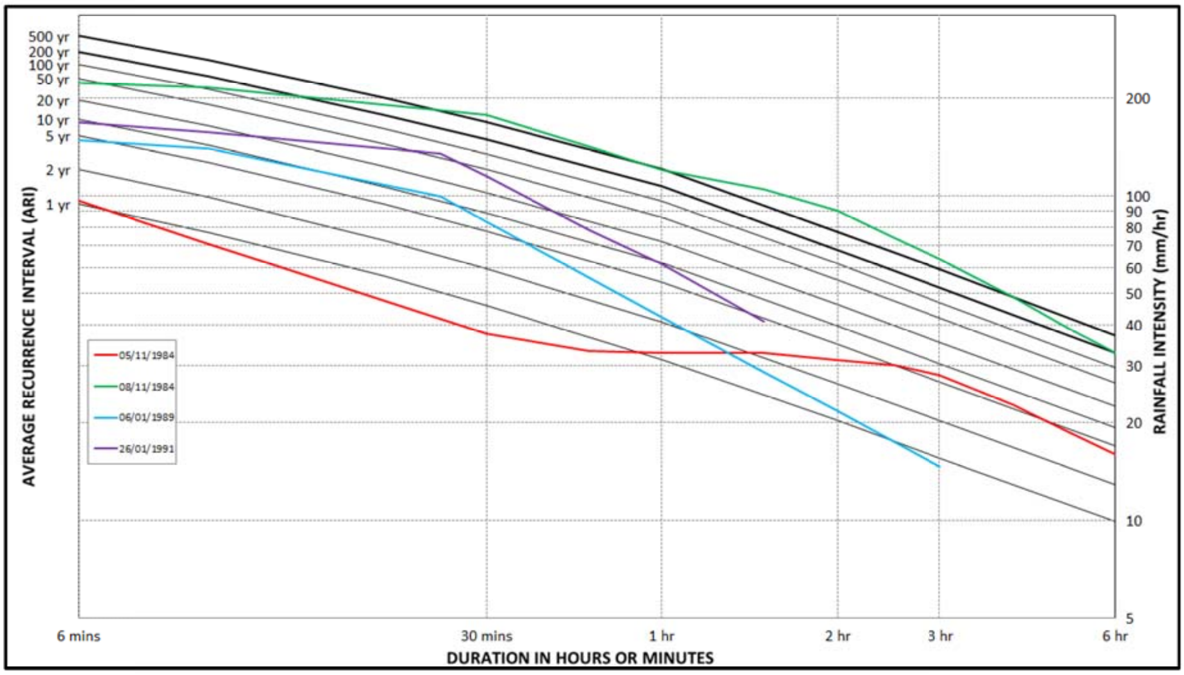


Figure 2-7 Rainfall analysis for SWC historical flood database events

2.4 Review of Historical Newspaper Articles (TROVE)

Newspaper articles can provide a valuable insight to key historic flood events and flooding behaviour. A literature review of available archived Australian media publications on the TROVE database maintained by the National Library of Australia was undertaken to obtain anecdotal information of flooding.

Over 15 relevant articles were found dating from as far back as 1877. Appendix B presents the full list of articles found and includes a more detailed account of the findings, with results of the review summarised in Figure 2-8. This figure shows the areas documented to be flood affected which are:

- Circular Quay – 1-4 feet deep;
- Pitt Street – reported flooded in 1912, 1913, 1938, 1949;

Other details taken from the articles are as follows:

- Main flow paths have been identified at Market Street, Elizabeth Street and Park Street from Hyde Park.

Results of the historical newspaper review cannot be relied upon to provide quantitative model calibration as wide-spread land use and stormwater infrastructure changes across the catchment will have altered the flood behaviour. Furthermore, the reports are anecdotal and referenced to general areas rather than precise addresses. However, these articles provide a valuable data set for model verification and identifying key areas where some flood affectation would still be anticipated today.

2.5 Site Inspections

A number of site inspections were undertaken throughout the course of the Flood Study to gain a better appreciation of local features influencing flood behaviour. Some of the key observations accounted for during the site inspections include:

- Presence of local structural hydraulic controls;
- Location and characteristics of surface drainage pits and pipes;
- Location of existing development and infrastructure on the floodplain;
- General nature of the contributing catchment.

This visual assessment was useful for defining hydraulic properties within the hydraulic model and ground-truthing of topographic features identified from the ALS data.

2.6 Community Consultation

The success of a floodplain management plan hinges on its acceptance by the community, residents within the study area, and other stake-holders. This can be achieved by involving the local community at all stages of the decision-making process. This includes the collection of their ideas and knowledge on flood behaviour in the study area, together with discussing the issues and outcomes of the study with them.

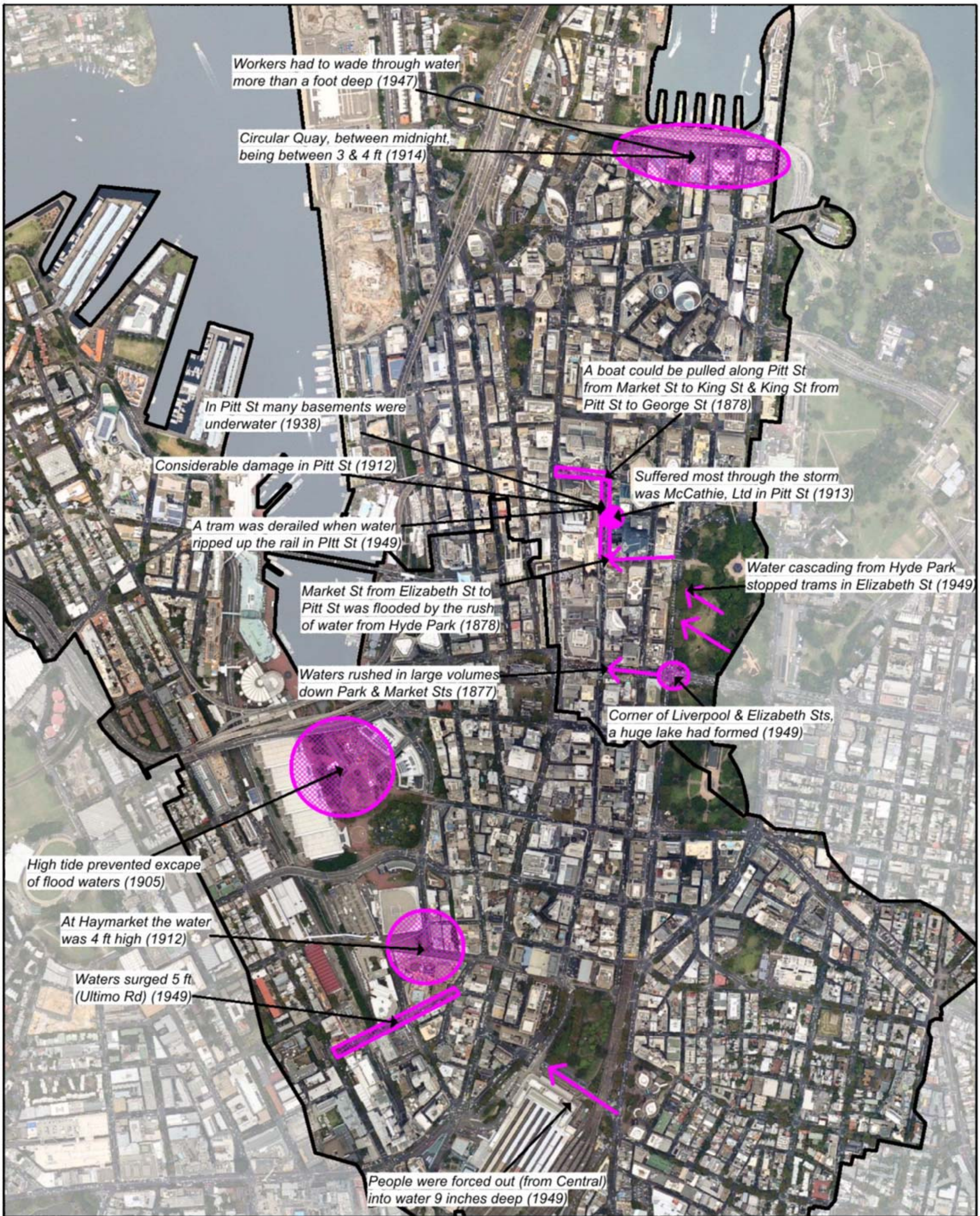
The key elements of the consultation program undertaken for the study are discussed in Section 3.

