ATTACHMENT A

GREEN SQUARE-WEST KENSINGTON FLOOD STUDY

CITY OF SYDNEY **RANDWICK CITY COUNCIL**

GREEN SQUARE & WEST KENSINGTON (SHEAS CREEK - VICTORIA BRANCH)

FLOOD STUDY

APRIL 2008

Department of Environment & Climate Change NSW

WEBB, McKEOWN & ASSOCIATES PTY LTD

CITY OF SYDNEY **RANDWICK CITY COUNCIL**

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Webb, McKeown & Associates Pty Ltd
Level 2, 160 Clarence Street, SYDNEY 2000
Telephone: (02) 9299 2855
Facsimile: (02) 9262 6208
24037:GSWKFS_FinalReport.wpd

Prepared by: ___________________________

Verified by: ___________________________

GREEN SQUARE & WEST KENSINGTON (SHEAS CREEK - VICTORIA BRANCH) FLOOD STUDY

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FOREWORD

The NSW State Government's Flood Policy provides a framework to ensure the sustainable use of floodplain environments. The policy is specifically structured to provide solutions to existing flooding problems in rural and urban areas. In addition, the Policy provides a means of ensuring that any new development is compatible with the flood hazard and does not create additional flooding problems in other areas.

Under the Policy, the management of flood liable land remains the responsibility of local government. The State Government subsidises flood mitigation works to alleviate existing problems and provides specialist technical advice to assist Councils in the discharge of their floodplain management responsibilities.

The Policy provides for technical and financial support by the Government through four sequential stages:

1. *Flood Study*
    - determine the nature and extent of the flood problem.
2. *Floodplain Risk Management Study*
    - evaluates management options for the floodplain in respect of both existing and proposed development.
3. *Floodplain Risk Management Plan*
    - involves formal adoption by Council of a plan of management for the floodplain.
4. *Implementation of the Plan*
    - construction of flood mitigation works to protect existing development,
    - use of Local Environmental Plans to ensure new development is compatible with the flood hazard.

The following Green Square and West Kensington Flood Study constitutes the first stage of the management process for this catchment area. Webb, McKeown & Associates were commissioned by Randwick City Council and City of Sydney to prepare this flood study on behalf of the Green Square and West Kensington Floodplain Risk Management Committee. Funding for this study was provided from the Commonwealth and State Governments Flood Risk Management Program and both Randwick City Council and the City of Sydney. This report documents the work undertaken and presents outcomes that define flood behaviour for existing catchment conditions.

EXECUTIVE SUMMARY

The NSW Government's Flood Policy provides:

- a framework to ensure the sustainable use of floodplain environments,
- opportunities for the development of solutions to flooding problems, and
- a means of ensuring that new development is compatible with the flood hazard and does not adversely affect existing flood risk.

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

The Green Square – West Kensington (GSWK) Flood Study was initiated as a joint project between Randwick City Council and the City of Sydney. This report has prepared on behalf of both Councils by Webb McKeown and Associates.

The specific objectives of the Green Square – West Kensington Flood Study are to:

- define flood behaviour within the study catchment,
- prepare mapping showing the nature and extent of flooding,
- prepare suitable models of the catchment and floodplain suitable for use in subsequent Floodplain Risk Management Studies and Plans.

Description of Catchment:
The Green Square and West Kensington study catchment covers 250 hectares and drains predominantly from east to west. The upper reaches (east of South Dowling Street), are predominantly zoned for residential usage. The area immediately west of South Dowling Street was once dominated by industrial premises. Significant redevelopment of this area in the form of medium and high density housing as well as commercial premises has been undertaken in recent years. The study area extends west to Botany Road and O'Riordan Street below the proposed Green Square Town Centre precinct.

Prior to extensive development, drainage through the lower reaches of the study area was provided by a series of interconnected dams and natural swamps. The majority of the catchment drains to a trapped depression located in Joynton Avenue. Once the capacity of the local trunk drainage system is exceeded, flood waters from this trapped depression flow overland through to Botany Road and across the plaza at Green Square Railway Station.

The Key Phases of the Green Square – West Kensington Flood Study that have been undertaken are summarised in the following.

Collation and Review of Available Data:
A review of past reports, Council records and photographs was undertaken. A comprehensive range of datasets was also compiled including topographic survey information from multiple sources, details of the drainage network and historical rainfall and flood level information.

Preparation of Computer Models:
A rainfall-runoff modelling approach was adopted due to the absence of long term historical flood records. This approach involved the setting up of two modelling platforms – a hydrologic model to convert rainfall to runoff and hydraulic models to then determine flow distributions, flood levels and velocities throughout the floodplain. The performance of the models was validated against available data from the November 1984 storm events.

Determination of Design Flood Behaviour:
Design rainfall data from Australian Rainfall and Runoff (1987) was obtained for design floods ranging from the 50% AEP (1 in 2 year) flood to the 1% AEP (1 in 100 year) flood and the Probable Maximum Flood (PMF) event. This information was input into the hydrologic/hydraulic models to determine design flood behaviour in terms of flood levels, flows and velocities throughout the floodplain.

The likely accuracy of the modelling results is expected to be within ±0.5m for areas within the City of Sydney LGA and in most of the significant trapped low points within the Randwick City Council LGA. Outside of these areas the accuracy is likely to be in the order of ±1.0m.

Flood Problem Areas:
Urbanisation has dramatically altered the nature of available drainage within the catchment. Consideration of the natural drainage systems present prior to development provides the context for many of the flood problems known to exist in the area today.

Flood problems within the West Kensington portion of the catchment typically result from ponding in trapped low-points such as those found in Milroy Avenue, McDougall Street and the Lenthall Street underpass below South Dowling Street. Ponding also occurs at various locations along the eastern side of South Dowling Street.

Within the City of Sydney portion of the catchment, similar ponding behaviour also occurs at South Dowling Street (opposite the Supacentre), at Lachlan St and in Botany Road (adjacent to the Green Square Railway Plaza). The most significant trapped low point is located within Joynton Avenue which receives runoff from a significant portion of the study catchment. The Joynton Avenue low-point was known to have experienced severe flooding in the storm of November 1984 events.

In the floodplain west of South Dowling Street, overland flow paths typically follow the existing road network. However in the southern portion of the floodplain between Link Road and Joynton Avenue, a number of uncontrolled overland flow paths form when the capacity of the trunk drainage system is exceeded. Significant overland flow paths also form between Portman Street and Botany Road when ponding in Joynton Avenue causes flood waters to overtop Portman Street. Overtopping of the Botany Road trapped low point also results in overland flow along the Green Square Railway Station Plaza.

Outcomes:

The main outcomes of this Flood Study include:

- full documentation of the methodology and results,
- preparation of flood maps defining the nature and extent of flooding for the majority of the floodplain, and
- modelling tools and information suitable for use in the preparation of a Floodplain Risk Management Study and Plan.

1. INTRODUCTION

The Victoria Branch of Sheas Creek is a tributary of the Cooks River. The Victoria Branch catchment extends across the southern Sydney suburbs of Waterloo, Moore Park, Zetland, Kensington and Rosebery (Figure 1). The catchment also incorporates the proposed Green Square Town Centre (GSTC) area bounded by Joynton Avenue and Botany Road.

A number of stormwater related investigations and studies have been undertaken within the catchment to date (References 1, 2 and 3). Based on the information then available, these studies have broadly defined stormwater and flooding behaviour throughout the study area.

On behalf of the City of Sydney (CoS) and Randwick City Council (RCC), Webb McKeown and Associates have been commissioned to prepare a Floodplain Risk Management Plan for the Sheas Creek-Victoria Branch catchment draining to downstream of the Green Square Town Centre (GSTC) development precinct.

An important first stage in the development of this Plan is to define the design flood behaviour for the existing catchment conditions. In this context, the following Green Square - West Kensington (GSWK) Flood Study documents the approach and outcomes of the technical work undertaken to achieve this. In accordance with the Floodplain Development Manual (Reference 8), the primary objectives of this Flood Study are to:

- define the flood behaviour of the study catchment by quantifying flood levels, flows and velocities for a range of design flood events under existing catchment conditions,
- to establish suitable hydrologic/hydraulic model(s) that can be used in a subsequent Floodplain Risk Management Study and the assessment of redevelopment options for the proposed Green Square Town Centre area.

This report details the methodology and results of the Flood Study with the key elements being:

- a summary of available data,
- an outline of the overall methodology adopted including details on the numerical models established,
- a description of the design flood behaviour throughout the study area, and
- documentation of the assumptions made to derive the information and conclusions presented herein.

2. BACKGROUND

2.1 Catchment Description

The Green Square and West Kensington study catchment has an area of approximately 250 hectares (Figure 1). The catchment drains predominantly from east to west. South Dowling Street runs north-south through the middle of the catchment dividing the City of Sydney and Randwick City Local Government Areas (LGA's). 57% of the study catchment lies within the City of Sydney LGA, with 43% being within the Randwick City Council LGA. The upper reaches of the catchment (east of South Dowling Street), are predominantly zoned for residential usage. This area also includes the Australian Golf Course and the Moore Park Supacentre. The area immediately west of South Dowling Street was once dominated by industrial premises. Significant redevelopment of this area in the form of medium and high density housing as well as commercial premises has been undertaken in recent years. This includes the Victoria Park and ACI site redevelopments. The study area extends west to Botany Road and O'Riordan Street which represents the downstream limit below the proposed GSTC area.

The Raleigh Park residential development and the Australian Golf Course represent two major sites within the Randwick City Council LGA. The remainder of the catchment within this LGA consists mainly of older residential development. This portion also contains a number of trapped low points such as those found at the corner of Balfour Road and Todman Avenue and at Milroy Avenue and McDougall Street.

Prior to extensive development, drainage through the lower reaches of the study area was provided by a series of interconnected dams and natural swamps (Figure 2). Historical records locate the "Big Waterloo Dam" at the southern end of Portman Street where Joynton Avenue is now located. Waterloo Swamp is located upstream of the "Big Waterloo Dam", extending east to Dowling Street (now South Dowling Street), south to Epsom Road and north almost to Lachlan Street. Another dam was also located at the site of what is now Link Road.

As per the historical pattern of drainage, the majority of the study catchment drains to a trapped depression located in Joynton Avenue where the "Big Waterloo Dam" was once located (Figure 3). Once the capacity of the local trunk drainage system is exceeded, flood waters from this trapped depression flow overland through the proposed GSTC area to Botany Road and across the plaza at Green Square Railway Station. For the purposes of the present study, the three main sub-catchments draining to the Joynton Avenue trapped depression have been denoted as the northern, eastern and southern sub-catchments (refer to Figure 1). The contributing catchments downstream of Joynton Ave have been denoted as the 'middle' and 'western' sub-catchments.

The northern sub-catchment is predominantly high density housing or commercial and industrial in land use. This sub-catchment includes:

- the medium to high density mixed use development of Victoria Park,
- the industrial and commercial areas around Joynton Avenue and O'Dea Avenue,
- the medium to high density mixed use development on the former ACI site,
- the Moore Park Supacentre,
- a portion of the Moore Park Golf Course north and south of Dacey Avenue,
- a small section of low to medium density residential area bounded by South Dowling Street and Todman Avenue in Kensington.

The eastern sub-catchment includes the north west area of Kensington and a section of Zetland between Link Road and Joynton Avenue. The sub-catchment is mainly low to medium density residential land use and includes the Raleigh Park residential development. The northern end of The Australian Golf Course is also located within this sub-catchment.

The southern sub-catchment is comparatively smaller and includes the area south of Epsom Road between Rothschild Avenue and Rosebery Avenue. This sub-catchment is a mixture of commercial and medium to high density residential land use.

The sub-catchments downstream of the Joynton Avenue depression (incorporating much of the proposed GSTC area) are typically old industrial in character. These areas contain a number of commercial and light industrial premises. The area also incorporates a range of government and public infrastructure including the Waverley Council Works Depot, NSW Police Complex and the Green Square Railway Station.

2.2 Causes of Flooding

Urbanisation has dramatically altered the nature of available drainage within the catchment. Consideration of the natural drainage systems present prior to development, provides the context for many of the flood problems known to exist in the area today. In this regard, urbanisation of the area has led to:

- a major increase in the proportion of paved area and consequent reduction in pervious areas, resulting in corresponding increases in runoff (in terms of both peak flows and volumes),
- the removal of the swamps and dams that once dominated the lower reaches of the catchment reducing the provision for storage of stormwater thereby increasing flows to downstream areas,
- development within the trapped depressions that were once swamps or dams, resulting in flood problems in these areas. The Joynton Avenue trapped depression (Figure 3) provides a specific example of this issue. Given it's proximity to the proposed GSTC development precinct, this particular trapped depression is discussed in further detail in the following section.

2.3 Joynton Avenue Trapped Depression

The Joynton Avenue depression is located just upstream of the proposed GSTC area (Figure 3). The local topography of the area forms a significant natural depression that acts to trap and attenuate overland flows during storm events.

Previous studies of the system identified the potential flood regime of the area as being a significant constraint on the future development in terms of both flood inundation (flood depth) and the management of overland flow paths (flow conveyance).

For large flood events, the flood behaviour is determined by a combination of localised features (which trap and control the incoming stormwater) and the available storage provided by the ground topography. Due consideration of these two aspects is required to properly assess design flood behaviour.

