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BARDWELL CREEK 2D FLOOD STUDY REVIEW

FINAL REPORT

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MARCH 2019

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Project **Bardwell Creek 2D Flood Study Review**	**Project Number** 118004
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BARDWELL CREEK 2D FLOOD STUDY REVIEW

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LIST OF ACRONYMS

AEP	Annual Exceedance Probability
ARI	Average Recurrence Interval
ARR	Australian Rainfall and Runoff
BoM	Bureau of Meteorology
DEM	Digital Elevation Model
DRAINS	Hydrologic Model
FFA	Flood Frequency Analysis
GIS	Geographic Information System
GPT	Gross Pollutant Trap
HEC-RAS	1D Hydraulic Model
IFD	Intensity, Frequency and Duration (Rainfall)
ILSAX	Hydrologic Model
LGA	Local Government Area
LiDAR	Light Detection and Ranging (airborne survey method)
LPI	Land and Property Information
m	metres
m^3/s	cubic metres per second
mAHD	metres above Australian Height Datum
MHL	Manly Hydraulics Laboratory
MHWS	Mean High Water Spring tide
MIKE-11	Hydraulic Model
OEH	Office of Environment and Heritage
PMF	Probable Maximum Flood
RUBICON	1D Hydraulic Model
SES	State Emergency Services
SWC	Sydney Water Corporation
SWSOOS	South and Western Suburbs Ocean Outfall Sewer
TUFLOW	Hydraulic Modelling software
WBNM	Watershed Bounded Network Model (hydrologic modelling software)
XP- RAFTS	Hydrologic Model
1D/2D	1 Dimensional and 2-Dimensional hydraulic modelling

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 Bardwell Creek Overland Flow Flood Study constitutes the first stage of the management process for the catchment. This study has been prepared by WMAwater for Bayside Council and was undertaken to provide the basis for future management of flood liable lands within the study area.

EXECUTIVE SUMMARY

BACKGROUND

The Bardwell Creek Flood Study Review catchment area is located within the Bayside Council Local Government Area (LGA). The study area includes the suburbs of Bexley North, Bardwell Park, Bardwell Valley and Turrella, as well as parts of Kingsgrove, Bexley, Arncliffe and Wolli Creek. Bardwell Creek is a tributary of Wolli Creek with its confluence near the railway bridge at the end of Hannam Street, Bardwell Valley. Wolli Creek is in turn a tributary of the Cooks River with its confluence at the Tempe railway bridge crossing the Cooks River. The study area contains the portion of Bardwell Creek and Wolli Creek within Bayside Council LGA and covers an area of approximately 713 hectares (7.1 km^2). The upper catchment includes parts of Hurstville, Penshurst, Beverly Hills and Narwee within the Georges River LGA. The northern side of Wolli Creek includes parts of the suburbs of Roselands and Earlwood within the Canterbury Bankstown LGA.

The primary objectives of this study are to:

- prepare suitable models of the catchment and floodplain for use in a subsequent Floodplain Risk Management Study;
- provide results for flood behaviour in terms of design flood levels, depths, velocities, flows and flood extents within the study area;
- prepare maps of provisional hydraulic categories and provisional hazard categories;
- determine provisional residential flood planning levels and flood planning area;
- prepare preliminary emergency response classifications for communities; and
- assess the sensitivity of flood behaviour to potential climate change effects such as increases in rainfall intensities and sea level rise.

COMMUNITY CONSULTATION

In collaboration with Bayside Council a questionnaire was distributed to residents in the study area in May 2018. The purpose of the questionnaire was to identify which residents had experienced problems with flooding and to collate historical flood data. 158 responses were received from the distributed questionnaires, via both written and online submissions.

Of the responses received, 70 respondents had observed local flooding within the catchment and 38 had experienced flooding of their properties; including 10 where the building was affected. 27 respondents indicated that flooding had caused damage to their property.

MODELLING SUMMARY

The study uses hydrologic and hydraulic modelling techniques in order to define flood behaviour in the study area. The modelling programs used in the study are:

- WBNM (Hydrologic) – the model converts rainfall to runoff and the flow hydrographs are input into the TUFLOW model.
- TUFLOW (Hydraulic) – The 1D/2D hydraulic model was established to assess the

complex overland flow regimes of the urban catchments to analyse flooding behaviour in the study area.

MODEL CALIBRATION

The models were calibrated against historical flood data. The November 1984, December 1992, February 1993, January 1996 and October 2014 events were chosen for model calibration/validation, and the modelled flood behaviour was compared to observed flood marks, stream gauge data (for some events), and qualitative community descriptions of the flooding.

DESIGN FLOOD MODELLING AND MAPPING

The models were used to assess design flood behaviour for a range of events, including the 1% AEP and PMF. Comprehensive mapping of the design flood information across the catchment is provided. The results were interpreted to produce information relevant for informing Council's planning and development assessment processes, including identification of lots subject to flooding for 10.7 planning certificates.

1. INTRODUCTION

The study was commissioned by Bayside Council, with the assistance of the NSW Government Office of Environment and Heritage (OEH). Additional information has been provided by Sydney Water Corporation (SWC).

The Flood Study comprises the development of computational hydrologic and hydraulic models that define design flood behaviour for the 20% AEP (0.2 EY), 10% AEP, 5% AEP, 1% AEP and 0.5% Annual Exceedance Probability (AEP) design storms and the Probable Maximum Flood (PMF) in the Bardwell Creek and Wolli Creek catchments and to:

- prepare suitable models of the catchment and floodplain for use in a subsequent Floodplain Risk Management Study;
- provide results for flood behaviour in terms of design flood levels, depths, velocities, flows and flood extents within the study area;
- prepare maps of provisional hydraulic categories and provisional hazard categories;
- determine provisional residential flood planning levels and flood planning area;
- prepare preliminary emergency response classifications for communities; and
- assess the sensitivity of flood behaviour to potential climate change effects such as increases in rainfall intensities and sea level rise.

The specific tasks undertaken for the study were as follows:

- the collection and collation of existing information relevant to the study which includes the data already held by Council as well as other information, such as rainfall data;
- the preparation of hydrologic and hydraulic models capable of defining the flood behaviour for the study area for a wide range of design flood probabilities;
- undertaking sensitivity analysis;
- the interpretation and presentation of model results to describe and categorise flood behaviour and hazard for a range of design storm events for the existing catchment conditions;
- analysis of hot-spots;
- flood control lot mapping and ground truthing;
- investigating and ultimately determining the Flood Planning Area extent.

A discussion of the AEP terminology and a glossary of other flood-related terms is provided in Appendix A.

2. BACKGROUND

2.1. Study Area

The Bardwell Creek and Wolli Creek catchments are situated within the highly urbanised southern suburbs of Sydney (see Figure 1). The Bardwell Creek Overland Flood Study includes the suburbs of Bexley North, Bardwell Park, Bardwell Valley and Turrella, as well as parts of Kingsgrove, Bexley, Arncliffe and Wolli Creek. The Bardwell and Wolli Creek catchment is located north of the Bonnie Doon catchment and drains to the Cooks River which flows into Botany Bay. This study area covers approximately 713 hectares (7.1 km^2), with the total catchment area of Bardwell Creek and Wolli Creek comprising some 2,090 hectares (20.9 km^2).

The catchment generally flows from west to east, with Bardwell Creek running north-east through the middle of the study area, and Wolli Creek running along the northern boundary of the study area. The two creeks are located in relatively well-defined valleys. Elevations in the upper part of the catchment (to the south) reach approximately 70 mAHD (mapping of the topography from LiDAR aerial survey is shown in Figure 2). The topography within the study area has moderately steep terrain, where grades of approximately 5% in the suburban areas are common.

Flooding in the area has previously been investigated by Webb, McKeown and Associates (now WMAwater) in the 1996 Wolli Creek, Bardwell Creek and Bonnie Doon Flood Study (Reference 1). The present study updates the 1996 flood study to incorporate recent flood events and current best practice floodplain management guidelines. Significant development within the Wolli Creek catchment has occurred since the 1996 study and this has been incorporated into the current study. Flood problems have been experienced at a number of locations within the catchment during periods of heavy rainfall.

The land use within the catchment consists primarily of medium density urban residential development and commercial developments (including some light industrial areas), together with areas of open space such Bexley Golf Club, Bardwell Golf Club and several parks. High density urban residential developments and shopping complexes are a notable feature of the lower catchment in the suburbs of Wolli Creek and Turrella. Piped drainage systems which flow into a series of culverts and concrete lined open channels are prevalent in the upper catchment of both Wolli Creek and Bardwell Creek.

Drainage elements in the catchment include natural creek channels, kerbs and gutters, pits and pipes, and a network of trunk drainage elements including culverts and concrete-lined or otherwise modified open channels. These trunk drainage assets are primarily owned by Sydney Water Corporation (SWC) and Bayside Council, with drainage assets in the catchment to the west and north of the study area owned by Georges River Council and Canterbury-Bankstown Council, respectively.

2.1.1. Bardwell Creek

In Bardwell Creek the urban drainage network collects surface runoff and discharges into two small concrete lined open channels downstream of Croydon Road. These channels combine at the Bexley Golf Club near the upstream extent of the study area and flow through a series of culverts before discharging into a semi-natural creek downstream of Ellerslie Road. Bardwell Creek then passes under the Bexley Road bridge and is piped under a portion of the Bardwell Valley Golf Course via twin 2.5 m diameter culverts. Bardwell Creek then passes under Bardwell Road and the railway bridge at the end of Hannam Street before joining Wolli Creek.

2.1.2. Wolli Creek

In the upstream portion of the study area, Wolli Creek consists of a concrete lined open-channel which extends for approximately 1.2 kilometres between Kingsgrove Road and Bexley Road. The channel is crossed by a series of pedestrian bridges and a gross pollutant trap near Nairn Street, which was constructed in 1993 (Reference 2). Wolli Creek passes through a series of culverts under Bexley Road and continues downstream through a densely vegetated, meandering natural creek corridor. This natural creek follows the railway line, passing under Harthill Law Avenue bridge. Wolli Creek is joined by Bardwell Creek near Hannam Street. Turrella Weir, located at Henderson Street, defines the tidal and non-tidal portions of Wolli Creek. Immediately downstream, Wolli Creek passes under the Turrella Footbridge and continues around an industrial area at Turrella. Wolli Creek is crossed by the historic SWC Wolli Creek Sewage Aqueduct, which is part of the Southern and Western Suburbs Ocean Outfall System (SWSOOS), before the confluence with the Cooks River near the Tempe railway bridge.

2.1.3. M5 Motorway East

The M5 Motorway East was constructed between 1998 and 2002. As part of this development the concrete lined portion of Wolli Creek was widened and realigned upstream of Bexley Road. The northern portion of the catchment draining to this section of the creek was channelled through several large culverts and piped drainage systems.

2.1.4. East Hill Railway Noise Wall

Noise walls were erected along substantial stretches of the northern and southern sides of the railway corridor as part of the East Hills Rail line duplication in 2000/2001. These noise walls act as a barrier to overland flow for parts of the catchment area to the south of the railway.

2.2. Historical Flooding

Flooding in Wolli Creek and Bardwell Creek can occur when intense local rainfall generates runoff exceeding the capacity of drainage channels and creeks, producing overbank flow or overland flooding. Flooding in some areas may be exacerbated by the blockage of hydraulic structures and the presence of obstructions to overland flow paths.

The catchment has a history of flooding, particularly around the concrete lined sections of Wolli

Creek and Bardwell Creek. The catchment has experienced several floods of note since 1983 including floods in 1984, 1986, 1988, 1991, 1992, 1996, 1998, 2005, 2014 and 2015. Prior events have occurred but there are limited records. Flood events within the Bardwell Creek catchment frequently result in inundation causing damage to both residential and commercial properties. Overland flooding within the Wolli Creek catchment can result in inundation of bridges, with Bexley Road and Turrella footbridge commonly closed to traffic during flood events.

A record of all flooding observations in the area was obtained from Sydney Water. Sydney Water records of historical floods within the study area were available from 1945 to 2005 and these are summarised in Table 1.

Table 1: Sydney Water flood records within study area

Location	**Date of Storm**	**Comments**
Public Reserve Bexley Rd, Nth Bexley (culvert under)	1/04/1945	Road under water
10 Beaumont St, Kingsgrove	21/04/1952	
Public Reserve Bexley Rd, Nth Bexley (culvert under)	21/04/1952	Flooding occurred due to silting up of the natural channel downstream
10 Beaumont St, Kingsgrove	6/05/1953	Severe flooding.
Public Reserve Bexley Rd, Nth Bexley (culvert under)	6/05/1953	Flooding occurred due to silting up of the natural channel downstream
Public Reserve Bexley Rd, Nth Bexley (culvert under)	9/02/1956	Water flowing over Bexley Rd.
Public Reserve Bexley Rd, Nth Bexley (culvert under)	8/02/1958	Downstream end of existing construction water rose to .56m above footpath level.
Public Reserve Bexley Rd, Nth Bexley (culvert under)	18/02/1959	Severe flooding
Lot 112 Kooreela St, Kingsgrove (Councils footbridge)	18/02/1959	Severe flooding & bridge damaged
Public Reserve Bexley Rd, Nth Bexley (culvert under)	4/06/1963	Flooded above coping
Public Reserve Bexley Rd, Nth Bexley (culvert under)	5/06/1963	Flooded above coping
Public Reserve Bexley Rd, Nth Bexley (culvert under)	26/06/1963	Flooded above coping
Public Reserve Bexley Rd, Nth Bexley (culvert under)	29/08/1963	Water lapping top of headwall & rising
Public Reserve Bexley Rd, Nth Bexley (culvert under)	20/12/1963	No street flooding or damage to property
Public Reserve Bexley Rd, Nth Bexley (culvert under)	20/12/1963	Flooded over coping but not onto roadway.
Public Reserve Bexley Rd, Nth Bexley (culvert under)	15/04/1969	Road flooded.
Public Reserve Bexley Rd,	13/11/1969	Water at least 0.2m above roadway, safety fence on

Location	Date of Storm	Comments
Bexley North (culvert under)		both sides washed away. Road & footpath scoured by flood waters.
44 Bobadah St, Kingsgrove	13/11/1969	Water level was .41m over footbridge. Sewer aqueduct slightly bent in this area.
222 Kingsgrove Rd, Kingsgrove	13/11/1969	Boards channel completely under water.
10 Nairn St, Kingsgrove	13/11/1969	Front fence damaged. Fence between property & S/W channel washed away. A hole of 0.13m scoured behind S/W channel wall. Water rose to within 3" of floor level of his house.
Public Reserve Bexley Rd, Bexley North (culvert under)	6/03/1970	Road flooded.
10 Nairn St, Kingsgrove	6/03/1970	Channel flooded, no damage caused.
30 Canonbury Rd, Bexley	29/10/1972	25 feet of paling fence washed away. Scouring to a depth of 0.76m occurred behind channel wall
Bexley Rd, Bexley North	10/03/1975	Flood waters blocked road due to restriction of unformed creek downstream.
6 Oliver St, Bexley North	10/03/1975	Yard flooded
Public Reserve Bexley Rd, Bexley North (culvert under)	4/03/1977	Flooded.
Lot 111 Kooreela St, Kingsgrove	4/03/1977	Was not flooded but the raised southern coping is leaning dangerously inwards.
Public Reserve Bexley Rd, Bexley North (culvert under)	5/08/1986	Road flooded. Car washed into downstream creek.
Lot 111 Kooreela St, Kingsgrove	5/08/1986	Channel flowed about 1.2m out of channel.
Lot 28-29 Lundy Ave, Bexley North (GPT)	17/02/1993	Severe flooding
Lot 28-29 Lundy Ave, Bexley North (upstream of GPT)	17/02/1993	Severe flooding
Public Reserve Bexley Rd, Bexley North (culvert under)	2/01/1996	Flooding occurred blocking the roadway to traffic. Water flowed about 1.5 - 1.8 m deep over upstream headwall. Fence on upstream side of culvert ripped from its mounting plates. A car observed in adjacent park, & possibly 3 cars washed away.
Lot 112 Kooreela St, Kingsgrove (Downstream of Footbridge)	2/01/1996	Debris in adjacent parks.
Lot 111 Kooreela St, Kingsgrove	2/01/1996	6-7 panels of fencing damaged or washed away.
Lot 112 Kooreela St, Kingsgrove (at footbridge)	2/01/1996	The abutments of footbridge scoured.
Lot 28-29 Lundy Ave, Bexley North (GPT)	2/01/1996	Bark debris around edges of GPT.
Lot 112 Kooreela St, Kingsgrove (at major council inlet)	2/01/1996	Inlet of major Council system at York St, Debris on fencing, flooding caused severe scouring behind channel walls.
9 Coveney St, Bexley North	9/04/1998	Upstream - water above coping
12 Coveney St, Bexley North	9/04/1998	Downstream - water above coping

Location	Date of Storm	Comments
2 Laycock St, Bexley North	9/04/1998	Jumped out of channel opposite large outlet
6 Oliver St, Bexley North	9/04/1998	Over coping into yard
10 Rye Ave, Bexley	10/04/1998	Report by 7 Rye Ave. Water through Council Depot
15 Rye Ave, Bexley	10/04/1998	Water entered property
17 Dowsett Rd, Kingsgrove	10/04/1998	Water came across park and down driveway and through garage
1 East Dr, Bexley North	10/04/1998	Street totally flooded
59 Edward St, Bexley North	10/04/1998	Stormwater overflowed off street and into garage and pool
Public Reserve Bexley Rd, Bexley North (culvert under)	9/05/1998	Flood water over top of culvert
Lot 28-29 Lundy Av, Bexley North (GPT)	9/05/1998	Flood water to water hydrant near gate to GPT
63 Arinya St, Kingsgrove	9/05/1998	Water over bridge between Arinya st and Kooreela St

2.2.1. Notable Features in Bardwell Creek

- Concrete lined channels (Croydon Road to Ellerslie Road) – The concrete lined channels upstream of Ellerslie Road are interspersed with a series of culverts which pass under several roads, and a long culvert reach covering a length of approximately 480 m under Bexley Golf Course. Debris entering these channels and culverts can lead to blockage resulting in increased flood levels upstream. The effect of blockage increasing flood levels was observed in the October 2014 event when significant quantities of debris, including a car and a water tank, were observed in the lined channel near Coveney Street. In this event, floodwaters overtopped the channel causing significant damage to properties adjacent to the creek (refer Section 3.10), although this may have been due to the flow rate exceeding the channel capacity, in addition to any exacerbating effects the blockage may have had.
- Semi-natural creek (Ellerslie Road to confluence with Wolli Creek) – Flooding in this section of Bardwell Creek is known to be particularly problematic for residents in Hillcrest Avenue. During the development of Bardwell Valley Golf Course overbank areas of the creek were filled for the construction of greens and fairways and twin concrete pipes were installed through the golf course. Any overflow above the pipes will therefore occur across the fairways. A levee was constructed in 1988 by Rockdale City Council at the end of Hillcrest Avenue to protect houses upstream of the golf course from potential flooding. A blockage prevention device was constructed at the upstream inlet of the twin 2.5 m diameter culverts circa 2000.

2.2.2. Notable Features in Wolli Creek

- Concrete lined channel (between Kingsgrove Road and Bexley Road) – Bexley Road is frequently overtopped during flood events. The M5 Motorway which was constructed (circa 1999-2001) to the north of the study area also affects flow behaviour during larger flood events (Reference 3).

- North of East Hills Railway Line – Flows from north of the railway line are constrained by the presence of the noise walls and rail embankment, which act as a barrier to overland flow. Several culverts have been installed under the noise walls at Poweys Avenue (Bardwell Park), and under the railway line at Kingsgrove and Bexley North community centre (Bexley North). A gap under the noise walls at the commuter car park at Kingsgrove also permits overland flows to enter the rail corridor at this location.
- Natural creek channel (between Bexley Road bridge and confluence with Bardwell Creek) – The noise walls along the southern side of the railway tracks in this section of Wolli Creek act as a barrier to overland flow. This generally reduces the impact of mainstream flooding due to overtopping of the creek but results in localised overland flooding issues in some areas. Flooding affecting the East Hills rail line has resulted in closures of train services in several recent events, including the October 2014 flood event (refer Section 3.10).
- Natural creek (between confluence with Bardwell Creek and the Cooks River) – Some low-lying properties within this area have been inundated by flooding. Commercial districts in the suburbs of Turrella and Wolli Creek are relatively frequently affected.

2.3. Previous Studies

Numerous flood studies have been completed which include areas within the Bayside Council, Canterbury-Bankstown and Georges River Council LGAs. A brief summary of previous studies relevant to the current investigation are provided below.

2.3.1. Wolli Creek, Bardwell Creek and Bonnie Doon Flood Study

This study was undertaken by Webb, McKeown and Associates (References 1 and 2) in 1996, to determine design levels, flows and velocities for the 20%, 5%, 2%, 1% AEP floods and an extreme flood event.

The study used a WBNM hydrologic model to estimate runoff hydrographs and a quasi-2D (1D) RUBICON hydraulic model to define flood behaviour. A limited calibration of the hydrologic and hydraulic models was undertaken using the available historical data for five historic events.

The study indicated that due to the urbanised nature of the catchment, major flooding around Bardwell Creek and Wolli Creek was generally as a result of shorter more intense storms, or intense bursts within longer duration events.

The study concluded that a lack of quality historical flood data limited the accuracy of design flood levels obtained.

2.3.2. Southern Bardwell Creek Drainage Study

This 1997 study by Webb, McKeown and Associates (Reference 4) covered a catchment area of approximately 223 hectares with all drainage systems ultimately exiting to Bardwell Creek. An ILSAX hydrologic model was established which provided peak pipe and overland flows. No calibration data were available. The outcomes of the present study will supersede those from this 1997 study. Due to the different modelling approaches undertaken the results from the present study cannot be readily compared to those from this 1997 study. The same pipe network and drainage sub catchments used in the 1997 study have been adopted in the present study where applicable.

A subsequent study (Southern Bardwell Creek Drainage Study - GIS Implementation - Reference 5) was completed in July 2000. This later study revised the hydrologic modelling undertaken in the 1997 study and produced mapping showing flood affected properties.

2.3.3. Northern Bardwell Creek Piped Drainage and Overland Flow Analysis

This 2003 study by Webb McKeown and Associates (Reference 6) covered a catchment area of approximately 117 hectares and comprised the area immediately downstream and north of the 1997 Southern Bardwell Creek Drainage Study (Reference 4) catchment. A DRAINS hydrologic model (superseded ILSAX) was established and design flood levels were obtained from HEC-RAS 1D backwater model. No model calibration was undertaken due to the lack of historical data. From this study mapping could be produced showing the flood liable properties.

Due to the different modelling approaches undertaken the results from the present study cannot be readily compared to those from this 2003 study. The same pipe network and drainage sub catchments used in the 2003 study have been adopted in the present study where applicable.

2.3.4. Update of Wolli Creek Pipe Drainage and Overland Flow Study

This 2008 study by Webb McKeown and Associates (Reference 7) supersedes the earlier 2001 Wolli Creek Piped Drainage and Overland Flow Analysis (Reference 8) and was undertaken to investigate the effects of duplication of the East Hills rail line (two track to four track) and in particular the effect of the noise walls on drainage across the track. The study used inflows from the DRAINS hydrologic model input to the Mike-11 1D hydraulic model to determine design flood levels and the impact of the duplication works.

The report concluded that the East Hills rail line duplication works had increased flood levels upstream by restricting the flow across the track and filling of the floodplain due to track construction.

2.3.5. Cooks River Flood Study

This 2009 study by MWH Parsons Brinckerhoff (Reference 9) used a WBNM hydrologic model and a TUFLOW hydraulic model to determine design flood levels in the Cooks River and up to Bexley Road on Wolli Creek. The models were calibrated to the November 1961 and March 1983 recorded flood data on the Cooks River but no calibration was undertaken on Wolli Creek.

This study provides the most current design flood levels in the Cooks River, however it should be noted that the results are based on the ARR1987 design flood methodology and may change if the ARR2016 methodology was undertaken.

2.3.6. Wolli Creek Flood Study

This 2015 study by Hydrostorm (Reference 3) was undertaken for Sydney Water and the foreword states that as Sydney Water Corporation owns and maintains a large number of stormwater assets in the Wolli Creek catchment. A flood study has been undertaken to assess the risk associated with the open channel and the pipe drainage assets in this catchment. The study area was defined as the catchment of Wolli Creek to Bexley Road with an area of 11.4 km^2.

The following major tasks defined the study methodology:

- collation of all relevant data from various authorities;
- review of data and site visit to identify major hydraulic controls in the study area;
- definition of the flood behaviour for the existing conditions in the catchment;
- definition of the extent of flooding, flood levels, velocity and flow distribution for the 100yr, 20yr and 5yr ARI events together with the PMF;
- establishing provisional flood hazard for the floodplain.

The modelling used LiDAR survey obtained from Hurstville Council in 2013. The RAFTS hydrologic model was used to determine hydrologic inflows to a TUFLOW hydraulic model and adopted the ARR1987 design methodology with an initial loss of 10 mm and a continuing loss of 2.5 mm/h. The storm durations of 1 hour, 1.5 hour and 2 hour were identified to be critical for the 100yr, 20yr and 5yr ARI events respectively. For the PMF the 30 minute, 45 minute and the 1 hour durations were identified to be critical.

Open channels and the pipe trunk drainage systems were modelled in 1D in TUFLOW with the remainder in a 3 m by 3 m 2D grid. No original survey was collected as part of the study with reliance on data in prior models and reports. Residential buildings were modelled with a high roughness rather than excluding them from the grid but for other buildings they were excluded from the grid.

Calibration was not undertaken as the historic flood data are for events prior to the M5 construction and the topographical data which describes the floodplain prior to the construction of the M5 motorway was not available.

The results of the study are based on the following assumptions:

- Hydraulic modelling is based on the LiDAR data provided by Hurstville Council. The accuracy of the survey data is reflected in the model results;
- Hydraulic model calibration could not be undertaken due to lack of suitable data. Calibration of the model should be undertaken when suitable historic data becomes available;
- Design flood levels are based on a grid cell size of 3m x 3m and this should be kept in mind when deriving flood levels from the 2D model results;
- The flood study is a broad-scale catchment wide study. Model results for assessing flood behaviour for individual properties should be used with caution;

- The provisional flood hazard presented in the report is solely based on the hydraulic characteristics of the flood i.e. depth and velocity of flood waters. Several other factors play a role in defining the 'true' flood hazard for an area;
- The model results show that the M5 motorway may be affected by flooding in a significant flood event. A detailed local flood study is required to confirm this flood behaviour;
- Climate Change impact assessment is based on the interim guidelines provided by ARR. This assessment would need to be updated for any future update of the guidelines
- Study results should not be used for any other purposes than those specified in this report.

2.3.7. Overland Flow Flood Study for Hurstville, Mortdale and Peakhurst Wards

This 2016 study by SMEC and CSS (Reference 10) was undertaken for the 22.8 km^2 study area, which included the upstream parts of Wolli and Bardwell Creeks, with the following objectives:

- Define the flood behaviour under historical (where available) and existing floodplain conditions in the study area;
- Address the possible future variations in flood behaviour due to climate change;
- Produce flood information that includes:
  - Flood levels and extents, velocities and flows for the PMF, 1%, 2%, 10% and 20% AEP events;
  - Hydraulic categories for the 1% AEP and PMF events;
  - Provisional and Preliminary true hazard categories for the 1% AEP and PMF events;
  - Flood emergency response classification of communities for the PMF, 1%, 2%, 10% and 20% AEP events;
  - Preliminary residential flood planning level and flood planning area (based upon 1% AEP plus a freeboard);
  - Flood levels and extents due to climate change;
  - Tidal inundation extents (where relevant) for existing conditions and for conditions incorporating sea level rise planning projections adopted by the Council (where relevant);
  - The sensitivity of flood behaviour to changes in flood producing rainfall events due to climate change;
- Collect compile and review all available data such as survey, aerial photography and satellite imagery;
- Investigate the mainstream, local overland flow and tidal inundation flooding regimes;
- Discussion with Council on the relevant freeboard to be adopted based on sensitivity runs;
- Assessment of the flood planning level extent to be discussed with Council for steep and flat terrain;
- Investigate the overland flow flooding and the capacity of existing major stormwater infrastructure.

Model calibration was undertaken for the April 1988, February 2012 and October 2014 events, though none of the recorded levels were within the study area of the present study. Hydrologic inputs were obtained from XP-RAFTS and DRAINS modelling to validate the results from a 2m x 2m TUFLOW hydraulic model using the "direct rainfall" approach. The 2 hour duration was determined as critical for the 1% AEP event with 10mm initial loss and 2.5mm/h continuing loss adopted for pervious surfaces. Depth dependent Manning's "n" values were adopted and buildings were represented using a wall on the upstream side. An automated approach was employed to approximate fence alignments with all flow up to 0.5m deep to be 50% blocked and above to be not blocked.

A public consultation program was undertaken to collect historical flood data and 223 questionnaires were returned out of approximately 8,900 sent out. 16% of the respondents indicated that they were flood affected.

2.4. Community Consultation

In collaboration with Bayside Council, a newsletter and questionnaire were distributed to residents within the catchment in May 2018. The newsletter described the role of the Flood Study and requested information on experiences of flooding in the catchment. 158 responses were received from the distributed questionnaires via both hardcopy and online submissions.

Of the responses received, 70 respondents had observed local flooding within the catchment and 25 had been directly affected; including 7 people who had been isolated or evacuated due to flooding. 38 respondents indicated that flooding had affected their property with 10 indicating that the building was affected. These results are summarised in Figure 3A to Figure 3C.

Many respondents identified rising waters in parks and roads as their flooding experience. It is likely that some of the survey respondents who reported flooding of their properties experienced local drainage issues rather than overland flooding which is the subject of this study.

The survey responses identified several key areas of concern:

- Flood inundation was more frequently observed in the upper parts of the Bardwell Creek catchment, particularly just upstream of Bardwell Valley golf course and near the concrete-lined channel between Laycock Street and Preddys Road;
- Several residents believed that dredging of the creek or removal of debris from waterways would help to solve their flooding problems;
- Some residents have had their daily routines affected and believe that their safety has been put at risk due to localised overland flooding;
- Most flood damage was to backyards, but some properties experienced flooding of garages as well as the ground floors of houses;
- Some affected residents have employed their own flood mitigation measures, including installing extra drainage.

In addition to these areas of concern, a significant number of survey respondents identified that their properties were affected during the storm event on the 14th October 2014. As a result, that storm event has been included in historical rainfall comparisons with design rainfall intensities and is discussed in Section 3.11.

Further data obtained through the community consultation process, including flood marks and photographs, are discussed in Section 3.10.

3. AVAILABLE DATA

3.1. Overview

The first stage in the investigation of flooding matters is to establish the nature, size and frequency of the problem. On larger urban river systems such as the Hawkesbury River there are generally stream height and historical records dating back a considerable period, in some cases over one hundred years. However, in smaller urban catchments stream gauges and/or official historical records are generally not available, and there is more uncertainty about the frequency and magnitude of flood problems. Additionally, overland flooding in urban areas is highly dependent on localised changes to development, intensification of development (i.e. increased building sizes and more paved surfaces), and localised drainage features such as kerbs and guttering in roadways. These features are subject to relatively frequent modification and renewal, making it difficult to compare flood behaviour over time.

The Bardwell Creek and Wolli Creek catchments contain several pluviometers surrounding the catchment. There is one pluviometer situated within the catchment at Bexley Bowling Club which was installed in 1990 and captured data for the 1992, 1993, 1996 and 2014 storm events. Where this pluviometer data was not available, as for the 1984 storm event, temporal pattern data from the surrounding pluviometers was utilised. An understanding of historical flooding was obtained from an examination of Council records, previous flood assessment reports, rainfall records and local knowledge obtained through community consultation (see Section 2.4.)

Ground level and survey information supplied as part of the study was of mixed usability. Airborne Light Detection and Ranging (LiDAR) data in urbanised areas and detailed cross-section survey of some watercourses (collected as part of previous studies) was generally able to be immediately utilised for modelling. Other datasets had gaps, such as the Council GIS database (inverts of pits and pipes generally not available) and ground levels in creek areas not previously covered by survey. Such gaps are common for flood studies, since collected detailed information about drainage networks is expensive and time consuming, and often beyond the resources available to Council. As part of this study, analysis of the available data along with site visits were undertaken to address the limitations of the data in key areas.

It should be recognised that while the information about the drainage system for this study is not perfect, this is often not a critical issue, since the majority of runoff cannot be contained within the formal drainage network. Sub-surface drainage networks are typically only designed to cater for the 20% AEP flow. Therefore, caution must be exercised when applying the broad catchment modelling results at individual properties, particularly for smaller floods or in areas where the pit/pipe drainage network plays a significant role in the flood behaviour.

3.2. Data Sources

Data utilised in the study has been collated from a variety of sources. Table 2 provides a summary of the type of data sourced, the supplier, and its application for the study.

Table 2: Data Sources

Type of Data	Source	Application
Ground levels from LiDAR data (2013)	Digital Elevation Model - DEM (LPI)	Hydrologic and hydraulic models
Bardwell Creek Cross-section Data	SWC, Cooper and Richards Surveyors	Hydraulic model
Wolli Creek Cross-section Data	SWC, Cooper and Richards Surveyors, OEH	Hydraulic model
Pits, Pipes and Hydraulic Structures	GIS (Bayside Council, Georges River Council), Cooper and Richards Surveyors, P Bolan Surveyors	Hydrologic and hydraulic model
GIS Information (Cadastre)	GIS (Bayside Council)	Hydraulic model
Historic Flood Level Data	SWC, Public Works, State Rail, Rockdale Council, Canterbury Council, H Wong, Local Residents	Hydraulic model
Rainfall Gauge (Daily)	Spreadsheet (BoM and SWC),	Hydrologic model
Pluviometer (Continuous rainfall)	Spreadsheet (BoM and SWC)	Hydrologic model
ARR Design Rainfalls	Tabulated (BoM)	Hydrologic model

3.3. Topographic Data

Airborne Light Detection and Ranging (LiDAR) survey of the catchment and its immediate surroundings was obtained from Land and Property Information (LPI), which is a division of the Department of Finance, Services and Innovation (NSW Government). It was indicated that the data were collected in 2013. These data typically have accuracy in the order of:

- +/- 0.15 m (for 70% of points) in the vertical direction on clear, hard ground; and
- +/- 0.75 m in the horizontal direction.