2.7 Development of Computer Models

2.7.1 Hydrological Model

Traditionally, for the purpose of the Flood Study, a hydrologic model is developed to simulate the rate of storm runoff from the catchment. The output from the hydrologic model is a series of flow hydrographs at selected locations such as at stormwater drainage pit inlets, which form the inflow boundaries to the hydraulic model.

In recent years the advancement in computer technology has enabled the use of the direct-rainfall approach as a viable alternative (also referred to as rainfall-on-grid). With the direct-rainfall method the design rainfall is applied directly to the individual cells of the 2D hydraulic model. This is particularly useful for overland flow studies where model results are desired in areas with small contributing catchments. This study has adopted the direct-rainfall approach for modelling hydrology, details of which are discussed in Section 4. Verification of the direct-rainfall approach against traditional hydrological modelling is shown in Section 5.9.



Title:

Darling Harbour and City Area Catchment Historic Reports of Flooding (TROVE)

Figure: 2-8

Rev: A

0 375 750m

Approx. Scale

BMT WBM

www.bmtwbm.com.au

Filepath : S:\WATER\PROJECTS\S20012 - Water - Darling Harbour Catchment Flood Study\Documents\Figures

2.7.2 Hydraulic Model

The TUFLOW hydraulic model (discussed in Section 4) developed for this study includes:

- two-dimensional (2D) representation of the entire City Area catchment; and
- one-dimensional (1D) representation of the stormwater pit/pipe network.

The hydraulic model has been applied to determine flood levels, velocities and depths across the study area for historical and design events.

2.8 Model Calibration/Validation and Sensitivity Analysis

The hydraulic model has been validated against available historic flood event data to establish the values of key model parameters and to confirm that the model is adequately representing the runoff processes within the catchment.

The following criteria are generally used to determine the suitability of historical events to use for calibration or validation:

- The availability, completeness and quality of rainfall and flood level event data;
- The amount of reliable data collected during the historical flood information survey; and
- The variability of events – preferably events would cover a range of flood sizes.

Since the amount of reliable historic flood level data was limited, a full model calibration has not been possible for this study. Flood information collected from the community questionnaire that is not specific to particular rainfall and flood events has been used to aid the model validation process. The validation of the hydraulic model is presented in Section 5.

A series of sensitivity tests have also been carried out to evaluate the model. These tests have been conducted to examine the performance of the model and determine the relative importance of different hydrological and hydraulic parameters. The sensitivity testing of the model is presented in Section 8.

2.9 Establishing Design Flood Conditions

Design floods are statistical-based events which have a particular probability of occurrence. For example, the 1% Annual Exceedance Probability (AEP) event, which is sometimes referred to as the 1 in 100 year Average Recurrence Interval (ARI) flood, is the best estimate of a flood with a peak discharge that has a 1% (i.e. 1 in 100) chance of occurring in any one year. For the City Area catchment, design floods have been based on design rainfall estimates according to Australian Rainfall and Runoff (Pilgrim, DH, 2001).

The design flood conditions form the basis for floodplain management in the catchment and in particular design planning levels for future development controls. The estimated design flood conditions are presented in Section 7.

2.10 Mapping of Flood Behaviour

Design flood mapping is undertaken using output from the hydraulic model. Maps are produced showing water level, water depth and velocity. The maps present the peak value of each parameter. Provisional flood hazard categories and hydraulic categories are derived from the hydraulic model results and are also mapped. The mapping outputs are described in Section 7 and presented in Appendix A.

2.11 Conclusion

The City Area catchment is heavily urbanised and is predominantly comprised of residential and commercial development. Low rise and high rise buildings, which pose as significant flow obstructions, are common features in the central business area. The natural overland drainage features have been heavily modified and the entire catchment is now drained by an extensive stormwater drainage network. There are no open channels within the study area. When the capacity of the stormwater drainage network is exceeded, overland flow will occur predominantly along the road network.

Availability of historical flooding and flood data in the City Area catchment is limited. The largest historical event identified in the catchment occurred in November 1984.

3 COMMUNITY CONSULTATION

3.1 The Community Consultation Process

Community consultation has been an important component of the current study. The consultation has aimed to inform the community about the development of the flood study and its likely outcome as a precursor to subsequent floodplain management activities. It has provided an opportunity to collect information on community members' flood experiences in the catchment and to collect feedback on concerns regarding flooding.

The key elements of the consultation process have been as follows:

- Distribution of a questionnaire to landowners, residents and businesses within the study area via mail delivery and online from the City of Sydney website;
- Regular presentations of progress to the Floodplain Management Committee, which includes community representatives and Council staff; and
- Review of the draft Flood Study by the Floodplain Management Committee.

These elements are discussed in detail below. Copies of relevant consultation material are included in Appendix C

3.2 Community Questionnaire

Council distributed a questionnaire in May 2013 to all residential properties and businesses within the study area to collect information on their previous flood experience and flooding issues. The focus of the questionnaire was historical flooding information that may be useful for correlating with predicted flooding behaviour from the modelling. A copy of the questionnaire is provided in Appendix C.

A total of 21,250 community questionnaires were mailed to residents and businesses within the combined study areas of Darling Harbour and the City Area. A total of 358 responses were received equating to a response rate of 2%, with 58 of the responses from the City Area catchment.

The responses have been compiled into a database to allow for a quantitative assessment of flooding experiences. Questions 2 to 6 are particularly useful in characterising the respondents and their flood affectation. The charts provided in Figure 3-1 present the results of these questions.

It is noted that some respondents did not fully complete the questionnaire though effort was made to most fully utilise the responses.

Figure 3-1 Results from the Community Consultation

Results of the community consultation indicate that the median period of residency is 8 years. The largest historic rainfall event occurred in November 1984 which is almost 30 years ago and the most recent of the historic rainfall events is February 2001 which is over 10 years ago. Accordingly, residents were unlikely to have been living at their current address during the key historic rainfall events and this is potentially why responses failed to obtain significant new information on these events.

Approximately 40% of residents are at least aware of flooding in there catchment and street (Qu4&5), though the flooding is rarely dangerous or above floor level and is mostly reported as regular (Qu6). The responses suggest minor nuisance flooding rather than flooding from the key identified historic flood events. Only 2 responses indicated above floor level inundation, however, the respondents failed to identify the event for these occurrences.