In terms of inflows, the area receives overland flows from a number of sources including the northern, southern and eastern sub-catchments. The primary overland flow path from Joynton Avenue through to Portman Street is via the car park along the northern boundary of the Royal South Sydney Community Health Complex. Based upon a site inspection and review of available data, the ability of stormwater to flow downstream from Joynton Avenue to beyond Portman Street is likely to be controlled by several key features including:

- the level and width of the confined flow path on the site of the former Royal South Sydney Community Health Complex (Photograph 1),
- the ground levels and potential critical overtopping controls along Portman Street immediately upstream of the Waverley Council Works Depot and the adjacent NSW Police Complex (Photograph 2).

Photo 1: View showing overland flow path along the northern boundary of the old Royal South Sydney Community Health Site.

Photo 2: View along Portman Street looking south. Overland flows downstream are controlled by the ground levels on the western side of Portman St.

The representation of these features in any hydraulic model can influence the peak flood levels expected upstream of the depression and also the magnitude of overland flow discharged to sites downstream, including the proposed GSTC area.

2.4 Previous Studies

There are a considerable number of stormwater related investigations that have preceded the current study. These studies have been carried out to assess the overall flood behaviour within the catchment and investigate stormwater issues at particular problem locations or in separate areas undergoing redevelopment. The main reports that have been researched and considered as part of the present study include:

- South Sydney Stormwater Quality and Quantity Study - Cooks River Major Catchment - SWC 89 - Shea Creek Sub-catchment Report, Hughes Trueman and Perrens Consultants (2003),
- Green Square Town Centre Stormwater Management Report, Hughes Trueman (2003),
- O'Dea / Joynton Avenue Stormwater Drainage Design Feasibility Study for South Sydney City Council, Gutteridge, Haskins and Davey (2003),
- Green Square Public Domain Plans, South Sydney City Council - Stormwater Drainage Concept Report, Lachlan Street to Tilford Street (Draft), Northrorp Engineers (2003),
- Victoria Park Zetland Stormwater Management Plan, Hughes Trueman Reinhold (1999),
- Victoria Park Stormwater Infrastructure Masterplan Report, Hughes Trueman Reinhold (1999),
- ACI Site Waterloo Stormwater Management Plan, Jeff Moulsdale and Associates (1999)
- West Kensington Flooding Drainage Works Investigation, Public Works Department NSW, (1985).
- Sheas Creek Flood Study, Webb, McKeown and Associates (1991).

Several of the above Hughes Trueman reports make reference to a drainage study undertaken as part of the construction for the Eastern Distributor (titled "Drainage Study - South Dowling Street (Upper Sheas Creek Catchment) Document No. N641/RP/D/CV/038C" prepared by Maunsell Pty. Ltd., March 1998). Although Hughes Trueman and Maunsell Pty. Ltd. were approached during the course of this Flood Study, no copy of the 1998 Drainage Study report could be provided for review.

3. AVAILABLE DATA

3.1 Drainage Information

As part of the present study a comprehensive drainage assets database was developed for the drainage network located within the Randwick City Council LGA. This data was collected by AWT Survey and included details of all drainage inlet pits and pipes for the Randwick catchment.

A considerable amount of data also existed for the portion of the drainage network within the City of Sydney LGA (albeit in a number of different formats). This data was sourced from a combination of models established for previous studies, survey plans and design drawings. An extensive review of the available data was undertaken to identify deficiencies. Based on this review, AWT Survey were commissioned to obtain outstanding information that was deemed critical for the present study. This included a detail survey of the trunk drainage system extending downstream from Portman St through to Bowden Street.

A database of drainage infrastructure details that covered all of the trunk drainage system and the majority of the minor street drainage system was ultimately prepared.

3.2 Aerial Survey Data

3.2.1 Photogrammetry

To provide broad coverage of topographic details and building footprints within the City of Sydney portion of the catchment, a photogrammetry survey was commissioned by the City of Sydney and flown in March 2006, the extents of which are indicated in Figure 4. This survey was undertaken by QASCO Pty. Ltd. The mapping outputs include

- a Digital Terrain Model (DTM) that represents the ground topography based on spot heights and breaklines, and
- delineation of existing building footprints and roof heights.

The aerial photography upon which the photogrammetry was based was captured at 1:6000 scale. For well defined points mapped in clear areas, the expected typical point accuracies (based on a 90% confidence interval) are in the order of:

- Vertical Accuarcy: +/- 0.10m (approx.)
- Horizontal Accuracy: +/- 0.15m (approx.)

However, it should be noted that the above tolerance limits can be adversely affected by the nature and density of ground vegetation.

3.2.2 Aerial Laser Scanning (ALS) Survey

Randwick City Council commissioned AAMHATCH Pty. Ltd. to undertake an Aerial Laser Scanning (ALS) survey within the extents of the Randwick LGA (refer Figure 4). The survey was flown in December 2005 at a 1:2000 scale flying height. The resultant mapping was provided to Council in March 2006. In terms of ground level information the ALS survey provides numerous ground level spot heights, from which a Digital Terrain Model (DTM) can be constructed.

For well defined points mapped in clear areas, the expected nominal point accuracies (based on a 68% confidence interval) are in the order of:

- Vertical Accuracy: ±0.15 m
- Horizontal Accuracy: ±0.57 m

When interpreting the above, it should be noted that the accuracy of the ground definition can be adversely affected by the nature and density of vegetation and/or the presence of steeply varying terrain.

3.3 Detail Survey Data

The following survey plans were used to define the piped drainage network and establish the overland flow paths for the present study:

- Stormwater Data Collection Green Square Flood Studies, Drawing No. 041006B (1 sheet), Sydney Water Survey (AWT) (2004).
- Stormwater Data Collection Green Square Area Flood Study - Area 5, Drawing No. 041006 (1 sheet), Sydney Water Survey (AWT) (2004).
- Detail Survey along part of Sheas Creek S.W.C. 89E - Bowden Street, Alexandria to Portman Street, Zetland, Drawing No. 050545 (4 sheets), AWT Survey (2005).
- Green Square Town Centre Survey Base, supplied by Lester Firth & Associates, April 2005.
- Details and Levels Epsom Road, Rothschild Avenue, Crewe Place, Rosebery Avenue, Dalmeny Avenue and Kimberley Grove Rosebery, City of Sydney Council-City Development Department, 2004.
- Plan showing detail and levels over Bourke Street, Lachlan Street, South Dowling Street and O’Dea Avenue Waterloo, Drawing No. 289470A01.dwg (13 sheets), Degotardi, Smith and Partners (2002).
- Detail and levels McEvoy Street, Bourke Street, Botany Road, Allen Street, George Street, Elizabeth Street, Short Street, Hawksley Street Waterloo, Drawing No. S5-587/435 (8 sheets), City of Sydney Council-City Works Department.

The first two plans were prepared by AWT following a review of available data in the area and the need for further information, as outlined in the preceding section. These plans contain detail survey of the area between Joynton Avenue and Link Road. It was important to collect additional detail in this area to accurately model flow behaviour at the Joynton Avenue trapped depression.

3.4 Design Data

Significant developments undertaken recently in the area include the Victoria Park redevelopment of the old Navy Stores site and the Meriton redevelopment of the former ACI site. Design drainage information for these redevelopments was provided by Council in the following drawings:

- Victoria Park Zetland Infrastructure Commercial Stage Detail Design, Project No. 99S700, Hughes Trueman Reinhold (2001),
- Victoria Park Zetland Infrastructure Stage 1 Detail Design, Project No. 99S700, Hughes Trueman Reinhold (2001),
- Proposed Residential Development ACI Site, South Dowling Street Waterloo - Stage 1 and Stage 2, Job No. 99012, Jeff Mousdale and Associates (1999).

3.5 Rainfall Data

The first stage in the investigation of flooding matters is to establish the nature, size and frequency of the problem. On large river systems such as the Hawkesbury River there are generally stream height and historical records dating back to the early 1900's, or in some cases even further. However, in smaller urban catchments such as the GSWK study area there are often no stream gauges or official historical records available. A picture of flooding must therefore be obtained from an examination of rainfall records and local knowledge.

3.5.1 Overview

Rainfall data is recorded either daily (24hr rainfall totals to 9:00am) or continuously (pluviometers measuring rainfall in 0.5 m rainfall increments). Daily rainfall data have been recorded for over 100 years at many locations within the Sydney basin, including at Observatory Hill since 1858. In general, pluviometers have only been installed since the 1970's. Together these records provide a picture of when and how often large rainfall events have occurred in the past.

However, care must be taken when interpreting historical rainfall measurements. Rainfall records may not provide an accurate representation of past events due to a combination of factors including local site conditions, human error or limitations inherent to the type of recording instrument used. Examples of limitations that may impact the quality of data used for the present study are highlighted in the following:

- Rainfall gauges frequently fail to accurately record the total amount of rainfall. This can occur for a range of reasons including operator error, instrument failure, overtopping and vandalism. In particular, many gauges fail during periods of heavy rainfall and records of large events are often lost or misrepresented.

- Daily read information is usually obtained at 9:00am in the morning. Thus if the storm encompasses this period it becomes “split” between two days of record and a large single day total cannot be identified.

- In the past, rainfall over weekends was often erroneously accumulated and recorded as a combined Monday 9:00am reading.

- The duration of intense rainfall required to produce flooding in the Green Square-West Kensington catchment is typically less than two hours. This is termed the “critical storm duration”. For a much larger catchment (such as the Parramatta River) the critical storm duration may be from 24 to 36 hours. For the Green Square-West Kensington catchment a short intense period of rainfall can produce flooding but if the rain stops quickly (as would be typical of a thunderstorm), the daily rainfall total may not necessarily reflect the magnitude of the intensity and subsequent flooding. Alternatively the rainfall may be relatively consistent throughout the day, producing a large total but only minor flooding.

- Rainfall records can frequently have “gaps” ranging from a few days to several weeks or even years.

- Pluviometer (continuous) records provide a much greater insight into the intensity (depth vs time) of rainfall events and have the advantage that the data can generally be analysed electronically. These data have much fewer limitations than daily read data. The main drawback is that many of the relevant gauges have only been installed since 1990 and hence have a very short period of record compared to the daily read data. The Sydney Observatory and Sydney Water Board Head Office gauges were installed in 1970 but unfortunately are located too far away to provide a representative indication of rainfalls occurring over the Sheas Creek catchment. Pluviometers can also fail during storm events due to the extreme weather conditions.

- Rainfall bursts likely to cause flooding in the Green Square-West Kensington catchment are expected to be relatively localised and as such only accurately “registered” by a nearby gauge. Gauges sited only a few kilometres away can show very different intensities and total rainfall depths.

3.5.2 Available Rainfall Data

There are no official rain gauges located within the study area of the broader Sheas Creek catchment. However, there are several gauges in adjacent catchments. Table 1 presents a summary of official rainfall gauges located close to, or within the catchment. These gauges are (or have been) operated either by Sydney Water (SW), the University of New South Wales (UNSW) or the Bureau of Meteorology (BoM). Of the 45 gauges listed in Table 1 over 58% (26) have now closed. The gauge with the longest record is Observatory Hill, operating from 1858 to the present.

Table 1: Listing of Rainfall Stations

Station No	Owner	Station	Elevation (mAHD)	Date Opened	Date Closed	Type
66139	BOM	Paddington	5	Jan-68	Jan-76	Daily
566041	SW	Crown St Reservoir	40	Feb-1882	Dec-60	Daily
566032	SW	Paddington (Composite Site)	45	Apr-61		Continuous
566032	SW	Paddington (Composite Site)	45	Apr-61		Daily
566009	SW	Rushcutters Bay Tennis Club	0	May-98		Continuous
566042	SW	Sydney H.O. Pitt St	15	Aug-49	Feb-65	Continuous
66015	BOM	Crown St Reservoir		Feb-1882	Dec-60	Daily
66006	BOM	Sydney Botanic Gardens	15	Jan-1885		Daily
66160	BOM	Centennial Park	38	Jun-00		Daily
566011	SW	Victoria Park @ Camperdown	0	May-98		Continuous
66097	BOM	Randwick Bunnerong Rd		Jan-04	Jan-24	Daily
66062	BOM	Sydney (Observatory Hill)	39	??		Continuous
66062	BOM	Sydney (Observatory Hill)	39	Jul-1858	Aug-90	Daily
66033	BOM	Alexandria (Henderson Rd)	15	May-62	Dec-63	Daily
66033	BOM	Alexandria (Henderson Rd)	15	Apr-99	Mar-02	Daily
66073	BOM	Randwick Racecourse	25	Jan-37		Daily
566110	SW	Erskineville Bowling Club	10	Jun-93	Feb-01	Continuous
566010	SW	Cranbrook School @ Bellevue Hill	0	May-98		Continuous
566015	SW	Alexandria	5	May-04	Aug-89	Daily
66066	BOM	Waverley Shire Council		Sep-32	Dec-64	Daily
66149	BOM	Glebe Point Syd. Water Supply	15	Jun-07	Dec-14	Daily
566099	SW	Randwick Racecourse	30	Nov-91		Continuous
66052	BOM	Randwick Bowling Club	75	Jan-1888		Daily
566141	SW	SP0057 Cremorne Point	0			Continuous
66021	BOM	Erskineville	6	May-04	Dec-73	Daily
	SW	Gladstone Park Bowling Club	0	Jan-01		Continuous
566114	SW	Waverley Bowling Club	0	Jan-95		Continuous
566043	SW	Randwick (Army)	30	Dec-56	Sep-70	Continuous
566077	SW	Bondi (Dickson Park)	60	Dec-89	Feb-01	Continuous
566065	SW	Annandale	20	Dec-88		Continuous
66098	BOM	Royal Sydney Golf Club	8	Mar-28		Daily
66005	BOM	Bondi Bowling Club	15	Jul-39	Dec-82	Daily
66178	BOM	Birchgrove School	10	May-04	Dec-10	Daily
66075	BOM	Waverton Bowling Club	21	Dec-55	Jan-01	Daily
66187	BOM	Tamarama (Carlisle St)	30	Jul-91	Mar-99	Daily
66179	BOM	Bronte Surf Club	15	Jan-18	Jan-22	Daily
566130	SW	Mosman (Reid Park)	0	Jan-98	Jun-98	Continuous
566030	SW	North Sydney Bowling Club	80	Apr-50	Sep-95	Daily
66007	BOM	Botany No.1 Dam	6	Jan-1870	Jan-78	Daily
66067	BOM	Wollstonecraft	53	Jan-15	Jan-75	Daily
66061	BOM	Sydney North Bowling Club	75	Apr-50	Dec-74	Daily
566027	SW	Mosman (Bradleys Head)	85	Jun-04		Continuous
566027	SW	Mosman (Bradleys Head)	85	Jun-04		Daily
566006	BOM	Bondi (Sydney Water)	10	Jun-97		Operational
66175	BOM	Schnapper Island	5	Mar-32	Dec-39	Daily

BOM = Bureau of Meteorology
SW = Sydney Water

3.5.3 Analysis of Recent Storms

As noted previously, pluviometer records provide a more detailed description of temporal variations in rainfall. Table 2 lists the maximum storm intensities for several recent rainfall events from both the pluviometers and daily read gauges in proximity of the Green Square-West Kensington catchment.