The accuracy of the LiDAR data can be influenced by the presence of open water or vegetation (tree or shrub canopy) at the time of the survey.

The 1 m by 1 m Digital Elevation Model (DEM) generated from the LiDAR, which formed the basis of the two-dimensional hydraulic modelling for the study, is shown in Figure 2.

There are some developments which took place after 2013, particularly in the lower areas around the suburbs of Wolli Creek and Turrella. The LiDAR data did not capture the ground level of these new developments. The Bexley Road South Motorway Operations complex which was installed as part of the New M5 WestConnex upgrade works was also identified as a development which could potentially affect flood levels on Wolli Creek during the site visit to Bexley Road. However this was very localised and minor adjustments to the model were made to reflect this.

3.4. Hydraulic Structures

Structures including bridges and culverts can have a significant impact on flood behaviour. Therefore, appropriate representation of these structures is essential for the accuracy of the hydraulic model. Data for hydraulic structures was obtained from:

- Wolli Creek, Bardwell Creek and Bonnie Doon Channel Flood Study (1996, Webb, McKeown and Associates);
- Wolli Creek and Bardwell Creek Flood Study Cross-sections (1995, Cooper and Richards Surveyors and Consulting Engineers);
- Update of Wolli Creek Pipe Drainage and Overland Flow Study (2008, Webb, McKeown and Associates);
- Sydney Water Corporation (Works-As-Executed drawings).

During the inspection of the study area WMAwater measured key hydraulic structures along Bardwell Creek and Wolli Creek to verify that the dimensions of hydraulic structures were consistent with the available 1995 and 1996 data. The locations of these structures are shown on Figure 2. A summary of the dimensions of hydraulic structures are provided in Table 3 and Table 4 for Bardwell Creek and Wolli Creek, respectively. Photos of the major structures obtained during a site visit are presented in Appendix B.

Table 3: Hydraulic Structures in Bardwell Creek

Location	Structure Type	Width/Diameter (m)	Height (m)	Number	U/S Invert (mAHD)	D/S Invert (mAHD)
Ada Street	Box Culvert	1.6	1.5	2	33.2	32.9
Unwin Street	Box Culvert	1.6	1.5	2	31.4	31.0
Moore Street (1)	Box Culvert	1.6	1.5	2	29.8	26.3(4)
Bexley Golf Course (2)	Box Culvert	2.0	1.6	1	27.3	26.3(4)
Laycock Street (2)	Box Culvert	2.1	1.9	2	26.3(4)	23.4
Oliver Street	Box Culvert	2.1	1.9	2	22.2	21.8
Coveney Street	Box Culvert	2.1	1.9	2	20.7	20.2
Preddys Road	Box Culvert	2.1	1.9	2	19.4	18.2
Bexley Road	Bridge	22.64		1	10.33	10.33
Bardwell Golf Course (3)	Culvert	2.5 (3)	-	2	5.7	4.2
Bardwell Road	Culvert	2.8	-	2	1.41	1.31
Railway Bridge (at confluence)	Bridge	10.5	-	1	0.42	0.42

Notes: (1) The culverts start at Moore St and exit at Laycock Street (Bridge Street Branch)

(2) The culverts start within the Golf Course and exit at Laycock Street (Croydon Road Branch)

(3) A 30 m section is sleeved with a 2.18 m steel insert. The culverts were each modelled as 2.3 m diameter. This is identical to the approach taken in the 1996 flood study.

(4) This junction is underneath the golf course. Invert interpolated from available data.

Table 4: Hydraulic Structures in Wolli Creek

Location	Structure Type	Width / Diameter (m)	Height (m)	No.	U/S Invert (mAHD)	D/S Invert (mAHD)
Bexley Road	Culvert	3.1	2.7	3	3.0	2.6
Harthill Law Avenue	Bridge	49.1	-	1	22.93	22.93
Turrella Footbridge and Weir	Bridge and Weir	28.33	-	1	1.00	-0.44

During the site inspection it was identified that some of the key structures affecting flood behaviour in Wolli Creek included the M5 Motorway and the noise walls along the East Hills Rail Line. Several pipes discharge water directly into the rail corridor, which runs parallel to Wolli Creek, and these flows are discharged into Wolli Creek via a series of culverts. These features were included in the model.

3.5. Cross-Section Survey

Within the Bardwell Creek and Wolli Creek catchments, the topography of the open watercourse areas are typically not accurately captured by the LiDAR data, as most of the watercourses are covered or surrounded by heavy vegetation, thus affecting the LiDAR accuracy. Channel cross-sections of Bardwell Creek and Wolli Creek were available from previous studies (see Reference 11 for details), which was supplemented with data from Sydney Water, and processed channel cross-section data were available in the TUFLOW model of the 2015 Wolli Creek Flood Study prepared for Sydney Water (Reference 3). Surveyed cross-sections from previous studies were available and these are listed in Table 5.

Table 5: Surveyed Cross-Sections from Previous Studies

Location	Flood Study	Surveyor	Date
Bardwell Creek (concrete lined channel)	Wolli Creek and Bardwell Creek Flood Study (WMAwater, 1996)	Cooper and Richards	1995
Wolli Creek (near Cooks River confluence)	-	Clement and Reid Consultants for Public Works (OEH website)	1989
Wolli Creek	Wolli Creek and Bardwell Creek Flood Study (WMAwater, 1996)	Cooper and Richards	1995
Wolli Creek (concrete lined channel)	Wolli Creek Flood Study (Hydrostorm, 2015)	Sydney Water	2001

3.6. WestConnex Stage 2: New M5

Since the completion of the 1996 study (Reference 1), the main concrete-lined channel of Wolli Creek has been realigned due to the construction of the M5 Motorway. In addition, as part of the Westconnex New M5 project, several temporary and permanent structures have been constructed which could potentially affect the hydraulic behaviour of Wolli Creek upstream of

Bexley Road.

3.7. Pit and Pipe Data

A database of stormwater pits and pipes within the catchment was provided by Bayside Council (see Figure 20.). Additional pits and pipes data for stormwater assets upstream of the study area was provided by Georges River Council. The pits and pipes data did not have any invert information although the dimensions were generally available. In cases where pipe dimensions were unavailable the data was supplemented with tabulated pipe dimension data held by WMAwater from previous studies. In cases where invert levels were not present inverts were estimated based on LiDAR data. The majority of pit inlets and pipe sizes were determined from the following principles:

- In cases where invert level data were not available pipes were modelled as having a depth of cover of 0.5 m below the recorded ground level at pits and junctions;
- Pit inlets were modelled as having an invert at recorded ground level;
- Pit inlet dimensions were not available for many pits and therefore pit inlet dimensions of 1.2 m x 0.15 m were assumed for all inlet pits for consistency;
- Pipes without a size supplied in Council's dataset were sized based on tabulated data held by WMAwater where such data existed or estimated based on the sizing of connected upstream and downstream pipes.

Following this initial estimation, further corrections to pit inverts were undertaken to correct pipes with negative slope or pipes that were located above ground in the model.

3.8. Lusty Street Detention Tank

A 700 m^3 detention tank was installed in Lusty Street (Wolli Creek) circa 2014 to address frequent stormwater drainage issues at this location. This subsurface detention tank is situated in a low lying position near the confluence of Wolli Creek with the Cooks River. The operation of the tank is dependent on pumps to discharge stored water into Wolli Creek. In large flood events elevated tailwater levels within Wolli Creek are likely to prevent operation of this tank at the peak of the storm. It is also unlikely that the pumps can match the inflow rate in more intense storms such as a 1% AEP event. In addition pump failure may occur during storm events which would severely mitigate the effectiveness of this tank.

The tank was therefore assumed to full for the duration of the design flood events modelled, and not included specifically in the modelling. A sensitivity test was undertaken, which found that including an empty tank at the start of the 1% AEP event would reduce peak flood levels by less than 0.01 m.

3.9. NSW Tidal Planes Analysis

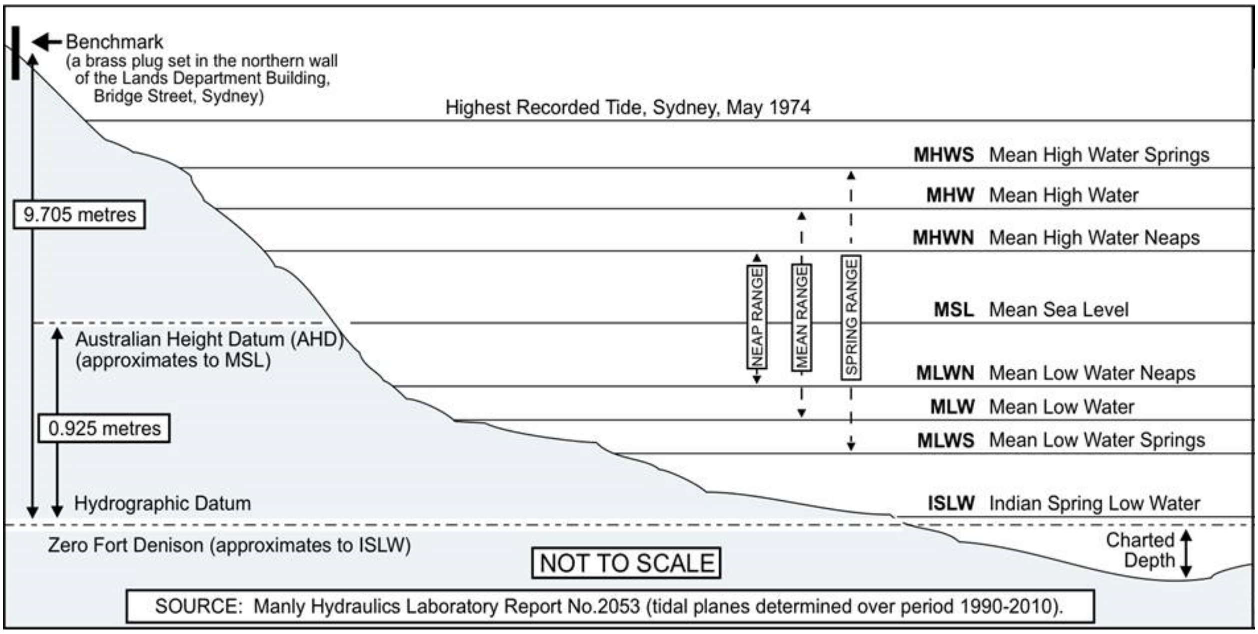
Manly Hydraulics Laboratory prepared the *NSW Tidal Planes Analysis: 1990-2010 Harmonic Analysis* report on behalf of OEH. It was released in October 2012 and was based on data from 188 tidal monitoring stations from 1st July 1990 to the 30th June 2010. Data from the relevant stations are shown in Table 6 with a tidal plane diagram shown as Diagram 1. The tidal limit in

Wolli Creek is the weir at the end of Henderson Street at Turrella.

Table 6: Tidal Planes Analysis Results (MHL, 2012)

Tidal Planes	Annual Average Amplitude (mAHD)		
	Ocean Tide Gauge Port Jackson (213470)	Ocean Tide Gauge Port Hacking (213473)	Cooks River at Tempe Bridge (213415)
High High Water Solstices Springs (HHWSS)	1.00	1.04	1.06
Mean High Water Springs (MHWS)	0.65	0.68	0.70
Mean High Water (MHW)	0.52	0.56	0.57
Mean High Water Neaps (MHWN)	0.40	0.44	0.45
Mean Sea Level (MSL)	0.02	0.07	0.06
Mean Low Water Neaps (MLWN)	-0.36	-0.31	-0.33
Mean Low Water (MLW)	-0.48	-0.43	-0.46
Mean Low Water Springs (MLWS)	-0.61	-0.55	-0.58
Indian Spring Low Water (ISLW)	-0.86	-0.81	-0.84

Diagram 1: Tidal Planes Diagram



3.10. Historical Flood Level Data

In order to calibrate and validate the models, data from historical events is required. Flood marks for historical events prior to 1998 were available from Reference 2 and are shown on Figure 4. The original source, accuracy and nature of the flood mark (debris, mark by resident etc.) are unknown.

A water level recorder was installed upstream of the weir / bridge at Henderson Street, Turrella by Sydney Water which captured data from 1992 to 2003. Thus water level data from this gauge are available for the December 1992, February 1993 and January 1996 events. The entire period of record (parts are missing) is provided on Figure 5.

The community consultation undertaken as part of this study also identified respondents with awareness of flood marks and/or possession of photos which were considered as part of the calibration/validation of the modelling. Many locations with potential overland flood affectation were identified. Residents were particularly concerned about flooding near Bexley Road, Bardwell Park Station, Hilcrest Avenue and in the lined channel between Laycock Street and Preddys Road. While some community members identified specific dates and locations many simply identified flooding occurring in heavy rainfall. Often residents identified the occurrence of flooding in parks, golf courses and drainage reserves.

Most responses received as part of the community consultation did not contain specific flood marks against which the flood models could be measured, or where flooding was described the date was not specified. Several community members expressed awareness of the October 2014 event, so in many cases these observations were assumed to be from this storm, which produced a relatively large recent event within the catchment. These descriptions of flooding were used for qualitative validation of the model results.

An overview of the flooding hot spots identified in the community consultation process is presented in Figure C6. A description of each flooding observation obtained through the community consultation process is also provided in Table 7.

Table 7: Records of Historical Flooding from Community Consultation

ID	Description of Flooding
W_0024	Flooding over Bardwell Road by Bardwell Creek
W_0001	Flooding on Veron Road to ~ 2 m in downstairs.
W_0005	Significant damage to property affected by flooding on Oliver St
W_0013	Flooding at Bexley Road
W_0016	Even in most severe storms, flooding never reached Unwin St, Bexley in over 30 years
W_0023	Flooding of the path below rail bridge in Tempe
W_0026	No flooding observed at Henderson St, Turrella
W_0034	Canal overtopped reaching level of ~ 3 m
W_0040	flooding in the 1980s but not affected at Beaumont St, Kingsgrove
W_0041	flooding not observed at Heath St in > 30 years
W_0043	flooding not observed at Walker St in 10-20 years
W_0049	Floodwaters have reached the rear of properties on Edith St that back onto Bardwell Valley Creek
W_0061	Flooding at Kingsgrove Ave with blocks inundated prior to street being macadamised and guttered
W_0066	Flooding causing major traffic delays on Bexley Road near the M5
W_0068	No flooding observed at Turrella St for ~ 45 years
W_0079	No awareness of flooding at Berith St in over 30 years
W_0081	No awareness of flooding at Henderson St in 5-10 years
W_0090	Flooding up to 2 feet
W_0100	No awareness of flooding in 5-10 years
W_0104	No awareness of flooding at Preddys Rd for 10 - 20 years
O_0004	Flooding at a level of > 1 m reached lots on Hannan St causing significant damages to property
O_0007	Minor flooding in basement car parks
O_0013	Properties flooded in parts of Bardwell Park/Bexley North reaching a level of < 1 m

ID	Description of Flooding
O_0014	Floodwaters reached a level of 30cm at a property near Bardwell Park and up to the platform at the train station
O_0017	Land of properties on Slade Rd has been affected in the past. Stormwater easement pipe has since been repaired and no issues since
O_0024	Property consistently flooded after rain prior to drainage alteration undertaken by the resident
W_0002	Land was affected due to pipe blockages along the golf course and lack of maintenance causing damage to landscaped areas
W_0003	Extreme flooding at the rear of the golf club carpark which knocked down a fence
W_0006	Floodwaters encroached lawn and reached metres from house at Turrella St
W_0035	Land affected occasionally during winter at the M5 entrance. Worst in 2014
W_0053	Land affected to a depth of 45-50cms at the intersection of Mimosa St and Downey St
W_0088	Flooding at Bexley North Rd causing isolation of residents
W_0098	Flooding has occurred 3 times in the past 6 years from the creek behind lots on Edith St causing damages to property
W_0098	Flooding inundated land up to land on Edith St to ~ 1 m at the rear of property
W_0105	Local train stations experience flooding causing cancellations and delays
O_0006	Intersection of Guess Ave and Arncliffe St in Wolli Creek is often flooded and impassable via car or by foot
O_0008	Major flooding at Soudan St and Coveney St due to stormwater blockage affecting properties below street level
O_0009	Observed flooding at Coolabah Reserve and Bardwell Park Station
O_0012	Flooding observed at rail line between Bexley North and Bardwell Park Stations in 2015, Bexley road between Kingsgrove Ave and Barnsbury Grove causing southbound road closures in 2013, Bexley road between Slade Rd and Homer St causing road closures in both directions in 2016
O_0015	Bexley Rd often inundated at Wolli Creek blocking the M5 thus congesting residential roads
O_0016	Flooding often occurs at the Bexley Rd Slade Rd intersection
O_0020	Observed flooding at Bexley Rd
O_0022	Regular flooding at Bexley Rd at the M5 entrance in wet weather. Flooding 150 m from house causing serious property damage in 2016. Sudden and dangerous inundation at Bardwell Park station in 2015
O_0026	Regular flooding at intersection of Kingsgrove Ave and Bexley North. Drains on Bexley Road, especially opposite the Metro service station overflows in prolonged rain
O_0029	Observed flooding at Wolli creek and Bardwell Creek inundating Bardwell Rd at Coolibah Reserve and reaching the fence of 50 Hannan St
O_0031	Flooding observed at the Golf Course
O_0032	Floodwaters rise rapidly at Turrella and Bardwell Park stations
O_0033	Flowpath in Whitbread Park during storms. Bexley Rd frequently inundated. Bardwell Velley Parklands canal often affects properties on Preddys road and other streets
O_0034	Major flowpath in Whitbread park to stormwater drain. Flooding at Bexley North Station and Bexley Rd
O_0036	Bardwell Park Station and Bexley Rd at the M5 often floods
W_0011	Blockages in canal between Oliver St and Coveney St Bexley North can cause flooding
W_0031	Floors flooded next to Slade Rd between Bexley North and Bardwell Park Stations
W_0038	Flooding affected land on Beaumont St Kingsgrove in the 1980s
W_0050	Major flooding of Bardwell Park station
W_0052	Flooding of Wolli creek at Bexley North and at the intersection of Slade and Bexley Rd affecting business at 238 Slade Rd
W_0056	Minor flooding on the corner of Albert and Westbourne streets overtopping the gutter into the park.
W_0057	Observed flooding but not affected at Downey St
W_0058	Corner of Arncliffe St and Guess Ave often floods after rain. Arncliffe St near Woolworths totally flooded after heavy rain

ID	Description of Flooding
W_0086	Flooding of Wolli Creek caused inundation of balconies at units 25 and 26. Bardwell Creek broke its banks at the rear of the Glen Village covering Shepherd Reserve to a depth of two feet
W_0094	Shepherd Reserve flooded 3 times since 2012 uprooting trees and affecting units to a depth of 2 feet
W_0099	Flooding in the reserve between the creek and the Glen Village removed large concrete manhole cover
W_0087	Observed creek flooding to a level of 3-4 m in park behind Edith St affecting property on several occasions
W_0093	Observed flooding but not affected at Water St
W_0107	Bexley Rd near the M5 entrance often floods. Water pooled in Backyard of property on Fortescue St
W_0108	Observed flooding at Bardwell Park Station
W_0109	Flooding entered property from railway line in 2014 reaching a height of 0.1 m and damaging property
W_0113	Floodwaters reached a height of 3 m in October 2014 causing $ 1.5 million in damages to the lower level

These observations are compared spatially against the October 2014 model results on Figure C6 to Figure C11. Hotspots of particular concern to members of the community are presented in Figure C12 to Figure C15.

Based on the magnitude of this flood event within the catchment and the availability of historical flood level data, the following events were selected for the model calibration process:

- November 1984;
- December 1992;
- February 1993;
- January 1996;
- October 2014.

Commentary and photographs of historical flooding were provided by the community during the consultation process. A selection of photographs obtained from Bayside Council, media reports and as part of the community consultation process is presented in Photo 1 to Photo 12 below.

Photo 1: 1984 - The Glen Village, Bardwell Valley (Bardwell Creek)

Photo 2: 2012 - Flooding on Bexley Road (Wolli Creek)

Photo 3: 2012 - Flooded railway between Bexley North and Bardwell Park Station (Wolli Creek)

Photo 4: 2012 - Turrella Footbridge (Wolli Creek)

Photo 5: 2014 - Car swept from driveway at Coveney St, Bexley North (Bardwell Creek)

Photo 6: 2014 - Bexley Road, Kingsgrove (Wolli Creek)

Photo 7: 2015 - Flooding over Bexley Road (Wolli Creek)

Photo 8: 2015 - Bardwell Park along East Hills rail line (Wolli Creek)

Photo 9: 2015 - Bardwell Park Station (Wolli Creek)

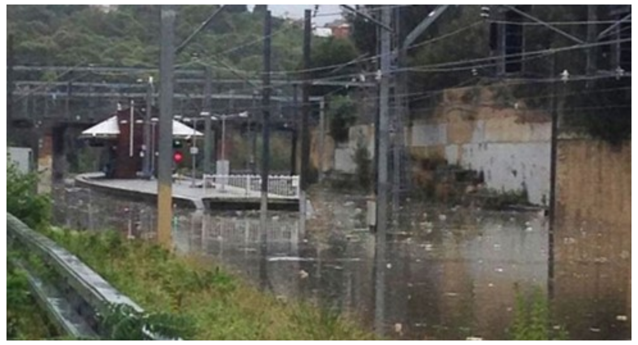


Photo 10: 2015 – Bardwell Park Station (extracted from CCTV video) (Wollli Creek)

Photo 11: 2012 – Turrella Reserve looking North (Wolli Creek)

Photo 12: Floodwaters behind Levee at Hillcrest Avenue, Bardwell Valley (Bardwell Creek)

3.11. Historical Rainfall Data

3.11.1. Overview

Rainfall data is recorded either daily (24-hour rainfall totals to 9:00 am) or continuously (pluviometers measuring rainfall in small increments – less than 1 mm). Daily rainfall data has been recorded for over 100 years at many locations within the Sydney basin. However, pluviometers have generally only been installed for widespread use since the 1970s. Together these records provide a picture of when and how often large rainfall events have occurred in the past.

Care must be taken when interpreting historical rainfall measurements. Rainfall records may not provide an accurate representation of past flooding 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 9:00 am in the morning. Thus if a single storm is experienced both before and after 9:00 am, then the rainfall is "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 9:00 am reading.
- The duration of intense rainfall required to produce overland flooding in the study area is typically less than 6 hours (though this rainfall may be contained within a longer period of rainfall). This is termed the "critical storm duration". For a larger catchment (such as the Parramatta River) the critical storm duration may be greater (say 9 hours). For the study area a short intense period of rainfall can produce flooding but if the rain starts and stops quickly, 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. This data has much fewer limitations than daily read data. Pluviometers, however, can also fail during storm events due to the extreme weather conditions.

Intense rainfall events which cause overland flooding in highly urbanised catchments are usually localised and as such are only accurately represented by a nearby gauge, preferably within the catchment. Gauges sited even only a kilometre away can show very different intensities and total rainfall depths.

The rainfall data described in the following sections pertains to information that was used in model calibration.

3.11.2. Rainfall Stations

There are a number of rainfall stations located across the Sydney metropolitan area, including daily read and pluviometer gauges. The continuous pluviometer stations record rainfall in sub-daily increments (with output typically reported approximately every 5 minutes). These records were used to create detailed rainfall hyetographs, which form the model input for historical events against which the model is calibrated. The nearby continuous pluviometers used in the calibration process are shown in Table 8 as well as the availability of historical records for the calibration events.

The locations of these gauges are shown in Figure 6. Only one gauge at the Bexley Bowling Club is located within the catchment.

Table 8: Pluviometer Rainfall Stations

Station Number	Station Name	Authority	Nov-84	Dec-92	Feb-93	Jan-96	Oct-14
566047	Mortdale Bowling Club	SWC	Y	Y	Y	Y	Y
566062	Bexley Bowling Club	SWC		Y	Y	Y	Y
566026	Marrickville (SPS)	SWC	Y	Y	Y	Y	Y
566020	Enfield (Composite Site)	SWC	Y	Y	Y	Y	Y
566091	Kyeemagh Bowling Club	SWC		Y	Y	Y	Y
566113	Canterbury Racecourse	SWC				Y	Y
566110	Erskineville Bowling Club	SWC				Y	Y
566028	Mascot Bowling Club	SWC	Y	Y	Y	Y	Y
66037	Sydney Airport	BoM	Y	Y	Y	Y	Y

“Y” indicates that data are available from that gauge for the respective historical event.

There are also a number of daily read rainfall stations located within or close to the catchment that were used in the calibration process and most have data available for the calibration events of interest. Details of these gauges are summarised in Table 9 (also mapped on Figure 6).

Rainfall isohyets are provided on Figure 7 to Figure 11 and temporal patterns on Figure 12 to Figure 16 for the calibration events.

Table 9: Daily Rainfall Stations

Station Number	Station Name	Operating Authority	Date Opened	Date Closed
66004	Bexley Bowling Club	BoM	1931	2008
66036	Marrickville Golf Club	BoM	2001	-
66037	Sydney Airport (MO)	BoM	1929	-
66058	Sans Souci Public School	BoM	1899	-
66070	Strathfield Golf Club	BoM	1952	-
66076	Wiley Park (Roselands)	BoM	1949	1987
66148	Peakhurst Golf Club	BoM	1999	-
66181	Oatley (Woronora Pde)	BoM	1981	2014
66194	Canterbury Racecourse AWS	BoM	1995	-
66204	Green Point	BoM	1998	-

3.11.3. Analysis of Daily Rainfall Data

A summary of the 10 largest daily rainfall totals at the daily read Bexley Bowling Club (66004) station is provided in Table 10. However none of the selected calibration events are included in this list.

Table 10: Large Daily Rainfall Totals at Bexley Bowling Club (66004)

Bexley Bowling Club (1983 to date)		
Rank	Date	Rainfall (mm)
1	30/04/1988	223
2	6/08/1986	215
3	25/09/1995	145
4	31/01/2001	126
5	31/08/1996	116
6	5/02/2002	112
7	11/04/1998	100
8	19/05/1998	98
9	22/03/1983	98
10	24/03/1984	95

Rainfall bursts during these events were either not intense enough to produce flooding or flooding occurred but no floodmarks were recorded for these events. For example the peak burst intensity of the 18/05/1998 rainfall event was less than 1EY over a 2 hour duration at the Bexley Bowling Club gauge despite this event being the 8th highest recorded daily total at this gauge.

The rainfall totals for each calibration event at each available rain gauge were used to create rainfall isohyets for the entire catchment (Figure 7 to Figure 11) and subsequently the rainfall depths for each individual sub-catchment in the hydrologic model. The rainfall isohyets were developed using the natural neighbour interpolation technique. In cases where a subcatchment was situated outside the interpolated isohyets, such as for WCKFS001, rainfall depths were taken to be equal to the average rainfall depth for the nearest adjacent subcatchments (i.e. the average of WCKFS002, WCKFS003 and WCKFS004).

Continuous pluviometer records provide a detailed description of temporal variations in rainfall. The temporal patterns of each of the storm events of interest were analysed and are presented in Figure 12 to Figure 16. The Bexley Bowling Club pluviometer was used to describe the temporal pattern for all events except November 1984 where the Mortdale pattern was used, due to the lack of data from the Bexley gauge.

3.11.4. Analysis of November 1984 Rainfall Event

An analysis of the available pluviometer data at Marrickville and Mortdale pluviometers (Figure 12) indicated that for the November 1984 storm the temporal patterns of the rainfall burst were very consistent and the Mortdale pluviometer was representative of the temporal pattern of rain falling around the catchment for the purpose of calibration.

Figure 7 also indicates that the 48 hour rainfall was greater to the east than the west. No data was available from the Bexley Bowling Club pluviometer but the daily gauge recorded 113 mm for a 48 hour total.

An analysis of the equivalent AEP Rainfall Design Intensities (ARR2016) in different pluviometers surrounding the catchment for the November 1984 event is presented in Table 11.

Table 11: Equivalent AEP Rainfall Design Intensities (ARR2016) – November 1984

Station Number	Station Name	Operating Authority	Equivalent Design Rainfall Intensity			
			30 mins	1 hour	2 hour	3 hour
566047	Mortdale Bowling Club	SWC	0.2 EY	10% AEP	5% AEP	10% AEP
566062	Bexley Bowling Club	SWC	N/A	N/A	N/A	N/A
566026	Marrickville (SPS)	SWC	0.2 EY	5% AEP	5% AEP	10% AEP
566020	Enfield (Composite Site)	SWC	0.2 EY	0.2 EY	0.2 EY	0.2 EY
566091	Kyeemagh Bowling Club	SWC	N/A	N/A	N/A	N/A

3.11.5. Analysis of December 1992 Rainfall Event

For the December 1992 event the Marrickville and Bexley patterns were similar (Figure 13) but the Mortdale pattern differed as the rain occurred slightly earlier. The total rainfall for this event (Figure 8) was relatively small (24 hour total of less than 60 mms in the catchment) with little rain outside the catchment. The short, intense rainfall burst lasting approximately 30 mins produced flooding in some parts of Bardwell Creek and Wolli Creek.

An analysis of the equivalent AEP Rainfall Design Intensities (ARR2016) in different pluviometers surrounding the catchment for the December 1992 event is presented in Table 12.

Table 12: Equivalent AEP Rainfall Design Intensities (ARR2016) – December 1992

Station Number	Station Name	Operating Authority	Equivalent Design Rainfall Intensity			
			30 mins	1 hour	2 hour	3 hour
566047	Mortdale Bowling Club	SWC	<1 EY	<1 EY	<1 EY	<1 EY
566062	Bexley Bowling Club	SWC	2% AEP	10% AEP	0.2 EY	0.5 EY
566026	Marrickville (SPS)	SWC	0.2 EY	0.5 EY	<1 EY	<1 EY
566020	Enfield (Composite Site)	SWC	0.2 EY	1 EY	<1 EY	<1 EY
566091	Kyeemagh Bowling Club	SWC	N/A	N/A	N/A	N/A

3.11.6. Analysis of February 1993 Rainfall Event

For the February 1993 event the Mortdale, Marrickville and Bexley patterns were similar (Figure 14). Approximately 60mm of rainfall was recorded at Bexley Bowling Club and there was a gradient from east to west (Figure 9).

An analysis of the equivalent AEP Rainfall Design Intensities (ARR2016) in different pluviometers surrounding the catchment for the February 1993 event is presented in Table 13.

Table 13: Equivalent AEP Rainfall Design Intensities (ARR2016) – February 1993

Station Number	Station Name	Operating Authority	Equivalent Design Rainfall Intensity			
			30 mins	1 hour	2 hour	3 hour
566047	Mortdale Bowling Club	SWC	<1 EY	1 EY	0.5 EY	1EY
566062	Bexley Bowling Club	SWC	1EY	0.5EY	0.2EY	0.2EY
566026	Marrickville (SPS)	SWC	2% AEP	1% AEP	2% AEP	5% AEP
566020	Enfield (Composite Site)	SWC	<1EY	<1EY	<1EY	<1EY
566091	Kyeemagh Bowling Club	SWC	0.5EY	0.2EY	5%AEP	10%AEP

3.11.7. Analysis of January 1996 Rainfall Event

For the January 1996 event the Mortdale, Marrickville and Bexley patterns were similar (Figure 15) but the spatial pattern indicates that the storm moved as the timing of the rainfall varied. A 24 hour total of 77 mm was recorded at Bexley bowling club and there was a gradient from west to east.

An analysis of the equivalent AEP Rainfall Design Intensities (ARR2016) in different pluviometers surrounding the catchment for the January 1996 event is presented in Table 14.

Table 14: Equivalent AEP Rainfall Design Intensities (ARR2016) – January 1996

Station Number	Station Name	Operating Authority	Equivalent Design Rainfall Intensity			
			30 mins	1 hour	2 hour	3 hour
566047	Mortdale Bowling Club	SWC	10% AEP	5% AEP	1% AEP	>1% AEP
566062	Bexley Bowling Club	SWC	2% AEP	2% AEP	5% AEP	10% AEP
566026	Marrickville (SPS)	SWC	0.2 EY	0.5 EY	0.5 EY	0.5 EY
566020	Enfield (Composite Site)	SWC	>1% AEP	>1% AEP	1% AEP	1% AEP
566091	Kyeemagh Bowling Club	SWC	1 EY	1 EY	1 EY	<1 EY

3.11.8. Analysis of October 2014 Rainfall Event

For the October 2014 event the Mortdale, Marrickville and Bexley patterns were similar (Figure 16). Table 15 indicates that the 24 hour total at Bexley Bowling Club pluviometer recorded an intense burst of rainfall during this storm event which exceeded a 1% AEP equivalent design rainfall intensity. The total rainfall recorded at this pluviometer over a 24 hour period was 170 mm for this event which was greater than in the surrounding areas (also refer to Figure 11).

An analysis of the equivalent AEP Rainfall Design Intensities (ARR2016) in different pluviometers surrounding the catchment for the October 2014 event is presented in Table 15.

Table 15: Equivalent AEP Rainfall Design Intensities (ARR2016) – October 2014

Station Number	Station Name	Operating Authority	Equivalent Design Rainfall Intensity			
			30 mins	1 hour	2 hour	3 hour
566047	Mortdale Bowling Club	SWC	10% AEP	2% AEP	>1% AEP	>1% AEP
566062	Bexley Bowling Club	SWC	1% AEP	>1% AEP	>1% AEP	>1% AEP
566026	Marrickville (SPS)	SWC	0.5 EY	0.2 EY	10% AEP	5% AEP
566020	Enfield (Composite Site)	SWC	5% AEP	2% AEP	>1% AEP	>1% AEP
566091	Kyeemagh Bowling Club	SWC	1 EY	0.2 EY	5% AEP	2% AEP

3.12. Design Rainfall Data

The design rainfall intensity-frequency-duration (ARR 2016 IFD) data were obtained from the BoM online design rainfall tool and are provided on Table 16.