Regarding the historic events which caused reports of flooding, respondents rarely reported the precise time and date of the flooding. For the instances where a month and year were reported, historic rainfall records where reviewed to determine the likely magnitude of the contributing event. To gain an appreciation of the significance of the identified events, the recorded rainfall is compared with the design IFD data for the catchment as shown in Figure 3-2.

The most significant events reported include:

- 12 February 2010 ~10% AEP (10 year ARI),
- 8 March 2012 ~2 year ARI,
- 3 April 2013 ~1 year ARI.

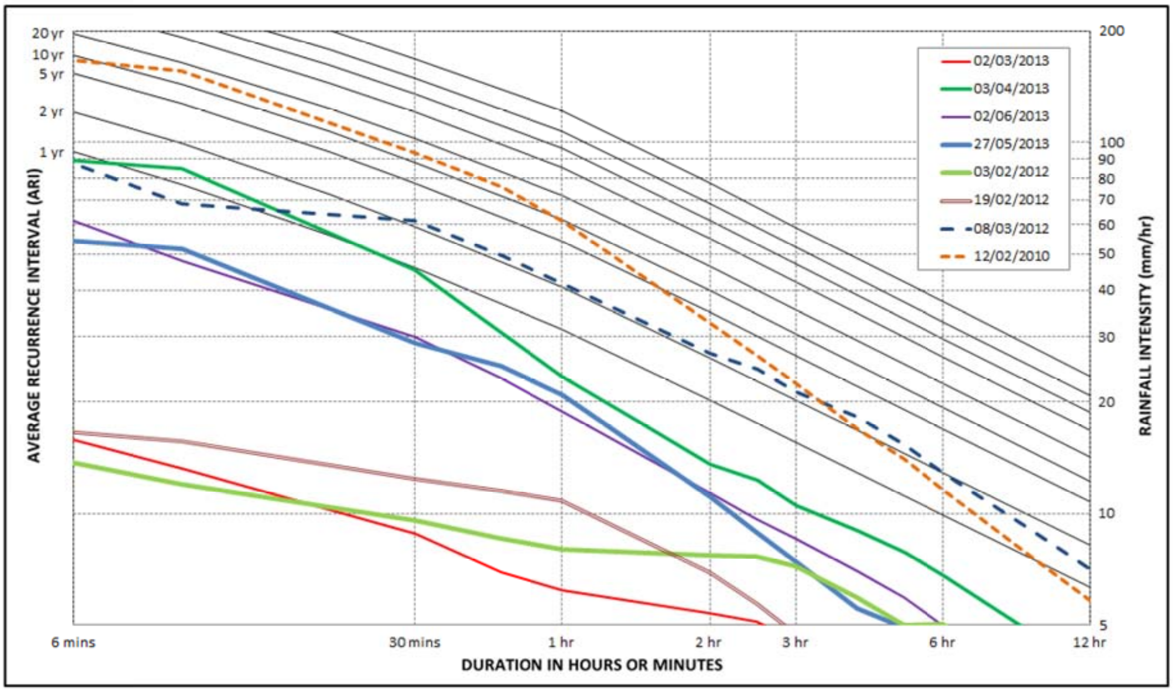


Figure 3-2 IFD analysis of events identified in community consultation

The locations of all respondents, including whether or they are flood affected, are shown in Figure 3-3. This has been prepared by linking the addresses of respondents with the addresses in Council's cadastre database.

Title:

City Area Catchment
Location of Community Consultation Respondents

Figure: 3-3

Rev: A

0 250 500m
Approx. Scale

BMT WBM
www.bmtwbm.com.au

Filepath : S:\WATER\PROJECTS\S20022 - Water - Sydney CBD Catchment Flood Study\Documents\Figures\

3.3 Conclusion

Community Consultation undertaken during the study has aimed to collect information on historical flooding and previous flooding experiences, and to inform the community about the development of the flood study and its likely outcome as a precursor to floodplain management activities to follow. The key element of the consultation process involved the distribution of a questionnaire relating to historical flooding. The number of responses from the questionnaire was very low (2%) with minimal additional historical flood information obtained. This is likely to be representative of a combination of the following:

- The relatively low number of significant rainfall and flooding events within the City Area catchment in recent years;
- The relatively low median period of residency.

Demographic statistics were explored to help understand the low return rate of questionnaire and also the low median period of residency. Basic Community Profile data was obtained from the 2011 Census for the postcode area 2000 (ABS, 2011) which supports the assumption that the population is transient. Only 55% of residents in the 2011 Census reported living in the same address 1 year prior and this number reduced to 23% when reporting if living in the same address 5 years prior. Short term residents are generally unable to contribute long term accounts of flooding. Furthermore, short term residents are likely to be less interested in the outcomes of the Flood Study and subsequent Floodplain Risk Management Study and Plan and may not have participated in the consultation process.

4 MODEL DEVELOPMENT

4.1 Introduction

In the absence of long term stream flow data, computer models are usually the most accurate, cost-effective and efficient tools to assess a catchment's flood behaviour. Traditionally, for the purpose of the Flood Study, a hydrologic model and a hydraulic model are developed.

The **hydrologic** model simulates the catchment rainfall-runoff processes, producing the stormwater flows which are used in the hydraulic model.

The **hydraulic** model simulates the flow behaviour of the drainage network and overland flow paths, producing flood levels, flow discharges and flow velocities.

In recent years the advancement in computer technology has enabled the use of the direct-rainfall approach as a viable alternative over the use of "traditional" hydrological models (e.g. XP-RAFTS, WBNM). With the direct-rainfall method the rainfall depths are applied directly to the individual cells of the 2D hydraulic model. This is particularly useful for overland flow studies where model results are desired in areas with small contributing catchments. This study has adopted the direct-rainfall approach for modelling the catchment hydrology and therefore only a single TUFLOW model has been developed which implicitly performs both hydrologic and hydraulic computation. The TUFLOW model developed for this study has been calibrated by addressing hydrological and hydraulic aspects of the calibration interactively.

Information on the topography and characteristics of the catchment, drainage network and floodplain are built into the model. Recorded historical flood data, including rainfall and flood levels, are used to simulate and validate the model. The model produces as output, flood levels, flows rates and flow velocities.

Development of a hydraulic model follows a relatively standard procedure:

- Discretisation of the catchment, drainage network, floodplain, etc.
- Incorporation of physical characteristics (stormwater pipe details, floodplain levels, structures etc.).
- Establishment of hydrographic databases (rainfall, flood flows, flood levels) for historic events.
- Calibration to one or more historic floods (calibration is the adjustment of parameters within acceptable limits to reach agreement between modelled and measured values).
- Verification to one or more other historic floods (verification is a check on the model's performance without further adjustment of parameters).
- Sensitivity analysis of parameters to measure dependence of the results upon model assumptions.

Once model development is complete it may then be used for:

- establishing design flood conditions;
- determining levels for planning control; and
- modelling development or management options to assess the hydraulic impacts (as part of the floodplain risk management study).

4.2 Hydrological Model

The hydrological model simulates the rate at which rainfall runs off the catchment. The amount of rainfall runoff from the catchment is dependent on:

- the catchment slope, area, vegetation, urbanisation and other characteristics;
- variations in the distribution, intensity and amount of rainfall; and
- the antecedent moisture conditions (dryness/wetness) of the catchment.