Table 2: 5 November 1984, 8/9 November 1984, January 1989, and January 1994 Maximum Recorded Storm Depths (in mm)

Station Location	5 Nov 1984		8/9 Nov 1984		6 Jan 1989		26 Jan 1991	
	30 min	60 min	30 min	60 min	30 min	60 min	30 min	60 min
Paddington	36	51	54	91	53	54	52	53
Observatory Hill	20	32	90	119	42	42	60	65
Sydney Airport	-	-	85	100	6	6	11	12
Marrickville	28	31	26	38	1	1	37	38
Mascot Bowling Club	43	48	34	47	36	37	17	18
UNSW (Avoca St)(1)	65	112	41	58	-	-	-	-
UNSW (Storey St)(1)	65	90	33	46	-	-	-	-

Station Location	24 hour Totals to 0900 hrs				
	5 Nov 1984	8 Nov 1984 (2)	9 Nov 1984 (2)	6 Jan 1989	26 Jan 1991
Royal Botanic Gardens	-	37	248	49	59
Sydney Airport	121	20	132	85	53
Observatory Hill	98	44	234	47	65
Paddington	108	71	208	63	54

Notes:
(1) Data manually interpreted from Reference 6.
(2) The November 1984 event consisted of two separate rainfall bursts (between 6:00am and 10:00am and 9:00pm and midnight). Both produced flooding but the second burst was the most intense. One possible reason why there are so few recorded flood levels is that the second burst occurred at night and thus few would have been outside to view the flood extent or record levels.

The above data indicate that for January 1989 and January 1991 the peak 30 minute rainfall comprised the majority of the daily rainfall. However for the two major events in November 1984 the 30 minute peak was part of a much larger rainfall event.

Comparison with design rainfall intensities indicate that the January 1989 and January 1991 events were less than a 20 year ARI design intensity for the 30 minute and 60 minute intensities, except at Observatory Hill in January 1991 which approached a 40 year ARI for the 30 minute intensity.

The 8th-9th November 1984 storm was a significant rainfall event across the Sydney and Wollongong region and is well documented in Reference 4. Table 3 shows that this storm had an approximate ARI of 100 years across several locations in Sydney. The storm was separated into two distinct bursts (6:00am to 10:00am and 9:00pm to midnight). The latter was the most intense period and flooding was reported throughout the catchment, though the actual timing of the flooding is unknown.

Table 3: ARI Estimates of the 8th November 1984 Rainfall (Reference 5)

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

3.6 Historical Flood Records

Previous catchment studies have investigated historical flooding in the area including studies undertaken on behalf of the Public Works Department (Reference 1), or by Webb McKeown (Reference 2) and Hughes, Trueman and Perrens (References 3 & 4). As part of these investigations a range of flood-related information was originally sourced from Sydney Water Corporation, South Sydney Council and local residents. The following summarises the available data for a number of past events known to have caused flooding within the study area.

15 June 1949
Lachlan Street east of Bourke Road was flooded and water entered part of the Australian Glass Company Property. Flooding also took place in Dowling Street adjacent to the tram sheds (now the site of the Supacentre). Water rose to a depth 0.8 m above road level.

20 November 1961
Lachlan Street was impassible to traffic for a short period. Stormwater flowed south along Ameila Street, meeting the runoff from Dowling Street and ponding to a depth of 0.4 m around Reed Paper Products Ltd. Most of the flood was diverted by temporary damming and by smashing of the factory downpipes to allow the ponded water to enter the private drainage system. However, some damage was sustained to stored cardboard cartons, etc.

Stormwater ponded in Dowling Street outside the Board's survey depot and flowed through the yard and lower garage to a depth of approximately 0.2 m. No damage was sustained.

11 March 1975
This particular storm event is known to have resulted in flooding across many parts of metropolitan Sydney and areas along the coast, particularly to the south of the Sydney CBD. The 1991 Sheas Creek Flood Study (Reference 2) documents significant flooding at a number of locations in the lower reaches of the Sheas Creek catchment (beyond the downstream extent of the catchment examined in the present study).

Although there is little documented evidence of specific flooding within the GSWK catchment, Reference 2 acknowledges that the severity of flooding experienced in the lower reaches of the Sheas Creek catchment reflects the significant runoff drained to this area from the upper GSWK catchment.

8 - 9 November 1984

Records indicate that this storm began at 10:30pm on 8 November and continued through to 1:00am on the following morning. Very high rainfalls occurred in the Paddington area whilst lower falls were experienced at Mascot and Marrickville.

This event is known to have flooded 83 properties in the West Kensington area including locations in McDougall Street, Milroy Avenue, Lenthall Street and Balfour Street (Reference 1). 27 of these properties were flooded above the main floor level. Flood heights, anecdotal observations and floor level information was collected from resident interviews and subsequent survey conducted shortly after the event and is documented fully in Reference 1.

Flooding occurred to a depth of 0.1 m above floor level of the premises known as Yorkstar Motors (Joynton Avenue) and to a depth of 1.0 m in a patient care area of the South Sydney hospital (Joynton Avenue). Both of these flood levels were reported on the 8 November 1984.

The storm recorded the greatest intensity at the Paddington pluviograph. Comparison to design rainfall intensities indicate that for a 1 hour duration it was approximately a 60 year ARI event. However, the observed intensities were found to exceed the 100 year ARI intensities for a storm duration of between 2-4 hours.

26 January 1991

On the afternoon of Saturday, 26th January 1991 an intense storm developed, centred on the eastern fringe of the metropolitan area. The storm caused racing activities at Randwick Racecourse to be abandoned. Joynton Avenue experienced flooding.

The greatest intensities were recorded at the Paddington pluviograph where 50 mm of rainfall was recorded in 30 minutes. Comparison to design rainfall intensities indicate that this corresponds to approximately a 20 year ARI event. This event was less than a 5 year ARI event for a 1 hour duration.

28 February 2001

Sometime around 4:00pm on Wednesday, 28th February 2001 a short duration rainfall event was recorded in the South Sydney area. Flooding was reported in Joynton Avenue to a level of approximately 17.0 mAHD, or 0.2 m to 0.3 m above the top of kerb level.

Photo 3: Minor flooding observed at Joynton Avenue trapped depression during February 2001 event

An assessment of pluviograph recordings of the storm event indicate that the most severe rainfall burst recorded by the pluviograph at Mascot Pluviograph Station (located at Sydney Airport) was less than a 1 year ARI event. However the pluviograph at Observatory Hill recorded a peak 5 minute burst that was estimated to be around a 5 year ARI event. The rainfall experienced over the study catchment may differ significantly from the reported intensities at these stations.

4. APPROACH ADOPTED

4.1 General

The analysis approach adopted for this study has been influenced by the study objectives and the quality and quantity of available data. The urbanised nature of the catchment with its mixture of pervious/impervious surfaces and the development of a piped drainage system has created a complex hydrologic-hydraulic flow system. The analysis is further complicated by:

- the need to identify flow generated from numerous sub-catchment areas,
- surcharging within the pipe system,
- a need to ascertain the proportion of the total flow which travels overland,
- a need to estimate the nature of overland flows at critical locations in the catchment in terms of flood levels, flows and velocities.
- the complexity of the overland flow paths in some parts of the catchment.

In an urban drainage catchment such as the Victoria Branch of Sheas Creek, there is rarely a historical flood record available and the use of a flood frequency approach for the estimation of design floods is not possible. A rainfall/runoff approach linking hydrologic and hydraulic models followed by a process of calibration and verification was not appropriate due to insufficient historical information (flood flows and/or level data). This situation is typical of the majority of urban drainage catchments.

In view of the above, the approach adopted for this study was to use a widely regarded hydrologic model (for urban situations) in conjunction with appropriate hydraulic models. In the absence of definitive information for historical flood events, the models were configured using typical or recommended parameters. A limited process of model validation was then undertaken based on the flood events of November 1984. The sensitivity of the model results to the adopted model parameters was also assessed for the 1% AEP design storm event.

4.2 Hydrologic Modelling

Techniques suitable for design flood estimation in an urban environment are described in ARR87 (Reference 7). These techniques range from simple procedures to estimate peak flows (e.g. Probabilistic Rational Method calculations), to more complex rainfall-runoff routing models that estimate complete flow hydrographs and can be calibrated to recorded flow data.

For the present study, the DHI software package MIKE-Storm has been used to estimate the catchment hydrology (Reference 8). The MIKE-Storm model has been configured to utilise a runoff routing formulation that is based on methodology contained in the ILSAX/DRAINS models (References 9 and 10). The ILSAX/DRAINS type method has been widely adopted in Australia for use in urban catchments, similar to that of the present study. Furthermore, the use of ILSAX/DRAINS style hydrology is consistent with the approaches taken in previous studies (e.g. References 1-3).

4.3 Hydraulic Modelling

4.3.1 Overview

As stated in Reference 2, the primary objectives of previous stormwater studies were to describe the stormwater behaviour to a level of detail sufficient to facilitate broader management strategies within the overall catchment. A DRAINS model of the trunk drainage system was established for this purpose. In this context, quantitative estimates of design flood behaviour were obtained making best use of the data then available.

Part of the scope of the present study was to produce more refined estimates of design flood behaviour throughout the catchment suitable for the preparation of a flood study. The outcomes are to facilitate the detailed analysis of potential flood management options. The hydraulic analysis for the present study has therefore been undertaken using more detailed and sophisticated modelling approaches compared to those used in previous studies. In part, this has been facilitated by the acquisition of more detailed survey data describing the catchment topography and the sub-surface drainage network.

The majority of potential overland flow paths within the upper catchment (upstream of South Dowling Street) are reasonably well defined consisting of formal drainage easements/reserves, roadways and a combination of both natural and constructed watercourses. In view of this, the hydraulic modelling of overland flows in the upper eastern reaches of the West Kensington catchment was undertaken using a one-dimensional (1D) modelling approach using the MIKE-Storm package.

However, for the lower portions of the catchment the ground topography within the flood prone area contains significant localised variations due in large part to the non-uniform nature of filling and reclamation of low-lying lands that has taken place since the early 1900's. Field inspections in combination with a review of the corresponding detailed survey indicates that potential overland flow paths through some areas are ill-defined and would reflect the nature of the complex localised controls formed by the ground topography and existing building footprints. In order to better represent the complexity of the overland flow behaviour in this area, a combined one- and two-dimensional (1D/2D) hydraulic modelling approach was employed. A 1D/2D hydraulic model was therefore established using the SOBEK modelling package (Reference 11) for the western-most portions of the Randwick LGA (adjacent to the Eastern Distributor/South Dowling Street) and the remaining portion of the catchment within the CoS local government area.

The MIKE-Storm and SOBEK models were linked (via appropriate boundary conditions) to provide an integrated and consistent set of model results to describe the design flood behaviour of the overall study area. Additional details of each of the hydraulic modelling packages used for the present study are provided in the following sections.

4.3.2 MIKE-Storm Modelling Software

MIKE-Storm is a stormwater specific adaption of the industry standard DHI MOUSE software widely used for pipe and open channel hydraulic simulation of unsteady flow conditions in network systems (Reference 8). It combines ILSAX/DRAINS style hydrology with the fully dynamic hydraulic modelling approach offered by the MOUSE software package.

The MIKE-Storm model established for the present study makes use of existing drainage information as well as additional datasets specifically collected by both Councils. In comparison to the DRAINS model utilised previously (Reference 3), the MIKE-Storm model includes definition of both the trunk drainage and the majority of the minor drainage system elements as well as the overland flow paths.

The MIKE-Storm software provides a fully dynamic description of flow within the underground drainage system elements (pipes, culverts, channels) and overland flow network. The formulation allows the proper flow capacity and distribution to be determined based on backwater conditions, the available storage and/or downstream controls. Importantly for the present study, this allows the MIKE-Storm model to better represent dynamic headlosses (at pits and along pipes) for both free surface and pressurised flow and account for the interactions between surface flow and pipe flow conditions at the pit inlet nodes.