Table 16: Rainfall IFD Data at the Catchment Centre (ARR 2016)

	Annual Exceedance Probability (AEP) Rainfall intensity in mm/h						
Duration	**63.20%**	**50% #**	**20% ***	**10%**	**5%**	**2%**	**1%**
1 min	139	154	199	229	258	296	324
2 min	116	127	161	184	206	236	259
3 min	107	117	150	171	193	221	242
4 min	100	110	142	163	183	210	230
5 min	94.7	104	135	155	174	200	219
10 min	74.6	82.7	108	124	140	160	176
15 min	62	68.8	89.5	103	116	133	146
30 min	42.3	46.8	60.7	69.9	78.8	90.3	98.9
1 hour	27.5	30.3	38.9	44.8	50.5	58	63.6
2 hour	17.5	19.3	24.8	28.6	32.3	37.3	41.1
3 hour	13.6	14.9	19.3	22.3	25.3	29.3	32.4
6 hour	8.89	9.84	12.9	15	17.2	20.1	22.4
12 hour	5.92	6.63	8.92	10.5	12.2	14.4	16.1
24 hour	3.94	4.48	6.19	7.39	8.59	10.3	11.6
48 hour	2.54	2.92	4.12	4.95	5.76	6.91	7.78
72 hour	1.91	2.21	3.13	3.75	4.36	5.21	5.85
96 hour	1.54	1.78	2.52	3.01	3.48	4.14	4.64
120 hour	1.3	1.49	2.1	2.5	2.88	3.4	3.8
144 hour	1.12	1.29	1.8	2.13	2.44	2.87	3.2

Note:
 # The 50% AEP IFD does not correspond to the 2 year Average Recurrence Interval (ARI) IFD. Rather it corresponds to the 1.44 ARI.
** The 20% AEP IFD does not correspond to the 5 year Average Recurrence Interval (ARI) IFD. Rather it corresponds to the 4.48 ARI.*

The ARR 2016 rural loss parameters were obtained from the ARR 2016 datahub and are provided on Table 17. These values were not used in the calibration process but are relevant for the design flood events.

Table 17: ARR 2016 losses at catchment centre

Storm Initial Losses (mm)	Storm Continuing Losses
32.0	2.1

4. MODELLING METHODOLOGY

4.1. Overview

The Bardwell Creek and Wolli Creek catchments have a mix of pervious and impervious surfaces and piped and overland flow drainage systems. This creates a complex hydrologic and hydraulic flow regime which requires a dual hydrologic and hydraulic analysis to address.

Estimation of flood behaviour in the catchment was undertaken as a two-stage process consisting of:

1. Hydrologic modelling to convert rainfall estimates to overland flow runoff;
2. Hydraulic modelling to estimate overland flow distributions, flood levels and velocities.

Inflow hydrographs serve as inputs at the boundaries of the hydraulic model. In a flood study where long-term gauged streamflow records are not available, a rainfall-runoff hydrologic model (converts rainfall to runoff) is generally used to provide these inflows. A range of runoff routing hydrologic models are available as described in ARR 2016 (Reference 12). These models allow the rainfall depth to vary both spatially and temporarily over the catchment and readily lend themselves to calibration against recorded data.

4.2. Hydrologic Model

Hydrologic modelling was undertaken using WBNM (Reference 13), a widely utilised hydrologic modelling software. The WBNM model has a relatively simple but well supported method, where the routing behaviour of the catchment is primarily assumed to be correlated with the catchment area. A hydrological model for the entire Wolli Creek and Bardwell Creek catchment was created and used to calculate the flows for each individual sub-catchment. An overview of the WBNM sub-catchments is provided in Figure 17.

4.3. Hydraulic Model

Hydraulic modelling was undertaken using TUFLOW (Reference 14), a widely utilised 1D and 2D flood simulation software. Runoff hydrographs from the WBNM hydrologic model were input into the TUFLOW model. Hydraulic modelling was carried out on a fixed 2 m grid. The TUFLOW modelling package includes a finite difference numerical model for the solution of the depth averaged shallow water flow equations in two dimensions. The TUFLOW software is produced by BMT WBM and has been widely used for a range of similar projects. The model is capable of dynamically simulating complex overland flow regimes. It is especially applicable to the hydraulic analysis of flooding in urban areas which is typically characterised by short duration events and a combination of supercritical and subcritical flow behaviour, and interactions between overland flow and the sub-surface drainage network.

In addition to 2D modelling of overland flows, TUFLOW can model drainage elements (pipes) as 1D elements as well as modelling creeks or open channels in 1D if required. The 1D and 2D components of the model can be dynamically linked during the simulation. In TUFLOW the ground topography is represented as a uniformly-spaced grid with a ground elevation and a Manning's "n" roughness value assigned to each grid cell. The grid cell size is determined as a balance between the model result definition required and the computer run time (which is largely determined by the total number of grid cells, and the number of "wet" cells). A cell size of 2 m by 2 m was found to provide an appropriate balance for this study.

4.4. Flood Frequency Analysis

Flood Frequency Analysis (FFA) uses the record of past flooding at a site to determine design event discharge. Through a statistical analysis of flood events, the AEP of a given discharge can be determined. This analysis can be used to confirm output design flows from the hydrologic model independent of the hydraulic model. FFA can also be useful for design flow estimation where the length and quality of the observed record and the accuracy of the rating curve are considered adequate.

There are no water level gauges present on Wolli Creek or Bardwell Creek which have had velocity gaugings undertaken in order to determine the flows, and therefore FFA could not be undertaken as part of this study.

4.5. Historical Event Calibration and Validation

In order to reconcile observed historical flooding, and the "design" flood events considered in this study, the flood model must be calibrated to and validated against historically observed data. Calibration involves a comparison of model results against observed historical floods, and modifying the model parameters if required to more accurately reflect the key flood mechanisms. If records are available from multiple storms, validation can be undertaken to ensure that the calibration model parameter values are acceptable in other storm events with no additional alteration of values.

Recorded rainfall and streamflow data are required for calibration of the hydrologic model, while historic records of flood levels, velocities and inundation extents can be used for the calibration of hydraulic model parameters. In the absence of such data, model verification using limited historical data is the only option and a detailed sensitivity analysis of the different model input parameters constitutes current best practice. Based on the available data, a joint calibration of the hydrologic and hydraulic model was undertaken. This involves simulating rainfall runoff with the hydrologic model and flood behaviour with the hydraulic model and modifying parameters in both models (within reasonable and acceptable ranges) in order to match observed flood levels and behaviour at particular locations.

The choice of calibration or validation events for flood modelling depends on a combination of the severity of the flood event and the quality of the available data. Based on the magnitude of the storm event within the catchment (Section 3.11) and the availability of historical flood level data (Section 3.10), the following events were selected for the model calibration process:

- November 1984;
- December 1992;
- February 1993;
- January 1996; and
- October 2014.

5. HYDROLOGIC MODEL SETUP

5.1. Introduction

Inflow hydrographs serve as inputs at the boundaries of the hydraulic model. In a flood study where long-term gauged streamflow records are not available, a rainfall-runoff hydrologic model (converts rainfall to runoff) is generally used to provide these inflows. A range of runoff routing hydrologic models are available as described in ARR 2016 (Reference 12). These models allow the rainfall depth to vary both spatially and temporarily over the catchment and readily lend themselves to calibration against recorded data.

The WBNM hydrologic runoff routing model was used to determine flows from each sub-catchment. As previously mentioned, the WBNM model has a relatively simple but well supported method, where the routing behaviour of the catchment is primarily assumed to be correlated with the catchment area. The WBNM model can be calibrated to streamflow data through adjustment of various model parameters including the stream lag factor, storage lag factor, and/or rainfall losses. Due to the absence of streamflow data it was not possible to perform an independent calibration of the hydrologic model to observed flows.

A hydrological model for the entire Bardwell Creek and Wolli Creek catchment was created and used to calculate the flows for each individual sub-catchment for inclusion in the TUFLOW model.

5.2. Sub-catchment delineation

The total catchment area covered by the WBNM model is approximately 20.9 km^2 consisting of 555 sub-catchments with an average sub-catchment size of 1.29 hectares within the 7.1 km^2 study area. This relatively fine-resolution sub-catchment delineation ensures that where significant overland flow paths exist in the catchment, they are accounted for and incorporated into hydraulic routing in the model. The sub-catchment delineation is shown in Figure 17. Larger sub-catchments were defined to represent the upstream boundaries to the north and west of the study area.

5.3. Impervious Surface Area

Runoff from connected impervious surfaces (such as roads, gutters, roofs or concrete surfaces) occurs significantly faster than from pervious surfaces. This disparity results in a faster concentration of flow within the downstream area of the catchment as well as increased peak flow in some situations. This is accounted for in the model through an estimate of the proportion of both impervious and pervious surfaces.

Determining the pervious and impervious areas of each sub-catchment was estimated by estimating the proportion of the sub-catchment area covered by different surface types (from Google maps and aerial photography supplied by Bayside Council) and then estimating the impervious percentage of each surface type as summarised in Table 18 below.

Table 18: Impervious Percentage per Land Use Type

Material	Impervious Percentage
Roads/Pavements	100%
Vegetation/Grass/Field	20%
Residential Medium Density	70%
Residential High Density	90%
Industrial/Commercial	100%

5.4. Rainfall Losses and WBNM Lag Parameters

Methods for modelling the proportion of rainfall that is "lost" to infiltration are outlined in ARR 2016 (Reference 12). The methods are of varying degrees of complexity, with the more complex options only suitable if sufficient data are available. The method most typically used for design flood estimation is to apply an initial and continuing loss to the rainfall. The initial loss represents the wetting of the catchment prior to runoff starting to occur and the continuing loss represents the ongoing infiltration of water into the saturated soils while rainfall continues.

Rainfall losses from a paved or impervious area are considered to consist of only an initial loss (an amount sufficient to wet the pavement and fill minor surface depressions). Losses from grassed and vegetated areas are comprised of an initial loss and a continuing loss. The adopted losses for calibration and design modelling are discussed in Sections 7 and 8 respectively.

WBNM requires a catchment lag parameter and a stream lag factor to be selected which describes the average travel time for runoff from the catchment surface. The lag parameter is applied to pervious surfaces and adjusted to apply to impervious surfaces by multiplication by an impervious lag factor. The WBNM parameters selected are summarised in Table 19.

Table 19: Adopted WBNM Parameters for Calibration and Design

WBNM Parameters	Value
Lag Parameter (C)	1.7
Stream Lag Factor (natural channels)	1.0
Stream Lag Factor (concrete lined channels)	0.8
Impervious Lag Factor	0.1

The parameter values applied are generally consistent with the recommended values in the WBNM manual. The WBNM manual recognises that the presence of concrete lined channels will result in increased flow velocities and decreased lag times from their natural values. In consideration of this a stream lag factor value of 0.8 was adopted for sub-catchments containing a mix of overland flow paths and concrete lined channels.

6. HYDRAULIC MODEL SETUP

6.1. TUFLOW

The study implemented a TUFLOW model with a cell size of 2 m by 2 m. This resolution provides an appropriate balance between providing sufficient detail for roads and overland flow paths and workable computational run-times. The model grid was established by sampling from a triangulation of filtered ground points from the 2013 LiDAR dataset.

The TUFLOW hydraulic model extends upstream to the western boundary of the study area, just upstream of Croydon Road and Kingsgrove Road. The model is bounded by Forest Road to the south and Homer Street to the north. The model extends downstream to the Cooks River in the northeast. The total area included in the 1D/2D model covers 9.55 km^2 and the extents of the TUFLOW model are shown in Figure 18.

6.2. Boundary Locations

The locations of the boundary conditions are shown in Figure 18.

6.2.1. Inflows

For sub-catchments within the TUFLOW model domain, local runoff hydrographs were extracted from the WBNM model (see Section 5.2). These were applied to the receiving area of the sub-catchments within the 2D domain of the hydraulic model. These inflow locations typically correspond with gutters, stormwater inlet pits, drainage reserves or open watercourses features which have typically been constructed to receive intra-lot drainage and sheet runoff flows from upstream catchment areas.

For inflows to Wolli Creek and the Moore Street branch of Bardwell Creek the upstream boundary of the model was extended sufficiently far such that the influence of boundary effects was minimised. Inflows to the Croydon Road branch of Bardwell Creek were applied directly to the Bexley Golf Course, as shown in Figure 18.

6.2.2. Downstream Boundaries

Two different type of downstream boundary conditions (Figure 18) were utilised in the model:

- **HQ Boundaries** – The outflow from this boundary is dependent on water level, using a rating curve in which the topographic gradient is assumed to equal the water level gradient (i.e. uniform flow); and
- **HT Boundary** – The water level at the boundary, which can be specified as a static or a varying water level over time.

HQ Boundaries

The HQ boundaries are identified below in Table 20 with the adopted slope values. These locations correspond to areas where cross-catchment flow occurs from the study area into adjacent urban catchment areas.

Table 20: HQ Boundary Locations and Adopted Slopes

HQ Boundary	Slope Adopted
Fripp Street	0.05
Guess Avenue bridge	0.005

HT Boundary

A downstream HT boundary was included along the eastern boundary of the model at the confluence of Wolli Creek with the Cooks River as shown on Figure 18. The tailwater levels at the downstream boundary are dependent on water levels in the Cooks River, and thus different tailwater assumptions were adopted for different events.

For the calibration events, the tailwater levels were set to a constant level which represents the highest Botany Bay tide level within the period of the storm (Table 21). Botany Bay tide levels for historical storms were obtained from the Public Works Department for the 1984, 1992, 1993 and 1996 events and from a tide chart for Botany Bay for the 2014 event.

Table 21: Calibration Tailwater Levels

Event	Tailwater Level (mAHD)
November 1984	0.78
December 1992	0.56
February 1993	0.56
January 1996	0.19
October 2014	0.48

6.3. Surface Roughness

The hydraulic efficiency of the flow paths within the TUFLOW model is represented in part by the hydraulic roughness or friction factor formulated as Manning's 'n' values. 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.

The Manning's 'n' values adopted for the study area are shown in Table 22. These values have been adopted based on site inspection and past experience in similar floodplain environments. The spatial variation in Manning's 'n' within the model boundary is shown in Figure 19.

Table 22: Manning's 'n' values adopted in TUFLOW

Surface	Manning's 'n' adopted
Grass	0.04
Light Vegetation	0.07
Waterways	0.05
Vegetated Creek	0.09
Urban Properties	0.065
Lakes/ Ponds	0.1
Industrial/ Roads	0.02
Railways	0.04
Concrete-lined channel	0.02

6.4. Hydraulic Structures

6.4.1. Buildings

Buildings and other significant features likely to obstruct flow were incorporated into the model based on building footprints defined from aerial photography. These types of features were modelled as impermeable obstructions to flow and thus were assumed to have no flood storage capacity. Building delineation was validated in key overland flow areas by site inspection and using Google StreetView photographs.

6.4.2. Fencing and Obstructions

Smaller localised obstructions (such as fences) can be represented in TUFLOW in several ways including as impermeable obstructions, a percentage blockage or as an energy loss. The obstructions may also be approximated generally by increasing Manning's roughness for certain land use areas (such as residential) to represent the typical type of fencing used in such areas.

The majority of fences in the catchment were not modelled, as they can be difficult to identify and generally do not affect flow behaviour significantly in areas of shallow flow. The concrete panel noise walls on the southern boundary of the rail easement between Bexley North and Kingsgrove Station are likely to be a barrier to overland flows entering the rail corridor. For this reason these noise walls were included in the TUFLOW model as solid obstructions. Noise walls with large gaps underneath were modelled as layered flow constrictions or solid obstructions with culverts which allows water to flow through these gaps in the model.

6.4.3. Bridges and Culverts

Schematisation of key hydraulic structures was included in the hydraulic model, at the locations indicated Figure 18. Bridges, sewer pipes and pedestrian crossing over watercourses were generally modelled as 2D layered flow constrictions except where they occurred within the 1D domain in sections of Wolli Creek and Bardwell Creek. In these cases they were modelled in 1D as bridges or automatically generated weirs in the model. The modelling parameter values for the bridges were based on the geometrical properties of the structures obtained from survey data, site visits and through the use of Google StreetView photographs where possible.

6.4.4. Surface and Sub-Surface Drainage Network

The stormwater drainage network, including concrete lined channels in the upstream portions of Bardwell Creek and Wolli Creek, was modelled in TUFLOW as a 1D network dynamically linked to the 2D overland flow domain. This stormwater network includes conduits such as concrete lined channels, pipes and box culverts, and stormwater pits, including inlet pits and junction manholes. The schematisation of the stormwater network was undertaken using the pit and pipe GIS layers supplied by Bayside Council which was supplemented with tabulated data from WMAwater. Figure 18 shows the location of major drainage features and hydraulic structures included as 1D elements in the TUFLOW model.

6.4.5. Inlet Pits

Details of the 1D solution scheme for the pit and pipe network are provided in the TUFLOW user manual (Reference 14). For the modelling of inlet pits the “R” pit channel type was utilised, which requires a width and height dimension for the inlet in the vertical plane. The width dimension represents the effective inlet length exposed to the flow, and the vertical dimension reflects the depth of flow where the inlet becomes submerged, and the flow regime transitions from the weir equation to the orifice equation. For lintel inlets, the width was based on the length of the opening which was assumed to be 1.2 m for all inlet pits.

A similar modelling approach to that used in Reference 3 was adopted to represent inflows from the large pipe and culvert systems entering Wolli Creek and Bardwell Creek from outside the study area. Inflows to nodes with large inlet capacities were included in the model such that the pipe capacity is the limiting factor to inflows. When the capacity of the pipe is exceeded, surcharging occurs at the location of inflows.

This approach was considered to provide a reasonable representation of inflows to the model however it does not accurately describe flood behaviour near the location of the inflow node. For this reason the model boundary was extended such that inflows are located sufficiently far from the area of interest to allow an accurate definition of flood behaviour within the study area.

6.4.6. Road Kerbs and Gutters

LiDAR typically does not have sufficient resolution to adequately define the kerb and gutter system within roadways. The density of the aerial survey points is in the order of one per square metre, and the kerb/gutter feature is generally of a smaller scale than this, so the LiDAR does not pick up a continuous line of low points defining the drainage line along the edge of the kerb.

To deal with this issue, Reference 15 provides the following guidance:

> *“Stamping a preferred flow path into a model grid/mesh (at the location of the physical kerb/gutter system) may produce more realistic model results, particularly with respect to smaller flood events that are of similar magnitude to the design capacity of the kerb and*

gutter. Stamping of the kerb/gutter alignment begins by digitising the kerb and gutter interval in a GIS environment. This interval is then used to select the model grid/mesh elements that it overlays in such a way that a connected flow path is selected (i.e. element linkage is orthogonal). These selected elements may then be lowered relative to the remaining grid/mesh."

The road gutter network plays a key role for overland flow in the Bardwell Creek and Wolli Creek catchments. In order to model the system effectively, the gutters were stamped into the mesh using the method described above. The method used was to digitise breaklines along the gutter lines, and reduce the ground levels along those model cells by 0.1 m, creating a continuous flow path in the model.

6.4.7. Pedestrian Underpasses Underneath M5

The pedestrian underpasses under the M5 motorway between Kingsgrove Road and Bexley Road were included as breaklines in the 2D domain.

6.4.8. Gross Pollutant Trap (GPT)

The GPT at Nairn Street was modelled as an additional branch of 1D channel with a high Manning's roughness value and additional form losses to represent the energy loss as water flows through the trash rack.

6.4.9. Turrella Weir and Footbridge

Turrella weir and footbridge are located at the end of Henderson Street, Turrella. The footbridge was reconstructed in 2014 to replace the previous footbridge which was damaged by floods. An image of the old footbridge during a 2012 flood event is presented in Photo 4 and an image of the new footbridge is presented in Appendix B (Image 18). The weir and footbridge were modelled as a layered flow constriction with the invert of the first layer at the level of the weir crest and the obvert at the deck of the bridge. Bridge dimensions were obtained from construction drawings provided by Bayside Council and survey. The data indicates that underside of new footbridge is at 2.7 mAHD, whereas the old footbridge was at 2.87 mAHD.

6.4.10. Sewer Line (SWSOOS)

The SWSOOS sewer line crosses the tidal portion of Wolli Creek at Turrella. This was modelled as a layered flow constriction in 2D. The SWSOOS passes under the rail line near Thompson Street. During large flood events flows from the creek can pass under the railway via the ~0.5 m wide gaps to either side of the sewer embankment. These gaps were modelled as 2 m wide breaklines carved through the rail line on either side of the SWOOS embankment. There are several culverts under the SWSOOS embankment which allow floodwaters to pass under the sewer line which were also included in the model.

6.4.11. Hillcrest Avenue – Levee and Pipes

The levee upstream of Bardwell Valley Golf Course was defined from the DEM as a thick (3 m) breakline at the 1D/2D connection to ensure that this structure is adequately defined in the model. The three pipes with non-return valves which drain water ponding behind the levee were included as culverts with unidirectional flow.

6.5. Calibration Debris Blockage Assumptions

Blockage of hydraulic structures can occur with the transportation of a number of materials by flood waters. This includes vegetation, garbage bins, building materials, cars and other urban debris. However, the disparity in materials that may be mobilised within a catchment can vary greatly.

Debris availability and mobility can be influenced by factors such as channel shear stress, height of floodwaters, severity of winds, storm duration and seasonal factors relating to vegetation. The channel shear stress and height of floodwaters that influence the initial dislodgment of blockage materials are also related to the AEP of the event. Storm duration is another influencing factor, with the mobilisation of blockage materials generally increasing with increasing storm duration (Reference 16).

The potential effects of blockage include:

- decreased conveyance of flood waters through the blocked hydraulic structure or drainage system;
- variation in peak flood levels;
- variation in flood extent due to flows diverting into adjoining flow paths; and
- overtopping of hydraulic structures.

Calibration modelling has generally been undertaken assuming no blockage of pipes, culverts and bridges greater than 300 mm in diameter. Pipes less than 300 mm in diameter were conservatively assumed to be completely blocked.

However for the October 2014 event, analysis of newspaper articles and community consultation responses revealed that during the October 2014 event a car and a water tank were swept into the lined-channel of Bardwell Creek between Coveney Street and Preddys Road in Bexley North (see Photo 13). For the 2014 event a blockage of 50% was applied to the culverts passing under Preddys Road and a blockage of 30% was applied to the Coveney Street culverts, to represent the blockage due to the car, water tank and assorted urban debris.

The sensitivity of hydraulic structures to blockage will be assessed in the next stage of this flood study.

Photo 13: Debris in channel between Coveney Street and Preddys Road (Bexley North)

(a) car (b) water tank

Blockage factors for the design flood events are discussed in Section 8.6.

7. MODEL CALIBRATION

7.1. Objectives

The objective of the calibration process is to build a robust hydrologic and hydraulic modelling system that can replicate historical flood behaviour in the catchment being investigated. If the modelling system can replicate historical flood behaviour then it can more confidently be used to estimate design flood behaviour. The resulting outputs from design flood modelling are used for planning purposes and for infrastructure design.

The choice of calibration events for flood modelling depends on a combination of the severity of the flood event and the quality of the data available. For this study, flood marks from several relatively recent historical events were available to use for calibration purposes; namely:

- November 1984;
- December 1992;
- February 1993;
- January 1996, and
- October 2014.

Typically, in urban areas calibration/validation information is lacking. Issues which may prevent a thorough calibration of hydrologic and hydraulic models are:

- There is only a limited amount of historical flood information available for the study area. For example, in the Sydney metropolitan area there are no long-term water level recorders in urban catchments similar to that of the study area;
- Rainfall records and particularly pluviometer records for past floods within the catchment are limited; and
- Changes to the catchment due to urban development may result in significant changes to land uses and drainage structures.

These limitations are typical of the majority of urban catchments and the calibration exercise undertaken here constitutes recommended practice as outlined in Reference 15.

7.2. Approach

Rainfall isohyets and temporal patterns for the five calibration events are provided on Figure 7 to Figure 16. To independently calibrate the hydrologic model would require a recorded peak flow measurement at some point within the catchment. Historical recorded flood level data were available from Reference 1 and a water level gauge was available just upstream of Turrella Weir which recorded water level data from 1992 to 2003. However no velocity gauging have been undertaken at this gauge to allow an estimation of the peak flows from the catchment to be obtained.

In consideration of the limited calibration data which was available a joint hydrologic/hydraulic calibration of the models was undertaken. No reliable surveyed peak flood levels were available for a large flood event (greater than 1% AEP) within the catchment. As no event had an extensive amount of high quality recorded data the approach adopted was to provide the best fit for all events. This was determined to represent the most reasonable approach rather than singling out a single event for calibration and the remainder as verification events. A limited calibration was undertaken using reasonable model parameter values. The only model change between each event was the rainfall data as no details are available of significant topographic or drainage structure changes in the period that would significantly affect the model results.

The rainfall depths for each event across the catchment were derived from the isohyets shown in Figure 7 to Figure 11. The rainfall inputs for the hydrologic model were varied spatially according to these isohyets. For each flood event, different temporal patterns were tested based on available pluviometer data. The temporal patterns adopted were from the pluviometer at Bexley Bowling Club where this gauge was available however for November 1984 the Mortdale pluviometer was adopted due to the absence of data from the Bexley pluviometer.

Rainfall loss parameters in the WBNM hydrologic model and the Manning's 'n' roughness values in the TUFLOW hydraulic model were adjusted along with other parameters until a reasonable match to most flood level marks was achieved.

For model calibration the adopted loss parameters are summarised in Table 23. These loss values are the same as those adopted in Reference 1, and are generally consistent with the parameters adopted in flood studies in similar catchments within the Sydney metropolitan area.

Table 23: Adopted Rainfall Loss Parameters for Calibration Events

Loss Parameter	Adopted Value
Impervious Area Initial Loss	0 mm
Pervious Area Initial Loss	10 mm
Continuing Loss	2.5 mm/hr

The model fits reasonably well to the recorded data at key locations in Bardwell Creek and Wolli Creek. However there were a number of limitations in the quality of the data including:

- Uncertainty regarding the original source and accuracy of much of the historical recorded flood level data;
- Uncertainty regarding the exact location of many historical flood marks;
- Lack of quality flood level data from recent historical flood events within the catchment;
- Sparsely positioned rainfall gauges which are often unable to adequately describe the spatial and temporal pattern of rainfall within the catchment.

Unless otherwise stated it was generally assumed that the recorded flood mark represents the peak flow within the main channel at the specified location on the flood data map presented in Figure 3 of Reference 1. These recorded flood marks are reproduced in Figure 4.

Community consultation responses identified overtopping of Bexley Road during flood events on Wolli Creek as a concern however no accurately surveyed peak flood level data were able to be obtained from the community consultation process.

For most events, the peak flood levels were found to be most sensitive to assumptions about the historical rainfall depths and temporal pattern, rather than to the other model parameters available for tuning the model calibration. This indicates that it is unreasonable to try and obtain a perfect fit in the model calibration results, since the available rainfall data is inherently unable to reflect the true spatial and temporal rainfall distribution across the catchment for the floods investigated. In light of this consideration, the adopted model parameters were not varied significantly from typical values used in similar studies in the region.

It should be noted that the original sources and accuracy of many of the recorded flood marks reported in the following sections were unable to be verified. Reference 1 suggests that the accuracy of the recorded levels is likely to range from ±0.1 m to ±0.5 m depending upon the type of the mark.

7.3. Bardwell Creek Calibration

The model fits reasonably well to the recorded data in Bardwell Creek with a few exceptions. A comparison of modelled and recorded flood levels for all of the selected calibration events in Bardwell Creek is presented in Table 24.

Table 24: Bardwell Creek - Comparison of Modelled and Recorded Flood Levels

Location	Recorded Level (mAHD)	Modelled Level (mAHD)	Difference (Modelled - Recorded Level) (m)
November 1984			
D/S Preddys Road	19.7	18.62	-1.08(1)
Hillcrest Avenue	11.43	11.95	0.52
Bridge D/S Hillcrest Avenue	11.3 to 11.5	11.93	0.43 – 0.63
Bardwell Road	5.25	5.57	0.32
December 1992			
Veron Road	14.3	13.00	-1.30(2)
February 1993			
N/A			
January 1996			
D/S Laycock Street	25	26.52	1.52
36 Canonbury Grove	17.35	17.56	0.21
21 Veron Road	13.25	13.44	0.19

(1) The main channel was overtopped by approximately 300 mm in the concrete lined section below Bexley pool complex. The recorded level was not accurately surveyed at the time of the flood.
(2) Half way up rear paling fence (accurately surveyed). No explanation could be provided on why the flood level reached such a high level at this location yet was not recorded elsewhere along Bardwell Creek (Reference 1).

Recorded flood levels in the semi-natural creek channel between Preddys Road and Bardwell Road are generally well matched in the model.

7.3.1. November 1984

There is a discontinuity between the recorded water levels and the surveyed levels downstream of Bexley Road in the channel below Bexley pool complex. Comments in Reference 2 suggest that during the November 1984 event the main channel was overtopped by 300 mm just upstream of the surveyed cross-section. However if this overtopping of the channel occurred at the location indicated on the flood marks map this would put the water level at closer to ~18 m. The peak modelled level in the relatively steep 1D channel immediately downstream of Preddys Road is 19.7 m and decreases to 17.4 m near 36 Canonbury Grove. This means that in the model the flow is contained completely within the channel as it exits the culvert downstream of Preddys Road and overtops the channel by approximately 0.7 m further downstream near 36 Canonbury Grove. The modelled results appear reasonable when the likely error band of the original measurement is considered.

No data was available which adequately describes the topography of the creek and floodplain near Hillcrest Avenue prior to the construction of the levee in 1988. The levee was included in the 2013 LiDAR data, which was used as the basis of the model topography at this location. Inclusion of the levee in the model for the 1984 event likely results in the slightly higher modelled peak flood levels immediately upstream of Bardwell Valley Golf Course.

A reasonable match was obtained for the peak flood level recorded on Bardwell Road. A comparison of modelled and recorded flood levels for this event is presented in Figure C1.

7.3.2. December 1992

One accurately surveyed recorded level was available for this event on Bardwell Creek just downstream of Veron Road. The modelled levels were substantially lower for this event than the recorded flood mark using reasonable model parameters. Refence 1 asserts that no explanation could be provided on why such a high peak flood level was recorded at this location and were also unable to achieve a match to this floodmark. Floodmarks were not recorded elsewhere along Bardwell Creek for this event which suggests that the flooding may have been highly localised. It seems plausible that the distribution of rainfall within the study area was not accurately captured for this event.

A comparison of modelled and recorded flood levels for this event is presented in Figure C2.

7.3.3. January 1996

The recorded water level of 25.00 m at this location suggests that water level in the channel reached a peak height at 0.3 m below the level of the Laycock Street culvert obvert. However the modelled peak flood level at this location is substantially higher at 26.5 m. Based on the rainfall and estimated flow, it is highly unlikely that the flow was contained in bank as suggested by the flood mark. The modelling reproduces observed flood levels well further downstream, where flow was out of bank. The reason for the mismatch here may be that the reported level was an observation of the level of flow exiting the culvert, where a hydraulic jump would be likely to occur. However the model does not distinguish a separate level within the channel at the culvert exit from the significant amount of overland flow rejoining the channel from across Laycock Street. The model also suggests that during the January 1996 the peak flood level from Bexley Golf Course may have overtopped the road however no data was available to corroborate this observation.

A reasonable match between modelled and recorded levels was attained at Canonbury Grove and Veron Road for the January 1996 event as shown in Figure C4.

7.4. Wolli Creek Calibration

As previously mentioned substantial modifications have been made to the concrete-lined section of Wolli Creek between Kingsgrove Road and Bexley Road between 1998 and 2002. Recent recorded historic flood marks are not available for flooding in Wolli Creek post M5 construction. Substantial changes to the topography and drainage network on the northern side of Wolli Creek occurred as part of the M5 East construction including the development of a raised road embankment and the installation of several large culverts passing under the M5.

As a result of data limitations it was not considered feasible to develop separate models which represent the existing and historic configuration of this section of the Wolli Creek channel. Rather the existing model of the Wolli Creek channel developed in Reference 3 was used to represent the existing channel configuration. This model was developed using the geometry from M5 WAE drawings and trunk drainage plan provided in Sydney Water's 1995 Capacity Assessment Report. This model was used for calibration against historic flood observations (Reference 3). The model was modified to include the WBNM inflows developed in Section 5 and extended in 2D from Bexley Road to the confluence of Wolli creek with the Cooks River.

The model fits reasonably well to recorded levels on Wolli Creek well downstream of Bexley Road. However recorded levels in the section of Wolli Creek between Kingsgrove Road and just downstream of Bexley Road were not consistently matched in the model. This is considered to be due to a combination of factors, discussed below, which complicate the modelling and analysis. The results of the limited calibration of the model against the selected historic flood events are presented in Table 25.

Table 25: Wolli Creek - Comparison of Modelled and Recorded Flood Levels

Location	Recorded Level (mAHD)	Modelled Level (mAHD)	Difference (Modelled - Recorded Level) (m)
Nov-84			
Bexley Road	7.5	8.88	1.38(1)
Harthill Law Avenue	5.7 to 6.2	6.20	Within range (2)
Turrella Footbridge	3.4 to 3.6	3.42	Within range (3)
Dec-92			
10 m D/S Kingsgrove Road*	14.75	14.68	-0.07(4)
Koreela Street Bridge*	14	14.58	0.58 (4)
50 m D/S Koreela Street Bridge*	12.93	12.58	-0.35(4)
70 m D/S Koreela Street Bridge*	12.58	12.55	-0.03(4)
80 m D/S Koreela Street Bridge*	12.48	12.53	0.05(4)
GPT*	11.17	10.47	-0.70(4)
20 m D/S GPT*	10.47	9.26	-1.21(4)
Flatrock Road Bridge*	9.76	NLE**	NLE**(4)
10 m D/S Bexley Road*	7.91	7.48	-0.43(4)
Feb-93			
GPT *	10.2	10.45	0.25(5)(6)
Jan-96			
Bonalbo Street Bridge*	11.9	13.49	1.59(5)
100 m U/S Bexley Road	7.75	9.72	1.97(5)
Bexley Road	8.36	9.62	1.26
5 m D/S Bexley Road	7.21	9.22	2.01(5)
Turrella Footbridge	3.26	3.61	0.35

(1) 500 mm over centre of Bexley Road
(2) 1 m below parking area on creek side of RSL club
(3) 300 mm over footbridge
(4) Level obtained from photographs of debris
(5) Level may not represent peak
(6) Level reached approximately the level of the coping in the GPT

* this section of the Wolli Creek lined channel was modified during the construction of the M5 motorway (circa 2000)

** No Longer Exists (Flat-rock Road bridge was removed during the construction of the M5 motorway)

A reasonable match was obtained to the recorded flood level at Turrella Footbridge for all events. It is indicated that many of the flood levels recorded between Kingsgrove Rd and just downstream of Bexley Road for the February 1993 and January 1996 events may not represent the peak flood height. For these events modelled peak flood levels are consistently slightly higher than recorded levels. Timing may explain this discrepancy.