A direct-rainfall (also referred to as rainfall-on-grid) approach has been adopted in the TUFLOW hydraulic model (refer to Section 4.3 for details of the model setup). The factors given above have been represented in the model by:

- The runoff routing and hydrological response of the catchment within the 2D model is driven by the surface type and underlying topography. Where appropriate, runoff is diverted into 1D pipe domains of the 2D/1D model (more detail is provided in Section 4.3).
- The amount and intensity of rainfall can be varied across the catchment based on available data and information.
- The antecedent moisture conditions are modelled by varying the amount of rainfall which is "lost" into the ground and "absorbed" by storages. For very dry antecedent moisture conditions, there is typically a higher initial rainfall loss.

The general modelling approach and adopted parameters are discussed in the following sections.

4.2.1 Catchment Delineation

The City Area catchment drains an area of approximately 1.99 km^2 via a piped stormwater drainage network to Sydney Harbour.

Discretisation of the study area into sub-catchments has not been required for this study given that rainfall is being applied directly to the 2D domain and traditional rainfall-runoff modelling is not being used. However, the delineation of the overall catchment boundary is important for defining the limits of the hydraulic model and the associated direct-rainfall input. The precise study area catchment boundary is not clearly or easily defined due to the presence of some low points at the catchment boundaries. During significant rainfall events these low points collect runoff which cannot be adequately drained by the formalised drainage network. The low points act as storages which can overflow to the Darling Harbour catchment, the neighbouring catchments or both during significant rainfall events.

The hydrologic catchment boundary and the hydraulic model extent have been sufficiently extended to account for the potential interactions with the neighbouring catchments.

4.2.2 Rainfall Data

Rainfall information is the primary input and driver of the hydrological model which simulates the catchment's response in generating surface run-off. Rainfall characteristics for both historical and design events are described by:

- Rainfall depth – the depth of rainfall occurring across a catchment surface over a defined period (e.g. 270mm in 36 hours or average intensity 7.5mm/hr); and
- Temporal pattern – describes the distribution of rainfall depth at a certain time interval over the duration of the rainfall event.

Both of these properties may vary spatially across the catchment during any given event and between different events.

The procedure for defining these properties is different for historical and design events. For historical events, the recorded hyetographs at continuous rainfall gauges provide the observed rainfall depth and temporal pattern (refer to Figure 2-2 for rainfall gauge locations).

For design events, rainfall depths are most commonly determined by the estimation of intensity-frequency-duration (IFD) design rainfall curves for the catchment. Standard procedures for derivation of these curves are defined in Australian Rainfall and Runoff (AR&R) (EA, 1987). Similarly AR&R defines standard temporal patterns for use in design flood estimation.

The rainfall inputs for the historical calibration/validation events are discussed in further detail in Section 5 with design events discussed in Section 6.

4.2.3 Rainfall Losses

The antecedent catchment condition reflecting the degree of wetness of the catchment prior to a major rainfall event directly influences the magnitude and rate of runoff.

The total rainfall which falls in an event does not all contribute to run-off. Many precipitation loss processes occur which reduce the effective rainfall converted to run-off. Some rainfall fills depression storages on the ground surface, some is lost by interception from vegetation while some infiltrates into the ground. A conceptual model known as the "Initial Loss – Continuing Loss model" is widely used in Australia and is adopted for this study.

The initial loss component represents a depth of rainfall effectively lost from the system and not contributing to runoff and simulates the wetting up of the catchment to a saturated condition. The continuing loss represents the rainfall lost through soil infiltration once the catchment is saturated and is applied as a constant rate (mm/hr) for the duration of the runoff event.

To determine the correct volume of rainfall run-off, the two most important land categories in this study are roads and roof tops which together represent greater than 55% of the total area.

The remaining land categories for defining rainfall losses have been derived based on the City of Sydney Local Environmental Plan (LEP) Zones.

The rainfall loss parameters for the historical calibration/validation events and design events are discussed in further detail in Section5.

4.3 Hydraulic Model

BMT WBM has applied the fully-2D software modelling package TUFLOW. The 2D model has distinct advantages over 1D and quasi-2D models in applying the full 2D unsteady flow equations. This approach is necessary to model the complex interaction between watercourses and floodplains and converging and diverging of flows through structures. The floodplain topography is defined using a high resolution Digital Terrain Model (DTM) for greater accuracy in predicting flows and water levels and the interaction of stormwater drainage network and floodplain areas.

4.3.1 Topography

The ability of the model to provide an accurate representation of the flow distribution on the floodplain ultimately depends upon the quality of the underlying topographic model. For the City Area catchment, a 2m by 2m gridded DTM has been derived from the ALS survey provided by Council.

The ground surface elevation for the TUFLOW model grid points are sampled directly from the DTM. It is a representation of the ground surface and does not include features such as buildings or vegetation. In the context of the overland flow path study, a high resolution DTM is important to suitably represent available flow paths, such as roadway flows that are expected to provide significant flood conveyance within the study area. Experience has proved this to be a successful approach and enables detailed simulation of flooding from overland flow paths.

Owing to some limitations of the ALS data capture method, preparation of the DTM for the City Area study area required additional ground level points and breaklines to be defined to ensure a coherent and correct DTM was achieved for this study. In particular, focus was given to ensuring that the full flow width along the road network was correctly defined.

The resulting topography of the hydraulic model is illustrated in Figure 2-3.

4.3.2 Buildings

The influence of buildings and other obstacles to the passage of flow in urban floodplains is an important issue in the context of urban floodplain management (Engineers Australia, 2012a). In a typical urban floodplain, some buildings will be elevated on fill and totally obstruct the passage of floodwater, others may be inundated with floodwater ponding inside the building, whilst others may be elevated on piers allowing flow under the building.

Based on a visual assessment of the range of buildings throughout the City Area catchment and the likely effect of buildings on the passage of floodwater, buildings have been represented in the TUFLOW model by removing the building footprints from the active model area. This assumption means that floodwater does not pass through and must flow around buildings.

The building footprints across the study area have been based on the footprints provided by Council. Buildings not contained within Council's building footprint dataset have been manually defined using available NearMap aerial photography dated July 2013.

Removing the buildings from the active model area impacts on the underlying assumptions with using the direct-rainfall approach adopted for the hydrological modelling component of the City Area model, whereby the model will not account for rain falling on model cells within the building footprints. Flow originating from rainfall on buildings has been included in the model using the methods described in Section 4.3.6.

4.3.3 Underground Carparks

The Sydney City Area catchment has numerous underground car parks. In large flood events the car parks may be inundated and act as temporary flood storages if the entrance level is below the flood level. Car parks however are not intended to be inundated in large floods and therefore have not been included in the modelling.

Upon delivery of this flood study, future works can assess the suitability of current flood protection afforded by car park entrance levels and recommend upgrades if necessary to make the car parks flood free.

4.3.4 Stormwater Drainage Network

This study required the modelling of the stormwater drainage system across the catchment. Information on the pit and pipe drainage network has been compiled from various sources, as discussed in Section 2.2.9.

The review of the available stormwater drainage system found the data to be largely complete along the main drainage lines. In areas where no pipe survey was available pipe size details were assumed from upstream and downstream configurations. The invert levels were interpolated between known locations, maintaining the upstream and downstream pipe gradients where appropriate. These were then cross-checked against the DTM elevations to take account of any local topographic features and to maintain minimum cover levels. Model results demonstrate limited sensitivity to adopted conduit parameters (Section 8) and therefore the pipe assumptions are considered to provide an appropriate representation of the pipe system.