MIKE-Storm provides several key advantages for the proposed drainage studies including:

- fully dynamic 1D and quasi 2D flow modelling allowing the proper distribution of pipe and overland flows to be simulated depending on backwater conditions, storage, downstream controls, etc.,
- the inclusion of more definitive headloss formulations (at pits and along pipes) for both free surface and pressurised flow for dynamic conditions,
- true, dedicated links to Geographical Information System (GIS) and database software as standard capabilities (using industry compliant features), simplifying manual handling of data and facilitating the interpretation of model results,
- facilities for both design mode modelling or continuous simulation modelling to better assess the impacts of management strategies based on Water Sensitive Urban Design (WSUD), on-site detention or rainwater interception principles.

4.3.3 SOBEK Modelling Software

The SOBEK modelling package includes a finite difference numerical model for the solution of the depth averaged shallow water flow equations in two dimensions. The SOBEK software is produced by WL|Delft Hydraulics (Reference 11). SOBEK has been widely used for a range of similar projects both internationally and within Australia. The model is capable of dynamically simulating complex overland flow regimes and interactions with sub-surface drainage systems. It is especially applicable to the hydraulic analysis of flooding in urban areas which is typically characterised by short-duration events and a combination of supercritical and sub-critical flow behaviour.

For the hydraulic analysis of complex overland flow paths (such as those identified in the present study downstream of South Dowling Street), a combined 1D/2D model such as SOBEK provides several key advantages when compared to a traditional 1D only model. For example, in comparison to a purely 1D approach, a combined 1D/2D approach can:

- provide localised detail of any topographic and /or structural features that may influence flood behaviour,
- better facilitate the identification of the potential overland flow paths and flood problem areas,
- dynamically model the interaction between the drainage system and complex overland flowpaths, including surcharging effects, and
- inherently represent the available flood storage within the 2D model geometry.

Importantly, a 2D hydraulic model can better define the spatial variations in flood behaviour across the study area. Information such as flow velocity, flood levels and hydraulic hazard can be readily mapped across the model extent. This information can then be easily integrated into a GIS based environment enabling the outcomes to be readily incorporated into Council's planning activities. Furthermore, the model developed for the present study provide a more flexible modelling platform to properly assess the impacts of any overland flow management strategies within the floodplain (compared to those models established as part of previous investigations).

5. MIKE-STORM MODEL CONFIGURATION

5.1 Sub-catchment Layout

A detailed hydrological model representing the overall drainage system network within the study catchment was established using the MIKE-Storm software. The hydrological model covers a total catchment area of 250ha and comprises over 550 sub-catchments. The layout of the hydrological model sub-areas and corresponding drainage network is shown in Figures 5 and 6.

A sub-catchment area was specified at each pit or node accepting inflow into the system. This meant that every inlet pit, pipe inlet and channel junction in the model had an associated sub-catchment surface area producing inflow into the drainage system. Sub-catchment boundaries were manually delineated based on interpolation of the available topographic data, aerial photography and other similar information. For each sub-catchment, the portion of impervious area for each sub-catchment was determined from an inspection of aerial photographs and land use types from GIS information supplied by Council. The adopted indicative percentage paved for each land use type are tabulated in Table 4. It should be noted that these are only generic and were sometimes varied for particular sub-catchments where appropriate.

Table 4: Land Use Paved Percentage

Land Use	Percentage
General Residential	70
Road Reserve	75
Parkland and Open Space	10
Commercial and Industrial	85-95
Medium to High Density Residential	40-95

Note: Commercial and Industrial and Medium to High Density Residential were assessed on an individual basis as they tended to vary considerably. The percentages shown indicate the range in values determined.

5.2 Drainage Network and Catchment Definition

The drainage network and sub-catchment areas were defined utilising the asset data and detail survey collected by AWT, existing plans and reports (documented in Section 3) and topographic map information. The representation of the drainage system elements and overland flow paths in the MIKE-Storm model is discussed in the following sections.

5.2.1 Drainage System Elements

Figure 6 shows the location and extent of branches within the study catchment which have been included in the MIKE-Storm model. The drainage system defined in the model comprises:

- over 870 pits and nodes, including surface inlets, junctions, headwall inlets and outlets,
- over 880 links representing underground conduits (circular pipe or box) or channel lengths between nodes.

The MIKE-Storm drainage system model extends downstream as far as Mandible St (refer to Figure 6). For this study however, the MIKE-Storm hydraulic model was only used to produce results in the upper catchment area (refer to Figure 7). Due to the distance between the upper catchment area and the downstream extent of the model, the downstream boundary has little influence on the MIKE-Storm results presented in this study. For the remainder of the study area, the performance of the drainage system and overland flowpaths was determined using the SOBEK modelling software (refer to Section 6).

There are some cases where pits within the surveyed drainage network have buried lids or lids that could not be removed and hence the invert levels of these pits and pipes could not be surveyed. In these instances an estimation of the pit/pipe invert level was made based on an assumption of a cover of 400 mm to the top of the pipe. An additional check was made to ensure that pipe reach graded downstream (invert levels were adjusted where necessary).

The 400 mm cover assumption noted above is considered reasonable since it is conservative as it is the minimum pipe cover that would be generally expected.

The pits and nodes (inlets, bends and junctions) modelled in MIKE-Storm can be classified as being surface inlet pits (on-grade or sag) or otherwise (junctions and outlets).

Surface inlets located at low points are termed *sag inlets*. The inlet capacities for all pits (sag or on-grade) were determined based on a free overflow weir control with an effective weir length based on the inlet dimensions. For on-grade inlets, the effective weir length was reduced to account for the momentum of flow travelling past the pit (based on a 30% factor). The potential for pit blockages within the system was then accounted for by adopting a 20% blockage factor for on-grade pits and a 50% blockage factor for pits located at sag points. These blockage factors are typical of the values commonly adopted for these types of studies in other similar urban catchments.

Approximately 30% of all the pits in MIKE-Storm were modelled as *junction pits*. A junction pit is defined where there is no inlet to allow surface or bypass inflow (e.g. where two upstream branches combine or where two different sized conduits join), or where there is a significant bend in the alignment.

Being a fully dynamic model, MIKE-Storm calculates the headloss at pits for each time step. The total energy loss calculated is based on the sum of losses due to change in flow direction, change in elevation and losses associated with the expansion and contraction of flow as it passes through the pit.

Direct private property connections into Council's pipe system were not taken into account due to the lack of appropriate information. Hence, the present model configuration only allows runoff to enter the drainage system via street surface inlets. For the purposes of design flood estimation, this assumption is considered to be conservative given that a proportion of the runoff would enter the system via direct pipe connections from private properties, particularly for some of the larger industrial/commercial buildings.

A simplified representation of the drainage system was established for the catchment areas located to the south of Epsom Road due to the limitations of the available data. However, these areas have been conservatively represented in the model enabling the flow regime in Epsom Road to be established to a sufficient level of accuracy.

5.2.2 Definition of Overland Flow Paths

The overland flow paths defined in the MIKE-Storm model are shown in Figure 6. The definition of these overland flow paths was based on the locations of pits and the layout of roads, drainage reserves and other potential flow paths identified from site inspections, topographic information and available survey data. The extent of overland flow paths represented in the MIKE-Storm model was limited to the upper catchment area east of South Dowling Street. Downstream of South Dowling Street, the hydraulic behaviour of overland flows was assessed using a 2D modelling approach using SOBEK (refer to Section 6).

Apart from some detail survey at trapped low points, there was limited other topographic survey information available when the MIKE-Storm model was established in 2005. Formal flow paths such as roads, footpaths and drainage reserves were therefore defined based on "typical" cross-sections representing standard sections as per the following:

- full road,
- half road,
- footpath alone,
- road less footpath,
- drainage reserve (of varying width),
- flow path through private property.

In most cases, the particular flow path was modelled as a single branch (extending from pit to pit) that was linked into the overall network. However, the individual streets and roads were often represented in the model by two branches (left and right) with a sufficient number of interconnecting weirs to ensure that the flood behaviour along the roads was properly reproduced. The length and grade of each branch was based on the topographic data available in each location.

It should also be noted that the MIKE-Storm model was established prior to the collection of more detailed ALS/photogrammetry data covering South Dowling St and the Eastern Distributor roadway (and adjacent areas). However, overland flowpaths in these areas have been incorporated into the SOBEK model based on the ALS/photogrammetry surveys.

5.3 Key Model Parameters

5.3.1 Rainfall Losses and Soil Type (MIKE-Storm Hydrologic Component)

Losses from paved areas are considered to comprise only of an initial loss (an amount sufficient to wet the pavement and fill minor surface depressions). Losses from grassed areas are more complex. They are made up of both an initial loss and a continuing loss. The continuing loss was calculated within the model using Horton's infiltration relationship which is based on the estimated representative soil type and antecedent moisture condition. Being an event-based model, it is necessary to define an antecedent moisture condition to reflect the level of saturation of the soils within the pervious portions of the catchment at the start of the event.

For consistency with previous studies undertaken within the Sheas Creek catchment, it was assumed that the soil in the sub-catchments has a moderate rate of infiltration potential and the antecedent moisture condition was considered to be saturated (i.e. a soil type of 2 and an Antecedent Moisture Condition of 4 was adopted - refer to Table 5 for details). The latter was justified by the fact that the peak rainfall burst can typically occur within a longer storm event that possibly has a duration of a few days. The adopted parameters are summarised in Table 8.

Table 5: Adopted MIKE-Storm Hydrologic Model Parameters

RAINFALL LOSSES	
Paved Area Depression Storage (Initial Loss)	1 mm
Grassed Area Depression Storage (Initial Loss)	5 mm
SOIL TYPE	2
Moderate infiltration rates and moderately well-drained. This parameter, in conjunction with the Antecedent Moisture Condition, determines the continuing loss (defined by Horton's infiltration equation).	
ANTECEDENT MOISTURE CONDITIONS (AMC)	4
Description	Saturated
Total Rainfall in 5 Days Preceding the Storm	Over 25 mm

5.3.2 Time of Concentration (MIKE-Storm Hydrologic Component)

Overland travel times for surface runoff within a sub-catchment were calculated using the kinematic wave equation. This relationship is based on the nature of the sub-catchment and accounts for different travel times with varying rainfall intensities.

5.3.3 Manning's Roughness for Overland Flow Paths (MIKE-Storm Hydraulic Component)

Flow roughness parameters adopted for the overland flow paths (Manning's 'n' values which represent the friction resistance) were based on previous investigations and experience in similar catchments. In general, the adopted values applied to the standard cross-sections used to represent overland flow paths in the model were between 0.015 for roads and 0.035 for grassed areas.

6. SOBEK MODEL CONFIGURATION

6.1 Model Extents

As stated previously, a SOBEK hydraulic model was established for a large part of the study area, extending from just upstream (east) of South Dowling Street (including the Lenthall Street underpass) to downstream of Botany Road at Green Square (refer to Figures 6 and 7). The SOBEK hydraulic model incorporates the sub-surface drainage system and the overland flow paths within this area. These two components are dynamically linked such that the model takes into account interactions between the drainage system and overland flow behaviour.

The inflow boundary conditions for the SOBEK model were based on the results obtained from the MIKE-Storm model. Key model parameters and further details of the boundary conditions adopted for the SOBEK model are presented in the following.

6.2 Drainage System Elements

For consistency, the sub-surface drainage network for the SOBEK model was initially imported from the MIKE-Storm model. The basic topography and structure of the drainage system is consistent for both models, including invert levels and geometry for each element (refer to Section 5.2.1). As per MIKE-Storm, the sub-surface system has been modelled in 1D using a combination of pipe reaches and either surface-inlets or junctions/outlets nodes.

Unlike MIKE-Storm however, the SOBEK model does not implicitly calculate energy losses at pits in the pipe drainage network. Typically these types of losses result from changes in flow direction, changes in elevation and losses associated with the expansion and contraction of flow as it passes through the pit. It was therefore necessary to modify the SOBEK model configuration to account for these types of losses by incorporating an orifice at each exit from a pit. The geometry of the orifice was based upon the cross section of the pipe immediately downstream of the pit. Representative orifice coefficients were selected based on calibration against corresponding pit losses calculated in MIKE-Storm and in DRAINS.

Surface inlets to each pit were represented in a manner consistent with the MIKE-Storm model (described previously in Section 5.2.1).

6.3 Definition of Overland Flow Paths

In the main, overland flow paths were represented in the SOBEK model using a 2D digital elevation model although 1D elements were used in a limited number of locations. The 2D component of the model was established based upon on a digital terrain model (DTM) compiled from the available survey information, incorporating photogrammetry, ALS, and detailed survey as appropriate. The extents of the SOBEK model grid are shown in Figure 7. The model topography was derived using a regular grid of 2 m x 2 m cells across the model extent. This fine spatial resolution was adopted to better resolve significant localised ground details and other hydraulic control features.

Large buildings and other significant features likely to act as flow obstructions were also incorporated into the model network based on surveyed building footprints and available aerial photography. These types of features were modelled as impermeable obstructions to the flood waters.

Certain flow paths within the model domain were represented using 1D channel reaches to better represent the flow behaviour in some instances. Examples of these types of locations include the open stormwater channel downstream of Link Road and the access easement running along the rear of properties between Lenthall Street and Ingram Street, downstream of Virginia Street. Cross-sections for these reaches were based on available survey.