7.4.1. November 1984

A reasonable match was obtained between modelled and recorded peak flood levels at Bexley Road, Harthill Law Avenue and Turrella Footbridge.

A comparison of the modelled and recorded flood level for this event is presented in Figure C1.

7.4.2. December 1992

All floodmarks available for this event were obtained from photographs of debris taken between Kingsgrove Road and just downstream of Bexley Road. This section of Wolli Creek has undergone extensive modification during the construction of the M5 motorway between 1998 and 2002. As a result it was not possible to match recorded floodmarks upstream of Bexley Road for this event.

The modelled flood levels for this event were generally lower than the recorded levels. This may indicate that the rainfall pattern within the catchment was not accurately captured at nearby rain gauges for this event.

A comparison of modelled and recorded flood level for this event is presented in Figure C2.

7.4.3. February 1993

A reasonable match was obtained to the single recorded flood level at the Gross Pollutant Trap for this event. However it should be noted that, as previously mentioned, this section of Wolli Creek has undergone extensive modification. Additionally, this flood mark is approximate and may not represent the peak of the flood.

A comparison of modelled and recorded flood level for this event is presented in Figure C3.

7.4.4. January 1996

Several flood levels were recorded on Wolli Creek between Kingsgrove Road and Turrella Footbridge. Data available from Reference 1 suggests that many of these levels may not represent the peak. Accordingly modelled flood levels were generally higher than recorded flood marks. A reasonable match was obtained to the recorded flood marks at Bexley Road and Turrella Footbridge.

A comparison of modelled and recorded flood level for this event is presented in Figure C4.

7.5. Turrella Water Level Gauge

Joint calibration of the hydrologic and hydraulic models was undertaken by comparing the modelled flood levels with the stage hydrograph recorded upstream of Turrella weir for the December 1992, February 1993 and January 1996 events (see shows a reasonable match between the recorded and modelled stage hydrograph in terms of both the shape and magnitude of the recorded data. The height water height recorded at the gauge was slightly higher the modelled peak height for the December 1992 event, and slightly lower for the January 1996 and February 1993 events. The shallower recession limb observed for the recorded levels may be due to the effects of the small weir just upstream of Turrella footbridge, which is difficult to accurately capture in the 2 m x 2 m 2D schematisation. The results were considered to present a reasonable match, given the uncertainty associated with the rainfall data across the catchment.

7.6. October 2014 Validation

The results shown in Figure 3E to 3H shows a comparison of the data collected from the community consultation (Section 2.4) against modelled flooding behaviour for the October 2014 flood event. There is generally good agreement between most flood observations and modelled flood behaviour for the October 2014 event. Some of the older historic flooding observations collected as part of the community consultation process are not reflected in the modelling due to changes in the catchment, such as modifications to drainage infrastructure or floodplain morphology. Flood descriptions for many locations refer to significant overland flow paths which are generally captured in the model.

Many community responses were received relating to the October 2014 event, particularly relating to flooding in the Bardwell Creek catchment. The burst of rainfall which occurred during this event resulted in runoff which resulted in overland flows and runoff which exceeded the capacity of drainage channels. The community consultation process identified several key locations in Bardwell Creek and Wolli Creek which were flood affected during this event. These flooding 'hot-spots' included Bardwell Park Station, Bexley Road (Wolli Creek), Bardwell Creek between Laycock Street and Preddys Road and Hillcrest Avenue. A brief discussion of flooding at each of these locations is provided.

7.6.1. Bardwell Park Station

Flooding at Bardwell Park Station in 2014 resulted in train closures. Media reports and community consultation responses indicate that floodwaters flowed to a significant depth across the railway line at Bardwell Park Station, almost reaching the level of the platform. Earlwood Bardwell Park (EBP) RSL Club reported flooding to a height of 3 m which caused extensive damage to the ground floor of the building. These observations are generally well captured in the model for the October 2014 event.

A selection of community comments and flood photos of Bardwell Park Station are presented with October 2014 model results in Figure C12.

7.6.2. Bexley Road (Wolli Creek)

Community consultation responses indicate that Bexley Road is frequently overtopped during flood events in Wolli Creek. This observation is well represented in the model with Bexley Road overtopped in every calibration event.

A selection of community comments and flood photos of Bexley Road are presented with October 2014 model results in Figure C13.

7.6.3. Laycock Street to Preddys Road

The section of culverts and concrete lined channel between Laycock Street and Preddys Road flooded during the October 2014 event. An intense burst of rainfall resulted in flows exceeding the capacity of the channel in this section of Bardwell Creek. The blockage of culverts with urban debris, which included a water tank and car, exacerbated the effects of flooding near Coveney Street.

A selection of community comments and flood photos of Bardwell Creek between Laycock Street and Preddys Road are presented with October 2014 model results in Figure C14.

7.6.4. Hillcrest Avenue

Properties adjacent to the levee at the bottom of Hillcrest Avenue were flooded during the October 2014 event. Floodwaters overtopped the levee upstream of Bardwell Valley Golf Course causing sudden inundation. Above floor level flooding to a significant depth occurred at 20 Hillcrest Avenue.

A selection of community comments and flood photos at Hillcrest Avenue are presented with October 2014 model results in Figure C15.

7.7. Summary

Due to the lack of streamflow and sparse availability of peak flood height data, only a limited calibration of the hydrologic and hydraulic models was possible. Generally, the model reproduces flooding behaviour as described by residents and recorded peak flood levels. Although there were some discrepancies between the recorded and modelled peak flood levels, the reasonably consistent match in most locations between modelled and recorded levels is reasonable. There are some localised discrepancies for various storm events that are discussed in the previous sections. The limited recorded flood data availability and limited rainfall data for the catchment were significant factors in the calibration process. The substantial discrepancies between modelled and recorded flood levels in some locations are generally explained by known changes in the morphology of the catchment, such as the construction of levees or changes to drainage channel structures, or uncertainty about the observations.

The most resident flood observations were reproduced in the model, with the exceptions being local drainage issues generally occurring on high ground rather than significant overland flow paths. Given both of these factors, it is considered that the model has been reasonably calibrated to historical flooding in the catchment.

A number of problems with the data were identified including conflicting flood levels at some locations for the same flood event, lack of a sufficient number of accurate peak levels recorded for a single event along the length of the creeks and a general paucity of quality historical flood data. Most recorded floods within the catchment occurred as a result of short, localised rainfall bursts which may not have been accurately captured by surrounding pluviometers.

As with all flood studies, the accuracy of the model in reproducing catchment flood behaviour could be improved by the inclusion of additional high quality historical flood and rainfall data. The re-installation of a continuous water level gauge within the catchment, such as the Henderson Road gauge at Turrella, would assist in the data collection process in the future. However the maintenance of such gauges can be expensive, and there needs to be a commitment that the gauges will be operational for a long period to be most effective. The data is most useful if accompanied by stream velocity measurements obtained during floods, but such readings are almost impossible to obtain in practice due to the lack of warning time and the quick rise of flooding. As a result of these limitations there are very few active stream gauges in similar urban catchments.

It is recommended that following future flood events within the catchment a program of data collection could be implemented which includes the collection of accurately surveyed peak flood levels as soon as practicable following large flood events.

8. DESIGN EVENT MODELLING

8.1. Temporal Patterns

Temporal patterns are a hydrologic tool that describe how rainfall falls over time and are often used in hydrograph estimation. Previously in ARR1987, a single burst temporal pattern has been adopted for each rainfall event duration. However ARR2016 (Reference 12) discusses the potential inaccuracies with adopting a single temporal pattern, and recommends an approach where an ensemble of different temporal patterns are investigated.

8.1.1. ARR1987 Temporal Patterns

The 1987 temporal patterns obtained from ARR87 (Reference 17) were developed using the Average Variability Method (AVM). The AVM divides Australia into 8 zones and provides two temporal patterns for 20 storm durations for ARI ≤ 30 years and ARI > 30years.

The AVM provides a pattern that describes the rainfall pattern of the most intense burst within a storm event and should not be considered representative of a typical rainfall pattern. A limitation with the AVM, as discussed in ARR2016 (Reference 12), is that it assumes that the variability of the pattern is of less importance than the central tendency, that is the central value of the probability distribution of rainfall volume. In reality, the runoff response can be very catchment-specific and therefore it is recognised that a representative pattern will not necessarily produce the median response from an ensemble of patterns. The AVM temporal patterns should only be used in conjunction with the 1987 IFD tables.

8.1.2. ARR2016 Temporal Patterns

Temporal patterns for this study were obtained from ARR2016 (Reference 12). The revised 2016 temporal patterns attempt to address the key concerns practitioners found with the 1987 temporal patterns. It is widely accepted that there are a wide variety of temporal patterns possible for rainfall events of similar magnitude. This variation in temporal pattern can result in significant effects on the estimated peak flow. As such, the revised temporal patterns have adopted a different method to the 1987 AVM and provide an ensemble of design rainfall events. Given the rainfall-runoff response can be quite catchment specific, using an ensemble of temporal patterns attempts to produce the median catchment response.

As hydrologic modelling has advanced, it is becoming increasingly important to use realistic temporal patterns. The 1987 temporal patterns only provided a pattern of the most intense burst within a storm, whereas the 2016 temporal patterns look at the entirety of the storm including pre-burst rainfall, the burst and post-burst rainfall. There can be significant variability in the burst loading distribution (i.e. depending on where 50% of the burst rainfall occurs an event can be defined as front, middle or back loaded). The 2016 method divides Australia into 12 temporal pattern regions, with the Bardwell Creek and Wolli Creek catchment falling within the East Coast South region. Each region was analysed to determine the proportion of front, middle and back loaded events and was separated into events shorter and longer than 6 hours. Table 26 provides the burst loading distribution for the East Coast South region. Table 27 details the gauge and event information used to derive the temporal patterns for the East Coast South region.

Table 26: Burst loading distribution for the East Coast South region

Region	Duration	Front Loaded (%)	Middle Loaded (%)	Back Loaded (%)
East Coast South	≤ 6hr	26.5	57.1	16.4
	> 6hr	17.1	58.6	24.3

Table 27: Number of gauges and events within the temporal pattern region

Region	Number of gauges	Number of station years	Number of events	Average number of events per station
East Coast South	331	8,067	19,856	2.46

An ensemble of 10 temporal patterns are applicable across four AEP ranges for durations ranging from 15 mins to 7 days within each region. The four AEP categories are as follows with a diagram of the temporal pattern ranges shown in Diagram 2:

- Frequent - more frequent than 14.4% AEP,
- Intermediate - between 3.2% AEP and 14.4% AEP,
- Rare - rarer than 3.2% AEP, and
- Very Rare – rarest 10 within the region.

Diagram 2: Temporal Pattern Ranges

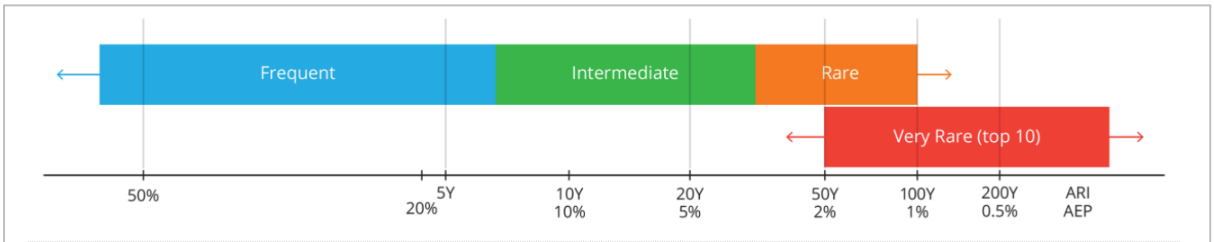


Figure 2.5.12. Temporal Pattern Ranges

The ARR 2016 Temporal Patterns were used in this study for design storm modelling.

8.2. Design Rainfall Losses and Pre-Burst Rainfall

For the design events, the initial and continuing loss rates were adopted from ARR2016. Rainfall losses are dependent on the physical properties of the surface which is affected by antecedent conditions of the catchment and pre-burst rainfalls prior to a rainfall burst event. Losses are generally in the order of 0 mm to 30 mm for initial loss, and 2 to 3 mm/hour for continuing loss. Losses were modelled for design events in WBNM using the ARR2016 method by applying first applying the 75% pre-burst rainfall values produced as part of the ARR2016 revision project. The pre-burst rainfall effectively reduces the initial loss for urban pervious areas in the design storm event. Pre-burst values are dependent on the AEP and duration of design event.

The losses applied in design events after application of pre-burst values typically varied from 0 mm to 15 mm for urban pervious areas. An initial loss of 0 mm was applied to impervious surfaces. Continuing loss values of between 2.1 mm/h to 2.5 mm/h were applied which are consistent with the regional storm continuing losses provided in ARR2016. Losses were applied to each subcatchment based on the estimated proportion of directly connected areas, indirectly connected areas and pervious area as shown in Table 28.

Table 28: ARR2016 effective impervious area estimation

Surface	Pervious Area (%)	Indirectly Connected Impervious Area (%)	Effective Impervious Area (%)
Medium Density Residential	0	30	70
High Density Residential	0	15	85
Vegetated Creek	70	0	30
Industrial	0	10	90
Park/ Golf Course	100	0	0
Railway	15	30	55

The rainfall loss and pre-burst values selected are considered reasonable and conservative for the Bardwell Creek and Wolli Creek catchment.

8.3. Critical Duration

To determine the critical storm duration for various parts of the catchment (i.e. produce the highest flood level), modelling of the 20% AEP (0.2 EY), 10% AEP, 5% AEP, 1% AEP and 0.5% events from separate temporal pattern bins was undertaken for a range of design storm durations from 30 minutes to 3 hours. Each duration utilised ten temporal patterns from AR&R 2016 (Reference 12). The following process was undertaken in order to determine the critical duration for each temporal pattern bin:

1. Run 10 temporal patterns for each duration for the 20% AEP (0.2 EY), 10% AEP, 5% AEP, 1% AEP and 0.5% AEP events.
2. Determine the mean peak flows at several representative sub-catchments within the catchment from each duration modelled.
3. Determine the mean peak flows and critical durations for each representative sub-catchment.
4. Select a single representative duration based on an analysis of peak flows and critical durations at each sub-catchment.
5. Analyse the peak flows of the ensemble of 10 temporal patterns for consistency about the mean peak flow for both the representative duration and the critical duration at each sub-catchment.
6. Examine the hydrographs produced at each sub-catchment for consistency.
7. A single temporal pattern and duration were selected for each event to reflect the catchment behaviour, consistent with the representative subcatchments.

It was found that for the 20% AEP event the 45 min duration event was critical and for the 10% AEP, 5% AEP, 1% AEP, 0.5% AEP and PMF event the 60 min duration event was critical.

The critical durations selected are shown in Table 29

Table 29: Design Event Critical Duration

Design Event	Critical Duration
20% AEP	45 min
10% AEP	60 min
5% AEP	60 min
1% AEP	60 min
0.5% AEP	60 min
PMF	60 min

The temporal pattern selected for each design event and duration is shown in Table 30.

Table 30: Temporal Pattern Selected

Design Event	Temporal Pattern ID
20% AEP	4548
10% AEP	4568
5% AEP	4568
1% AEP	4561
0.5% AEP	4561
PMF	GDSM Method

8.4. Design Results

The results from this study are presented as:

- Peak flood depths and levels in Figure D1 to Figure D6;
- Peak flood velocities in Figure D7 to Figure D12;
- Hydraulic hazard (FDM) in Figure D13 to Figure D18;
- Hydraulic hazard (ADR) in Figure D19 to Figure D24;
- Hydraulic categories in Figure D25 to Figure D30; and
- Preliminary flood emergency response classification of communities in Figure E7.

The results were provided in digital format compatible with Council's Geographic Information Systems. The digital data should be used in preference to the figures in this report as they provide more detail.

8.4.1. Summary of Results

Peak flood levels, depths and flows at key locations within the catchment are summarised below. These key locations coincide with the key locations used for the sensitivity analysis discussed in Section 9. A tabulated summary of peak flood levels, depths and flows at selected locations as shown in Figure 21 are detailed in Table 31, Table 32 and Table 33, respectively.

Table 31: Peak Flood Levels (mAHD) at Key Locations

ID	Location	20% AEP	10% AEP	5% AEP	1% AEP	0.5% AEP	PMF
H001	Ada Street (Bardwell Creek)	35.4	35.5	35.6	35.7	35.7	36.6
H002	Unwin Street (Bardwell Creek)	33.4	33.5	33.6	33.7	33.7	34.6
H003	Moore Street over road (Bardwell Creek)	32.0	32.0	32.1	32.2	32.3	33.3
H004	Bexley Golf_Course (Bardwell Creek)	30.2	30.4	30.6	30.9	30.9	32.1
H005	Stoney Creek Road over road (Bardwell Creek)	28.9	28.9	28.9	29.0	29.0	30.2
H006	Laycock Street over road (Bardwell Creek)	27.4	27.4	27.4	27.5	27.6	28.5
H007	Oliver Street (Bardwell Creek)	25.1	25.2	25.4	26.4	26.4	28.2
H008	Coveney Street (Bardwell Creek)	23.7	23.7	23.9	25.5	25.6	27.4
H009	Preddys Road downstream of road (Bardwell Creek)	23.1	23.1	23.1	23.6	23.7	25.3
H010	Ellerslie Road (Bardwell Creek)	16.0	16.0	16.0	16.3	16.4	19.2
H011	Orpington Street (Bardwell Creek)	13.8	13.8	13.8	14.1	14.3	17.8
H012	Bexley Road (Bardwell Creek)	12.8	12.8	12.8	13.1	13.3	17.3
H013	Hillcrest Avenue (Bardwell Creek)	10.6	10.9	11.1	11.9	12.2	16.0
H014	Bardwell Valley Golf Course (Bardwell Creek)	10.2	10.6	11.0	11.9	12.2	15.8
H015	Pile Street (Bardwell Creek)	6.3	6.4	6.3	6.5	6.5	10.7
H016	Wilsons Road (Bardwell Creek)	5.3	5.5	5.5	5.7	5.7	8.6
H017	Bardwell Road over road (Bardwell Creek)	5.4	5.4	5.4	5.4	5.5	8.2
H018	Hannam Street (Bardwell Creek)	3.8	4.1	4.1	4.4	4.6	8.0
H019	York Street (Wolli Creek)	14.7	14.8	14.9	14.9	14.9	16.8
H020	Kooreela Street (Wolli Creek)	14.6	14.8	14.8	14.8	14.8	16.7
H021	Girraween Street (Wolli Creek)	12.6	12.9	13.0	13.3	13.4	15.9
H022	Bonalbo Street (Wolli Creek)	12.6	12.8	12.9	13.2	13.3	15.7
H023	Nairn Street (Wolli Creek)	10.6	10.8	11.0	11.3	11.4	15.4
H024	Beaumont Street (Wolli Creek)	9.3	9.5	9.7	10.1	10.3	14.6
H025	Bexley Road over road (Wolli Creek)	7.8	8.2	8.4	9.0	9.2	13.3

ID	Location	20% AEP	10% AEP	5% AEP	1% AEP	0.5% AEP	PMF
H026	Bardwell Park Station (Wolli Creek)	5.9	6.2	6.4	6.9	7.1	10.2
H027	Harthill-Law Avenue (Wolli Creek)	4.8	5.1	5.3	5.7	5.9	9.8
H028	D/S Bardwell Confluence (Wolli Creek)	3.6	3.8	3.9	4.2	4.3	7.8
H029	Henderson Street (Wolli Creek)	2.7	2.9	3.1	3.4	3.5	6.8
H030	SWSOOS (Wolli Creek)	1.9	2.0	2.3	2.4	2.5	5.3
H031	St Georges Road (Bardwell)	47.8	47.8	47.8	47.8	47.8	48.2
H032	Stoney Creek Road/Preddys Road (Bardwell)	35.8	35.8	35.8	35.9	35.9	36.9
H033	Binnamitalong Gardens (Bardwell)	14.5	14.5	14.5	14.6	14.7	17.4
H034	Hillcrest Avenue (Bardwell)	17.3	17.3	17.3	17.3	17.3	17.3
H035	Fatima Church (Wolli)	19.0	19.0	19.0	19.1	19.1	20.3
H036	Gilchrist Park/Bexley Comm Centre (Wolli)	18.3	18.3	18.3	18.4	18.4	18.6
H037	New Illawarra Rd (Wolli)	18.4	18.4	18.4	18.4	18.4	18.7
H038	Kingsland Rd North (Wolli)	10.6	10.6	10.6	10.7	10.8	12.2
H039	Poweys Avenue (Wolli)	6.7	6.7	6.9	7.3	7.4	9.6
H040	Guess Avenue (Wolli)	2.4	2.4	2.4	2.4	2.4	4.6
H041	Downey St (Bardwell)	44.0	44.0	44.0	44.1	44.1	44.6
H042	Iliffe St (Bardwell)	40.3	40.3	40.3	40.3	40.3	40.5
H043	Todd St (Wolli)	26.9	26.9	26.9	26.9	26.9	27.2
H044	Caroline St (Wolli)	26.3	26.3	26.4	26.4	26.4	26.5
H045	St Kilda St (Wolli)	24.2	24.2	24.2	24.2	24.2	24.3
H046	Slade Rd (Wolli)	10.6	10.6	10.6	10.7	10.7	10.9
H047	Darley Rd (Wolli)	11.9	11.9	11.9	11.9	11.9	12.0
H048	Water St (Wolli)	8.6	8.6	8.6	8.7	8.7	9.6
H049	Abercorn St (Bardwell)	32.8	32.8	32.8	32.9	32.9	33.4

Table 32: Peak Depths (m) at Key Locations

ID	Location	20% AEP	10% AEP	5% AEP	1% AEP	0.5% AEP	PMF
H001	Ada Street (Bardwell Creek)	2.20	2.23	2.32	2.43	2.46	3.34
H002	Unwin Street (Bardwell Creek)	2.03	2.05	2.15	2.28	2.32	3.18
H003	Moore Street over road (Bardwell Creek)	0.79	0.81	0.90	1.04	1.09	2.15
H004	Bexley Golf_Course (Bardwell Creek)	0.21	0.33	0.57	0.85	0.91	2.07
H005	Stoney Creek Road over road (Bardwell Creek)	0.00	0.00	0.02	0.14	0.18	1.34
H006	Laycock Street over road (Bardwell Creek)	0.38	0.39	0.43	0.54	0.56	1.50
H007	Oliver Street (Bardwell Creek)	2.95	2.99	3.20	4.18	4.23	6.02
H008	Coveney Street (Bardwell Creek)	2.97	3.00	3.23	4.80	4.93	6.68
H009	Preddys Road downstream of road (Bardwell Creek)	0.53	0.53	0.54	1.02	1.14	2.74
H010	Ellerslie Road (Bardwell Creek)	2.44	2.45	2.43	2.71	2.83	5.65
H011	Orpington Street (Bardwell Creek)	3.35	3.37	3.35	3.67	3.84	7.35
H012	Bexley Road (Bardwell Creek)	2.44	2.47	2.47	2.78	2.96	7.00
H013	Hillcrest Avenue (Bardwell Creek)	3.79	4.07	4.32	5.12	5.41	9.21
H014	Bardwell Valley Golf Course (Bardwell Creek)	4.60	4.97	5.32	6.21	6.52	10.16
H015	Pile Street (Bardwell Creek)	2.50	2.59	2.52	2.64	2.69	6.86
H016	Wilsons Road (Bardwell Creek)	3.38	3.55	3.60	3.77	3.82	6.71
H017	Bardwell Road over road (Bardwell Creek)	0.00	0.00	0.00	0.07	0.11	2.79
H018	Hannam Street (Bardwell Creek)	3.20	3.46	3.54	3.85	3.97	7.41
H019	York Street (Wolli Creek)	3.63	3.77	3.85	3.85	3.86	5.78
H020	Kooreela Street (Wolli Creek)	4.21	4.35	4.38	4.38	4.37	6.26
H021	Girraween Street (Wolli Creek)	3.03	3.27	3.44	3.69	3.80	6.30
H022	Bonalbo Street (Wolli Creek)	3.41	3.64	3.76	4.03	4.14	6.51

ID	Location	20% AEP	10% AEP	5% AEP	1% AEP	0.5% AEP	PMF
H023	Nairn Street (Wolli Creek)	1.92	2.14	2.31	2.64	2.80	6.72
H024	Beaumont Street (Wolli Creek)	1.35	1.57	1.71	2.14	2.34	6.61
H025	Bexley Road over road (Wolli Creek)	0.91	1.30	1.47	2.06	2.26	6.39
H026	Bardwell Park Station (Wolli Creek)	0.18	0.49	0.65	1.16	1.33	4.48
H027	Harthill-Law Avenue (Wolli Creek)	3.36	3.67	3.81	4.27	4.44	8.29
H028	Downstream Bardwell Confluence (Wolli Creek)	2.91	3.15	3.23	3.54	3.65	7.08
H029	Henderson Street (Wolli Creek)	3.13	3.39	3.53	3.81	3.91	7.25
H030	SWSOOS (Wolli Creek)	3.46	3.59	3.88	4.03	4.09	6.88
H031	St Georges Road (Bardwell)	0.01	0.02	0.03	0.05	0.05	0.45
H032	Stoney Creek Road/Preddys Road (Bardwell)	0.13	0.15	0.17	0.24	0.27	1.28
H033	Binnamitalong Gardens (Bardwell)	1.74	1.74	1.76	1.86	1.90	4.59
H034	Hillcrest Avenue (Bardwell)	0.00	0.00	0.00	0.00	0.00	0.01
H035	Fatima Church (Wolli)	0.05	0.05	0.06	0.13	0.16	1.31
H036	Gilchrist Park/Bexley Comm Centre (Wolli)	0.07	0.08	0.08	0.10	0.11	0.31
H037	New Illawarra Rd (Wolli)	0.03	0.03	0.03	0.04	0.04	0.32
H038	Kingsland Rd North (Wolli)	0.16	0.17	0.18	0.28	0.35	1.74
H039	Poweys Avenue (Wolli)	0.02	0.02	0.25	0.61	0.72	2.93
H040	Guess Avenue (Wolli)	0.00	0.00	0.00	0.00	0.00	2.19
H041	Downey St (Bardwell)	0.09	0.10	0.11	0.18	0.21	0.67
H042	Iliffe St (Bardwell)	0.00	0.01	0.01	0.04	0.04	0.22
H043	Todd St (Wolli)	0.06	0.06	0.07	0.09	0.09	0.31
H044	Caroline St (Wolli)	0.03	0.03	0.04	0.05	0.05	0.14
H045	St Kilda St (Wolli)	0.04	0.04	0.04	0.06	0.07	0.21
H046	Slade Rd (Wolli)	0.05	0.05	0.06	0.07	0.07	0.33
H047	Darley Rd (Wolli)	0.02	0.03	0.03	0.03	0.03	0.08
H048	Water St (Wolli)	0.00	0.01	0.02	0.04	0.04	0.95
H049	Abercorn St (Bardwell)	0.24	0.26	0.28	0.33	0.35	0.82

Table 33: Peak Flows (m^3/s) at Key Locations

ID	Location	20% AEP	10% AEP	5% AEP	1% AEP	0.5% AEP	PMF
Q001	Ada Street	14.0	14.5	14.4	17.2	18.4	73.6
Q002	Unwin Street	19.7	20.7	23.7	31.8	35.2	174.5
Q003	Moore Street	5.1	6.1	9.5	16.4	19.2	133.6
Q004	Bexley Golf_Course	28.2	28.8	29.1	43.9	48.8	247.3
Q005	Stoney Creek Road	26.7	26.9	27.9	44.3	49.4	253.0
Q006	Laycock Street	26.8	27.0	28.0	44.3	49.5	253.7
Q007	Oliver Street	28.3	28.5	27.3	45.0	50.6	290.4
Q008	Coveney Street	29.1	29.5	28.1	45.5	51.6	277.2
Q009	Preddys Road	29.9	30.1	28.7	45.3	51.2	280.1
Q010	Ellerslie Road	39.1	39.6	38.7	53.2	60.6	380.3
Q011	Orpington Street	40.3	40.9	40.1	53.1	60.5	392.9
Q012	Bexley Road (Bardwell)	40.6	41.2	40.5	53.0	60.0	390.8
Q013	Hillcrest Avenue	47.6	48.6	48.5	61.3	68.7	446.1
Q014	Bardwell Valley Golf Course	39.7	41.9	40.1	46.9	50.4	448.9
Q015	Pile Street	41.5	43.5	40.8	43.9	44.9	467.9
Q016	Wilsons Road	40.7	43.2	40.5	44.4	45.6	487.9
Q017	Bardwell Road	39.2	41.6	38.8	47.0	49.8	504.9
Q018	Hannam Street	35.5	37.6	36.4	42.9	44.8	436.8
Q019	York Street	66.4	80.4	89.9	119.5	133.2	486.5
Q020	Kooreela Street	74.3	91.6	107.3	132.8	150.1	636.6

Q021	Girraween Street	69.2	83.5	105.9	123.0	138.8	615.2
Q022	Bonalbo Street	69.1	84.3	95.4	124.4	137.9	540.1
Q023	Nairn Street	69.1	84.3	96.4	124.7	138.6	635.6
Q024	Beaumont Street	69.0	84.5	97.3	124.8	138.4	673.5
Q025	Bexley Road (Wolli)	77.4	97.1	109.8	146.8	160.3	700.8
Q026	Bardwell Park Station	0.0	0.6	1.0	3.7	4.5	277.6
Q027	Harthill-Law Avenue	64.0	81.2	89.8	121.4	133.3	465.6
Q028	Downstream Bardwell Confluence	88.5	110.2	117.1	152.1	167.0	1104.1
Q029	Henderson Street	82.5	105.4	113.1	147.4	161.5	974.4
Q030	SWSOOS	79.0	100.8	109.3	140.8	153.5	919.1
Q031	St Georges Road	5.0	5.3	5.6	7.7	8.5	38.3
Q032	Stoney Creek Road/Preddys Road	8.1	8.5	9.2	12.5	13.7	74.6
Q033	Binnamitalong Gardens	7.3	7.8	8.6	10.6	11.5	48.4
Q034	Hillcrest Avenue	0.4	0.5	0.6	0.6	0.6	2.0
Q035	Fatima Church	5.3	5.5	6.0	8.8	9.8	43.0
Q036	Gilchrist Park/Bexley Comm Centre	5.5	5.8	6.3	8.1	9.1	42.2
Q037	New Illawarra Rd	3.6	3.9	4.3	5.1	5.6	23.5
Q038	Kingsland Rd North	2.2	2.3	2.5	3.2	3.5	15.2
Q039	Poweys Avenue	1.6	1.8	1.9	2.2	2.3	6.7
Q040	Guess Avenue	0.3	0.3	0.3	0.4	0.4	56.8
Q041	Downey St	5.5	5.8	6.2	8.4	9.3	41.7
Q042	Iliffe St	2.5	2.8	3.0	3.9	4.2	17.0
Q043	Todd St	2.8	3.1	3.4	4.1	4.5	19.8
Q044	Caroline St	1.1	1.2	1.3	1.6	1.7	6.8
Q045	St Kilda St	2.6	2.7	3.0	4.0	4.5	19.2
Q046	Slade Rd	69.4	88.1	97.3	132.3	147.1	735.5
Q047	Darley Rd	1.3	1.4	1.6	1.9	2.1	8.2
Q048	Water St	0.2	0.2	0.2	0.3	0.3	1.0
Q049	Abercorn St	4.5	4.8	5.4	6.5	7.1	29.6
Q050	Community Centre Rail	4.2	5.0	5.9	11.0	12.6	132.1
Q051	Commuter Carpark Rail	5.0	5.6	6.4	9.1	9.4	18.6

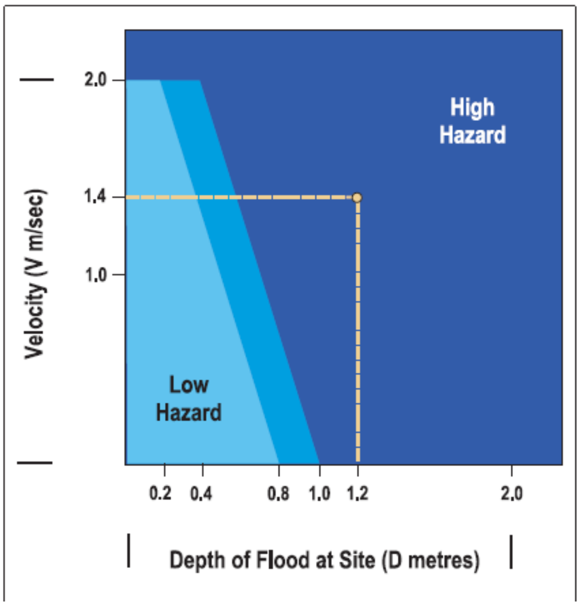
8.4.2. Provisional Hydraulic Hazard

Hazard classification plays an important role in informing floodplain risk management in an area. Provisional hazard categories have been determined for the Bardwell Creek and Wolli Creek catchment by two methods - one in accordance with the NSW Floodplain Development Manual (Reference 19), and the other in accordance with the Australian Disaster Resilience Handbook Collection (Reference 20). Each method of provisional flood hazard categorisation is discussed below.

8.4.3. Floodplain Development Manual

Provisional hazard categories have been determined in accordance with Appendix L of the NSW Floodplain Development Manual (Reference 19), the relevant section of which is shown in Diagram 3. For the purposes of this report, the transition zone presented in Diagram 3 was considered to be high hazard.