Tank Stream from Martin Place downstream to Sydney Cover is presented as a sample longitudinal profile in Figure 4-1. This figure depicts the invert and obvert levels according to culvert dimensions, the ground surface level as derived from the DTM, and a minimum cover level of 500mm.

All known stormwater pits and pipes within the study area have been included in the TUFLOW model. The study area contains a number of locations that would drain poorly without the inclusion of the pipe network. Modelling all pipes ensures that the drainage of these areas is well represented.

The pipe network, represented as a 1D layer in the model, is dynamically linked to the 2D domain at specified pit locations for inflow and surcharging, as illustrated in Figure 4-2.

The modelled pipe network, comprising approximately 2440 pipes and has a combined run length of over 27km, is shown in Figure 2-5.

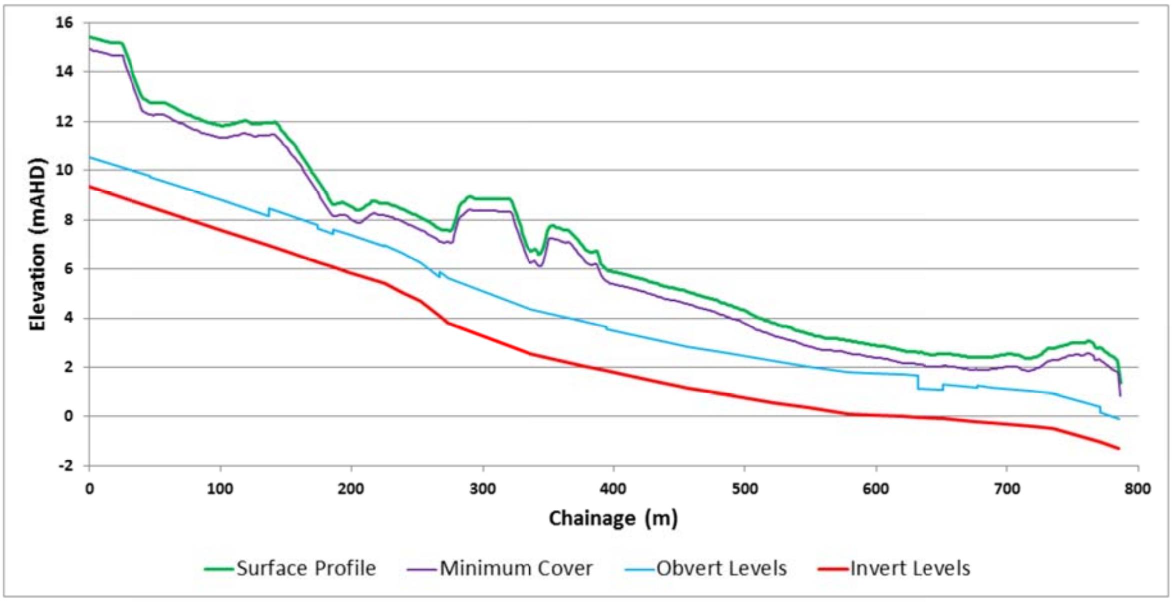


Figure 4-1 Sample Stormwater Drainage Line Longitudinal Profile

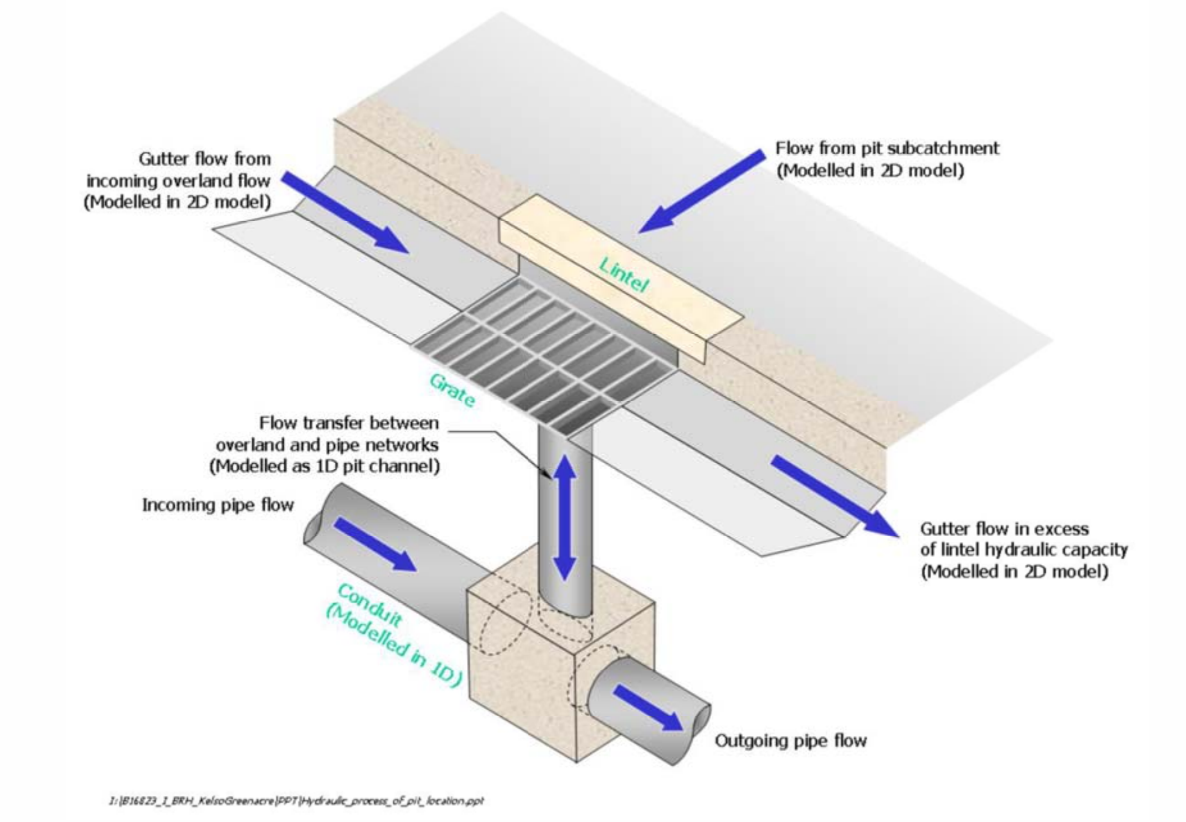


Figure 4-2 Linking underground 1D stormwater drainage network to the overland 2D domain

Pit inlet capacities have been modelled using lintel opening lengths and grate sizes based on the collected data. Pit inlet dimensions have been assumed where data were not available, based on site inspections and nearby pits. Pit inlet curves have been developed using an industry standard approach which rely on laboratory tests by the NSW Department of Main Roads and are considered sufficiently reliable for the purpose of this study. The pit inlet curves for a number of lintel opening and grate sizes, as applied in the TUFLOW model, are presented in Appendix D.

For the magnitude of events under consideration in the study, the pipe drainage system capacity is anticipated to be exceeded with the major proportion of flow conveyed in overland flow paths. Therefore any limitations in the available pipe data or model representation of the drainage system is expected to have little effect on results (see Section 8 full pit blockage sensitivity analysis).