6.3.1 Manning's Roughness for Overland Flow Paths (SOBEK)

The hydraulic efficiency of the flow paths within the SOBEK model is represented in part by the hydraulic roughness or friction factor formulated as Manning's 'n'. This factor describes the net influence of bed roughness and incorporates the effects of vegetation and other features which may affect the hydraulic performance of the particular flow path.

Much of the ground surface is paved and/or cleared ground within the SOBEK model extents. However, there numerous instances of small localised features and pockets of vegetation adjacent to the main roadways and within individual sites. In view of this, a Manning's 'n' of 0.015 was adopted within the road reserve (defined by Council's cadastre) and a higher value of 0.03 was adopted across the remainder of the model. The sensitivity of the model results to the assumed roughness factors is assessed later in Section 10.

7. MODEL VALIDATION

7.1 Overview

Ideally once the various models have been established, it is preferable to calibrate the model parameters using a suitable historical event. The performance of the calibrated model can then be verified against one or more other historical events. To calibrate/verify the models requires a sufficient amount of flood data for each historical event within the modelling extent.

For the present study, the November 1984 storms are the largest of recent events for which there is a limited amount of flood height data available. Due to the relative lack of detailed flood data in addition to the significant catchment changes that have taken place since these events, the following is a limited model validation only. However the outcomes are still useful as they provide an indication of the ability of the models to perform within reasonable limits.

When flooding occurs within the catchment in future, it is recommended that Council (or the relevant authority) undertake to collect any available information (rainfall data, flood heights, etc.) as soon as practicable after the event (including after smaller, more frequent flooding such as would be expected in the 50% AEP event).

7.2 Approach

The various models were validated using the storm events of 5th November 1984 and 8th and 9th November 1984. Compared to existing conditions, there have been a number of significant changes within the catchment since this time. In the absence of detailed information to accurately define historical conditions, key changes were identified using 1986 aerial photography and in consultation with Council/DECC officers. The following changes were made to the existing model configurations:

- the levels in proximity of the Eastern Distributor were adjusted to reflect the approximate levels of South Dowling Street,
- the noise walls adjacent to the Eastern Distributor were removed on either side of South Dowling Street,
- potential overland flow connections east of South Dowling Street (between Lenthall Street and Ingram Street) were reinstated,
- the additional flood storage provided by detention basins constructed since 1984 was removed from the model (including the Tote Park, Joynton Park and Nuffield park basins within Victoria Park).

As there is no continuous rainfall recording device within the study catchment, pluviometer records from several nearby stations were used to define the hydrology for the 1984 events. Given the spatial variation in both the timing and total depth of recorded rainfall, separate runs were undertaken in which the storm pattern was defined by individual station records. Following a review of the available data, rainfall records from pluviometers at Avoca Street (UNSW) and Paddington

(BoM) were selected for use as they provide a reasonable representation of variability of rainfall for these events (refer to Figure 9). The model runs of each event (5th November and 8th/9th November) were undertaken using the rainfall records from each pluviometer for a total of four validation runs.

7.3 Results and Discussion

The corresponding model results are compared to reported instances of flooding in Table 6. Note that the observed flood heights are associated with the event of 8-9 November 1984 (the model results for the November 5 event have been included for completeness).

Table 6: Model Validation Results - November 1984 Storms

Location	Recorded Ponding Depth (m)	Estimated Level (mAHD)	Model Results 5 Nov. 1984 (mAHD)		Model Results 8-9 Nov. 1984 (mAHD)	
			RUN A Avoca St. Pluvi. Station	RUN B Paddington Pluvi. Station	RUN C Avoca St. Pluvi. Station	RUN D Paddington Pluvi. Station
Joynton Ave. Patient Care Facility/ Footpath (Ref. 2)	1.0 / 1.2	18.8 - 19.3[(1)]	19.0	18.2	18.7	19.0
Milroy Avenue (Ref. 1)		25.2 - 25.5	25.6	24.4	24.7	25.2
McDougall St. (Ref. 1)		24.6 - 24.9			24.5	24.7
Lenthall St. (Ref. 1)		21.3 - 21.7			21.7	22.1
Balfour St.(Ref. 1)		25.1 - 25.3	24.6	24.5	24.5	24.6

Notes:

(1) Range of estimated levels based on available ground survey within property. To be confirmed should floor level of ex-patient care facility be obtained.

The comparisons in Table 6 suggest that the models reproduce the observed flood heights for the November 8/9 event reasonably well at a number of key locations including Joynton Avenue, Milroy Avenue and McDougall Street. The results obtained using the Paddington rainfall records were found to compare well with the available information whilst the use of the Avoca Street rainfall record typically produced lower flood level estimates.

Poorer comparisons between modelled and observed flood heights occurred at Lenthall Street and Balfour Street. At Lenthall Street, the model results were found to be at least 0.4 m higher than observed levels. A more detailed review of results in this area suggests that the tendency of the model to produce higher flood level estimates can be attributed to the ability of overland flow from the Lenthall Street low point to re-enter the main trunk stormwater channel on the downstream side of South Dowling St. The current access is via an inlet point underneath a building and is only approximately 0.3 m high and 2.0 m wide (refer to Photographs 4 and 5).

Photo 4: Inlet point for overland flow into stormwater channel downstream of South Dowling St and Lenthall St low point

Photo 5: View through inlet in Photo 4, looking downstream at stormwater channel.

A review of the 1986 aerial photography of this site indicates that the building shown in Photographs 4 and 5 above did not exist although it is not of sufficient detail to indicate the previous inlet configuration. However, it is conceivable that the ability of overland flow to enter the stormwater channel may have been very different to current conditions. A more efficient access at this location is likely to influence the level of ponding in this area and in the Lenthall Street low point upstream.

At Balfour Street, the model was found to underestimate the observed flood heights by at least 0.6m. A review of the model results in the broader area in comparison to the anecdotal evidence documented in Reference 1 suggests that this discrepancy may be attributed to the limited base survey information being used in the model for this area. Further comparison against any available detail survey is needed before a more definitive explanation of these discrepancies can be made.

Notwithstanding the above and given the reasonable results obtained in other areas of the catchment, the validated models are considered suitable for design flood estimation purposes. It is also recommended that the model performance be re-assessed against flood data obtained from any future floods within the catchment.

8. DESIGN EVENT MODELLING

8.1 Approach

The various models described previously were used to estimate the design flood behaviour across the study catchment under existing conditions. A number of design storm events were analysed from the 50% AEP event to the 1% AEP (1 in 100 year) event through to the Probable Maximum Flood (PMF).

The traditional ARR87 approach to design storm hydrology is based on the estimation of a peak flow generated by a critical duration peak burst rainfall pattern. The method assumes that antecedent rainfall prior to the critical duration burst does not impact upon the peak flow estimates (Reference 12). Several other studies indicate that a failure to incorporate antecedent conditions prior to the critical duration peak burst may result in the underestimation of peak flows for some catchments (References 13 and 14). As noted in Reference 12, this is particularly the case for catchments where the ARR87 critical burst durations are much shorter than the duration of historic flood-producing storms. For the Green Square-West Kensington catchment, there is a significant chance that high-intensity short duration storm bursts likely to cause major flooding will occur during a broader low intensity, longer duration storm.

To address these issues, this study adopts an alternative approach to design flood estimation whereby a critical duration design storm burst is embedded within a longer duration storm of the same ARI. This approach was originally presented in Reference 13 and has been further documented in Reference 12. Initially, the critical burst is embedded to coincide with the peak of the larger duration storm. To ensure that the average intensities reflect the original ARIs the intensities of the longer duration storm are adjusted on either side of the peak burst are adjusted such that the total rainfall depth is consistent with that of the original longer duration storm. Further details regarding the procedure can be found in References 12 and 13.

For the present study, the duration of the longer storm was selected based upon recorded rainfall patterns from the November 1984 events given that these storms were known to have caused significant flooding throughout the study catchment. Pluviograph records from the Paddington and Avoca Street (Randwick) stations indicate that the majority of rainfall fell within a period of between three to six hours in duration (refer Figure 9). On this basis a 6 hour duration storm was selected as the longer duration storm within which a shorter duration design burst was embedded. The use of a six hour duration storm also meant that computational run times for the detailed hydraulic models were kept within reasonable limits.

The sensitivity of the design flood results to the embedded design storm approach (compared to the standard ARR87 peak burst approach) is discussed in Section 10.

8.2 Boundary Conditions

8.2.1 Design Rainfalls (MIKE-Storm Hydrologic Component)

Design rainfall depths and temporal patterns across different durations for the study catchment were obtained from Australian Rainfall and Runoff 1987 (ARR87) for events up to and including the 500 year ARI event (Reference 7). Probable Maximum Precipitation (PMP) estimates were derived according to current BoM guidelines (Reference 15). A summary of the design rainfall data is provided in Table 7.

Table 7: Design Rainfall Data

Duration		Average Recurrence Interval						PMP
		2y	5y	20y	50y	100yr	500y	
30 minutes	intensity in mm/h	62	81	106	124	139	172	480
	depth in mm	31	40	53	62	69	86	240
1 hour	intensity in mm/h	43	57	75	89	100	125	350
	depth in mm	43	57	75	89	100	125	350
1.5 hours	intensity in mm/h	33	43	58	68	76	96	293
	depth in mm	50	65	87	102	114	144	410
2 hours	intensity in mm/h	27	36	47	56	63	79	235
	depth in mm	55	72	95	112	126	158	470
3 hours	intensity in mm/h	21	27	36	43	48	60	180
	depth in mm	63	81	108	128	143	179	540

The resulting rainfall hyetographs were converted by the MIKE-Storm hydrologic model into paved and grassed area runoff hydrographs as a function of the contributing surface area and rainfall losses. The paved and pervious area hydrographs are then superimposed to give total runoff hydrographs for each sub-catchment.

8.2.2 Inflow Hydrographs (MIKE-Storm Hydraulic Component)

The routing of the runoff from each sub-catchment through the drainage network and via overland flow paths was then assessed using the hydraulic models. The runoff hydrographs from each individual sub-catchment were used to define inflow boundary conditions to the MIKE-Storm model.

8.2.3 Downstream Boundaries (MIKE-Storm Hydraulic Component)

The downstream boundaries for the MIKE-Storm hydraulic modelling have been adopted based on the limited study extent defined under the original project brief. However, the scope of the current study has been extended such that the areas where the MIKE-Storm hydraulic model is being used to define design flood levels are located well beyond of the model boundaries. In effect, this means that the assumed downstream boundaries for the MIKE Storm model have no influence upon the MIKE-Storm model results in the upper reaches of the West Kensington catchment area.

8.2.4 Inflow Hydrographs (SOBEK Model)

To link the MIKE-Storm and SOBEK overland flow models and provide a consistent description of the design flood behaviour within the overall study area, the main inflow boundary conditions for the SOBEK model were derived from the MIKE-Storm model results.

The upper, eastern portions of the drainage system and overland flow paths enter the SOBEK model domain east of South Dowling Street (refer to Figure 8). At these locations, the flow hydrograph for each design event from the MIKE-Storm model results was used as the corresponding upstream inflow boundary for the SOBEK model. Boundaries defined in this manner included piped and overland flows from the Australian Golf Course, Lenthall Street, Virginia Street, Baker Street, Cooper Place and Todman Avenue.

For each of the local sub-catchments draining within the SOBEK model domain, local runoff hydrographs were extracted from the MIKE-Storm model and specified as inflow sources to the corresponding inlet pits in the SOBEK model.

Results from previous studies of adjoining catchments indicated that there was also the potential for runoff from an adjacent catchment to enter the study catchment via Bourke Street. An examination of the DRAINS model established for Reference 3 indicates the presence of a trapped low point at the intersection of Hunter Street and Powells Street. For larger events (greater than the 5% AEP event (approximately), a portion of the overland flows spilling from this depression travel down Bourke Road via Elizabeth Street. The existing DRAINS model was run for all the design recurrence intervals used in the present study. In the absence of data in the existing DRAINS model for the 0.2% AEP and PMF events, an inflow hydrograph was established by scaling the 1% AEP hydrograph proportionately. For each design event, the corresponding inflow hydrograph at this location was used to define the inflows into the SOBEK model along Bourke Road (refer to Figure 8).

8.2.5 Downstream Boundaries (SOBEK Model)

A range of downstream boundary conditions were adopted in the SOBEK model as shown on Figure 8. Following a site inspection and a review of available survey data, the locations of these boundaries were defined so as to minimise the influence of any boundary condition assumptions on the flood behaviour within the immediate study area.

For overland flow boundaries, boundary conditions were specified as either critical or uniform depth flow controls as appropriate based on available survey. For Wyndham Street, the limited survey available suggests that flows from the upper catchment are unlikely to overtop into the adjacent catchment except for events larger than the 1% AEP event (approx.). In the absence of more detailed survey information no open boundary was specified along this street. However, it is recommended that this condition be reviewed should more detailed survey in this area become available. In any case, the adopted boundary at this location would provide a conservative estimate of flood behaviour at the downstream reaches of the study area.

In terms of the drainage network in SOBEK, flows within the trunk drainage system discharge via the culvert headwall inlet located immediately upstream of Mandible Street (refer Figure 8). This inlet represents a hydraulic control at this point in the trunk drainage system. A stage-discharge relationship was therefore established based on the inlet dimensions and the characteristics of the overland flow path above the inlet. This particular boundary is located at a sufficient distance downstream such that the assumptions given in establishing this downstream boundary would have minimal influence on the modelled flow regime within the study area.