Diagram 3: Provisional “L2” Hydraulic Hazard Categories (FDM)

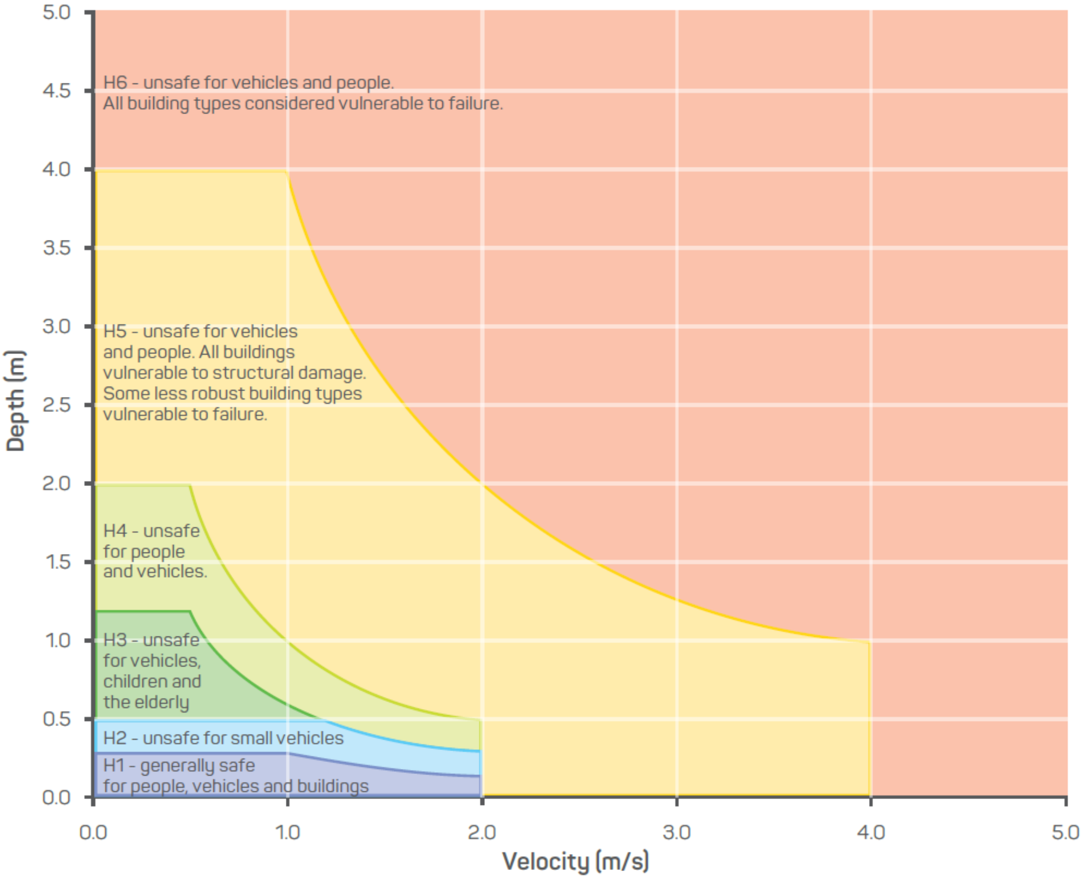


The provisional flood hazard maps utilising the Floodplain Development Manual (FDM) hazard categorisation are shown in Figure D13 to Figure D18 for the 20% AEP, 10% AEP, 5% AEP, 1% AEP, 0.5% AEP and PMF events. The FDM hazard categorisation has been included for applicability to existing council policy documents that may refer to this hazard classification. The results indicate that the high hazard areas are primarily located in parks, reserves and golf courses with substantial mainstream or overland flow paths. Some hazardous flow paths also occur in steep areas through residential areas, which typically follow well defined drainage lines. In less steep areas of the catchment high hazard areas can also occur due to the ponding of water to significant depths behind the rail embankment.

8.4.4. Australian Disaster Resilience Handbook Collection

In recent years, there have been a number of developments in the classification of hazards. Research has been undertaken to assess the hazard to people, vehicles and buildings based on flood depth, velocity and velocity depth product. The Australian Disaster Resilience Handbook Collection deals with floods in Handbook 7 (Managing the Floodplain: A Guide to Best Practice in Flood Risk Management in Australia). The supporting guideline 7-3 (Reference 20) contains information relating to the categorisation of flood hazard. A summary of this categorisation is provided in Diagram 4.

Diagram 4: General flood hazard vulnerability curves (ADR)



This classification provides a more detailed distinction and practical application of hazard categories, identifying the following 6 classes of hazard:

- H1 – No constraints, generally safe for vehicles, people and buildings;
- H2 – Unsafe for small vehicles;
- H3 – Unsafe for all vehicles, children and the elderly;
- H4 – Unsafe for all people and all vehicles;
- H5 – Unsafe for all people and all vehicles. All building types vulnerable to structural damage. Some less robust building types vulnerable to failure. Buildings require special engineering design and construction; and
- H6 – Unsafe for all people and all vehicles. All building types considered vulnerable to failure.

The hazard maps using the Australian Disaster Resilience (ADR) classification are presented in Figure D19 to Figure D24 for the 20% AEP, 10% AEP, 5% AEP, 1% AEP, 0.5% AEP and PMF events.

High hazard areas typically correspond to creeks, parks, drainage reserves and overland flowpaths, similarly to FDM hazard classification. Areas classified as, H2 or greater under the ADR classification often correspond to areas of high hazard under the FDM classification method, however the FDM method provides a greater level of practical information on the relative hazard categories.

8.4.5. Provisional Hydraulic Categorisation

The 2005 NSW Government's Floodplain Development Manual (Reference 19) defines three hydraulic categories which can be applied to different areas of the floodplain depending on the flood function:

- Floodways;
- Flood Storage; and
- Flood Fringe.

Floodways are areas of the floodplain where a significant discharge of water occurs during flood events and by definition, if blocked would have a significant effect on flood levels and/or distribution of flood flow. Flood storages are important areas for the temporary storage of floodwaters and if filled would result in an increase in nearby flood levels and the peak discharge downstream may increase due to the loss of flood attenuation. The remainder of the floodplain is defined as flood fringe.

There is no quantitative definition of these three categories or accepted approach to differentiate between the various classifications. The delineation of these areas is somewhat subjective based on knowledge of an area and flood behaviour, hydraulic modelling and previous experience in categorising flood function. A number of approaches are available, such as the method defined by Howells *et al* (Reference 21).

For this study, hydraulic categories were defined by the following criteria, which has been tested and is considered to be a reasonable representation of the flood function of this catchment.

- Floodway is defined as areas where:
    - o the peak value of velocity multiplied by depth (V x D) > 0.25 m^2/s, **AND** peak velocity > 0.25 m/s, **OR**
    - o peak velocity > 1.0 m/s **AND** peak depth > 0.1 m.

The remainder of the floodplain is either Flood Storage or Flood Fringe,

- Flood Storage comprises areas outside the floodway where peak depth > 0.2 m, and
- Flood Fringe comprises areas outside the Floodway where peak depth ≤ 0.2 m.

Figure D25 to Figure D30 show the provisional hydraulic categorisations for the Bardwell Creek and Wolli Creek catchment for the 20% AEP,10% AEP, 5% AEP, 1% AEP, 0.5% AEP and PMF events.

Hydraulic categories based on the above criteria are considered provisional and may be revisited as part of a subsequent FRMS/P.

8.4.6. Preliminary Flood Emergency Response Classifications

The design flood modelling was classified in accordance with guidelines for Emergency Response Planning (ERP) outlined in Reference 22. These guidelines are generally more applicable to riverine flooding where significant flood warning time is available and emergency response action can be taken prior to the flood, or where long-term isolation may occur requiring possible resupply or medical evacuation. It is unclear how to apply the classifications in flash flood areas where there is little or no warning, and isolation times will be relatively short.

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

The design modelling indicates that in the PMF event some properties will be subject to high hazard flooding with significant depths of water covering access routes, prior to potential flooding of buildings. If estimated depths were life-threatening, these properties would need to be classified as “Low Flood Island” according to Reference 22., as by the time above-floor inundation occurs the roadways at the property frontages would already be inundated with high hazard flooding.

If a property is unaffected by above floor flooding but nearby streets are flooded, vehicular access from the area may be blocked, causing inconvenience or potentially threatening life if emergency medical care is required during a flood. This issue of flood isolation is less critical for urban flash flooding than for rural flooding as it is unlikely that access will be cut for more than a few hours. For example it is unlikely that provision of food or other supplies to isolated areas will be required in the Bardwell Creek and Wolli Creek catchment. In addition, due to the steep nature of many parts of the Bardwell Creek and Wolli Creek catchment access to the many parts of the catchment is maintained even in the PMF due to the presence of access routes following high ridges along major roads such as Harthill-Law Avenue, Stoney Creek Road and Forest Road. The following four emergency response classifications were identified as the most appropriate for the Bardwell Creek and Wolli Creek catchment:

<u>Low Flood Island</u>
Low Flood Island was assessed as any property that was totally inundated in the PMF and with all potential evacuation routes unavailable at the peak of the flood, due to flood waters, topography or impassable structures. This corresponds approximately with the PMF High Hazard classification utilising the technique outlined in the Floodplain Development Manual (Reference 19).

<u>High Flood Island</u>
Any area totally surrounded by Low Flood Island that is not inundated with all access roads

closed and no overland or alternate road access possible. There is enough land higher that the flood level to cope with the number of people in the area.

Overland Escape Route
Any park, open space or recreation area that is not heavily inundated that can be used as an overland escape route.

Rising Road Access
The remaining area of the catchment where inhabited properties are above the predicted flood level. It is safe to assume that during the PMF that all areas of the catchment will be affected in some manner by a storm event of this magnitude, but these areas will still have all-weather uninterrupted rising road access.

For this preliminary assessment, some areas have been classified as “Low Flood Island” where it was assessed that there is a real risk of injury or death if residents become trapped in their homes during a flood. The SES does not provide definitive guidance on flood depth or velocity threshold before a road is “cut,” or on “acceptable” isolation times. For this study, roads have been assessed as potentially cut based on consideration of flood hazard in the PMF.

In light of these considerations, preliminary classification for the majority of the study area catchment is as “Rising Road Access” with some areas marked as “Low/High Flood Island” or as “Overland Escape” or “Overland Refuge” areas. Mapping of the classifications is shown on Figure E7.

8.4.7. Preliminary “True” Flood Hazard Categorisation

The provisional hazards were reviewed in this study to consider other factors such as rate of rise of floodwaters, duration, threat to life, danger and difficulty in evacuating people and possessions and the potential for damage, social disruption and loss of production. These factors and related comments are given in Table 34.

Table 34: Weightings for Assessment of True Hazard

Criteria	Weighting(1)	Comment
Rate of Rise of Floodwaters	High	The rate of rise in the creek channels and onset of overland flow along roads would be very rapid, which would not allow time for residents to prepare for the onset of flooding
Duration of Flooding	Low	The duration for local catchment flooding will generally be less than around 6 hours, resulting in inconvenience to affected residents but not necessarily a significant increase in hazard.
Effective Flood Access	High	Roads within the catchment will generally be inundated prior to property inundation, which may restrict vehicular access during a flood.
Size of the Flood	Moderate	The hazard can change significantly at some locations with the magnitude of the flood. However, these changes in hazard are generally captured by mapping a range of events

		using the provisional hazard criteria
Effective Warning and Evacuation Times	High	There is very little, if any, warning time. During the day residents will be aware of the heavy rain but at night (if asleep) residential and non-residential building floors may be inundated with no prior warning.
Additional Concerns such as Bank Erosion, Debris, Wind Wave Action	Low	These issues are a relatively minor consideration in urban environments like the Bardwell Creek and Wolli Creek catchment.
Evacuation Difficulties the Community	Low	Given the quick response of the catchment pre-flood evacuation is unlikely to occur. There may be significant difficulties evacuating people who become trapped in their houses, but only if the depth is sufficient to present a risk to life. This factor is already captured by the provisional hydraulic hazard classification, and therefore was not given significant weight for assessing true hazard.
Flood Awareness of the Community	Moderate	Urban communities in general have relatively low flood awareness and a short "community memory" for historical flood events. Community consultation responses indicate relatively high awareness of flooding in the Bardwell Creek and Wolli Creek catchment, however many newer residents have no awareness of flooding in the local catchment.
Depth and Velocity of Floodwaters	High	In areas of overland flow roads are subject to fast flowing water. In the main creek channels velocities and depth would be high. There is always a risk of a car or pedestrian being swept into the open channel while attempting to cross swiftly flowing waters at major creek crossings. However this factor is largely included in the provisional hydraulic hazard calculation metrics.

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

For the Bardwell Creek and Wolli Creek catchment, the factors with high weighting in relation to assessment of true hazard are generally related to the limited flood warning, the dangers of driving on flooded roads, and the potential for flooding of access to residential properties prior to above-floor flooding of buildings occurring. In many cases, it is likely that remaining inside the property will present less risk to life than attempting evacuation via flooded routes, as refuge can generally be taken on furniture above flooded areas. This strategy has been provided as general advice for most properties within the Rockdale City Local Flood Plan (Reference 23) There may be some properties where remaining inside would present a high risk to life due to very high flood depths, but these properties will generally already be classified as high hazard using provisional hazard criteria.

In general it was found that areas where a high flood hazard would be justified based on consideration of the high-weight criteria in Table 34, the area was already designated high hazard as a result of the depth/velocity criteria used to develop the provisional hazard. Therefore the preliminary "true" hazard categories were assessed to be the same as the provisional hydraulic hazard (see Section 8.4.3 and Section 8.4.4)

8.5. Road Inundation

An analysis of road inundation has been undertaken at key locations in the study area. These reporting locations can be seen in Figure E1. Stage hydrographs showing the depth for major crossings of Bardwell Creek and Wolli Creek, respectively are shown in Figure E2 to Figure E6.

Road access is maintained in the PMF event at Harthill-Law Avenue, Stoney Creek Road and Forest Road. Vehicles may enter or leave the study area via these access routes. Rising road access (RRA) is maintained for many residents due to the relatively steep, well defined topography of the catchment.

8.6. Blockage for Design Events

The availability of debris is dependent on factors such as the potential for soil erosion, local geology, the source area, the amount and type of vegetative cover, the degree of urbanisation, land clearing and preceding wind and rainfall. However, the type of materials that can be mobilised can vary greatly between catchments and individual flood events.

Observations of debris conveyed in streams strongly suggest a correlation between event magnitude and debris potential at a site. Rarer events produce deeper and faster floodwater able to transport large quantities and larger sizes of debris, smaller events may not be able to transport larger blockage material at all. Debris potential is adjusted as required for greater or lesser probabilities to establish the *most likely* and *severe* blockage levels for that event.

The likelihood of blockage at a particular structure depends on whether or not debris is able to bridge across the structure inlet or become trapped within the structure. The *most likely* blockage to occur at a structure is determined by considering the potential quantity and type of debris and the structure opening size as shown in Table 35.

Table 35: Most Likely Blockage Levels - BDES (Reference 12)

Control Dimension	At-Site Debris Potential		
	High	**Medium**	**Low**
$W < L_{10}$	100%	50%	25%
$L_{10} \leq W \leq 3 \times L_{10}$	20%	10%	0%
$W > 3 \times L_{10}$	10%	0%	0%

Notes: W refers to the opening diameter / width
L_{10} refers to the 10% percentile length of debris that could arrive at the site

For design flood modelling blockage factors of up to 20% for the PMF event and up to 10% for rare AEP flood events was applied to major bridges, culverts and sewer crossings (such as the SWSOOS) along Wolli Creek and Bardwell Creek. Blockage values were selected based on past experience and consideration of the ARR2016 guidance for blockage with consideration of the control inlet dimensions and AEP adjusted debris potential. The design blockages applied at each structure for each design event are summarised in Table 36. Sensitivity analysis was undertaken for these blockage assumptions in Section 9.3.3.

Table 36: Design blockages applied at mainstream hydraulic structures

Wolli Creek

Structure	Type	Design Blockage Factor					
		20% AEP	10% AEP	5% AEP	1% AEP	0.5% AEP	PMF
Bexley Road	Culverts	0%	0%	10%	10%	10%	20%
Harthill-Law Avenue	Bridge	0%	0%	0%	0%	0%	10%
Turrella Footbridge	Footbridge	0%	0%	0%	0%	0%	10%
SWSOOS	Sewer Crossing	0%	0%	0%	0%	0%	10%

Bardwell Creek

Structure	Type	Design Blockage Factor					
		20% AEP	10% AEP	5% AEP	1% AEP	0.5% AEP	PMF
Ada St	Culverts	0%	0%	10%	10%	10%	20%
Unwin St	Culverts	0%	0%	10%	10%	10%	20%
Moore St	Culverts	0%	0%	10%	10%	10%	20%
Bexley GC	Culverts	0%	0%	10%	10%	10%	20%
Laycock St	Culverts	0%	0%	10%	10%	10%	20%
Oliver St	Culverts	0%	0%	10%	10%	10%	20%
Coveney St	Culverts	0%	0%	10%	10%	10%	20%
Preddys Rd	Culverts	0%	0%	10%	10%	10%	20%
Bexley Rd	Bridge	0%	0%	0%	0%	0%	10%
Bardwell GC	Culverts	0%	0%	10%	10%	10%	20%
Bardwell Rd	Culverts	0%	0%	10%	10%	10%	20%
Railway Crossing	Bridge	0%	0%	0%	0%	0%	10%

Several significant overland flowpaths occur north of the noise walls in the Wolli Creek catchment. The only known significant openings beneath the continuous sections of noise walls occur at Kingsgrove Commuter Car Park, Kingsgrove and Bexley North Community Centre and at Powys Avenue. There are a large number of openings beneath the noise wall at Kingsgrove Commuter Carpark however the openings in the noise walls at the latter two locations are small and likely to be blocked by debris. In consideration of these factors, and the absence of reliable data, the design blockage levels shown in Table 37 were adopted for this study. These design blockages are consistent blockage assumptions in Reference 7. The sensitivity of peak flood levels to these blockage assumptions at culverts is assessed in Section 8.6.

Table 37: Design blockages for gaps and culverts under noise walls

Location	Design Blockage
Commuter Car Park	75%
Community Centre	90%
Powys Avenue	90%

8.7. Downstream Boundary Conditions

In addition to runoff from the catchment, downstream areas can also be influenced by high water levels within Botany Bay and the Cooks River. Consideration must therefore be given to accounting for the joint probability of coincident flooding from both catchment runoff and backwater effects.

The combined impact of these sources on overall flood risk varies significantly with distance from the ocean and the degree of ocean influence, which is in turn affected by the entrance conditions. Given the short duration of the critical storm burst, the approach of using a steady state downstream boundary set to an appropriate Cooks River flood level was considered sufficient. Consideration of the coincidence of local catchment and Cooks River flooding was undertaken by applying the tailwater levels shown in Table 38. The Cooks River design tailwater levels were obtained from Reference 9.

Table 38 : Combinations of Catchment Flooding and Cooks River Design Flood Scenarios

Design AEP (Bardwell Creek and Wolli Creek)	Downstream Boundary Condition (Cooks River) (mAHD)	Cooks River Flood Scenario
20%	1.6	39.35% AEP (2 year ARI)
10%	1.6	39.35% AEP (2 year ARI)
5%	2.0	5% AEP (20 year ARI)
1%	2.0	5% AEP (20 year ARI)
0.5%	2.0	5% AEP (20 year ARI)
PMF	2.3	1% AEP (100 year ARI)

9. SENSITIVITY ANALYSIS

9.1. Overview

A number of sensitivity analyses were undertaken to establish the variation in design flood levels and flow that may occur if different parameter assumptions were made. These sensitivity scenarios are summarised in Table 39.

Table 39: Overview of Sensitivity Analyses

Scenario	Description
Catchment Lag Factor, "C"	The catchment lag factor value was increased and decreased by 20%
Manning's "n"	The hydraulic roughness values were increased and decreased by 20%
Culvert and Bridge Blockage	Sensitivity to blockage of culverts and bridges on open channel sections was assessed for: • 0% blockage; and • 50% blockage.
Pit Inlet Blockage	Sensitivity to blockage of all pits was assessed for: • 50% blockage of all inlet pits.
Climate Change	Sensitivity to rainfall and runoff estimates were assessed by increasing the rainfall intensities by 10%, 20% and 30%. Sea level rise scenarios of 0.4 m and 0.9 m were assessed.

9.2. Climate Change Background

Intensive scientific investigation is ongoing to estimate the effects that increasing amounts of greenhouse gases (water vapour, carbon dioxide, methane, nitrous oxide, ozone) are having on the average earth surface temperature. Changes to surface and atmospheric temperatures are likely to change the future climate and sea levels. The extent of any permanent climatic or sea level change can only be established with certainty through scientific observations over several decades. Nevertheless, it is prudent to consider the possible range of impacts with regard to flooding and the level of flood protection provided by any mitigation works.

Based on the latest research by the United Nations Intergovernmental Panel on Climate Change, evidence is emerging on the likelihood of climate change and sea level rise as a result of increasing greenhouse gasses. In this regard, the following points can be made:

- greenhouse gas concentrations continue to increase;
- global sea levels have risen about 0.1 m to 0.25 m in the past century;
- many uncertainties limit the accuracy to which future rainfall intensity changes; and
- sea level rises can be projected and predicted.

9.2.1. Rainfall Increase

The Bureau of Meteorology has indicated that there is no intention at present to revise design rainfalls to take account of the impact of climate change, as the implications of temperature changes on extreme rainfall intensities are presently unclear, and there is uncertainty about whether the changes would in fact increase design rainfalls for major flood producing storms.

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

Projected increases to evaporation are also an important consideration because increased evaporation would lead to generally drier catchment conditions, resulting in lower runoff from rainfall. Mean annual rainfall is projected to decrease, which will also result in generally dryer catchment conditions.

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

In light of this uncertainty, the NSW State Government's advice recommends sensitivity analysis on flood modelling should be undertaken to develop an understanding of the effect of various levels of change in the hydrologic regime on the project at hand (Reference 24). Specifically, it is suggested that increases of 10%, 20% and 30% to rainfall intensity be considered.

There is no IFD data for events greater than the 1% AEP event for durations less than 24 hours, therefore a comparison of the suggested climate change increases can only be made with the 24 hour event. The 24 hr IFDs and the climate change increases are shown in Table 40

Table 40: 24 hr Duration and climate change comparison

1% AEP	1% AEP plus 10%	1% AEP plus 20%	1% AEP plus 30%	0.5 % AEP	0.2 % AEP	0.1% AEP	0.05% AEP
278 mm	306 mm	334 mm	361 mm	305 mm	345 mm	375 mm	407 mm

Table 40 indicates that for 1% AEP daily rainfalls:

- A 10% increase in rainfall is approximately equivalent to a 0.5% AEP event
- A 20% increase in rainfall is approximately equivalent to a 0.2% AEP event
- A 30% increase in rainfall is approximately equivalent to a 0.1 % AEP event

9.2.2. Sea Level Rise

The NSW Sea Level Rise Policy Statement (Reference 25) was released by the NSW Government in October 2009. This Policy Statement was accompanied by the Derivation of the NSW Government's sea level rise planning benchmarks (Reference 26) which provided technical details on how the sea level rise assessment was undertaken. Additional guidelines were issued by OEH, including the Flood Risk Management Guide: Incorporating sea level rise benchmarks in flood risk assessments 2010 (Reference 27).

The Policy Statement says:
"Over the period 1870-2001, global sea levels rose by 20 cm, with a current global average rate of increase approximately twice the historical average. Sea levels are expected to continue rising throughout the twenty-first century and there is no scientific evidence to suggest that sea levels will stop rising beyond 2100 or that current trends will be reversed… However, the 4th Intergovernmental Panel on Climate Change in 2007 also acknowledged that higher rates of sea level rise are possible" (Reference 25).

In light of this uncertainty, the NSW State Government's advice is subject to periodical review. As of 2012 the NSW State Government withdrew endorsement of sea level rise predictions but still requires sea level rise to be considered. In the absence of any other advice the previous NSW State Government benchmarks of sea level rise of 0.4 m by the year 2050 and 0.9 m by the year 2100 have been adopted in this study.

9.3. Sensitivity Analysis Results

The sensitivity scenario results were compared to the 1% AEP event. A summary of peak flood level and peak flow differences at various locations are provided in:

- Table 41 for variations in the catchment lag factor (C);
- Table 42 for variations in roughness;
- Table 43 and Table 44 for variations in pit/inlet and structure blockage; and
- Table 45 for variations in climate conditions.

9.3.1. Catchment Lag Parameter

Table 41: Sensitivity of 1% AEP catchment flows to the lag factor

Lag Factor (C)	Subcatchment WCKFS016		Subcatchment BCKFS002		Subcatchment BCKFS004	
	Mean Flow (m^3/s)	Critical Pattern Flow 60 min, TP4561 (m^3/s)	Mean Flow (m^3/s)	Critical Pattern Flow 60 min, TP4561 (m^3/s)	Mean Flow (m^3/s)	Critical Pattern Flow 60 min, TP4561 (m^3/s)
1.7 (Design Runs)	104.6	112.2	13.2	14.2	20.0	20.3
2.04 (+20%)	89.0	93.4	11.7	12.8	18.2	19.1
1.36 (-20%)	119.9	133.7	14.7	16.0	21.7	21.8

An increase in the lag factor results in a decrease in flows, of approximately 10% to 15%. Conversely, a decrease in the lag factor increases the catchment flows by up to 20%.

9.3.2. Roughness Variations

Overall peak flood level results were shown to be relatively insensitive to 20% variations in the roughness parameter. Varying the roughness parameter by 20% typically resulted in a peak flood height difference within ± 0.1 m. A slightly greater change in peak flood levels occurred on the natural creek sections of Wolli Creek and Bardwell Creek. This is likely due to the relatively high Mannings value selected for this location, which results in a large increase or decrease in Mannings value when a percentage variation is applied. The results for the roughness sensitivity analysis are shown in Table 42.

Table 42: Results of Roughness Sensitivity Analysis

ID	Location	1% AEP Peak Flood Level (mAHD)	Difference (m)	
			Roughness Decreased 20%	Roughness Increased 20%
H001	Ada Street	35.67	-0.01	0.00
H002	Unwin Street	33.69	-0.03	0.02
H003	Moore Street	32.21	-0.03	0.02
H004	Bexley Golf Course	30.88	-0.01	0.01
H005	Stoney Creek Road	28.99	-0.02	0.01
H006	Laycock Street	27.54	-0.03	0.03
H007	Oliver Street	26.36	-0.03	-0.02
H008	Coveney Street	25.49	0.03	-0.01
H009	Preddys Road	23.60	0.02	-0.02
H010	Ellerslie Road	16.27	-0.17	0.15
H011	Orpington Street	14.14	-0.21	0.18
H012	Bexley Road (Bardwell)	13.11	-0.14	0.14
H013	Hillcrest Avenue	11.92	0.04	-0.01
H014	Bardwell Valley Golf Course	11.85	0.06	-0.02
H015	Pile Street	6.46	-0.22	0.21
H016	Wilsons Road	5.68	-0.09	0.09
H017	Bardwell Road	5.44	-0.03	0.03
H018	Hannam Street	4.44	-0.12	0.11
H019	York Street	14.88	-0.01	-0.02
H020	Kooreela Street	14.80	-0.02	0.00
H021	Girraween Street	13.27	-0.01	0.00
H022	Bonalbo Street	13.17	0.00	0.00
H023	Nairn Street	11.28	0.00	-0.01
H024	Beaumont Street	10.11	-0.05	0.06
H025	Bexley Road (Wolli)	8.95	-0.29	0.25
H026	Bardwell Park Station	6.90	-0.22	0.17
H027	Harthill-Law Avenue	5.74	-0.24	0.19
H028	Downstream Bardwell Confluence	4.23	-0.12	0.10
H029	Henderson Street	3.35	-0.08	0.07
H030	SWSOOS	2.44	-0.07	0.07
H031	St Georges Road	47.83	0.01	0.00
H032	Stoney Creek Road/Preddys Road	35.87	0.01	-0.01
H033	Binnamitalong Gardens	14.63	-0.03	0.03

H034	Hillcrest Avenue	17.26	0.00	0.00
H035	Fatima Church	19.10	-0.02	0.01
H036	Gilchrist Park/Bexley Comm Centre	18.35	-0.02	0.01
H037	New Illawarra Rd	18.41	-0.01	0.00
H038	Kingsland Rd North	10.72	0.00	0.01
H039	Poweys Avenue	7.30	0.01	-0.01
H040	Guess Avenue	2.44	0.00	0.00
H041	Downey St	44.10	-0.01	0.00
H042	Iliffe St	40.31	0.00	0.00
H043	Todd St	26.94	0.00	0.01
H044	Caroline St	26.36	-0.01	0.00
H045	St Kilda St	24.18	-0.01	0.01
H046	Slade Rd	10.65	0.00	0.00
H047	Darley Rd	11.92	-0.01	0.01
H048	Water St	8.65	0.00	0.00
H049	Abercorn St	32.86	-0.01	0.01

9.3.3. Blockage Variations

There are multiple factors to be considered in assessing the potential for blockage of culverts and bridges. These considerations include:

- the type and mobility of debris that can be washed into the waterway to block the structure or inlet;
- the dimensions of the debris in comparison to the structure;
- dimensions of the structure in relation to the upstream and downstream channels;
- the presence of piers, service crossings, or other obstructions to flow on which debris can accumulate; and
- catchment land-use.

For the Bardwell Creek and Wolli Creek catchment, consideration of these factors generally indicates a medium risk of blockage. Culvert structures in Bardwell Creek are medium to large, with openings ranging from 1.5 m to 2.8 m. Structures in Wolli Creek are generally large with openings greater than 3 m wide.

Based on this assessment, the assumed design blockage factors for culverts in the main channels of Bardwell Creek and Wolli Creek were determined to generally vary from 0% to 10%, with slightly higher blockages applied for the PMF event. The applied blockage factors are consistent with the guidelines for blockage developed as part of the ARR2016 project. The blockage factors were determined based on medium at-site debris potential and large structures relative to the size of typical urban debris. The blockage factors applied for the openings and culverts under the Wolli Creek noise walls were higher in consideration of the relatively small openings, which are more likely to become blocked.

The culvert and bridge blockage sensitivity results are shown in Table 43.

Table 43: Culvert and Bridge Blockage Sensitivity Analysis

ID	Location	1% AEP Peak Flood Level (mAHD)	Difference (m)	
			0% blockage	50% blockage
H001	Ada Street	35.67	-0.03	0.10
H002	Unwin Street	33.69	-0.03	0.10
H003	Moore Street	32.21	-0.03	0.12
H004	Bexley Golf Course	30.88	-0.04	0.17
H005	Stoney Creek Road	28.99	-0.03	0.14
H006	Laycock Street	27.54	-0.01	0.05
H007	Oliver Street	26.36	-0.11	0.27
H008	Coveney Street	25.49	-0.15	0.34
H009	Preddys Road	23.60	-0.13	0.32
H010	Ellerslie Road	16.27	-0.04	0.10
H011	Orpington Street	14.14	-0.05	0.14
H012	Bexley Road (Bardwell)	13.11	0.00	0.18
H013	Hillcrest Avenue	11.92	-0.19	0.84
H014	Bardwell Valley Golf Course	11.85	-0.23	0.90
H015	Pile Street	6.46	0.12	-0.31
H016	Wilsons Road	5.68	0.05	-0.07
H017	Bardwell Road	5.44	0.02	0.02
H018	Hannam Street	4.44	0.06	-0.19
H019	York Street	14.88	0.01	-0.02
H020	Kooreela Street	14.80	-0.01	0.00
H021	Girraween Street	13.27	-0.01	0.00
H022	Bonalbo Street	13.17	0.00	0.00
H023	Nairn Street	11.28	-0.01	0.00
H024	Beaumont Street	10.11	0.00	0.02
H025	Bexley Road (Wolli)	8.95	0.00	0.01
H026	Bardwell Park Station	6.90	0.00	0.00
H027	Harthill-Law Avenue	5.74	0.00	-0.01
H028	Downstream Bardwell Confluence	4.23	0.03	-0.13
H029	Henderson Street	3.35	0.03	-0.12
H030	SWSOOS	2.44	0.02	-0.07
H031	St Georges Road	47.83	0.00	0.00
H032	Stoney Creek Road/Preddys Road	35.87	0.00	0.00
H033	Binnamitalong Gardens	14.63	0.00	0.00
H034	Hillcrest Avenue	17.26	0.00	0.00
H035	Fatima Church	19.10	0.00	0.00
H036	Gilchrist Park/Bexley Comm Centre	18.35	0.00	0.00
H037	New Illawarra Rd	18.41	0.00	0.00
H038	Kingsland Rd North	10.72	0.00	0.00
H039	Poweys Avenue	7.30	-0.20	-0.19
H040	Guess Avenue	2.44	0.00	0.00
H041	Downey St	44.10	0.00	0.00
H042	Iliffe St	40.31	0.00	0.00
H043	Todd St	26.94	0.00	0.00
H044	Caroline St	26.36	0.00	0.00

H045	St Kilda St	24.18	0.00	0.00
H046	Slade Rd	10.65	0.00	0.00
H047	Darley Rd	11.92	0.00	0.00
H048	Water St	8.65	0.00	0.00
H049	Abercorn St	32.86	0.00	0.00

Peak flood levels at most locations were found to be relatively insensitive to blockage, with a few notable exceptions, showing peak level differences of less than 0.2 m from design blockage conditions. The culverts under Bardwell Valley Golf Course were particularly sensitive to blockage with 50% blockage resulting in peak flood levels at Hillcrest Avenue approximately 0.8 m higher than for the design blockage of 10%. It is considered unlikely that this level of blockage will occur, particularly given the presence of the blockage prevention device at the inlet to the culverts (Section 2.2.1).

The following pit blockage scenarios was tested:

1. Inlets 50% blocked

Modelling indicates that the 50% blocking of on-grade inlet pits has minimal effect on peak flood levels due to the relatively steep topography and limited pipe capacity within many parts of the catchment. Peak flood levels in the 1% AEP event typically vary by less than 0.1 m in most locations. The effect of pit blockage was more generally more pronounced in areas where the capacity of the pipe network was greater. This result is consistent with previous studies which have shown that sub-surface drainage in the catchment is in most cases limited by the available pipe capacity within the catchment in the 1% AEP event (Reference 4 to Reference 8).