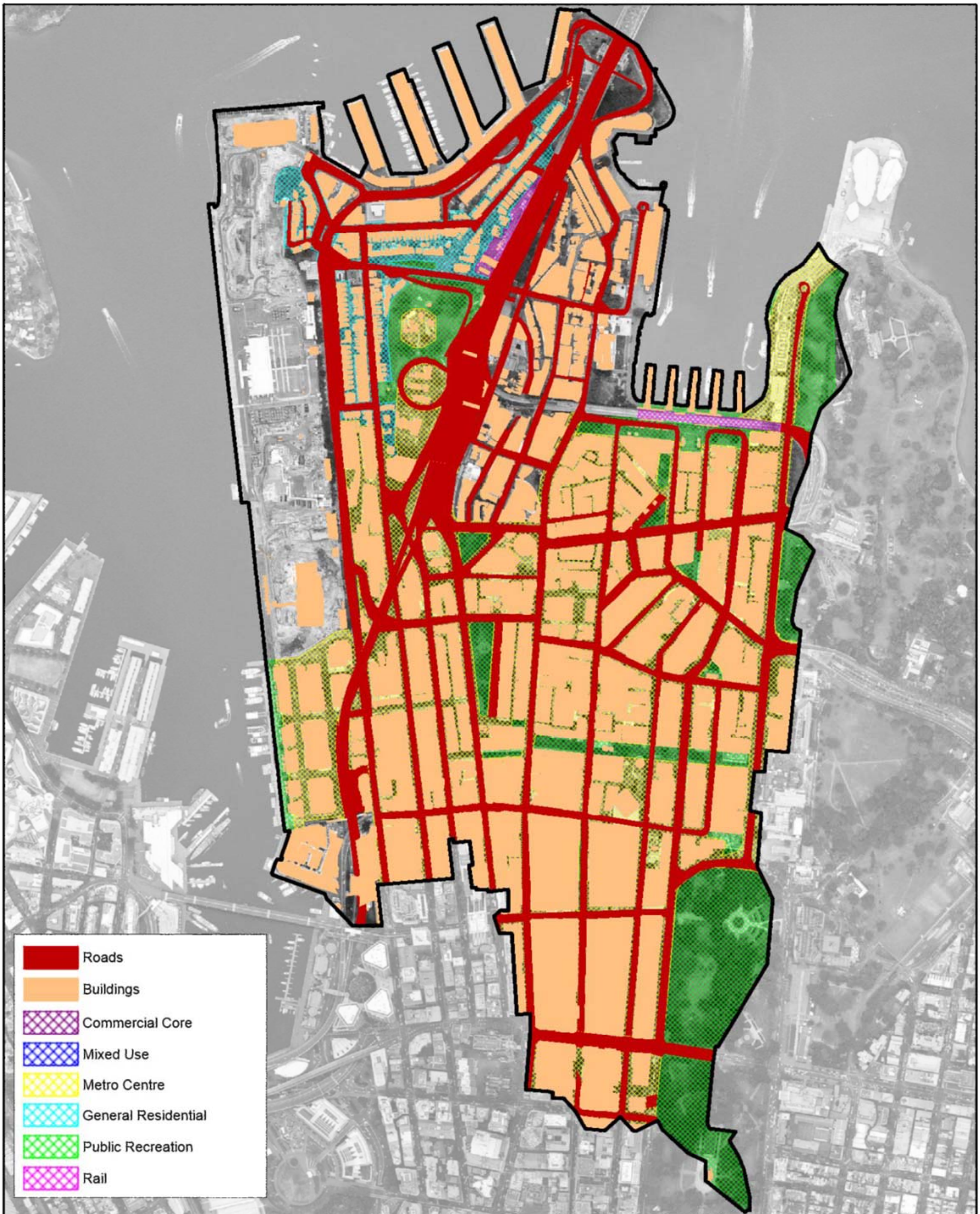
4.3.5 Hydraulic Roughness

The development of the TUFLOW model requires the assignment of different hydraulic roughness (Manning's 'n') zones. These zones are delineated from aerial photography and cadastral data identifying different land uses (e.g. vegetation, cleared land, roads, urban areas, etc.) for modelling the variation in flow resistance. The GIS layers and aerial photography supplied by Council has been used to generate the land use surface types and roughness zones for the study area. The base land use map used to assign the different hydraulic roughness zones across the model is shown in Figure 4-3.

The Manning's 'n' hydraulic roughness values adopted for each land use category are given in Table 4-1.

Table 4-1 Adopted Manning's 'n' hydraulic roughness values

Land Use Category	Manning's '*n*'
Roads	0.02
Public Recreation	0.05
Metro Centre	0.04
Rail Corridor	0.04
General Residential	0.04
Mixed Use	0.04
Commercial Core	0.04
Underground Pipes/Culverts	0.015



Title:

City Area Catchment Land Use Categories

Figure: 4-3

Rev: A

BMT WBM endeavours to ensure that the information provided in this map is correct at the time of publication. BMT WBM does not warrant, guarantee or make representations regarding the currency and accuracy of information contained in this map.

N

0 250 500m

Approx. Scale

BMT WBM

www.bmtwbm.com.au

Filepath : S:\WATER\PROJECTS\S20022 - Water - Sydney CBD Catchment Flood Study\Documents\Figures\

4.3.6 Boundary Conditions

The model boundary conditions are derived as follows:

- Inflow – the catchment runoff is determined through the hydrological component of the model. With the direct-rainfall approach, rainfall is applied directly to every cell in the hydrologic catchment extent, where it is routed as sheet flow until the runoff contribution is substantial enough to generate an overland flow path. Flow is automatically transferred to the 1D domain where sufficient pipe and inlet capacity is available. Surcharging will then occur from the 1D to the 2D domain once the pipe capacity has been exceeded.

- Downstream Water Level – the downstream model limit corresponds to the tidal water level in Sydney Harbour. A water level boundary has been applied at this location for the duration of the modelled events to both 1D and 2D model components.

As discussed in Section 4.2, a direct-rainfall approach has been adopted in the TUFLOW hydraulic model to determine the catchment inflows. As buildings have been removed from the TUFLOW model (refer to Section 4.3.2), rainfall volume corresponding to each building footprint is therefore not accounted for in the direct-rainfall input. Rain falling on buildings has been accounted for in the TUFLOW model by using appropriate boundary features to calculate the runoff from each building, allocating the calculated flow around the perimeter of each building. This method has ensured that all rain falling on the buildings has been accounted for and represented as contributing to overland flow.

5 MODEL CALIBRATION AND VERIFICATION

5.1 Introduction

A key stage of the model development is calibration and verification. This demonstrates the models ability to replicate flooding using recorded inputs from real historic storms.

In order to undertake a full calibration process, the two types of required information could be summarised as model inputs and accounts of flood behaviour.

Model Inputs

Model inputs include historic rainfall depths recorded from pluviometers and corresponding historic records of Harbour water levels. Land use conditions and details of the stormwater network current for each historic event are also required.

Accounts of Flood Behaviour

Accounts of flood behaviour include gauged flows at downstream catchment locations and surveyed peak water levels marks across the catchment. Anecdotal descriptions of flood behaviour are also important though can be a less reliable record of flooding.

For the City Area catchment, model inputs for the majority of key historic flood events are well known. Observatory Hill has a long record of rainfall data and long records of Harbour water levels recorded at Fort Denison are available. What is limiting, is the accounts of flood behaviour. The value of the calibration process in simulating historic flood events in the Flood Study model may be limited if the results cannot be compared with reliable accounts of the actual flood behaviour.

In the City Area catchment, there are not any flow gauges in the catchment to compare modelled flows and no survey of peak flood levels have been undertaken following historic flooding. Anecdotal accounts of flooding are available from Sydney Water records and from community consultation undertaken during the study.