9. DESIGN FLOOD RESULTS

9.1 Overview

The numerical models were run for a number of design events and the results used to provide a description of the design flood behaviour of the study area. Information such as peak flood levels, flows and velocities were extracted and have been documented as part of this report. In addition, the model results have also been produced in a digital format that can be readily imported into Council's GIS systems.

9.2 Critical Storm Duration

The determination of the critical storm duration for an urban catchment is more complex than for a rural catchment. Consideration must be taken of:

(1) the peak flow from the sub-catchment surface,
(2) the peak flow arriving at a surface inlet pit from upstream (conduit and overland flows),
(3) the peak flow in the pit,
(4) the volume temporarily collected in ponding areas,
(5) the location within the catchment.

Standard ARR87 storm burst durations ranging from 5 minutes to 3 hours embedded in a 6 hour storm were run for the 1% AEP event. The corresponding peak flow and water level estimates were then compared. The critical burst duration was found to vary across the catchment ranging from 45 minutes to 90 minutes. However, a detailed review of the results showed that the relative differences between these storm durations were only minor within the main study area (within 0.025 m). In addition, the 60 minute storm was found to be the critical storm burst duration in terms of peak flows and water levels at several key locations within the study area, including the ponding depth at Joynton avenue and the outflow at Portman Street in particular. The 60 minute in 360 minute embedded storm was therefore adopted as the representative critical duration for the study area to ensure consistency in results and reporting. **However, it is recommended that the full range of storm durations are considered if undertaking detailed investigations for drainage upgrade works within the catchment.**

9.3 Model Results

An overview of the design flood estimates obtained for a range of recurrence intervals is shown on Figures 10 to 23. The results are presented in terms of peak flows both within the drainage network and along overland flow paths in the upper West Kensington catchment. A tabulated summary of peak flows at selected locations throughout the catchment is also provided in Table 8. A longitudinal profile showing peak flood heights along the Raleigh Park overland flow branch is provided in Figure 24 (for the range of recurrence intervals analysed).

Table 8: Summary of Flows at Key Locations (m^3/s)

Location	50% AEP			20% AEP			5% AEP			2% AEP			1% AEP			0.2% AEP			PMF		
	Piped	Overland	Total	Piped	Overland	Total	Piped	Overland	Total	Piped	Overland	Total	Piped	Overland	Total	Piped	Overland	Total	Piped	Overland	Total
Portman Street Overflow	17.9	0.0	17.9	19.3	0.0	19.3	20.8	3.6	24.4	21.2	7.4	28.5	21.5	11.6	33.1	22.1	22.9	45.1	24.8	93.7	118.5
Epsom Road Outflows	-	2.0	2.0	-	3.0	3.0	-	4.3	4.3	-	4.9	4.9	-	5.5	5.5	-	6.9	6.9	-	36.3	36.3
Joynton Avenue (From South)	0.5	3.12	3.7	0.5	4.54	5.1	0.5	6.39	6.9	0.5	7.31	7.8	0.5	8.22	8.7	0.5	10.2	10.7	0.6	24.4	25.0
Joynton Avenue (From East)	8.6	0.0	8.6	8.8	0.4	9.2	9.2	5.0	14.2	9.2	7.8	17.0	9.2	10.1	19.3	9.3	15.4	24.8	9.3	41.8	51.0
Joynton Avenue (From North)	7.0	3.3	10.4	7.3	5.0	12.3	7.3	9.8	17.1	7.4	12.8	20.1	7.4	15.5	22.9	7.4	21.2	28.6	8.9	84.0	92.9
From Lachlan Street	1.9	0.1	2.0	1.9	1.1	3.0	1.9	3.3	5.2	1.9	4.4	6.3	2.0	5.6	7.5	2.0	8.2	10.2	2.1	28.9	31.0
O'Dea Avenue	1.4	0.0	1.5	1.5	0.8	2.3	1.5	2.5	4.1	1.5	3.5	5.0	1.6	4.5	6.1	1.6	6.7	8.2	1.6	19.1	20.7
Todman Avenue	-	0.1	0.1	-	0.2	0.2	-	0.4	0.4	-	0.4	0.4	-	0.5	0.5	-	0.7	0.7	-	2.0	2.0
Raleigh Park	2.0	0.1	2.1	2.2	1.8	4.0	2.2	4.2	6.4	2.2	5.5	7.7	2.2	6.6	8.8	2.3	9.1	11.4	2.6	23.7	26.3
Baker Street	1.8	-	1.8	2.0	-	2.0	2.1	-	2.1	2.1	-	2.1	2.1	-	2.1	2.1	-	2.1	2.4	-	2.4
Myrtle Street	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.2	0.3	0.1	0.6	0.7	0.1	0.9	1.0	0.1	2.6	2.7	0.2	17.3	17.6
Lenthall Street	0.3	0.4	0.7	0.3	0.6	0.9	0.3	0.9	1.2	0.3	1.0	1.3	0.3	1.2	1.4	0.3	1.5	1.8	0.3	4.5	4.8
The Australian Golf Course	1.8	1.3	3.0	1.8	3.4	5.2	1.7	5.8	7.5	1.7	7.1	8.8	1.7	8.2	9.9	1.7	10.8	12.5	1.7	20.9	22.6
Link Road Open Channel	7.5	-	7.5	9.2	-	9.2	12.4	-	12.4	14.1	-	14.1	14.8	-	14.8	15.7	-	15.7	18.2	--	18.2
Coopers Place, Victoria Park	1.4	0.0	1.4	2.0	0.0	2.0	2.2	0.0	2.2	2.3	0.1	2.4	2.5	0.2	2.6	2.4	0.5	2.9	3.1	2.9	5.9
Victoria Park Central Basin Outflows	3.5	0.0	3.5	3.8	0.0	3.8	3.9	0.0	3.9	4.0	0.1	4.0	3.7	0.4	4.1	3.6	2.5	6.2	6.1	19.3	25.4
From Virginia Street	-	0.2	0.2	-	0.4	0.4	-	1.8	1.8	-	3.0	3.0	-	3.9	3.9	-	5.1	5.1	-	8.8	8.8
City of Sydney Works Depot Piped	7.7	-	7.7	8.3	-	8.3	8.1	-	8.1	7.9	-	7.9	7.5	-	7.5	7.3	-	7.3	10.8	-	10.8
Bourke Street (inflow u/s boundary)	-	0.0	0.0	-	0.0		-	0.9	0.9	-	4.9	4.9	-	7.0	7.0	-	10.5	10.5	-	27.5	27.5
O'Riordan Street (outflow d/s boundary)	-	1.1	1.1	-	1.5	1.5	-	2.1	2.1	-	2.4	2.4	-	2.8	2.8	-	4.3	4.3	-	22.0	22.0
Bourke Street (outflow d/s boundary)	-	0.1	0.1	-	0.2	0.2	-	2.3	2.3	-	6.9	6.9	-	11.5	11.5	-	21.3	21.3	-	95.6	95.6
Todman Ave & Balfour St	1.0	2.3	3.3	1.0	3.7	4.7	1.1	5.5	6.5	1.0	6.4	7.5	1.0	7.5	8.5	1.0	10.0	11.0	1.3	26.4	27.7
Todman Ave & Baker St	2.4	0.3	2.6	2.8	1.3	4.1	2.8	4.0	6.7	2.8	5.4	8.1	2.8	6.5	9.3	2.8	10.1	12.9	3.0	21.9	25.0

Within the 2D model domain in the lower catchment, the model results have been presented in terms of peak flood heights, peak depths and peak flow velocities for each design event (shown in Figures 25 to 38).

For the purposes of floodplain risk management in NSW, the floodplain is broadly divided into one of three Hydraulic categories (floodway, flood storage or flood fringe) and two Provisional Hazard categories (Low or High). Further details of this process are outlined in the NSW Government's Floodplain Development Manual (Reference 16). Based on the design flood information produced from this Flood Study, it is envisaged that detailed hazard mapping and hydraulic categorisation would be undertaken as part of a subsequent Floodplain Management Study. However, in the interim, maps of the provisional hydraulic hazard (peak velocity x peak depth product) for the 1% AEP and the PMF have been produced (refer to Figures 39 and 40). For the purposes of the present study, this approach provides a conservative estimate of provisional flood hazard.

9.4 Accuracy of Estimated Flood Levels

The likely accuracy of the modelling results is expected to be within ±0.5 m for areas within the 2D portion of the hydraulic model and in those trapped low points within the Randwick City Council LGA that have been defined using detail survey information (i.e. most of the significant trapped low points). Outside of these areas (i.e. within much of the remaining 1D portion of the model) the accuracy is likely to be in the order of ±1.0 m.

9.5 Results at Joynton Avenue

A schematic summary of the modelled behaviour at Joynton Avenue for the embedded 60 minute 1% AEP design storm is shown in Figure 41. This schematic shows that the flow into the Joynton Avenue depression arrives from a number of sources including:

- flow along Joynton Avenue from the North,
- flow along Joynton Avenue from the South, and
- flows entering from the East (via the disused Council site).

To properly interpret the peak flow results, it is important to examine the corresponding flow hydrographs from the various component sub-catchments and drainage system elements. The total inflow and outflow hydrographs for the Joynton Avenue depression are shown in Figure 42. These hydrographs are presented in terms of conduit and overland flow components in Figure 43. Figure 44 shows the inflow hydrographs arriving at the Joynton Avenue depression from each of the major sub-catchments.

10. SENSITIVITY ANALYSES

10.1 Overview

The models established for the present study rely on a number of assumed parameters, the values of which are considered to be the most appropriate for urban catchments based on previous use and experience in other studies of similar catchments. Although a limited model validation has been performed, a range of sensitivity analyses were also undertaken to quantify the potential variation in the model results due to different assumptions in the key modelling parameters adopted.

The following scenarios were considered to represent the envelope of likely parameter values:

- ±20% change in design rainfall,
- increase amount of rainfall losses (low runoff potential) Initial Loss: paved = 2 mm, grassed = 10 mm, AMC = 1,
- decrease amount of rainfall losses (high runoff potential) Initial Loss: paved = 0 mm, grassed = 0 mm, AMC 4 (unchanged),
- Soil type = 1 (high infiltration, low runoff potential),
- Soil type = 4 (very slow infiltration, high runoff potential),
- ±20% change in Manning's 'n' value for overland flow paths.

When interpreting the results, it should be noted that undertaking sensitivity analyses for the drainage system may not always result in a change in peak flow attained downstream if for instance the size of the pipe or pit is the control and there is no change in the flow conveyed in the pipe. There may be a change in the overland flow but the effect further downstream will depend on the particular characteristics of the pit and pipe network. At some locations the change in upstream flow may not be reflected downstream due to the effects of ponding at sag pits or the relative timing of overland flows.

10.2 Results

For each of the above scenarios, the models were run for the 1% AEP embedded 60 minute duration design storm. A relative comparison of the resultant changes in peak overland flows and flood heights at various locations is provided in Tables 9 and 10.

Table 9: Sensitivity Analyses - Change in Peak Flow for 1% AEP Design Event (%)

Location	+20% Rain	-20% Rain	+Losses	-Losses	Soil 1	Soil 4	+20% Manning's	-20% Manning's
Portman Street Outflows	128%	77%	95%	101%	95%	106%	96%	104%
Epsom Road Outflows	120%	78%	99%	100%	99%	101%	94%	104%
Joynton Avenue South	114%	82%	99%	100%	99%	100%	96%	104%
Joynton Avenue East	123%	78%	94%	101%	94%	107%	95%	105%
Joynton Avenue North	120%	77%	93%	101%	94%	103%	96%	104%
From Lachlan Street	127%	70%	88%	101%	90%	106%	97%	103%
O'Dea Avenue	129%	69%	89%	101%	92%	107%	100%	101%
Todman Avenue	122%	67%	88%	96%	88%	102%	102%	100%
Raleigh Park	122%	75%	91%	101%	92%	107%	94%	107%
Baker Street	100%	99%	100%	100%	100%	100%	87%	108%
Myrtle Street	224%	41%	79%	103%	79%	124%	93%	118%
Lenthall Street	117%	78%	98%	97%	98%	99%	102%	99%
The Australian Golf Course	121%	78%	94%	101%	94%	106%	96%	105%
Link Road Open Channel	105%	88%	97%	100%	97%	102%	97%	102%
Victoria Park East	102%	81%	92%	98%	94%	95%	95%	100%
Victoria Park Central Basin Outflows	139%	99%	95%	99%	98%	103%	100%	99%
From Virginia Street	127%	55%	88%	101%	87%	111%	97%	108%
Link Road Piped and Overland	97%	107%	101%	100%	102%	99%	99%	101%
Todman Ave & Balfour St	123%	78%	97%	101%	97%	103%	98%	102%
Todman Ave & Baker St	121%	75%	91%	101%	92%	107%	94%	106%

Table 10: Sensitivity Analyses - Change in Peak Flood Height for 1% AEP Design Event (m)

Location	+20% Rain	-20% Rain	+Losses	-Losses	Soil 1	Soil 4	+20% Manning's	-20% Manning's
Joynton Avenue	0.12	-0.13	-0.03	0.01	-0.03	0.03	-0.01	0.00
Botany Road	0.16	-0.20	-0.04	0.01	-0.04	0.04	-0.01	0.00
Lenthall Street	0.09	-0.18	-0.04	0.01	-0.04	0.04	-0.01	0.01
Joynton Park Retention Basin	0.14	-0.26	-0.03	0.00	-0.03	0.03	0.01	-0.01
Lachlan Avenue	0.08	-0.09	-0.04	0.00	-0.03	0.02	0.01	-0.01
South Dowling Street	0.04	-0.06	-0.02	0.00	-0.01	0.01	0.01	-0.01
Cnr O'Dea and Joynton	0.03	-0.04	-0.01	0.00	-0.01	0.01	0.04	-0.05
Winkurra Street	0.14	-0.16	-0.02	0.00	-0.02	0.02	0.00	0.00
Epsom Road Warehouse/Council Depot	0.12	-0.12	-0.03	0.01	-0.04	0.04	0.00	0.00

The results from the sensitivity analyses can be summarised as follows:

- a ±20% change in the rainfall produces a corresponding 20% to 40% (approximately) change in peak overland flow,
- increasing the amount of rainfall losses and changing the AMC to 1 has reduced the peak overland flows by up to 60%,
- decreasing the amount of rainfall losses and maintaining the AMC to 4 typically has resulted in little change,
- by changing the soil type to 1, peak overland flows have generally decreased by up to 21% but typically has resulted in little change,
- alternatively the soil type 4 generally resulted in increased peak overland flows of up to 10%, as expected from the very slow infiltration, high runoff potential soil type,
- increasing the Manning's 'n' value for overland flow paths caused a greater attenuation of flows and generally resulted in a reduction in peak flows of up to 10%. However, there were some locations where the peak flows were increased. This could be attributed to the relative timing of overland flows from contributing sub-catchments. The converse of these observations holds true for the effect of decreasing Manning's 'n' values by a similar amount.