The results of the pit inlet blockage analysis are shown in Table 44

Table 44: Results of Pit Inlet Blockage Sensitivity Analysis

ID	Location	1% AEP Peak Flood Level (mAHD)	Difference (m)
			50% blockage
H001	Ada Street	35.67	-0.01
H002	Unwin Street	33.69	0.00
H003	Moore Street	32.21	0.00
H004	Bexley Golf Course	30.88	0.00
H005	Stoney Creek Road	28.99	0.00
H006	Laycock Street	27.54	0.00
H007	Oliver Street	26.36	0.01
H008	Coveney Street	25.49	0.00
H009	Preddys Road	23.60	0.01
H010	Ellerslie Road	16.27	-0.01
H011	Orpington Street	14.14	-0.02
H012	Bexley Road (Bardwell)	13.11	-0.02
H013	Hillcrest Avenue	11.92	-0.05
H014	Bardwell Valley Golf Course	11.85	-0.05
H015	Pile Street	6.46	-0.01
H016	Wilsons Road	5.68	-0.01
H017	Bardwell Road	5.44	0.00

H018	Hannam Street	4.44	-0.01
H019	York Street	14.88	0.00
H020	Kooreela Street	14.80	-0.01
H021	Girraween Street	13.27	-0.01
H022	Bonalbo Street	13.17	-0.01
H023	Nairn Street	11.28	-0.02
H024	Beaumont Street	10.11	0.00
H025	Bexley Road (Wolli)	8.95	-0.01
H026	Bardwell Park Station	6.90	-0.01
H027	Harthill-Law Avenue	5.74	-0.02
H028	Downstream Bardwell Confluence	4.23	-0.01
H029	Henderson Street	3.35	-0.01
H030	SWSOOS	2.44	-0.01
H031	St Georges Road	47.83	0.00
H032	Stoney Creek Road/Preddys Road	35.87	0.14
H033	Binnamitalong Gardens	14.63	0.01
H034	Hillcrest Avenue	17.26	0.00
H035	Fatima Church	19.10	0.04
H036	Gilchrist Park/Bexley Comm Centre	18.35	0.01
H037	New Illawarra Rd	18.41	0.00
H038	Kingsland Rd North	10.72	0.25
H039	Poweys Avenue	7.30	0.18
H040	Guess Avenue	2.44	0.00
H041	Downey St	44.10	0.01
H042	Iliffe St	40.31	0.02
H043	Todd St	26.94	0.00
H044	Caroline St	26.36	0.01
H045	St Kilda St	24.18	0.01
H046	Slade Rd	10.65	0.01
H047	Darley Rd	11.92	0.00
H048	Water St	8.65	0.01
H049	Abercorn St	32.86	0.06

9.3.4. Climate Variations

The effect of increasing the design rainfalls by 10%, 20% and 30% was evaluated for the 1% AEP rainfall event with impacts on peak flood levels observed throughout the study area. Generally speaking, each incremental 10% increase in rainfall results in an increase in peak flood levels at most of the locations analysed. The largest variation in flood level occurred at Bardwell Valley Golf Course and Hillcrest Avenue with modelled peak flood levels up to 0.9 m higher under the 30% rainfall increase scenario. Sea level rise scenarios have the greatest effect on the downstream reaches of the catchment, near the confluence of Wolli Creek with the Cooks River. The climate change sensitivity results are shown in Table 45.

Table 45: Results of Climate Change Analysis

ID	Location	1% AEP Peak Flood Level (mAHD)	Difference (m)				
			10% Rainfall Increase	20% Rainfall Increase	30% Rainfall Increase	0.4 m Sea Level Rise	0.9 m Sea Level Rise
H001	Ada Street	35.67	0.04	0.08	0.12	0.00	0.00
H002	Unwin Street	33.69	0.05	0.10	0.14	0.00	0.00
H003	Moore Street	32.21	0.05	0.10	0.15	0.00	0.00
H004	Bexley Golf Course	30.88	0.07	0.13	0.18	0.00	0.00
H005	Stoney Creek Road	28.99	0.05	0.10	0.15	0.00	0.00
H006	Laycock Street	27.54	0.02	0.04	0.07	0.00	0.00
H007	Oliver Street	26.36	0.07	0.22	0.26	-0.06	0.00
H008	Coveney Street	25.49	0.14	0.24	0.33	0.00	0.00
H009	Preddys Road	23.60	0.14	0.23	0.32	-0.01	0.00
H010	Ellerslie Road	16.27	0.14	0.27	0.40	0.00	0.00
H011	Orpington Street	14.14	0.19	0.36	0.53	0.00	0.00
H012	Bexley Road (Bardwell)	13.11	0.21	0.41	0.60	0.00	0.00
H013	Hillcrest Avenue	11.92	0.34	0.63	0.86	0.00	0.00
H014	Bardwell Valley Golf Course	11.85	0.35	0.67	0.91	0.00	0.00
H015	Pile Street	6.46	0.06	0.20	0.37	0.00	0.01
H016	Wilsons Road	5.68	0.05	0.15	0.26	0.00	0.01
H017	Bardwell Road	5.44	0.05	0.13	0.21	0.00	0.02
H018	Hannam Street	4.44	0.13	0.29	0.45	0.02	0.07
H019	York Street	14.88	0.04	0.12	0.09	-0.01	-0.01
H020	Kooreela Street	14.80	0.00	0.00	0.00	-0.01	-0.01
H021	Girraween Street	13.27	0.12	0.29	0.30	0.00	0.00
H022	Bonalbo Street	13.17	0.11	0.26	0.29	0.00	0.00
H023	Nairn Street	11.28	0.16	0.40	0.44	-0.01	0.00
H024	Beaumont Street	10.11	0.20	0.41	0.53	0.00	0.00
H025	Bexley Road (Wolli)	8.95	0.22	0.44	0.58	0.00	0.00
H026	Bardwell Park Station	6.90	0.19	0.32	0.45	0.00	0.01
H027	Harthill-Law Avenue	5.74	0.20	0.36	0.52	0.01	0.02
H028	Downstream Bardwell Confluence	4.23	0.13	0.27	0.41	0.02	0.09
H029	Henderson Street	3.35	0.12	0.24	0.38	0.09	0.26

H030	SWSOOS	2.44	0.07	0.16	0.24	0.27	0.65
H031	St Georges Road	47.83	0.01	0.02	0.03	0.00	0.00
H032	Stoney Creek Road/Preddys Road	35.87	0.05	0.16	0.25	0.00	0.00
H033	Binnamitalong Gardens	14.63	0.04	0.10	0.14	0.00	0.00
H034	Hillcrest Avenue	17.26	0.00	0.00	0.00	0.00	0.00
H035	Fatima Church	19.10	0.04	0.07	0.11	0.00	0.00
H036	Gilchrist Park/Bexley Comm Centre	18.35	0.01	0.02	0.03	0.00	0.00
H037	New Illawarra Rd	18.41	0.00	0.00	0.00	0.00	0.00
H038	Kingsland Rd North	10.72	0.08	0.15	0.25	0.00	0.00
H039	Poweys Avenue	7.30	0.13	0.24	0.35	0.00	0.00
H040	Guess Avenue	2.44	0.01	0.01	0.02	0.05	0.46
H041	Downey St	44.10	0.03	0.06	0.08	0.00	0.00
H042	Iliffe St	40.31	0.01	0.02	0.02	0.00	0.00
H043	Todd St	26.94	0.01	0.02	0.02	0.00	0.00
H044	Caroline St	26.36	0.01	0.01	0.01	0.00	0.00
H045	St Kilda St	24.18	0.01	0.02	0.03	0.00	0.00
H046	Slade Rd	10.65	0.00	0.01	0.01	0.00	0.00
H047	Darley Rd	11.92	0.00	0.00	0.00	0.00	0.00
H048	Water St	8.65	0.00	0.01	0.01	0.00	0.00
H049	Abercorn St	32.86	0.03	0.05	0.08	0.00	0.00

Modelling indicates that increases in rainfall intensity would have a significant impact on mainstream flood levels and a less substantial impact on peak flood levels in steep overland flow areas. Peak flood level increases upstream of Bardwell Valley Golf Course and at Hillcrest Avenue are particularly notable, with peak flood level increases between 0.3 m and 0.9 m, for the 10% to 30% rainfall increase scenarios. The impacts of sea level rise are generally restricted to the lower tidal reaches of Wolli Creek with low lying areas of the suburbs of Wolli Creek and Turrella also impacted. The effects of sea level rise on Bardwell Creek are minimal with peak flood level impacts of less than 0.1 m.

10. FLOODING HOT SPOTS

Some of the key areas where flooding is problematic, sometimes referred to as "hotspots," are discussed below in further detail. Figure F1 provides an overview of the locations discussed.

10.1. Wolli Creek

10.1.1. Noise Walls along Shaw Street

Noise Wall Overland Flooding Hot Spots are located to the Southern Side of the railway line along Shaw Street. There is a significant contributing catchment area with flows of 5.8 m^3/s in the 1% AEP design event passing through Gilchrist Park before ponding at the low point near Kingsgrove and Bexley North Community Centre. Gilchrist park and the Kingsgrove and Bexley North Community Centre are shown in Photo 14.

Photo 14: Gilchrist Park (right) and Kingsgrove and Bexley North Community Centre (left)

The noise walls and railway embankment act as a significant barrier to overland flow which previously drained to Wolli Creek over the East Hills Rail Line.
Overland flow originates from the following locations:

- Local catchment runoff;
- Overland flow originating from Park Street which flows north, passing through Gilchrist Park;
- Overland flow originating to the east and west of Shaw Street.

Flows from upstream of the noise walls may exit to the railway corridor through the 1350 mm stormwater pipe, through the narrow gaps in the noise wall behind Kingsgrove and Bexley North

Community Centre or through the Wolli Street vehicular access. The gaps beneath the noise walls behind the Community Centre are narrow and are likely to become blocked by debris during a flood event. A series of six culverts convey flow beneath the rail line. While the culverts appear to have substantial capacity, the noise walls may present an obstruction that prevents drainage from the area around the Community Centre. Options to remove flooding obstructions while retaining the noise mitigation function of the walls (for instance with a baffled arrangement) should be investigated further in a subsequent FRMS.

Figure F2 shows design flood behaviour for the 1% AEP event and the sub-surface drainage network at this location. Design flood levels at the low point, flows within the pipes underneath Shaw Street and overland flows over the railway embankment are summarised in Table 46.

Table 46: Design flood behaviour near Kingsgrove / Bexley North Community Centre sag point

Event	Peak Level (mAHD)	Peak Depth (m)	Peak Inflow (m^3/s)		Peak Outflow (Noise Walls) (m^3/s)		Peak Outflow (Rail Embankment) (m^3/s)	
	Sag Point		Pipe	Overland (Gilchrist Park)	Pipe	Noise Walls	Culverts	Overland (Rail Embankment)
20% AEP	16.70	1.33	3.13	3.54	3.13	1.22	3.70	0.45
10% AEP	16.73	1.35	3.21	3.82	3.21	1.43	3.92	1.03
5% AEP	16.74	1.37	3.29	4.19	3.29	2.18	4.24	1.66
1% AEP	16.81	1.44	3.58	5.84	3.58	5.99	5.44	5.55
0.5% AEP	16.83	1.45	3.70	6.72	3.70	7.38	5.74	6.85
PMF	17.68	2.30	4.40	38.68	4.40	50.26	9.33	122.77

Flood waters pond at the low point at the Kingsgrove and Bexley North Community Centre to a peak level of 16.81 mAHD in the 1% AEP event. The rail embankment level is approximately 2 m above ground level at this location and acted as a significant barrier to overland flow even prior to the installation of the noise walls.

Modelling indicates that the rail embankment would be overtopped in the 20% AEP event however the flow rate over the embankment is insufficient to prevent floodwaters from ponding to a significant depth. In the 1% AEP event several existing residential buildings are affected by flooding. However in the PMF event the number of affected properties increases, with the backwater effect of the railway embankment resulting in above floor level inundation of additional properties in low lying areas to the east and west of the sag point. Floor level survey comparisons would be needed to confirm how many properties would be affected by over-floor inundation for each event.

Note that there is limited overland flow across the railway embankment for events up to the PMF and prior to installation of the noise walls flows exceeding the capacity of the drainage network would have ponded to the south of the rail line.

This data suggests that design flood depths in the sag point could be reduced by increasing the cross-drainage capacity beneath the railway line, although this would involve considerable expense. Increasing the size of the openings beneath the noise walls behind the Kingsgrove and Bexley North Community Centre would reduce the likelihood of blockage however ponding of overland flows behind the embankment would still occur for flows exceeding the capacity of the culverts.

10.1.2. Bexley Road

The Bexley Road crossing occurs at a low point over the steep Wolli Creek gully. Bexley Road is frequently overtopped during flood events at this location resulting in road closures. Modelling indicates that overtopping of Bexley Bridge first occurs in the 20% AEP event.

Photo 15: Bexley Road (Wolli Creek)

Figure F3 shows the location of this flooding hotspot and design flood depths for the 1% AEP event. Design flood levels and flows on Bexley Road and flows through the culverts are summarised in Table 47.

Table 47: Design flood behaviour at Bexley Road (Wolli Creek)

Event	Peak Flood Level (mAHD)	Peak Flood Depth (m)	Peak Inflow (m^3/s)		Peak Outflow (m^3/s)
	Bexley Road		Culvert	Road	Creek
20% AEP	7.80	0.90	52.10	25.32	72.27
10% AEP	8.19	1.30	52.86	44.23	90.38
5% AEP	8.36	1.47	53.18	56.61	102.22
1% AEP	8.95	2.05	54.33	92.46	137.31
0.5% AEP	9.15	2.26	55.12	105.13	149.40
PMF	13.28	6.39	64.62	636.14	699.46

Flooding over the road prevents direct access to the north of the catchment however vehicle access for residents to the east of Kingsgrove Avenue reserve is maintained in the 1% AEP event to the south via the Bexley Road railway overpass.

Historically, consideration has been given to replacing the three cell Wolli Creek culverts with a two span bridge structure. However investigations determined that the downstream creek, which passes through a confined valley just downstream of the bridge and is congested with silt and vegetation, was the cause of flooding over the road rather than the culverts (Reference 28). Options for modification or management of the creek at this location should be considered as part of a subsequent FRMS in the catchment.

10.1.3. Intersection of Slade Road and Sarsfield Circuit, Bexley North

A significant overland flow path drains water through Whitbread Park and along both New Illawarra Road and Bexley Road in a northerly direction. Overland flow ultimately ponds at the natural low point near the intersection of Slade Road and Sarsfield Circuit. The high density residential and commercial buildings in this area act as obstructions to flow during flood events. Modelling indicates that ponding of flood waters to a significant depth may occur adjacent to the high density residential units at 232 Slade Road. There is a flow path and easement through the ground level carpark, which relieves the depth of flooding within Slade Road to some extent. The flow path through the building was included in the modelling using plans for the development provided by Bayside Council. There is an earth embankment between development and the railway line which acts as a hydraulic control and retains floodwaters within the low point. People and cars within the ground level carpark of this building may be at risk from flooding during significant flood events.

Photo 16: Sarfield Circuit / Slade Road Low point

Figure F4 shows design flood behaviour for the 1% AEP event and the sub-surface drainage network at this location.

Peak flood levels and piped and overland flows at the Sarfield Circuit and Slade Road low point are presented in Table 48.

Table 48: Design flood behaviour at the intersection of Sarsfield Circuit and Slade Road

Event	Peak Flood Level (m)	Peak Flood Depth (m)	Peak Inflow (m^3/s)		Peak Outflow (m^3/s)	
	Slade Rd		Pipe	Overland	Pipe	Overland
20% AEP	11.99	0.74	2.08	1.20	2.50	1.21
10% AEP	12.00	0.75	2.10	1.34	2.52	1.40
5% AEP	12.04	0.79	2.13	1.56	2.56	1.79
1% AEP	12.14	0.89	2.22	2.85	2.66	3.21
0.5% AEP	12.19	0.94	2.25	3.43	2.70	3.92
PMF	13.11	1.86	2.76	25.55	3.33	30.32

10.1.4. Bardwell Park Train Station

Bardwell Park Train Station is located adjacent to Wolli Creek near Harthill-Law Avenue bridge. Overtopping of the railway embankment occurs when overbank flows from Wolli Creek inundate the rail line at the low point adjacent to a bend in the creek upstream of the station. A significant flow path through Bardwell Park Station has been observed to occur during several recent flood events, including the October 2014 and April 2015 events. Photos and video available online indicate that the railway line was inundated at Bardwell Park Station to a substantial depth in both recent flood events. Flooding above floor level has also been reported at Earlwood Bardwell Park RSL Club in the October 2014 event.

Photo 17: Bardwell Park Station

Flooding over the tracks along the East Hills rail line due to flooding from Wolli Creek results in closures of the rail line in both directions and significant transport disruptions.

Figure F5 shows the location of this flooding hotspot and design flood depths for the 1% AEP event.

Flows from south of the rail line are conveyed towards the rail line via the subsurface drainage network. When the capacity of the drainage network is exceeded overland flows may spill onto the tracks. The rail line is inundated by flooding from Wolli Creek just upstream of Bardwell Park Station in the 20% AEP event. The rail line is also inundated at several other locations in the 20% AEP event between Kingsgrove Station and Bardwell Park Station, due to both mainstream and overland flooding.

Design flood levels and flows at Bardwell Park Station near the platform are summarised in Table 49.

Table 49: Design flood behaviour at Bardwell Park Station

Event	Peak Flood Level (mAHD)	Peak Flood Depth (m)	Peak Inflow (m^3/s)	Peak Outflow (m^3/s)
	Platform		U/S Platform	D/S Platform
20% AEP	5.92	0.19	0.03	0.00
10% AEP	6.23	0.50	0.59	0.00
5% AEP	6.39	0.66	1.01	0.15
1% AEP	6.90	1.17	3.72	1.58
0.5% AEP	7.07	1.34	4.51	3.97
PMF	10.22	4.49	277.63	257.96

10.1.5. Powys Avenue, Bardwell Park

Photo 18: Railway noise wall gaps – Powys Avenue, Bardwell Park

A natural low point exists at the end of Powys Avenue which allows ponding of water at this location as shown in Photo 18. The rail level is approximately 1.7 m above ground level at this location and acts as a significant barrier to overland flow. Twelve small culverts under the noise walls allow overland flows to drain into the rail corridor at Powys Avenue. The small gaps beneath the noise walls at this location are poorly defined and are likely to be blocked by debris. The small grates are likely to become partially blocked by debris which has been accounted for in the design blockage as outlined in Section 8.6.

Figure F6 shows design flood behaviour for the 1% AEP event and the sub-surface drainage network at this location. Design flood levels and flows at Powys Avenue are summarised in Table 50.

Table 50: Design flows and levels at Powys Avenue

Event	Peak Flood Level (mAHD)	Peak Flood Depth (m)	Peak Inflow (m^3/s)		Peak Outflow (m^3/s)	
	Powys Ave		Pipe	Overland	Pipe	Overland
20% AEP	6.64	0.82	0.53	1.06	1.54	0.00
10% AEP	6.67	0.85	0.57	1.19	1.57	0.00
5% AEP	6.94	1.12	0.59	1.29	1.58	0.00
1% AEP	7.30	1.47	0.66	1.52	1.73	0.00
0.5% AEP	7.41	1.58	0.70	1.60	1.78	0.00
PMF	9.62	3.80	1.46	5.24	2.53	0.05

The sensitivity of the culverts at Powys Avenue to blockage is assessed in Section 9.3.3.

10.1.6. SWSOOS (Turrella Street, Turrella)

The SWSOOS is located near the intersection of Turrella Street and Thompson Street. Due to the topography of the local area and lack of substantial trunk drainage infrastructure beneath the rail embankment, modelling indicates that overland flows from south of the railway will pond on Turrella Street and behind the SWOOS and railway embankments to a depth of approximately 1 m in the 1% AEP event. Several small openings to either side of the SWSOOS embankment allow water to flow under the railway embankment when water levels exceed approximately 2 mAHD. This flooding hotspot is shown in Photo 19.

Figure F7 shows design flood behaviour for the 1% AEP event and the sub-surface drainage network at this location.

Design flood levels, inflows to this hotspot and outflows via the pipe beneath the railway and through the railway embankment are summarised in Table 51.

Photo 19: Turrella Street, Turrella

Table 51: Design flood behaviour at the SWSOOS low point

Event	Peak Flood Level (mAHD)	Peak Flood Depth (m)	Peak Inflow (m³/s)		Peak Outflow (m³/s)	
	Turrella Street		Pipe	Overland	Pipe	Overland
20% AEP	2.48	0.14	0.53	0.63	0.77	0.12
10% AEP	2.57	0.23	0.57	0.77	0.80	0.13
5% AEP	2.67	0.33	0.59	1.20	0.66	0.33
1% AEP	2.79	0.45	0.66	1.86	0.71	0.62
0.5% AEP	2.84	0.50	0.70	2.16	0.73	0.79
PMF	5.89	3.55	1.46	74.13	0.81	2.95

The SWSOOS hot-spot is located at a low-point in the Wolli Creek catchment and is subject to the 1% AEP Cooks River flood (Reference 9).

Additional trunk drainage infrastructure would be required at this location to drain overland flood flows. However the installation of such drainage infrastructure without backflow prevention may leave low lying properties vulnerable to backwater flooding from the Cooks River.

10.1.7. Lusty Street, Wolli Creek

Lusty Street is situated at a low point in the high density residential area of the suburb of Wolli Creek. This portion of the suburb of Wolli Creek is bounded to the north and south-east by railway embankments, which act as a barrier to overland flow. The primary drainage infrastructure at this location is a single 900 mm pipe which passes under the railway embankment and discharges into Wolli Creek. Overland flow exceeding the capacity of the sub-surface drainage network ponds at low points on Lusty Street, resulting in frequent nuisance flooding. The capacity of drainage infrastructure at this location is exceeded in the 20% AEP event, resulting in ponding of floodwaters in streets and around buildings.

In the 1% AEP event water ponds to depths in excess of 0.5 m at some locations. Cross-catchment flows into the neighbouring Bonnie Doon catchment can occur via Guess Avenue with flows passing under the railway.

Photo 20: Lusty Street, Wolli Creek

Figure F8 shows design flood behaviour for the 1% AEP event and the sub-surface drainage network at this location.

Peak design flood levels and flows at Lusty Street are presented in Table 52.

Table 52: Design flood behaviour at Lusty Street low point

Event	Peak Flood Level (mAHD)	Peak Flood Depth (m)	Peak Inflow (m^3/s)		Peak Outflow (m^3/s)	
	Lusty Street		Pipe	Overland	Pipe	Overland
20% AEP	2.08	0.25	0.23	2.08	0.56	0.27
10% AEP	2.10	0.27	0.23	2.10	0.57	0.32
5% AEP	2.29	0.47	0.22	2.29	0.47	0.40
1% AEP	2.36	0.54	0.22	2.36	0.51	0.53
0.5% AEP	2.38	0.56	0.22	2.38	0.52	0.60
PMF	4.71	2.89	0.16	4.71	0.51	9.66

Pipe flows at this location are highly dependent on the tailwater applied since this hotspot is low lying and hence the efficiency of the piped drainage system is dependent on the water levels in Wolli Creek. Backflow prevention may be necessary at this location to prevent surcharging at pits in Lusty Street during flood events.

10.2. Bardwell Creek

10.2.1. Overland flow path to Bexley Aquatic Centre

A large overland flow path runs through a number of properties between the south-eastern corner of the study area and Bardwell Creek. A Tonkin 1166 mm pipe begins at St Georges Road, transitioning to a Tonkin 1549 mm pipe at Stoney Creek Road and a larger box culvert at Stoney Creek road as shown in Figure 20.

Photo 21: Stoney Creek Road Overland Flowpath

Modelling indicates that the capacity of the drainage infrastructure at this location is exceeded in the 20% AEP event. In the 1% AEP event water reaches depths of over 0.5 m at the rear of some properties with significant ponding of water at low points on St Georges Road, Mimosa Street, Preddys Road and Stoney Creek Road. A large depression at 138-140 Stoney Creek Road appears to effectively act as a detention basin, retaining a large volume of water. This flood storage is likely to mitigate the impact of overland flooding on Bexley Aquatic Centre.

Figure F9 shows design flood behaviour for the 1% AEP event and the sub-surface drainage network at this location.

Design flows are presented at several locations along this overland flow path in Table 53.

Table 53: Design flood behaviour along the Bexley Aquatic Centre overland flowpath

Event	Peak Flow (St Georges Rd) (m³/s)		Peak Flow (Downey St) (m³/s)		Peak Flow (Stoney Creek Rd) (m³/s)		Peak Overland Outflow (m³/s)
	Overland	Pipes	Overland	Pipe	Overland	Pipe	D/S Flood Storage
20% AEP	1.52	3.45	2.09	3.45	2.04	6.03	0
10% AEP	1.78	3.47	2.30	3.46	2.42	6.11	0
5% AEP	2.14	3.50	2.70	3.49	3.04	6.18	0
1% AEP	4.16	3.54	4.86	3.57	5.93	6.55	0
0.5% AEP	4.99	3.54	5.71	3.58	7.05	6.69	1.02
PMF	34.71	3.63	38.14	3.60	66.14	8.46	66.74

The capacity of the piped drainage system is exceeded in the 20% AEP event at this location, resulting in overland flows which follow the relatively steep terrain towards Bardwell Creek. Many properties in this overland flowpath are situated on steep terrain, with the ground elevation at the rear of the property substantially lower than street level.

10.2.2. Concrete lined channel between Stoney Creek Road and Preddys Road

Photo 22: Laycock Street, Bexley North

Bardwell Creek is piped under Bexley Golf Course and exits at Laycock Street into a concrete lined channel situated within a relatively steep valley as shown in Photo 22. The concrete lined channel passes within 10 m of residential buildings at this location. Overbank flooding may result in inundation of garages however habitable floor levels are located at a significantly higher elevation. The channel then passes through culverts under Oliver Street, Coveney Street and Preddys Road. Preddys road is overtopped by flooding from the channel in the 1% AEP event however ponding of water due to local catchment runoff occurs in more frequent events, with ponding of water occurring to a depth of approximately 0.4 m in the 20% AEP event.

Due to the steep terrain and complex interaction of fences immediately adjacent to the channel, overbank flows may be confined to the drainage reserve adjacent to the channel in some locations while in other locations overbank flows will enter properties when the channel capacity is exceeded. The resulting flooding may be exacerbated by the blockage of culverts with urban debris, such as occurred in the October 2014 event when a water tank and car entered the channel between Coveney Street and Preddys Road. Several properties were affected by flooding from the channel during this event. The sensitivity of this section of Bardwell Creek to blockage was investigated in Section 9.3.3.

Figure F10 shows the location of this flooding hotspot and design flood depths for the 1% AEP event.

Design flood levels and flows within this section of Bardwell Creek are summarised in Table 54.

Table 54: Design flood behaviour between Stoney Creek Road and Preddys Road

Event	Peak Flood Level (mAHD)	Peak Flood Depth (m)	Peak Flood Level (mAHD)	Peak Flood Depth (m)	Peak Inflow (Laycock Street) (m^3/s)		Peak Outflow (Preddys Road) (m^3/s)	
	Laycock Street Channel		Preddys Road Channel		Culverts	Road	Culvert	Road
20% AEP	25.25	1.96	22.50	3.10	26.47	0.32	29.64	0
10% AEP	25.29	1.99	22.52	3.12	26.64	0.36	29.82	0
5% AEP	25.47	2.17	22.85	3.45	24.81	3.15	28.44	0
1% AEP	26.42	3.12	23.74	4.34	26.31	18.02	32.77	12.49
0.5% AEP	26.48	3.18	23.88	4.48	26.78	22.67	33.27	17.86
PMF	28.28	4.98	26.05	6.65	27.36	226.38	37.02	240.28

It should be noted that the design blockage of 10% applied for the 5% AEP, 1% AEP and 0.5% AEP events results in lower peak culvert flows for the 5% AEP event than the 10% AEP and 20% AEP events. This is considered reasonable at this location due to the higher AEP adjusted debris potential in rarer flood events.

10.2.3. Bexley Road and Veron Road, Bexley

Photo 23: Binnamittalong Gardens

Bexley Road passes over Bardwell Creek at Bexley near Veron Road. The road is not subject to inundation from mainstream flooding at this location up to the 0.5% AEP event. Veron Road is situated just downstream of Bexley Road bridge with many properties backing onto Bardwell Creek. An earth-lined channel starting near the intersection of Kingsland Road South and Bexley Road runs through Binnamittalong Gardens parallel to Bexley Road. This channel drains stormwater from the catchment to the south of Bardwell Creek. The channel begins at the point just downstream of Bexley Road and runs adjacent to 21 Veron Road where it discharges into Bardwell Creek.

Figure F11 shows the location of this flooding hotspot and design flood depths for the 1% AEP event. Peak levels and flows at Bexley Road bridge (Bardwell Creek) and Binnamittalong Gardens are presented in Table 55.

Table 55: Design flood behaviour at Bexley Road (Bardwell Creek) and Binnamittalong Gardens

Event	Peak Level (mAHD)	Peak Depth (m)	Peak Level (mAHD)	Peak Depth (m)	Peak Inflow (Main Channel) (m^3/s)		Peak Inflow (Binnamittalong Gardens) (m^3/s)	
	Main Channel (U/S bridge)		Main Channel (D/S bridge)		Main Channel (bridge)	Over Road	D/S Bexley Road	D/S Veron Road
20% AEP	12.89	2.47	12.75	2.79	40.63	0	7.28	7.38
10% AEP	12.91	2.49	12.78	2.82	41.36	0	7.75	8.22
5% AEP	12.91	2.49	12.79	2.82	40.61	0	8.58	9.11
1% AEP	13.22	2.79	13.09	3.13	53.40	0	10.61	11.29
0.5% AEP	13.40	2.97	13.27	3.31	60.78	0	11.52	12.30
PMF	17.38	6.96	17.24	7.28	295.82	110.40	48.35	91.78

Most houses on Veron Road are located on high ground and are not affected by mainstream flooding above floor level in the 1% AEP event. However due to the steep terrain the backyards of several properties are flooded in the 1% AEP event with the flooded extent reaching the fence line of several properties.

10.2.4. Hillcrest Avenue, Bardwell Valley

A low point exists at the bottom of Hillcrest Avenue, near the levee embankment. Model results and community observations indicate that ponding of water to significant depths occurs behind the levee at the bottom of Hillcrest Avenue. The levee was designed to provide protection up the 20% AEP flood level (Reference 23), however overland flows which exceed the capacity of the drainage system will pond behind the levee which presents a flood risk to residents at 20 Hillcrest Avenue. During flood events the 1% AEP event this levee will be overtopped resulting in inundation of low-lying properties. Inundation of the two lowest properties on each side of Hillcrest Avenue has been observed to occur rapidly when the levee is overtopped. Frequent flooding of properties has been reported at this location, resulting in damage to fences and gardens. During several recent flood events, including the 2014 flood event, 20 Hillcrest Avenue was affected by flooding above floor level.

Flood mechanisms at this location include:

- Ponding of overland flows behind the levee embankment; and
- Overtopping of the levee by flood waters from Bardwell Creek.

Photo 24: Hillcrest Avenue

Figure F12 shows the location of this flooding hotspot and design flood depths for the 1% AEP event.

Peak flood levels and flows in the main channel and at the low point behind the levee are presented in Table 56.

Table 56: Design flood behaviour at Hillcrest Avenue

Event	Peak Level (mAHD)	Peak Depth (m)	Peak Level (mAHD)	Peak Depth (m)	Peak Inflow (m^3/s)			Peak Outflow (m^3/s)
	Main Channel		20 Hillcrest Ave		Main Channel	Overland	Levee	Pipe
20% AEP	10.59	3.79	10.27	0.98	49.81	0.44	0.04	0.71
10% AEP	10.87	4.07	10.66	1.37	51.53	0.46	0.07	0.73
5% AEP	11.12	4.33	10.77	1.48	52.38	0.55	0.08	0.74
1% AEP	11.92	5.12	11.88	2.59	65.13	0.57	3.26	0.87
0.5% AEP	12.21	5.41	12.18	2.89	70.32	0.60	4.25	0.89
PMF	16.01	9.22	15.88	6.59	473.06	1.97	17.91	1.22

Due to the rapid runoff response of the catchment, and the potential for the levee to be breached in rare flood events, it is likely that inundation of properties at the bottom of Hillcrest Avenue is will occur before evacuation is possible. It is noted that the house at 20 Hillcrest Avenue has recently been rebuilt with a habitable floor level at RL 13.65 m as a response to inundation of the ground floor of the property in recent flood events, including the October 2014 and April 2015 events.

11. PRELIMINARY FLOOD PLANNING AREA

11.1. Background

Land use planning is one of the most effective means of minimising flood risk and damages from flooding. The Flood Planning Area (FPA) identifies land that is subject to flood related development controls and the Flood Planning Level (FPL) is the minimum floor level applied to development proposals within the FPA.

The process of defining FPAs and FPLs is somewhat complicated by the variability of flow conditions between mainstream and local overland flow, particularly in urban areas. Traditional approaches that were developed for riverine environments and "mainstream" flow areas generally cannot be applied in steeper urban overland flow areas.

Defining the area of flood affectation due to overland flow (which by its nature includes shallow flow) often involves determining at which point it becomes significant enough to classify as "flooding" rather than just drainage of local runoff. The difference in peak flood level between events of varying magnitude may be minor in areas of overland flow, such that applying the typical freeboard of 0.5 m can result in a FPL much greater than the Probable Maximum Flood (PMF) level.

The FPA should identify properties where future development can potentially result in adverse impacts on flood behaviour in the surrounding area, and areas of high hazard that pose a risk to safety or life. Further to this, the FPL is determined with the purpose to decrease the likelihood of over-floor flooding of buildings and the associated damages.

Further consideration of flood planning areas and levels are typically undertaken as part of the Floodplain Management Study where council decides which approach to adopt for inclusion in their Floodplain Management Plan.

For this study, the approach for defining the FPA was based on identifying cadastral lots where flood affectation is significant enough to warrant planning controls on future development.

11.2. Identification of Flood Control Lots

Flood Tagging is the process where cadastral lots are identified as flood liable. The "tagged" lots will be subject to 10.7 Planning Certificate notification (under NSW Local Government Act) indicating that their properties are subject to flood-related development controls. This simply means that should development of the lots occur, flooding will need to be considered and Council's LEP, DCP and any other relevant flood related policies will apply.

Flood tagging was undertaken using the following process:

- Automated spatial analysis identifying the properties subject to flooding from the modelling results of the flood study;
- Filtering out of properties where the flood affectation is minor, such as very shallow flow;
- "Ground truthing" involving detailed assessment of the flood behaviour at individual lots

to determine the final tagging status.

This process is consistent with that adopted in a number of similar studies throughout the Sydney metropolitan area. Identification of properties subject to flood-related development controls is undertaken by using the 1% AEP model results, with filtering to remove nuisance or non-damaging levels of flow, then applying subsequent ground truthing to determine whether individual properties are tagged or not. For this study, there were no areas where typical mainstream flood techniques (adding freeboard and stretching the results) produced reasonable outcomes. Each of the properties identified were based on overland flow criteria as identified below.