5.2 Selection of Calibration Events

The selection of suitable historical events for calibration of computer models is largely dependent on available historical flood information. Ideally the calibration and verification process should cover a range of flood magnitudes to demonstrate the suitability of a model for the range of design event magnitudes to be considered.

Review of the available data for the City Area catchment, including the community consultation data, showed there are very few events with any recorded flood levels or observations of flood behaviour within the catchment. Table 5-1 summarises specific rainfall events identified from the community consultation which resulted in flooding of property in addition to events extracted from the Sydney Water Corporation Historic Flood Database. In most instances, exact dates were not reported by community respondents requiring the date to be assumed following analysis of available rainfall data.

Table 5-1 Available calibration data for the City Area catchment

Storm Event	Locations with Reported Flooding	Community Consultation	Sydney Water Corporation Database
March 2012	1	✓	
June 2013	1	✓	
22 August 1984	1		✓
5 November 1984	2		✓
8 November 1984	6		✓
6 January 1989	3		✓
26 January 1991	3		✓

Following assessment of available rainfall and tidal data and the events listed in Table 5-1, the 8 November 1984 and 26 January 1991 events were selected for the model calibration and verification process. Whilst there were no specific reports of flooding associated with the event, the 8 March 2012 event has been used to verify general flooding behaviour within the City Area catchment.

Referring to the feedback received from the community consultation exercise, not all respondents indicated the dates upon which the reported flooding behaviour occurred. To maximise the value of the community consultation, it was desirable to consider all reports of flooding from residents even when the flood event was not specified. Accordingly, reports of general flooding behaviour and observed flow paths, not attributed to any specific storm event, were considered in the model validation process. The 8 March 2012 was simulated as an additional model validation event for comparison with the community observations in relation to flow paths and general flooding behaviour.

The distribution of rainfall gauge locations in the vicinity of the City Area catchment is shown in Figure 2-2. Given the proximity of the Observatory Hill gauge to the City Area catchment, the rainfall data from Observatory Hill has been applied uniformly across the City Area catchment for all events assessed.

5.3 Model Parameters Adopted for Calibration

For all calibration events modelled, the same parameter values have been adopted for rainfall losses and hydraulic roughness. Given the paucity of calibration data across the study area, there was insufficient justification for varying values for these parameters between the different events being modelled. The values adopted for these parameters are summarised in Section 5.10.

5.4 Model Calibration – 8 November 1984

5.4.1 Rainfall and Harbour Water Level Data

Figure 5-1 shows the recorded Harbour water levels at Fort Denison and rainfall depths recorded at Observatory Hill. A total rainfall depth of approximately 190 mm fell over a 3 hour period with the peak of the rainfall occurring at 10:00 PM, coinciding with a low tide level of 0.4m AHD.

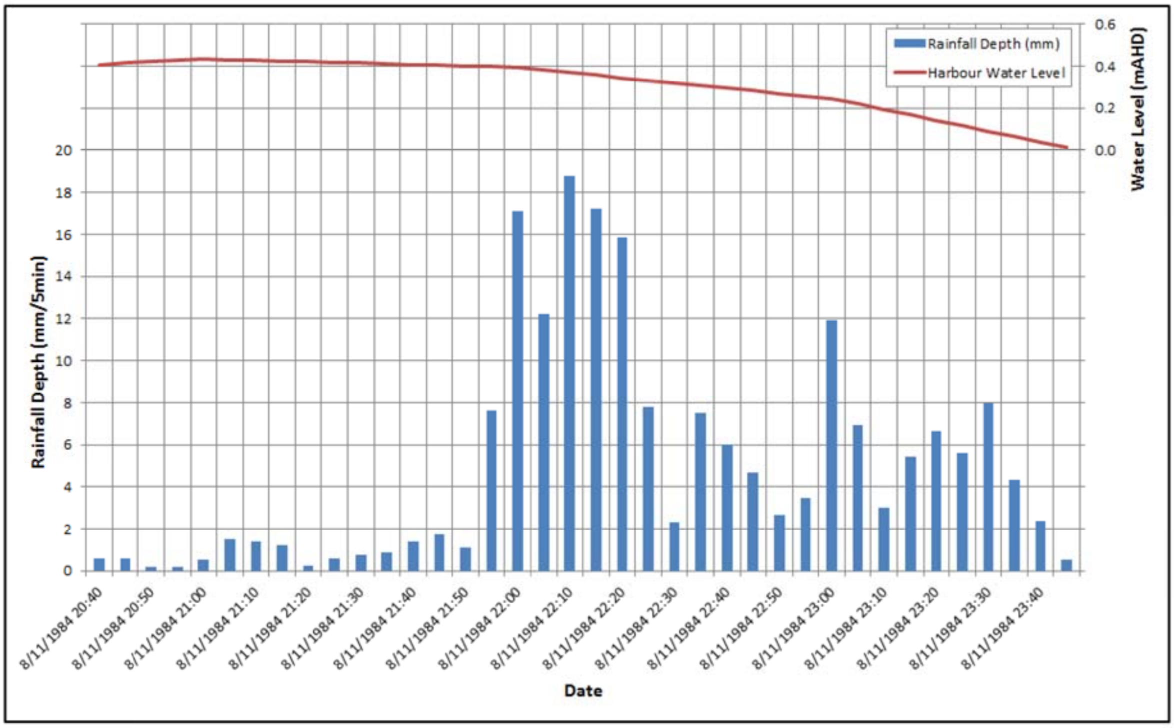


Figure 5-1 Recorded rainfall and harbour water level – 8 November 1984

The recorded rainfall depths at the Observatory Hill rainfall gauge have been compared with the design IFD data, as shown in Figure 5-2. This indicates that the rainfall event was of a magnitude comparable with a 500 year ARI design rainfall event for durations between 30 minutes and 3 hours. In the 4 days prior to the event, 220 mm of rainfall was recorded at Observatory Hill. This rainfall largely fell as part of the 5 November 1984 event which was noted in Table 5-1.