In terms of the corresponding impacts on flood height estimates, the greatest variations were caused by ±20% variations in the applied rainfall. For these rainfall scenarios, flood levels were found to vary by between ±0.1 m to ±0.3 m compared to the base case.

The outcomes indicated that the estimated flood levels were much less sensitive to variations in other model parameters with results for the other scenarios being typically within ±0.1 m of the base case results. In terms of assumed infiltration rates, the results show that the adopted parameters are reasonably robust and do not have a notable impact on estimated 1% AEP flood levels for this catchment. However, given the relatively sandy nature of the upper soils typically found in this and adjacent catchments it is recommended that opportunities for testing of soil infiltration and/or the monitoring of runoff behaviour in pervious open space areas be pursued in the future (in coordination with other relevant agencies).

10.3 Embedded Design Storm Hydrology

Results at key locations were compared, and the embedded storm approach was found to generally result in higher peak flows and flood levels across the catchment. Table 11 presents the flood results at the trapped low-point in Joynton Avenue in the lower part of the catchment. The flood behaviour at this location is critical to a number of major urban re-development projects planned in this area.

Table 11: Comparison of Embedded Storm vs. Burst Storm Results

Design Storm Type	Peak Flood Level at Joynton Avenue Depression (mAHD)	Peak outflow from Joynton Avenue west over Portman Street (m^3/s)
100yr ARI 60 minute design storm burst	18.90	7.9
100yr ARI 60 minute design storm burst embedded in 100yr ARI 360 minute design storm	18.96	11.7

It can be seen that the peak flow at Portman Street is nearly 50% greater for the embedded design storm than for the design storm burst alone. The flood level and Joynton Avenue shows less variability, but this is largely a reflection of the available flood storage in this location.

Based on previous studies and observations, the results when using the embedded storm approach are more consistent with other estimates for the 100yr ARI discharge at Portman Street.

11. COMPARISON OF RESULTS WITH PREVIOUS STUDIES

11.1 Overview

A number of stormwater related studies have been undertaken within the current study area. As described in Reference 2, the primary objectives of the more recent studies were to describe the stormwater behaviour within the catchment to a level of detail sufficient to facilitate broader development plans within the overall catchment. In this context, quantitative estimates of design flood behaviour were obtained using the DRAINS stormwater modelling software making best use of the data then available. A hydraulic analysis of the study area between Portman Street and Botany Road was also undertaken (Reference 3).

The following outlines the key differences between the results of the current study with those published previously for the 1% AEP design event. These comparisons have been undertaken using reported information at two key locations. The first location is the Joynton Avenue area which receives inflows from the West Kensington area and a significant portion of the upper catchment within the City of Sydney LGA. The flood estimates obtained for the area downstream of Portman Street through the proposed GSTC area are then compared to those obtained from previous studies.

11.2 Joynton Avenue Area

11.2.1 Comparison of Results

The DRAINS model results for the 1% AEP 60 minute duration are presented on Figures 42 to 44. The corresponding SOBEK results for the 1% AEP embedded design storm (60 min critical duration embedded within a 6 hour duration storm) are also shown. For comparison purposes, the SOBEK results have been plotted such that the start of the critical duration burst aligns with the start of the DRAINS model results.

In terms of the piped system, the results indicate that the DRAINS model responds slightly earlier, although during the middle of the event, the estimated piped inflows are reasonably consistent between the two models (compare the hydrographs between say t=20 min and t=40 min). It should be noted that the SOBEK pipe inflow hydrograph extends well beyond that of the DRAINS results due to the embedded design storm approach adopted in the SOBEK model (based on a 6 hour duration storm).

The most significant differences between the two models can be seen in terms of the estimated overland flows into the Joynton Avenue depression where the corresponding estimates of peak (overland) inflow were 34 m^3/s and 23 m^3/s for the DRAINS and SOBEK models respectively. In contrast to the single peak hydrograph obtained from the DRAINS model, the corresponding SOBEK results exhibit a broader double peaked hydrograph. Whilst the differences in the shapes of the overland flow hydrographs can be partly attributed to the embedded storm approach adopted in the SOBEK model, these discrepancies also reflect fundamental differences in terms of representation of flood storage and overland flow behaviour between the DRAINS and SOBEK models.

These differences are best illustrated by examining the relative timing of overland inflows from the major sub-catchments draining to Joynton Avenue (Figure 44). The DRAINS model results show that the inflows from each of the major sub-catchments peak at approximately the same time (particularly for the major contributions from the northern and eastern parts of the catchment). In contrast, the SOBEK model results show greater differences in the time-to-peak for each major sub-catchment. As expected inflows from the southern area peak first. This reflects the proximity of this area to Joynton Avenue. Inflows from the northern sub-catchment peak approximately 10 minutes later. However both the sub-catchments peak approximately 30 minutes prior to the overland flows entering from the east. These trends reflect differences between each of the sub-catchments. For the eastern area, overland flow paths are not well defined and there are a number of trapped low points (e.g. Lenthall Street). The effective flood storage and relatively low hydraulic efficiency of these features acts to attenuate the runoff from this portion of the catchment. In contrast, excess runoff from southern and northern parts of the catchment is mainly directed along roadways which are relatively much more efficient compared to the informal flow paths found in the eastern sub-catchment.

Table 12: Peak Flows at Joynton Avenue - Comparison of Results (1% AEP 60 min Storm)

	DRAINS (m^3/s)		SOBEK (m^3/s)	
	Peak Flow (m3/s)	Time to Peak (mins)	Peak Flow (m3/s)	Time to Peak (mins)
INFLOWS				
North - overland	16.8	30	15.5	35
North - piped	10.6	22	7.4	17
North - total	27.3	30	22.4	35
East - overland	15.5	32	10.1	67
East - piped	9.3	11	9.2	23
East - total	21.5	32	18.5	65
South - overland	4.4	26	8.2	27
South - piped	1.0	10	0.5	12
South - total	5.3	26	8.5	27
Portman St - overland	1.0	10	-	
Portman St - piped	-	-	-	
Portman St - total	1.0	10	-	
OUTFLOWS				
Overland (Portman Street)	23.1	45	11.6	57
Overland (Epsom Road)	3.4	47	5.5	28
Piped	26.2	44	21.2	42
TOTAL FLOWS				
Inflow - overland	36.8	30	22.5	35
Inflow - piped	19.6	13	16.8	18
Inflow - total	54.1	30	38.4	35
Outflow - overland	26.1	45	13.2	57
Outflow - piped	26.2	44	21.2	42
Outflow - total	52.2	45	34.2	57

11.2.2 Discussion

In view of the results discussed in Sections 8.1 and 8.2, the key differences between the predicted design flood behaviour for the Joynton Avenue trapped depression can be attributed to a range of factors including:

- the representation of temporary flood attenuation storage throughout the entire catchment system,
- the type of features assumed to control overland flows discharging from Portman Street,
- fundamental differences in the governing assumptions used in the two different software packages.

Representation of Distributed Storage Throughout the System

In addition to the trunk drainage system modelled previously using DRAINS, the models prepared for the present study also incorporates a majority of the minor drainage system. The use of a more detailed model has important implications in that it allows for:

- a more refined description of catchment behaviour due to the increased number of sub-catchments being modelled (i.e. many smaller sub-catchments that had previously been lumped together as larger sub-catchments with less opportunity for inflows to directly enter the system), and

- a greater resolution and improved representation of the distributed flood storage provided by the piped drainage network and overland flow paths.

The influence of these factors can be seen by comparing the nature of the estimated inflows into the Joynton Avenue depression. In comparison to the DRAINS model, the current models show significant differences in the response of the contributing sub-catchments. This can be attributed to the net effects of better representing flood storage throughout the floodplain and the propagation of floodwaters through the catchment.

Assumed Features Controlling Outflows from Portman Street

The current SOBEK model incorporates a different representation of the key features likely to control the discharge of overland flows downstream of Portman Street. Being a 2D model the SOBEK model better represents the flow distribution across Portman Street and the effects of the available storage within the Joynton Avenue area. In addition, the SOBEK model accounts for the restricted primary overland flow path between Joynton Avenue and Portman Street (along the northern boundary of the Community Health Complex site).

Different Underlying Assumptions

The differences between the two sets of model results are also a direct consequence of the different governing assumptions used to simulate the flow of stormwater through a drainage system.

For the piped drainage and overland flow components, the DRAINS model has a limited ability to allow for dynamic effects which may be of importance. For example, DRAINS does not fully represent backwater effects through all the elements of the drainage system. Furthermore, the DRAINS model does not directly simulate the dynamic interactions between pipe flow and free-surface (overland flows). Importantly, the propagation of overland flows through the system is estimated solely on the basis of a user defined lag time.

The estimation of this lag time has a direct influence on the relative timing of overland flow hydrographs from the main sub-catchments. This approach does not allow for backwater and/or storage effects likely to be experienced along the major overland flow paths within this catchment.

In contrast, the MIKE-Storm and SOBEK software provides a fully dynamic description of flow within the piped drainage and overland flow network. The formulation allows the proper flow capacity and distribution to be determined based on backwater conditions, the available storage and/or downstream controls.

11.3 Proposed GSTC Development Precinct

11.3.1 Comparison of Results

As noted in the previous sections, the latest estimates of the magnitude of overland flow entering the site of the proposed GSTC area via Portman Street are notably different from those reported in previously. In addition to this aspect, the estimated 1% AEP flood behaviour through the GSTC area was also found to be different from that reported in Reference 3.

Reference 3 documents the flood levels downstream of the proposed GSTC area (in the Botany Road trapped depression) and provides an estimated flood extent across the site for the 1% AEP event under existing conditions. The estimated 1% AEP flood level at the Botany Road sag is quoted as being 13.6 mAHD. The corresponding PMF level is quoted as being 13.9 mAHD. In contrast, the latest estimate of the flood level at this location from the current work suggests that the 1% AEP level could be as much as 0.7m above the previous estimate.

The preliminary estimates of the hydraulic behaviour obtained for the current study also suggest that the reported 1% AEP flood extents (documented in Drawing SK01 of Reference 3) are not correct. The greatest discrepancies occur across the northern portion of the site. Indicative flood extents derived from the current study are also shown for comparative purposes in Figure 45 (for both the 1% AEP design event and the PMF).

11.3.2 Discussion

Detailed information describing the technical analysis used to derive the results presented in Reference 3 was not documented and hence a thorough review of this component was not possible. However, when it is considered that the minimum level of the Botany Road sag is approximately 13.3 mAHD, the previous results indicate that only 300 mm of ponding occurs at this location during a 1% AEP event. This estimate would appear to underestimate the level of ponding that would typically be anticipated to occur as the critical level before water can escape from the area (past Green Square Station) is approximately 13.7 mAHD. To further clarify the previous result, a review of the DRAINS model used for the previous analysis was undertaken (Reference 2). It was found that a flood level of 14.4 mAHD was estimated in the Botany Road sag for the 1% AEP event. This is comparable to the corresponding flood level estimate of 14.3 mAHD obtained from the current Flood Study.

In terms of the estimated flood extents for existing conditions, the results from the current study better reflect the existing topography and are consistent with the expected flood behaviour across the site (inferred from several field inspections).

12. CONCLUSIONS

Detailed numerical models to quantify the hydrology and hydraulics of the Green Square and West Kensington catchment have been established making best use of the data currently available. These models have been used to define the design flood behaviour for existing conditions.

The current models are significantly more detailed and refined compared to others prepared for previous studies. Given the level of detail used in the present study and the ability of the current models to better represent dynamic flow and storage effects, the more recent results can be interpreted with a greater level of confidence than those published previously. Similarly, the use of a 2D model to represent the complex overland flow paths through much of the floodplain provides a detailed and more reliable description of the spatial variation in design flood behaviour in the area.