- Automated GIS Tagging: Lots were originally classified as "flood control lots" and therefore within the FPA, if they were affected by the modelled 1% AEP flood extent (after applying filtering). The flood depth map was filtered to remove areas less than 0.15 m deep. Properties were then identified as preliminary "flood control lots" where 10% or more of the property was affected by this filtered flood extent.

Detailed review of individual properties was then undertaken. The considerations applied during this process, and categories assigned to various properties as part of this process, are summarised in Table 57. The final lots identified for flood tagging are shown on Figure D31.

Table 57: Ground truthing classifications for flood control lot identifications process

Classification	Description
Initially tagged in automated GIS analysis. Tag retained.	
A1	Property reviewed and flood tagging confirmed, due to inundation from or proximity to significant flow path
Initially NOT tagged in automated GIS analysis. Tag added.	
B1	Ground levels for part or all of the lot are below the adjacent 1% AEP flood level plus 0.5 m freeboard, for a major flow path or localised depression/sag point.
B2	Adjacent properties are inundated, and the DEM within the lot contains incorrect higher levels or obstructions that were not apparent from site review. Inundation of property is likely to be consistent with adjacent properties.
B3	Site analysis identified a local sag point that was not apparent from the DEM, and therefore the modelling did not reflect likely or potential inundation.
B4	Building footprint occupies a large portion of the lot, and excludes inundation in the modelling. Review confirmed that adjacent flooding would be likely to cause inundation if the building were removed.
B5	Nearby properties identified as tagged, and review confirmed the lot would potentially be inundated via similar mechanisms.
B6	Property downstream of or adjacent to a sag point. Ground truthing identified that there would be a potential overland flow path resulting from flow exceeding the stormwater network capacity, or blockage of kerb inlets, pipes or gutters. Flood risk to adjacent properties could also potentially be exacerbated by blocking flow through the lot, requiring development controls to be applied.
B7	Railway corridor.

Classification	Description
Initially NOT tagged in automated GIS analysis, confirmed by ground truthing.	
C1	Flood depth on or surrounding the property is less than 150 mm. Deemed to be a shallow overland or local drainage flow path, without major risk of exacerbation of flood depth, and therefore not requiring tagging under 10.7 certification process.
C2	Review confirmed that ground levels of the property are greater than the adjacent flood level plus freeboard.
C3	Not flood affected in the 1% AEP and no ground truthing undertaken.
Initially tagged in automated GIS analysis. Tag removed.	
D1	Review found that initial tagging was due to DEM features or processing artefacts that did not reflect the true ground surface, and the inundation criteria for tagging were not met.
D2	Minor flow path adjacent to property reviewed, and judged to be likely to be contained within the road network or stormwater drains, or otherwise easily managed by localised works.
D3	Review found that the flood risk was not severe enough to require development controls through the 10.7 planning certificate process.

12. PUBLIC EXHIBITION

A draft version of this study was placed on Public Exhibition from 27 November 2018 to 7 Jan 2019. Local residents were informed of the public exhibition period and were invited to provide comments on the draft report. Letters were sent to affected residents and landowners, and notifications of the public exhibition period were included in The Leader local newspaper and on the Bayside Council website.

A website was set up (https://www.yoursayrandwick.com.au/BirdsFloodStudy) that included the Draft Flood Study document, an online submission option and a question and answer forum.

A community information session was also held on 11 December 2018 at Rockdale Library.. Council and WMAwater project staff were available to explain the study, present results and answer questions from the community.

A report summarising the public exhibition program, and a compilation of the submissions and Council responses can be found in Appendix G. Generally, the community had concerns regarding the flooding issues within the catchment and how these are to be managed. These issues are mainly concerned with drainage, including the blockage, maintenance and upgrade of the stormwater system. Consideration of potential mitigation of flood issues is part of the next phase – the Floodplain Risk Management Study and Plan.

13. ACKNOWLEDGEMENTS

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- Residents of the catchment;
- Bayside Council;
- NSW Office of Environment and Heritage;
- Sydney Water;
- Bureau of Meteorology; and
- State Emergency Services.

14. GLOSSARY

TERMINOLOGY OF FLOOD RISK

Australian Rainfall and Runoff (ARR, editors Ball et al, 2016) recommends terminology that is not misleading to the public and stakeholders. Therefore the use of terms such as “recurrence interval” and “return period” are no longer recommended as they imply that a given event magnitude is only exceeded at regular intervals such as every 100 years. However, rare events may occur in clusters. For example there are several instances of an event with a 1% chance of occurring within a short period, for example the 1949 and 1950 events at Kempsey. Historically the term Average Recurrence Interval (ARI) has been used.

Frequency Descriptor	EY	AEP (%)	AEP (1 in x)	ARI
Very Frequent	12			
	6	99.75	1.002	0.17
	4	98.17	1.02	0.25
	3	95.02	1.05	0.33
	2	86.47	1.16	0.5
	1	63.21	1.58	1
Frequent	0.69	50	2	1.44
	0.5	39.35	2.54	2
	0.22	20	5	4.48
	0.2	18.13	5.52	5
	0.11	10	10	9.49
Rare	0.05	5	20	20
	0.02	2	50	50
	0.01	1	100	100
Very Rare	0.005	0.5	200	200
	0.002	0.2	500	500
	0.001	0.1	1000	1000
	0.0005	0.05	2000	2000
Extreme	0.0002	0.02	5000	5000
			↓	
			PMP/ PMPDF	

ARR 2016 recommends the use of Annual Exceedance Probability (AEP). Annual Exceedance Probability (AEP) is the probability of an event being equalled or exceeded within a year. AEP may be expressed as either a percentage (%) or 1 in X. Floodplain management typically uses the percentage form of terminology. Therefore a 1% or 1 in 100 AEP event (sometimes referred to as a 100 year ARI), has a 1% chance of being equalled or exceeded in any year. ARI and AEP are often mistaken as being interchangeable for events equal to or more frequent than 10% AEP. The table below describes how they are subtly different.

For events more frequent than 50% AEP, expressing frequency in terms of Annual Exceedance Probability is not meaningful and misleading particularly in areas with strong seasonality. Statistically a 0.5 EY event is not the same as a 50% AEP event, and likewise an event with a 20% AEP is not the same as a 0.2 EY event. For example an event of 0.5 EY is an event which would, on average, occur every two years. A 2 EY event is equivalent to a design event with a 6 month Average Recurrence Interval where there is no seasonality, or an event that is likely to occur twice in one year.

The Probable Maximum Flood is the largest flood that could possibly occur on a catchment. It is related to the Probable Maximum Precipitation (PMP). The PMP has an approximate probability. Due to the conservativeness applied to other factors influencing flooding a PMP does not translate to a PMF of the same AEP. Therefore an AEP is not assigned to the PMF.

This report has adopted the approach recommended by ARR and uses % AEP for all events of 50% AEP or rarer and EY for all events more frequent than this.

GLOSSARY OF TERMS

Annual Exceedance Probability (AEP)	The chance of a flood of a given or larger size occurring in any one year, usually expressed as a percentage. For example, if a peak flood discharge of 500 m^3/s has an AEP of 5%, it means that there is a 5% chance (that is one-in-20 chance) of a 500 m^3/s or larger event occurring in any one year (see ARI).
Australian Height Datum (AHD)	A common national surface level datum approximately corresponding to mean sea level.
Average Annual Damage (AAD)	Depending on its size (or severity), each flood will cause a different amount of flood damage to a flood prone area. AAD is the average damage per year that would occur in a nominated development situation from flooding over a very long period.
catchment	The land area draining through the main stream, as well as tributary streams, to a particular site. It always relates to an area above a specific location.
consent authority	The Council, government agency or person having the function to determine a development application for land use under the EP&A Act. The consent authority is most often the Council, however legislation or an EPI may specify a Minister or public authority (other than a Council), or the Director General of DIPNR, as having the function to determine an application.
development	Is defined in Part 4 of the Environmental Planning and Assessment Act (EP&A Act). **infill development:** refers to the development of vacant blocks of land that are generally surrounded by developed properties and is permissible under the current zoning of the land. Conditions such as minimum floor levels may be imposed on infill development.

	new development: refers to development of a completely different nature to that associated with the former land use. For example, the urban subdivision of an area previously used for rural purposes. New developments involve rezoning and typically require major extensions of existing urban services, such as roads, water supply, sewerage and electric power. **redevelopment:** refers to rebuilding in an area. For example, as urban areas age, it may become necessary to demolish and reconstruct buildings on a relatively large scale. Redevelopment generally does not require either rezoning or major extensions to urban services.
discharge	The rate of flow of water measured in terms of volume per unit time, for example, cubic metres per second (m^3/s). Discharge is different from the speed or velocity of flow, which is a measure of how fast the water is moving for example, metres per second (m/s).
DRAINS	Stormwater Drainage System design and analysis program.
effective warning time	The time available after receiving advice of an impending flood and before the floodwaters prevent appropriate flood response actions being undertaken. The effective warning time is typically used to move farm equipment, move stock, raise furniture, evacuate people and transport their possessions.
emergency management	A range of measures to manage risks to communities and the environment. In the flood context it may include measures to prevent, prepare for, respond to and recover from flooding.
flash flooding	Flooding which is sudden and unexpected. It is often caused by sudden local or nearby heavy rainfall. Often defined as flooding which peaks within six hours of the causative rain.
flood	Relatively high stream flow which overtops the natural or artificial banks in any part of a stream, river, estuary, lake or dam, and/or local overland flooding associated with major drainage before entering a watercourse, and/or coastal inundation resulting from super-elevated sea levels and/or waves overtopping coastline defences excluding tsunami.
flood awareness	Flood awareness is an appreciation of the likely effects of flooding and a knowledge of the relevant flood warning, response and evacuation procedures.
flood education	Flood education seeks to provide information to raise awareness of the flood problem so as to enable individuals to understand how to manage themselves an their property in response to flood warnings and in a flood event. It invokes a state of flood readiness.
flood fringe areas	The remaining area of flood prone land after floodway and flood storage areas have been defined.
flood liable land	Is synonymous with flood prone land (i.e. land susceptible to flooding by the probable maximum flood (PMF) event). Note that the term flood liable land covers the whole of the floodplain, not just that part below the flood planning level (see flood planning area).
floodplain	Area of land which is subject to inundation by floods up to and including the probable maximum flood event, that is, flood prone land.
floodplain risk management options	The measures that might be feasible for the management of a particular area of the floodplain. Preparation of a floodplain risk management plan requires a detailed evaluation of floodplain risk management options.

floodplain risk management plan	A management plan developed in accordance with the principles and guidelines in this manual. Usually includes both written and diagrammetic information describing how particular areas of flood prone land are to be used and managed to achieve defined objectives.
flood plan (local)	A sub-plan of a disaster plan that deals specifically with flooding. They can exist at State, Division and local levels. Local flood plans are prepared under the leadership of the State Emergency Service.
flood planning area	The area of land below the flood planning level and thus subject to flood related development controls. The concept of flood planning area generally supersedes the Aflood liable land@ concept in the 1986 Manual.
Flood Planning Levels (FPLs)	FPL=s are the combinations of flood levels (derived from significant historical flood events or floods of specific AEPs) and freeboards selected for floodplain risk management purposes, as determined in management studies and incorporated in management plans. FPLs supersede the Astandard flood event@ in the 1986 manual.
flood proofing	A combination of measures incorporated in the design, construction and alteration of individual buildings or structures subject to flooding, to reduce or eliminate flood damages.
flood prone land	Is land susceptible to flooding by the Probable Maximum Flood (PMF) event. Flood prone land is synonymous with flood liable land.
flood readiness	Flood readiness is an ability to react within the effective warning time.
flood risk	Potential danger to personal safety and potential damage to property resulting from flooding. The degree of risk varies with circumstances across the full range of floods. Flood risk in this manual is divided into 3 types, existing, future and continuing risks. They are described below. **existing flood risk:** the risk a community is exposed to as a result of its location on the floodplain. **future flood risk:** the risk a community may be exposed to as a result of new development on the floodplain. **continuing flood risk:** the risk a community is exposed to after floodplain risk management measures have been implemented. For a town protected by levees, the continuing flood risk is the consequences of the levees being overtopped. For an area without any floodplain risk management measures, the continuing flood risk is simply the existence of its flood exposure.
flood storage areas	Those parts of the floodplain that are important for the temporary storage of floodwaters during the passage of a flood. The extent and behaviour of flood storage areas may change with flood severity, and loss of flood storage can increase the severity of flood impacts by reducing natural flood attenuation. Hence, it is necessary to investigate a range of flood sizes before defining flood storage areas.
floodway areas	Those areas of the floodplain where a significant discharge of water occurs during floods. They are often aligned with naturally defined channels. Floodways are areas that, even if only partially blocked, would cause a significant redistribution of flood flows, or a significant increase in flood levels.
freeboard	Freeboard provides reasonable certainty that the risk exposure selected in deciding on a particular flood chosen as the basis for the FPL is actually provided. It is a factor of safety typically used in relation to the setting of floor levels, levee crest levels, etc. Freeboard is included in the flood planning level.

habitable room	**in a residential situation:** a living or working area, such as a lounge room, dining room, rumpus room, kitchen, bedroom or workroom. **in an industrial or commercial situation:** an area used for offices or to store valuable possessions susceptible to flood damage in the event of a flood.
hazard	A source of potential harm or a situation with a potential to cause loss. In relation to this manual the hazard is flooding which has the potential to cause damage to the community. Definitions of high and low hazard categories are provided in the Manual.
hydraulics	Term given to the study of water flow in waterways; in particular, the evaluation of flow parameters such as water level and velocity.
hydrograph	A graph which shows how the discharge or stage/flood level at any particular location varies with time during a flood.
hydrology	Term given to the study of the rainfall and runoff process; in particular, the evaluation of peak flows, flow volumes and the derivation of hydrographs for a range of floods.
LiDAR	Surveying method that measures distances via laser.
local overland flooding	Inundation by local runoff rather than overbank discharge from a stream, river, estuary, lake or dam.
local drainage	Are smaller scale problems in urban areas. They are outside the definition of major drainage in this glossary.
mainstream flooding	Inundation of normally dry land occurring when water overflows the natural or artificial banks of a stream, river, estuary, lake or dam.

major drainage	Councils have discretion in determining whether urban drainage problems are associated with major or local drainage. For the purpose of this manual major drainage involves:
	$ the floodplains of original watercourses (which may now be piped, channelised or diverted), or sloping areas where overland flows develop along alternative paths once system capacity is exceeded; and/or
	$ water depths generally in excess of 0.3 m (in the major system design storm as defined in the current version of Australian Rainfall and Runoff). These conditions may result in danger to personal safety and property damage to both premises and vehicles; and/or
	$ major overland flow paths through developed areas outside of defined drainage reserves; and/or
	$ the potential to affect a number of buildings along the major flow path.

mathematical/computer models	The mathematical representation of the physical processes involved in runoff generation and stream flow. These models are often run on computers due to the complexity of the mathematical relationships between runoff, stream flow and the distribution of flows across the floodplain.
minor, moderate and major flooding	Both the State Emergency Service and the Bureau of Meteorology use the following definitions in flood warnings to give a general indication of the types of problems expected with a flood: **minor flooding:** causes inconvenience such as closing of minor roads and the submergence of low level bridges. The lower limit of this class of flooding on the reference gauge is the initial flood level at which landholders and townspeople begin to be flooded.

	moderate flooding: low-lying areas are inundated requiring removal of stock and/or evacuation of some houses. Main traffic routes may be covered. **major flooding:** appreciable urban areas are flooded and/or extensive rural areas are flooded. Properties, villages and towns can be isolated.
modification measures	Measures that modify either the flood, the property or the response to flooding. Examples are indicated in Table 2.1 with further discussion in the Manual.
peak discharge	The maximum discharge occurring during a flood event.
Probable Maximum Flood (PMF)	The PMF is the largest flood that could conceivably occur at a particular location, usually estimated from probable maximum precipitation, and where applicable, snow melt, coupled with the worst flood producing catchment conditions. Generally, it is not physically or economically possible to provide complete protection against this event. The PMF defines the extent of flood prone land, that is, the floodplain. The extent, nature and potential consequences of flooding associated with a range of events rarer than the flood used for designing mitigation works and controlling development, up to and including the PMF event should be addressed in a floodplain risk management study.
Probable Maximum Precipitation (PMP)	The PMP is the greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends (World Meteorological Organisation, 1986). It is the primary input to PMF estimation.
probability	A statistical measure of the expected chance of flooding (see AEP).
RAFTS	Runoff routing model for hydrologic and hydraulic analysis of storm water drainage and conveyance systems.
risk	Chance of something happening that will have an impact. It is measured in terms of consequences and likelihood. In the context of the manual it is the likelihood of consequences arising from the interaction of floods, communities and the environment.
RORB	General runoff and streamflow routing program used to calculate flood hydrographs from rainfall and other channel inputs.
runoff	The amount of rainfall which actually ends up as streamflow, also known as rainfall excess.
SOBEK	Integrated 1D/2D modelling suite for flood modelling, flood forecasting and optimisation of drainage systems.
stage	Equivalent to water level. Both are measured with reference to a specified datum.
stage hydrograph	A graph that shows how the water level at a particular location changes with time during a flood. It must be referenced to a particular datum.
TUFLOW	One-dimensional (1D) and two-dimensional (2D) flood and tide simulation software (hydraulic model).
survey plan	A plan prepared by a registered surveyor.
water surface profile	A graph showing the flood stage at any given location along a watercourse at a particular time.

15. REFERENCES

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Figures

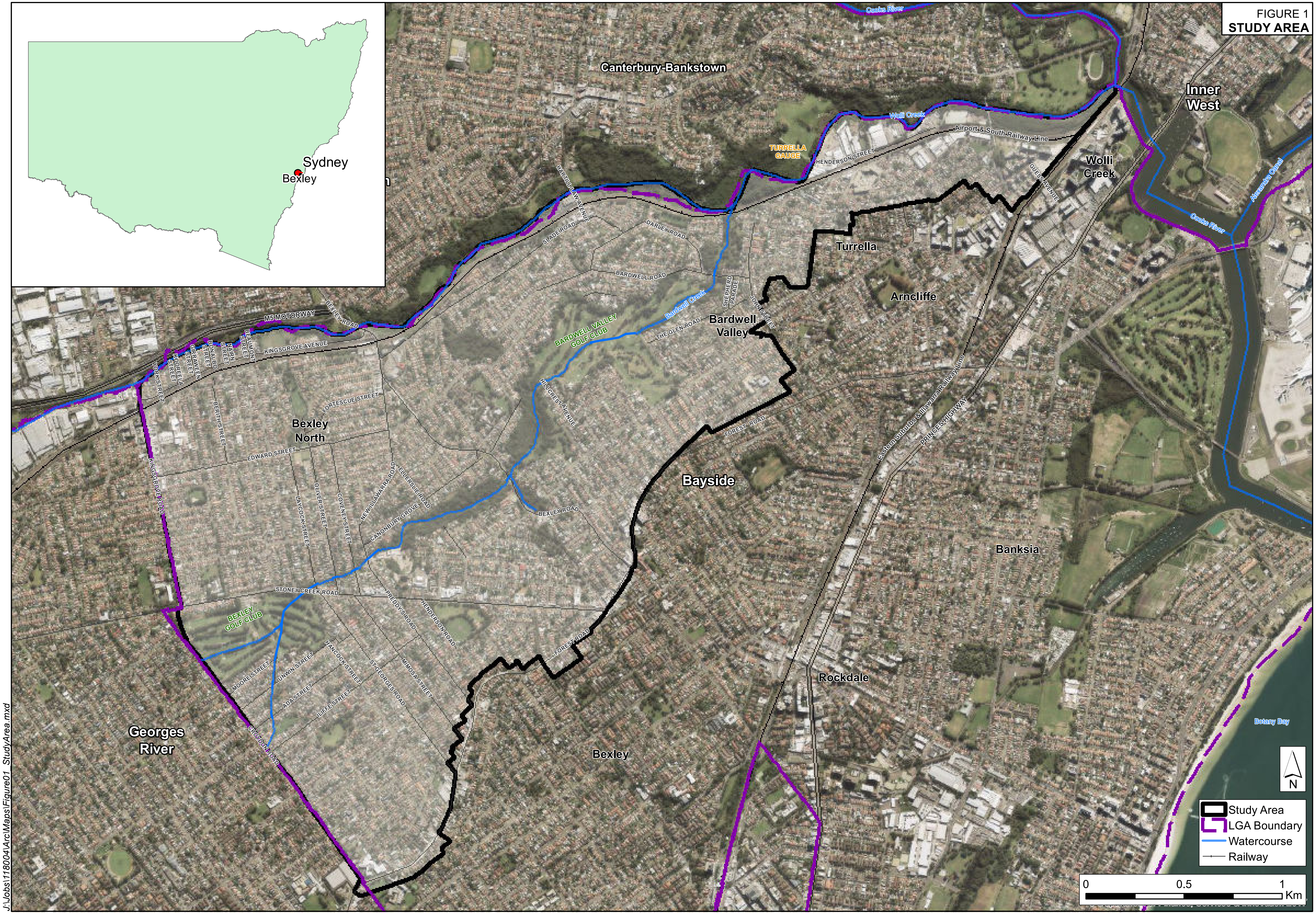

FIGURE 1
STUDY AREA

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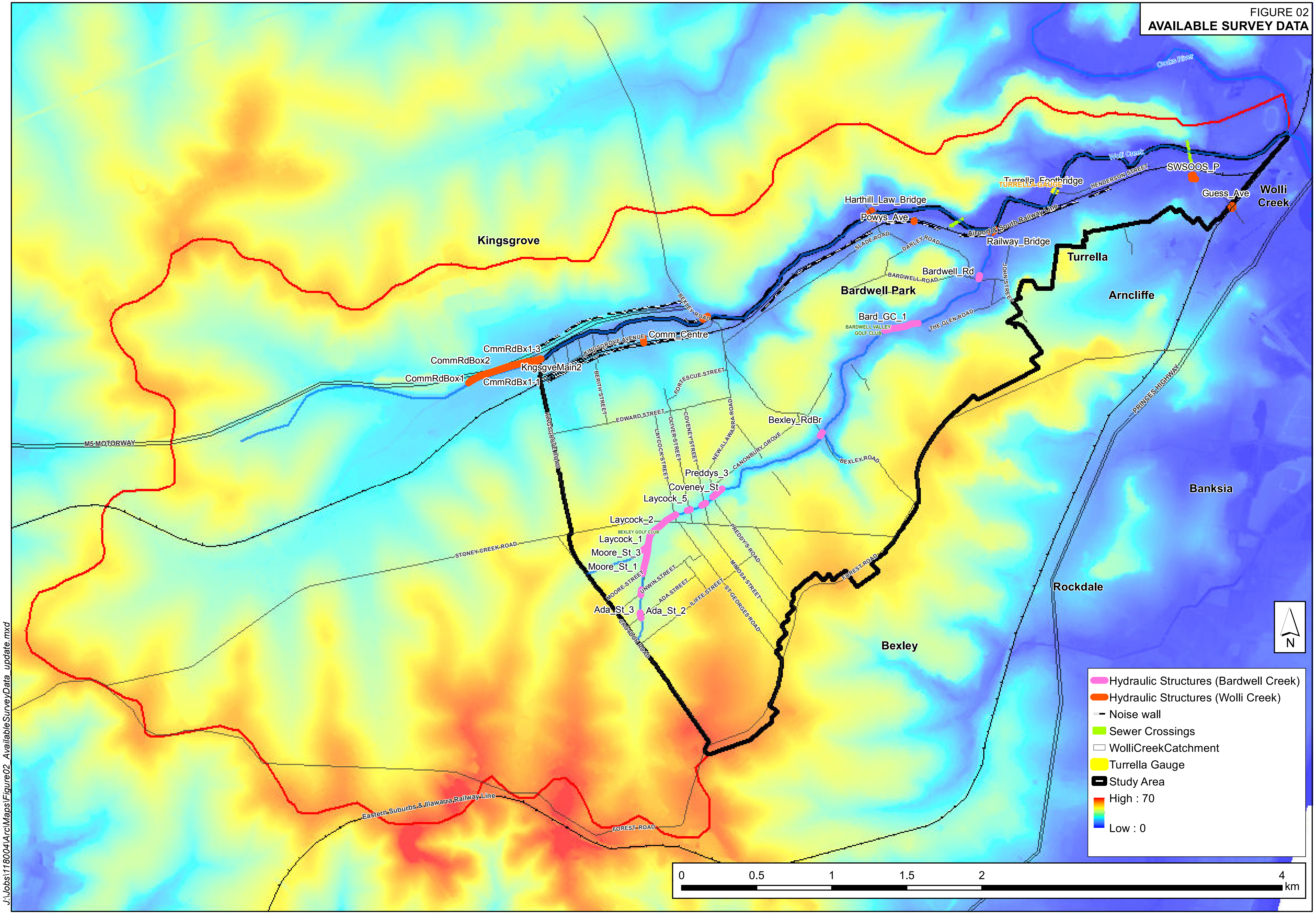

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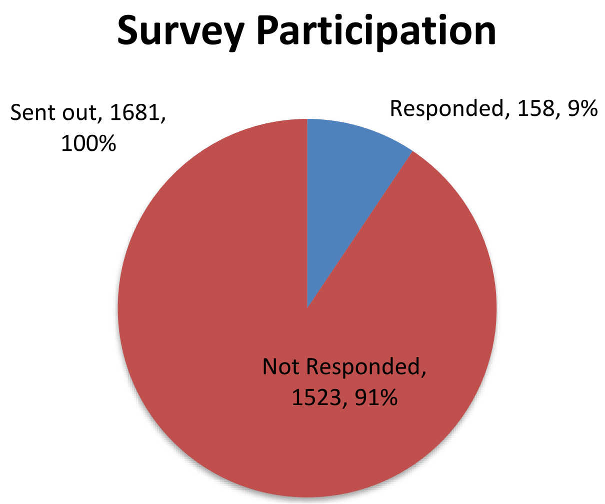
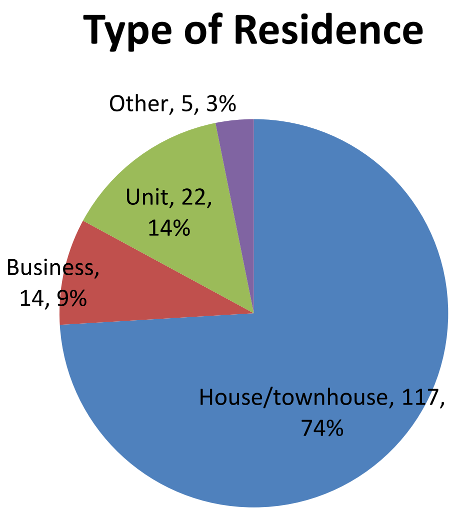
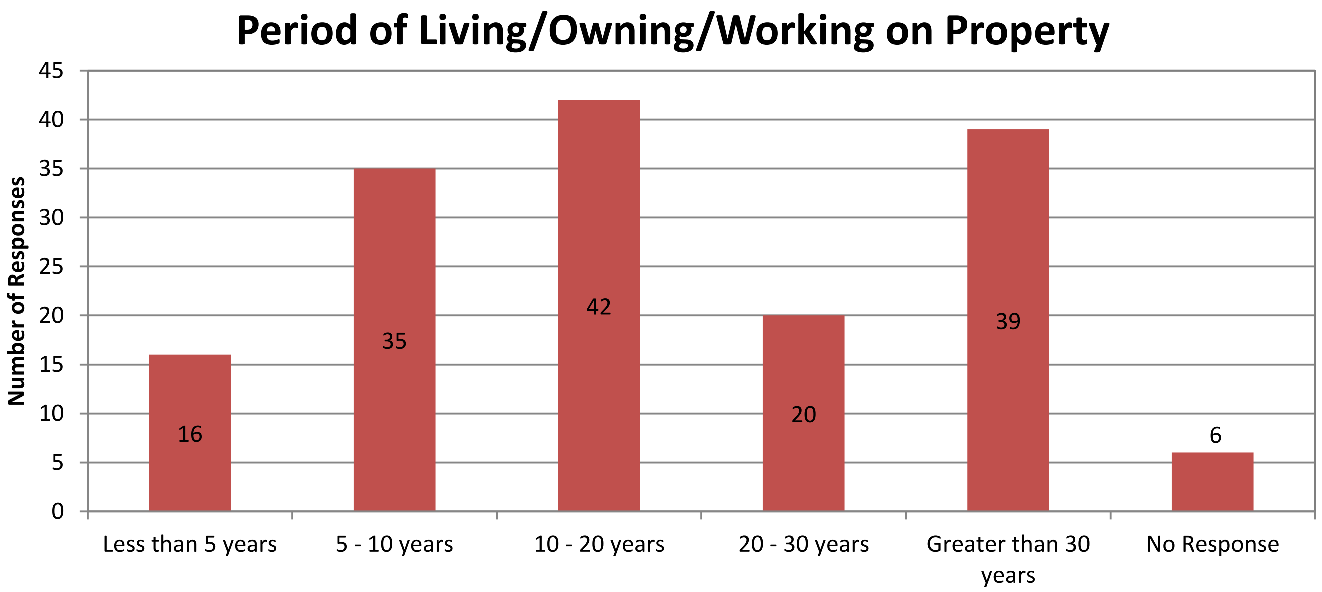
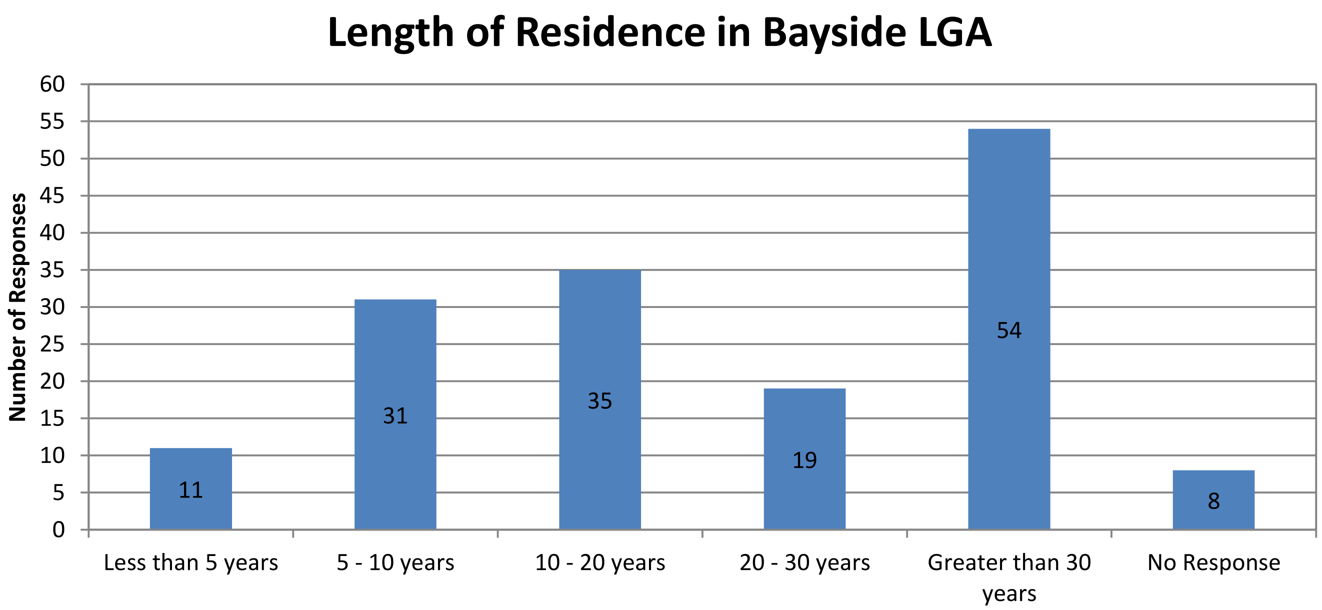
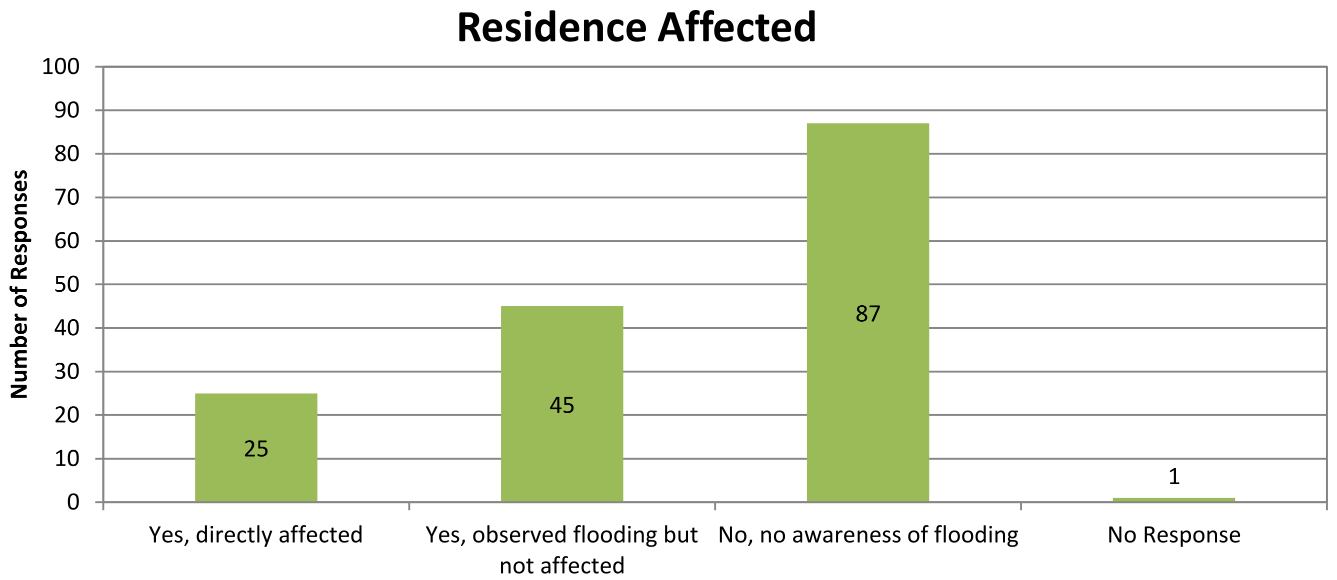
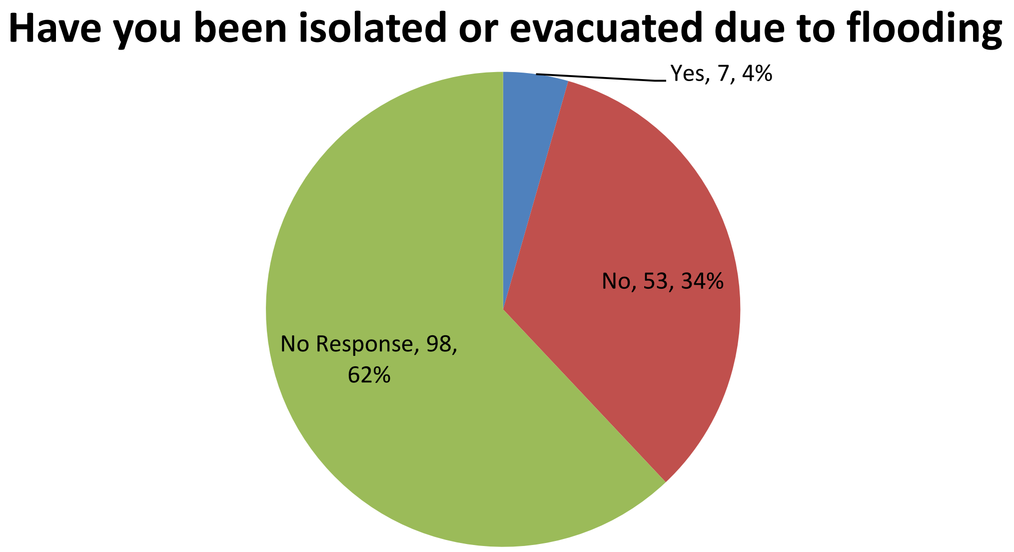