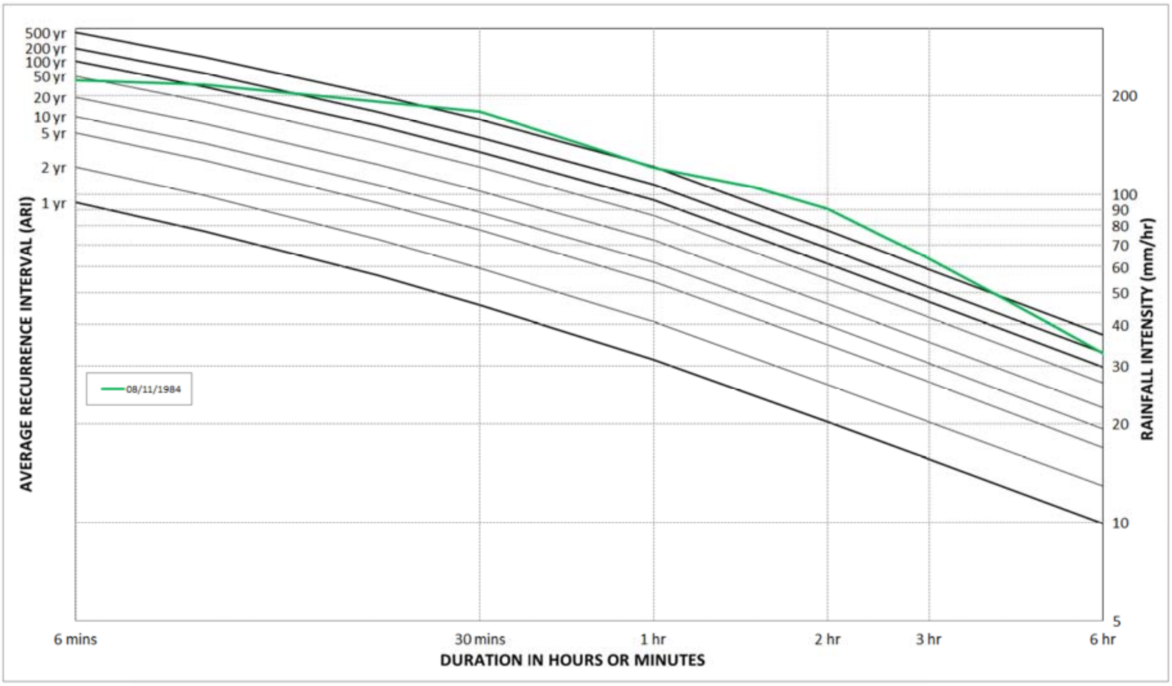


Figure 5-2 Comparison of 8 November 1984 rainfall with IFD relationships

BMT WBM

5.4.2 Observed and Simulated Flood Behaviour

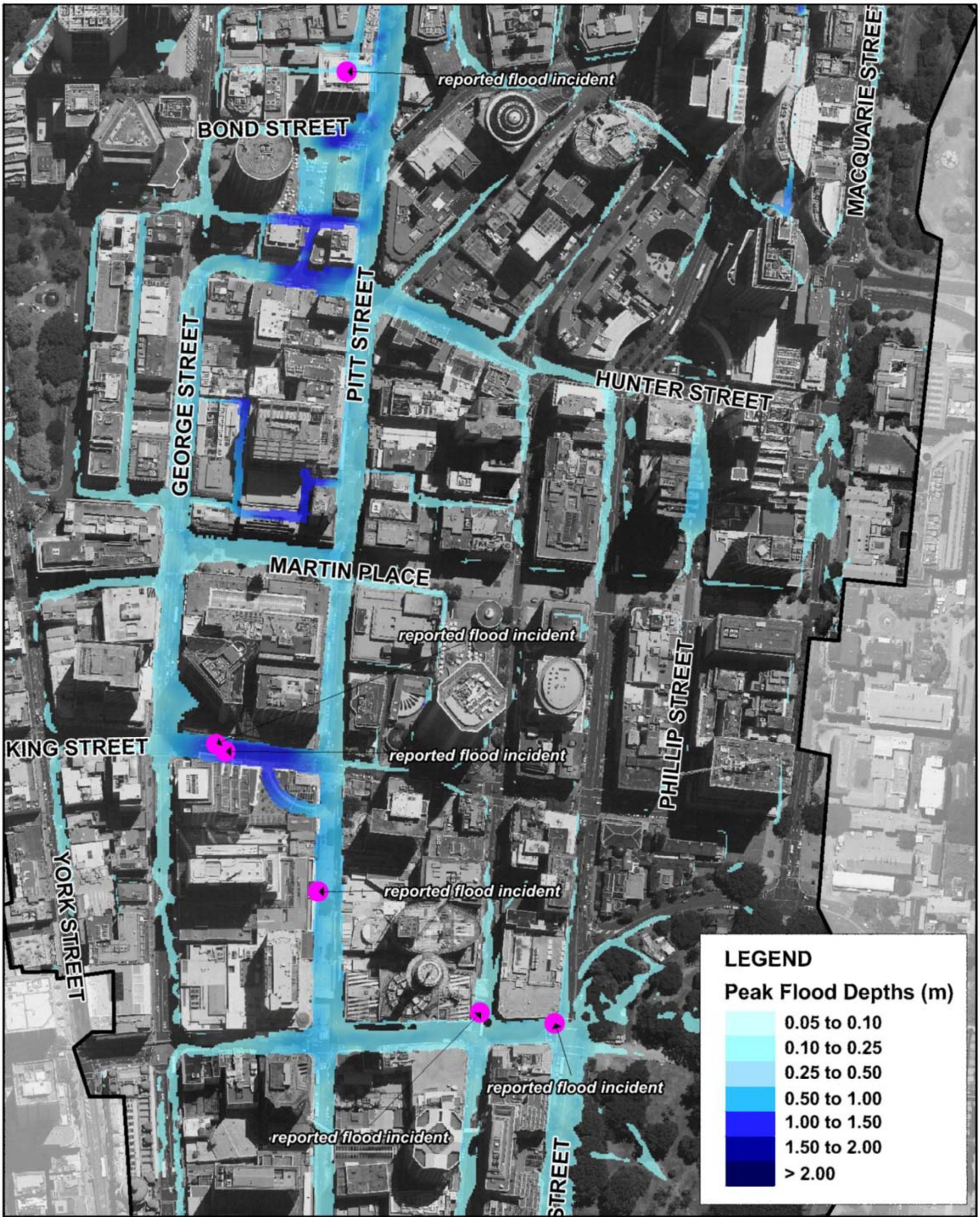
Six reports of flood behaviour for the 8 November event are available in the City Area catchment. These flooding reports are sourced from the Sydney Water Corporation Historic Flood Database and are presented below. Figure 5-3 shows the peak depth results from this calibration event and shows locations of each of these reports of flooding.

- Pitt Street (between Bond Street and Abercrombie Lane), Sydney: Build-up of water in the street that subsequently swept into the reported property.
- Pitt Street Mall, Sydney: Water flowed down Pitt Street above the footpath level and flooded shops on the George Street side. Water depths of at least 300 mm were observed.
- King Street (between George and Pitt Streets), Sydney: In King Street between George Street and Pitt Street: Water ponded in the sag to a depth exceeding the footpath level.
- Corner of Market Street and Elizabeth Street, Sydney: Flooding above footpath.
- Castlereagh Street (near Market Street), Sydney: Flooding above footpath.
- King Street (between George and Pitt Streets), Sydney: Build-up of water in King Street sag. Flood level exceeded entry level of car park for property associated to flooding incident.

As shown in Figure 5-3, the results of the 8 November 1984 calibration event compares well with the observed flooding behaviour, summarised as follows:

- On Market Street at its intersection with both Castlereagh Street and Elizabeth Street, the peak flood depth is approximately 0.2 m which would result in above kerb flooding.
- The flood depth along Pitt Street Mall ranges from 0.2 m to 0.5 m. This modelled depth correlates well with the estimated depth of 0.3 m reported in the Flood Database.
- At the sag on King Street between Pitt Street and George Street, the model is predicting a peak depth of 1.2 m. As discussed in Section 4, car parks have not been explicitly considered in this study; however the predicted peak flood depth at this location is likely to be sufficient to cause flooding of the car park.
- The flood level which resulted in the reported flooding at Pitt Street between Bond Street and Abercrombie Lane is not known. The modelling shows that over 0.5 m depth of water ponded in front of the building for this event.

Based on the available data, the model is considered to be adequately representing the observed flooding behaviour for the 8 November 1984 event.



Title:

Peak Flood Depth - Verification Event 8 November 1984

Figure: 5-3

Rev: A

N

0 75 150m

Approx. Scale

BMT WBM

www.bmtwbm.com.au

Filepath : S:\WATER\PROJECTS\S20022 - Water - Sydney CBD Catchment Flood Study\Drafting\WOR\Figures\FIGURE05-3_1984_8_Nov.wor