Importantly, the models developed for the current study are suitable for use in a subsequent Floodplain Risk Management Study and/or other assessments of redevelopment options within the catchment.

13. ACKNOWLEDGEMENTS

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- Green Square - West Kensington Floodplain Risk Management Committee,
- NSW Department of Environment and Climate Change (DECC), and
- Sydney Water.

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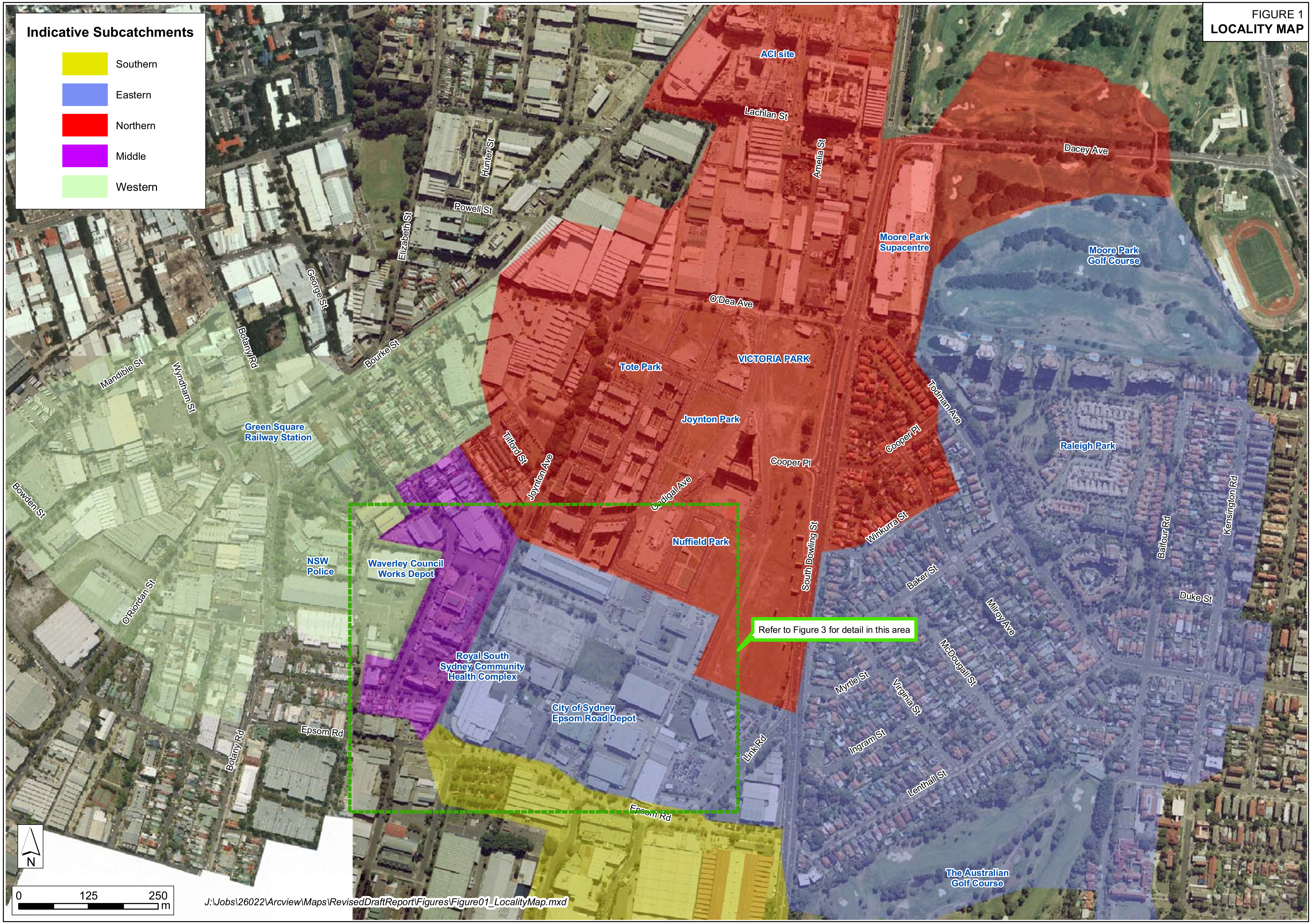

FIGURE 1
LOCALITY MAP
Indicative Subcatchments
Southern
Eastern
Northern
Middle
Western
ACI site
Lachlan St
Amelia St
Dacey Ave
Moore Park Supacentre
Moore Park Golf Course
O'Dea Ave
VICTORIA PARK
Tote Park
Joynton Park
Todman Ave
Cooper Pl
Raleigh Park
Kensington Rd
Balfour Rd
Duke St
Tilford St
Joynton Ave
Cooper Pl
Gadigal Ave
Winkurra St
South Dowling St
Nuffield Park
Baker St
Milroy Ave
McDougall St
Refer to Figure 3 for detail in this area
Myrtle St
Virginia St
Ingram St
Lenthall St
Link Rd
City of Sydney Epsom Road Depot
Royal South Sydney Community Health Complex
Waverley Council Works Depot
NSW Police
Green Square Railway Station
Elizabeth St
Hunter St
Powell St
George St
Bourke St
Botany Rd
Mandible St
Wyndham St
Bowden St
O'Riordan St
Epsom Rd
Epsom Rd
Botany Rd
The Australian Golf Course
N
0
125
250
m
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FIGURE 2
DRAINAGE WITHIN THE STUDY AREA (circa 1880)

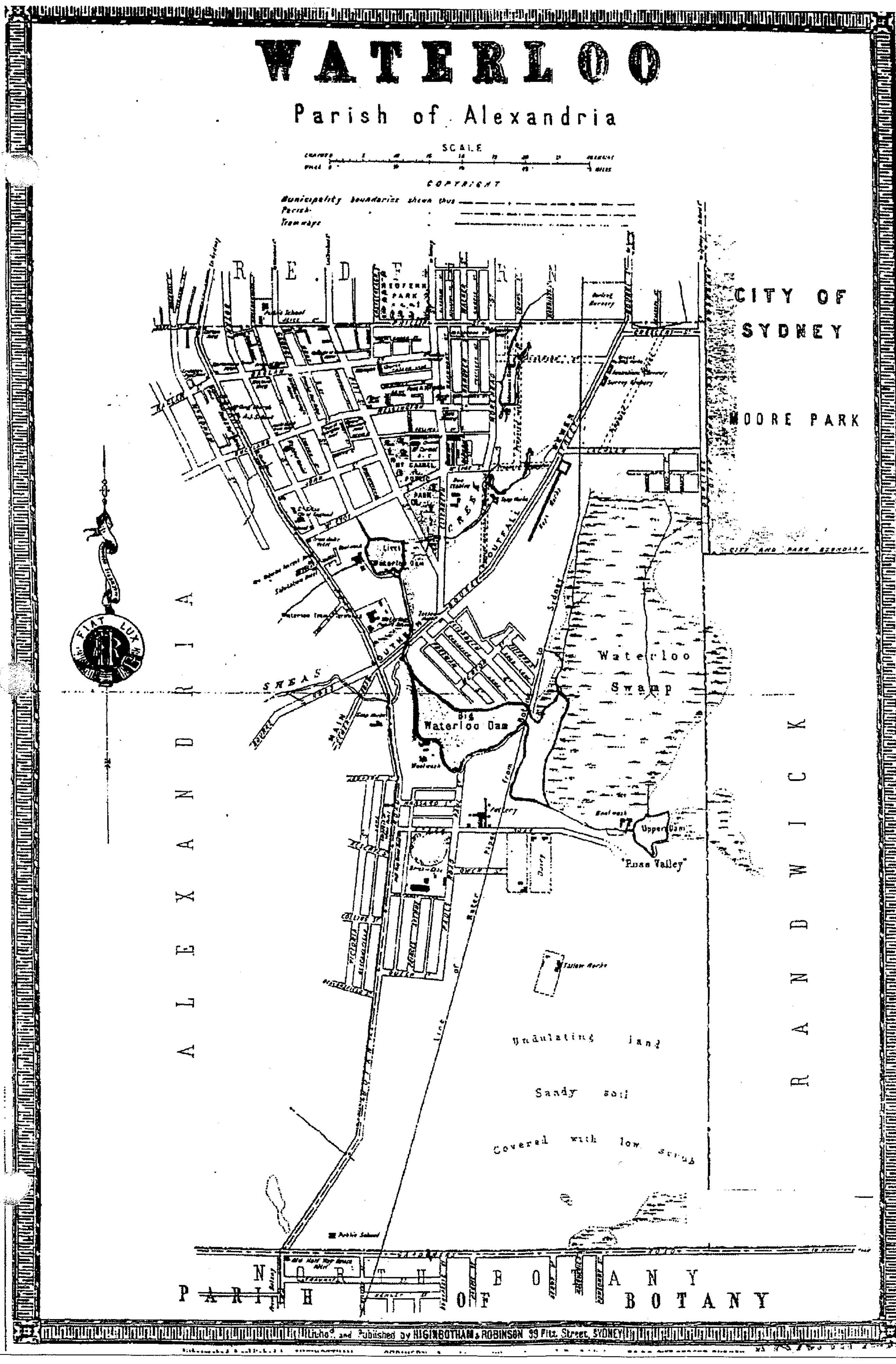

FIGURE 3

JOYNTON AVENUE TRAPPED DEPRESSION

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FIGURE 4
EXTENTS OF AERIAL SURVEY

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FIGURE 5
HYDROLOGIC MODEL SUB-CATCHMENT LAYOUT

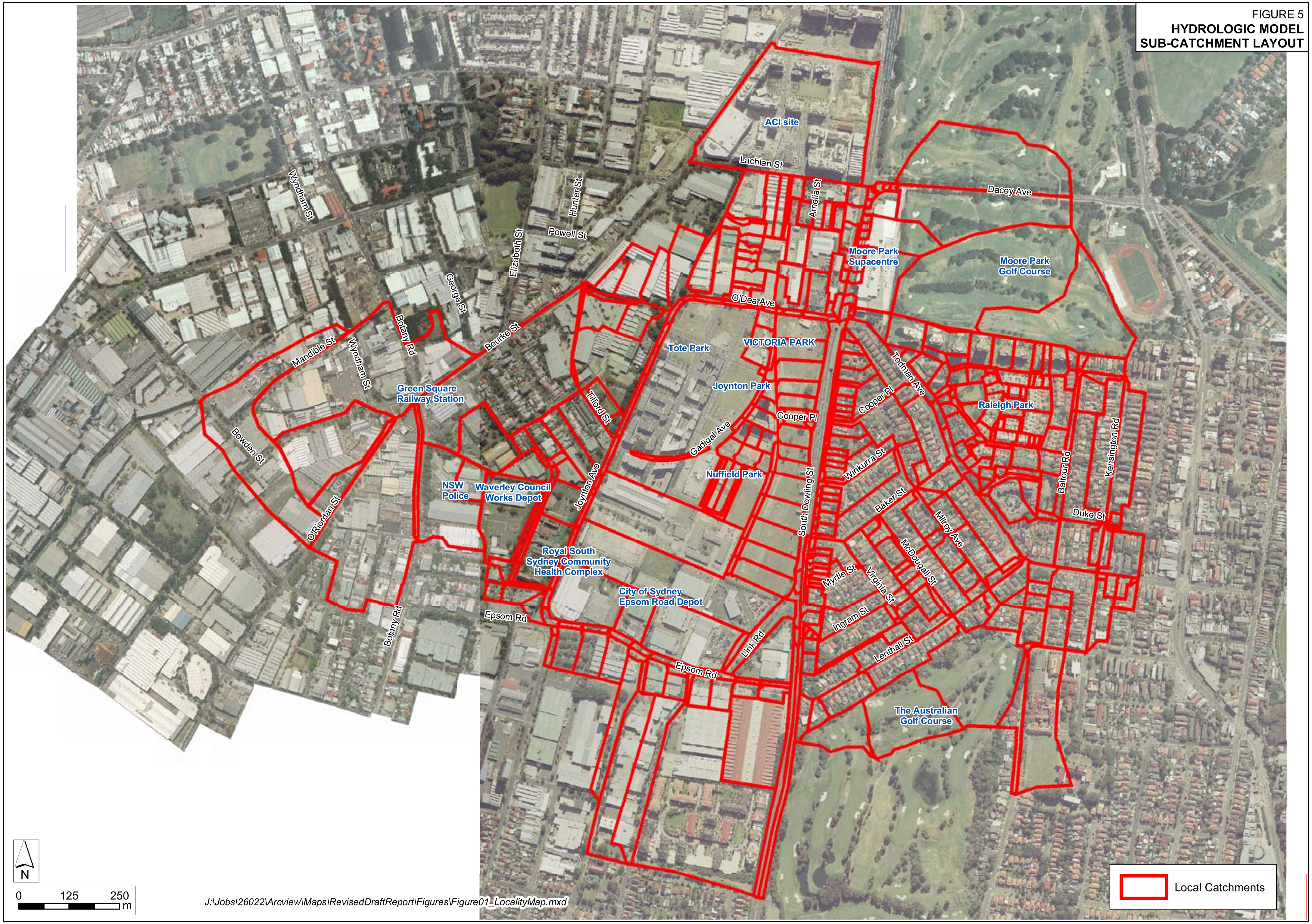

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FIGURE 6
DRAINAGE NETWORK LAYOUT

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