Survey Participation
Sent out, 1681, 100%
Responded, 158, 9%
Not Responded, 1523, 91%

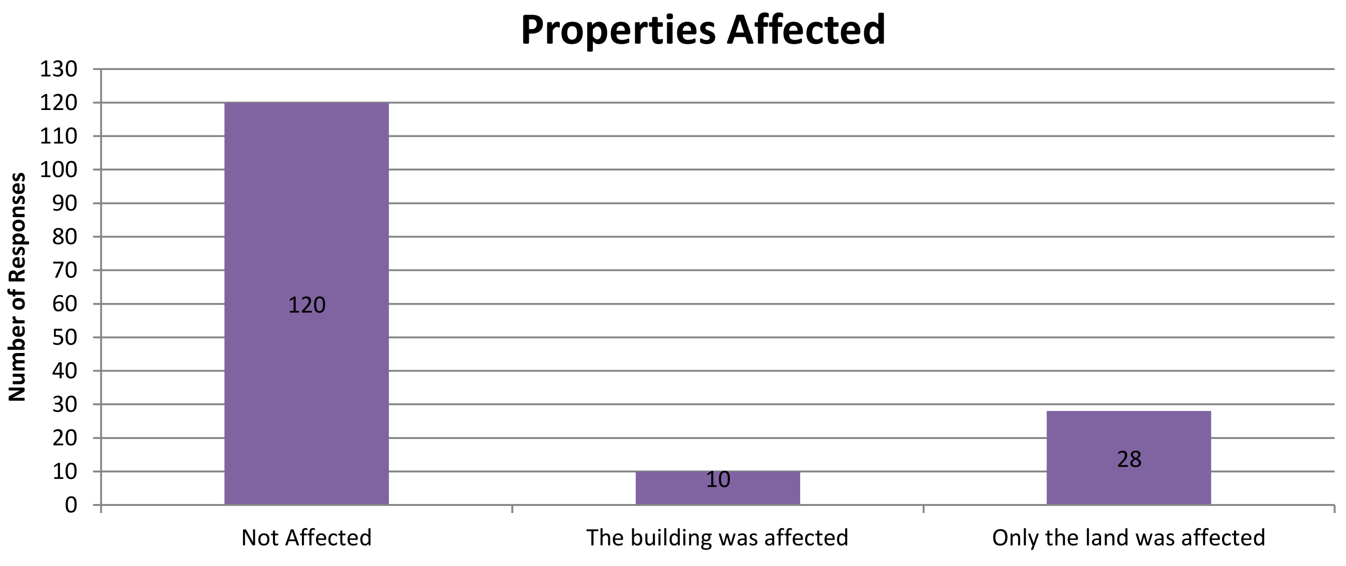

Type of Residence
Other, 5, 3%
Unit, 22, 14%
Business, 14, 9%
House/townhouse, 117, 74%

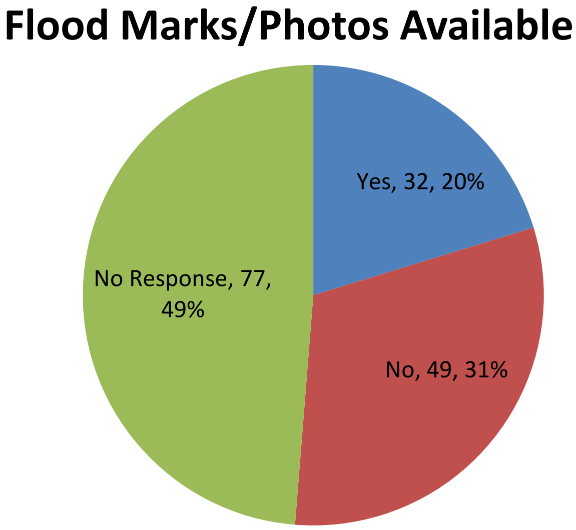

Period of Living/Owning/Working on Property
Number of Responses
45
40
35
30
25
20
15
10
5
0
16
35
42
20
39
6
Less than 5 years
5 - 10 years
10 - 20 years
20 - 30 years
Greater than 30 years
No Response

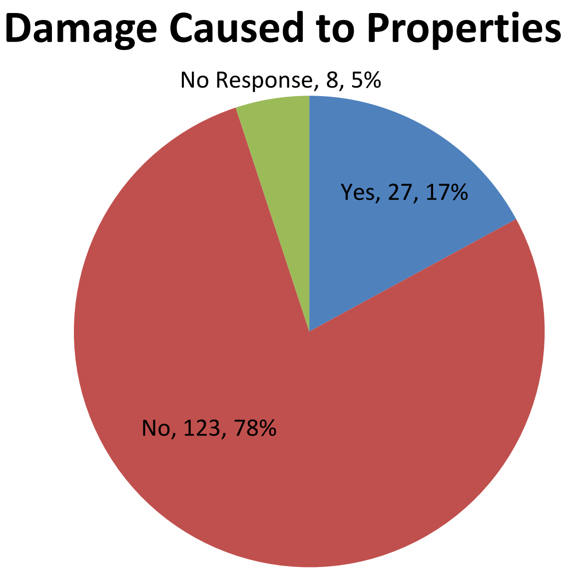

Length of Residence in Bayside LGA
Number of Responses
60
55
50
45
40
35
30
25
20
15
10
5
0
11
31
35
19
54
8
Less than 5 years
5 - 10 years
10 - 20 years
20 - 30 years
Greater than 30 years
No Response


Residence Affected
Number of Responses
100
90
80
70
60
50
40
30
20
10
0
25
45
87
1
Yes, directly affected
Yes, observed flooding but not affected
No, no awareness of flooding
No Response


Have you been isolated or evacuated due to flooding
Yes, 7, 4%
No, 53, 34%
No Response, 98, 62%


Properties Affected
Number of Responses
130
120
110
100
90
80
70
60
50
40
30
20
10
0
120
10
28
Not Affected
The building was affected
Only the land was affected


Flood Marks/Photos Available
Yes, 32, 20%
No, 49, 31%
No Response, 77, 49%


Damage Caused to Properties
No Response, 8, 5%
Yes, 27, 17%
No, 123, 78%

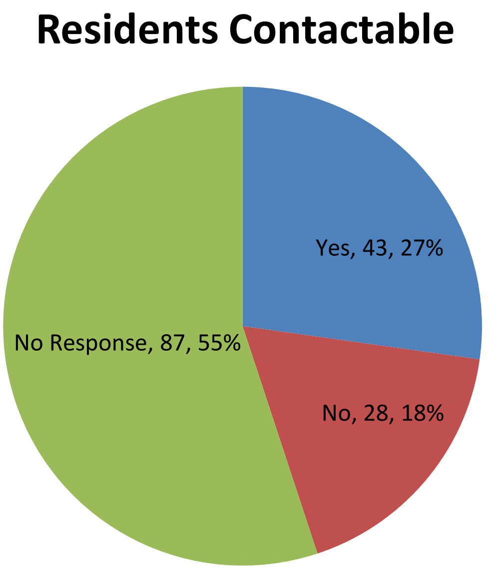
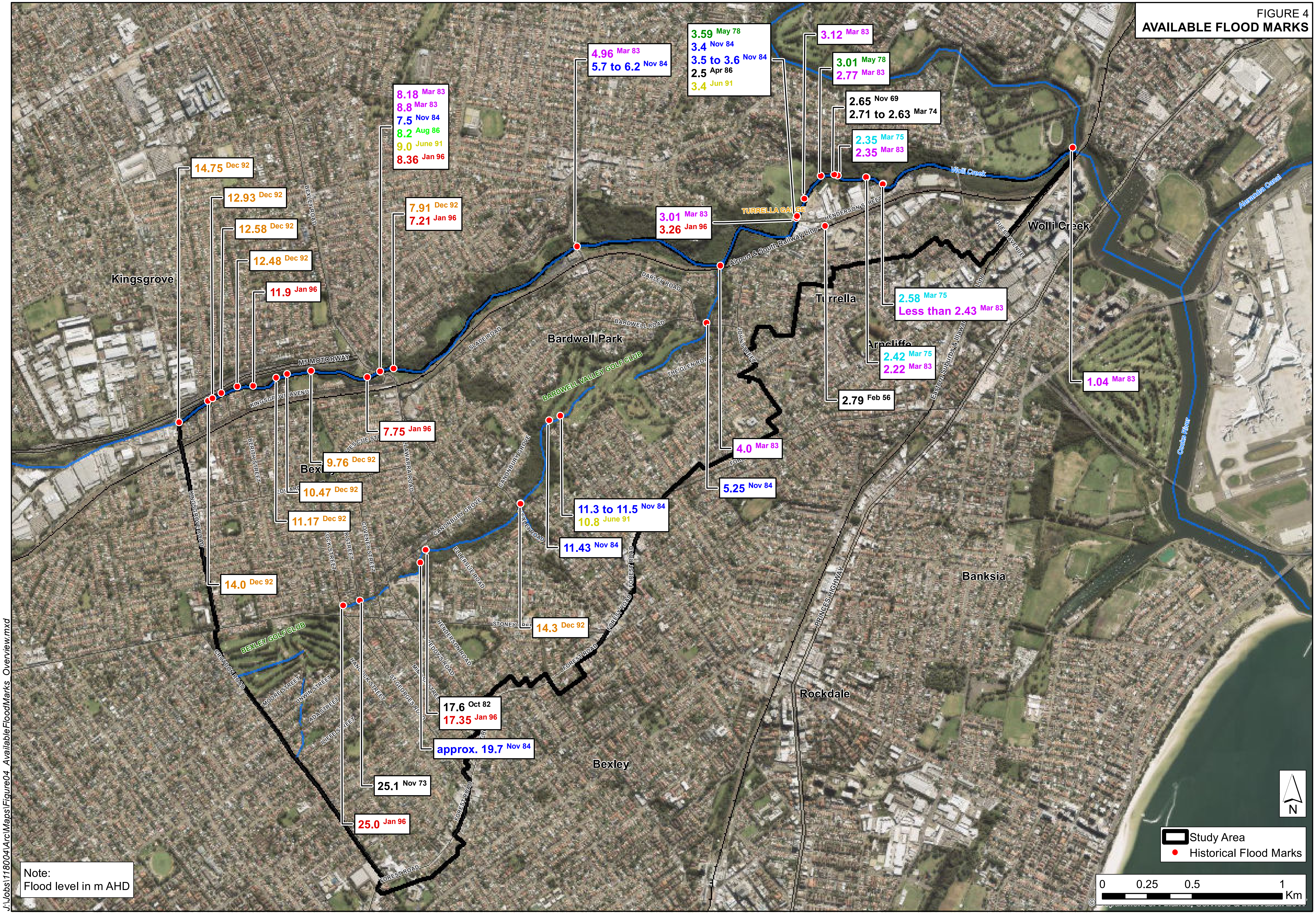

Residents Contactable
Yes, 43, 27%
No Response, 87, 55%
No, 28, 18%

FIGURE 4
AVAILABLE FLOOD MARKS



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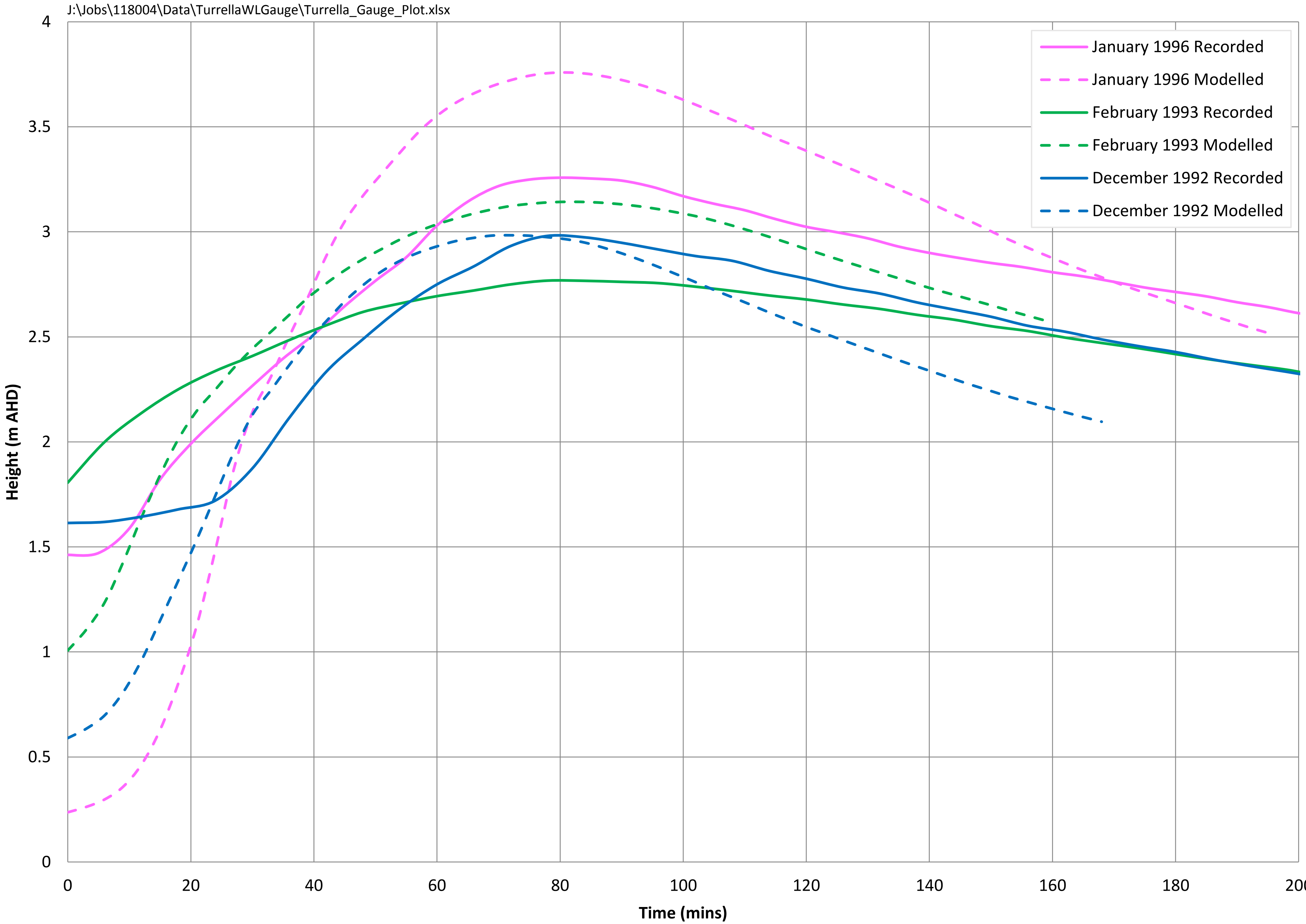
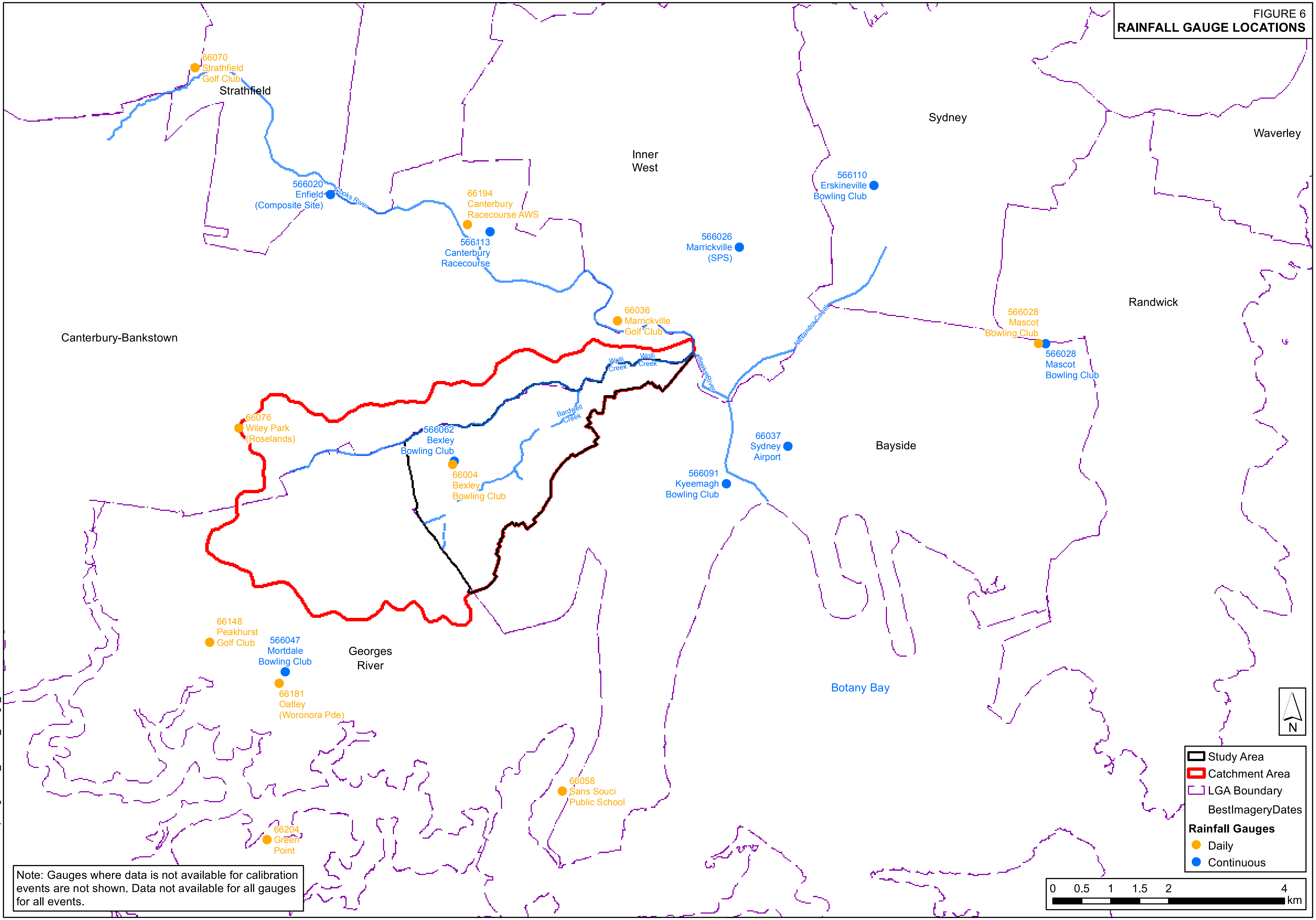


FIGURE C5
FLOOD LEVEL HYDROGRAPH
HENDERSON ROAD

FIGURE 6
RAINFALL GAUGE LOCATIONS



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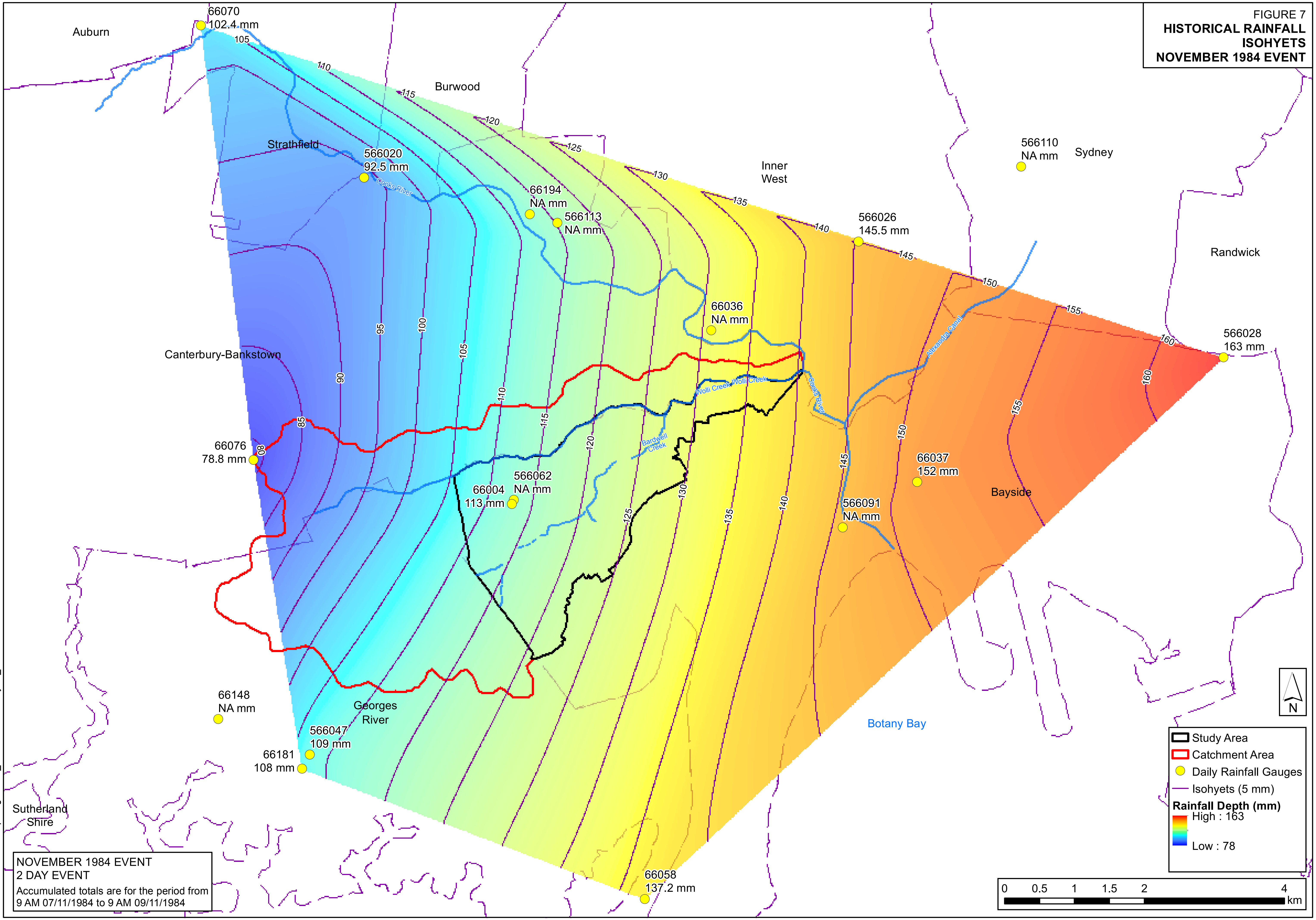
FIGURE 7
HISTORICAL RAINFALL ISOHYETS
NOVEMBER 1984 EVENT
Auburn
Burwood
Strathfield
Inner West
Sydney
Randwick
Canterbury-Bankstown
Bayside
Georges River
Botany Bay
Sutherland Shire
66070
102.4 mm
566020
92.5 mm
66194
NA mm
566113
NA mm
566110
NA mm
566026
145.5 mm
66036
NA mm
566028
163 mm
66076
78.8 mm
566062
NA mm
66004
113 mm
66037
152 mm
566091
NA mm
66148
NA mm
566047
109 mm
66181
108 mm
66058
137.2 mm
Cooks River
Wolli Creek
Bardwell Creek
Alexandra Canal
N
Study Area
Catchment Area
Daily Rainfall Gauges
Isohyets (5 mm)
Rainfall Depth (mm)
High : 163
Low : 78
0
0.5
1
1.5
2
4
km
NOVEMBER 1984 EVENT
2 DAY EVENT
Accumulated totals are for the period from
9 AM 07/11/1984 to 9 AM 09/11/1984
J:\Jobs\118004\ArcMaps\FigureF07_HistoricalRainIsohyets_Nov84.mxd

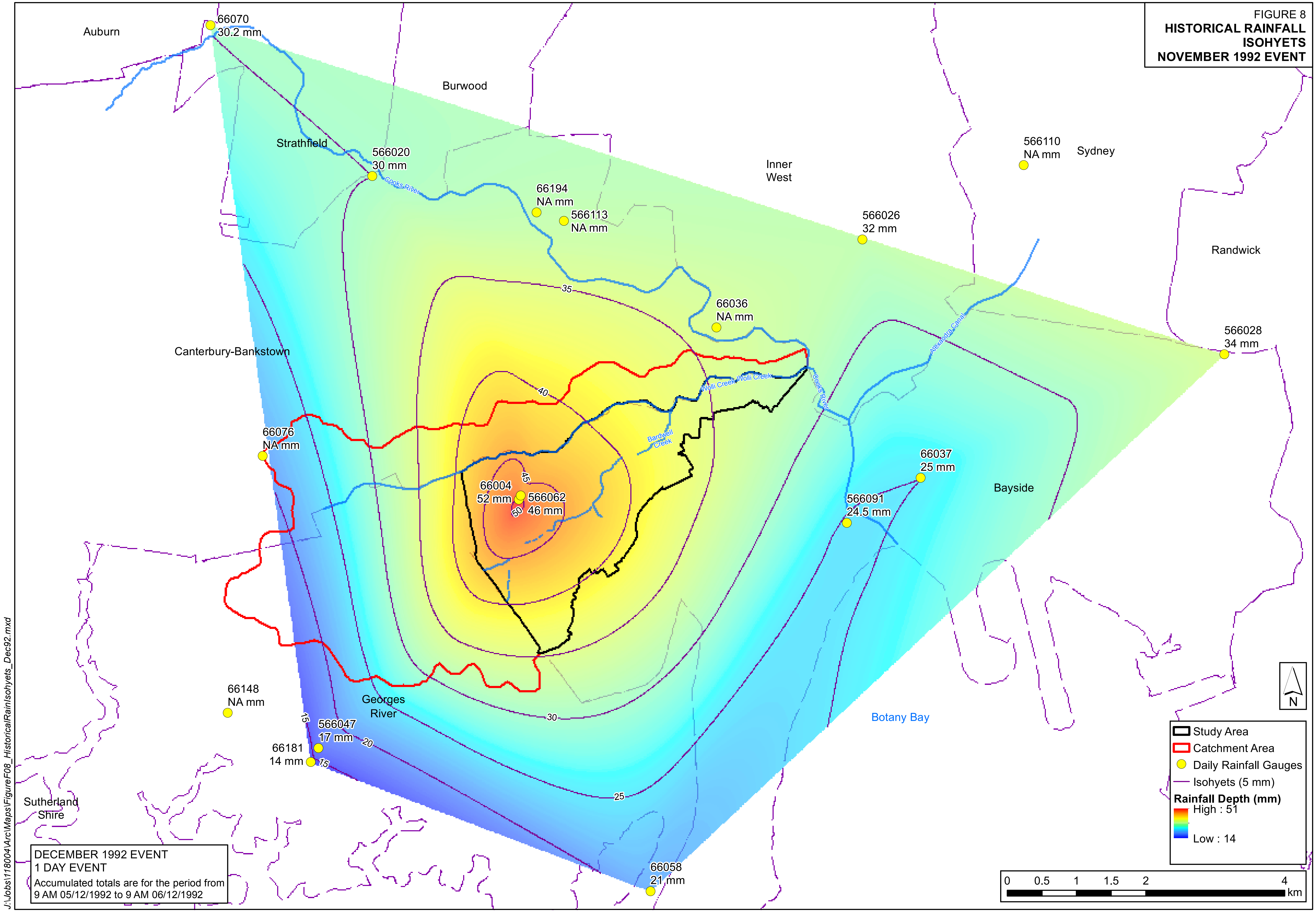

FIGURE 8
HISTORICAL RAINFALL ISOHYETS
NOVEMBER 1992 EVENT
Auburn
66070
30.2 mm
Burwood
Strathfield
566020
30 mm
Cooks River
66194
NA mm
566113
NA mm
Inner West
566110
NA mm
Sydney
566026
32 mm
Randwick
35
66036
NA mm
566028
34 mm
Canterbury-Bankstown
40
Wolli Creek
Alexandra Canal
Bardwell Creek
66076
NA mm
45
66004
52 mm
566062
46 mm
50
66037
25 mm
566091
24.5 mm
Bayside
30
Georges River
66148
NA mm
15
566047
17 mm
20
66181
14 mm
Botany Bay
25
Sutherland Shire
66058
21 mm
DECEMBER 1992 EVENT
1 DAY EVENT
Accumulated totals are for the period from 9 AM 05/12/1992 to 9 AM 06/12/1992
Study Area
Catchment Area
Daily Rainfall Gauges
Isohyets (5 mm)
Rainfall Depth (mm)
High : 51
Low : 14
0 0.5 1 1.5 2 4 km
N
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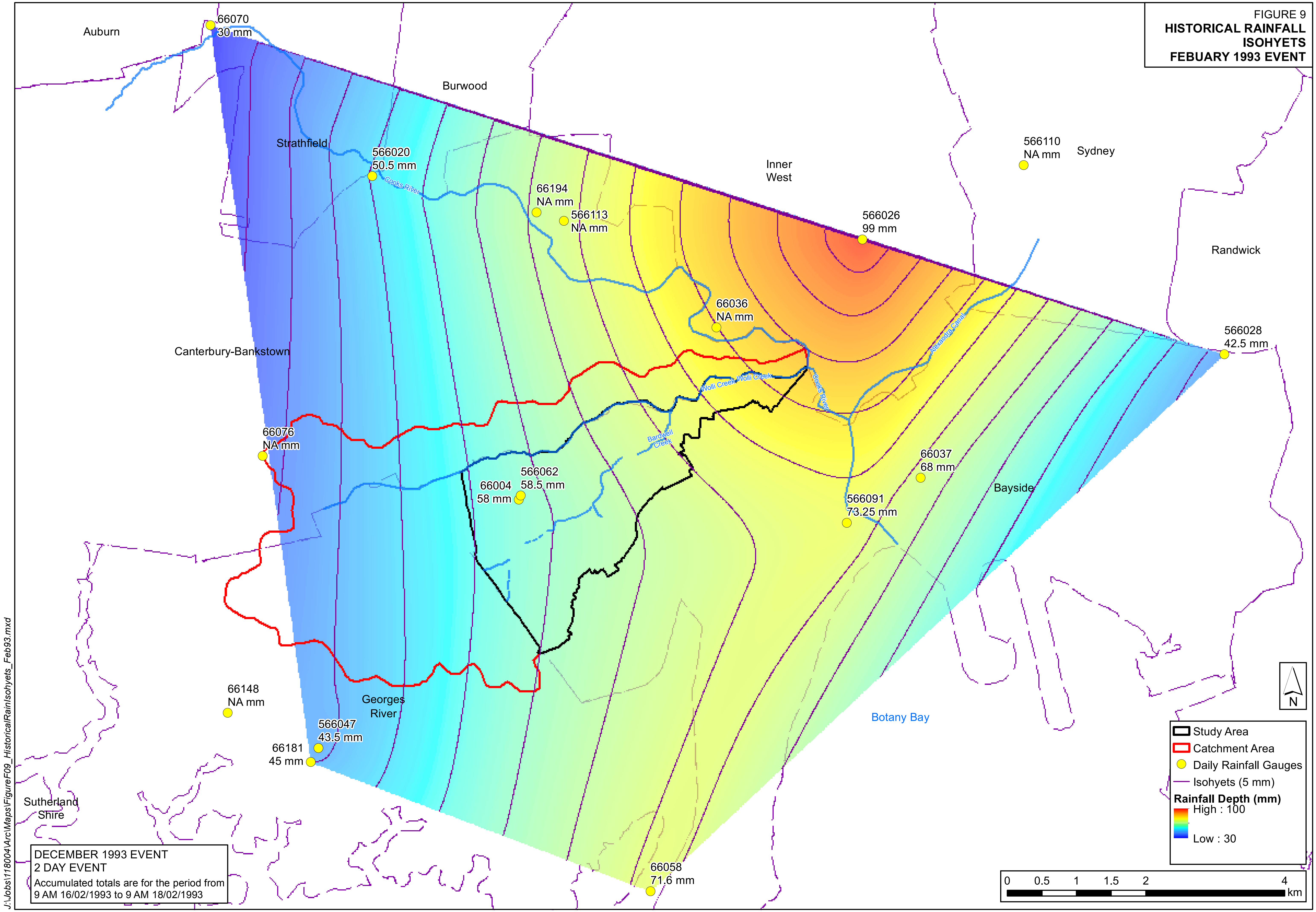


FIGURE 9
HISTORICAL RAINFALL ISOHYETS
FEBUARY 1993 EVENT
Auburn
66070
30 mm
Burwood
Strathfield
566020
50.5 mm
Cooks River
66194
NA mm
566113
NA mm
Inner West
566110
NA mm
Sydney
566026
99 mm
Randwick
66036
NA mm
Alexandra Canal
566028
42.5 mm
Canterbury-Bankstown
Wolli Creek
Cooks River
66076
NA mm
Bardwell Creek
566062
58.5 mm
66004
58 mm
66037
68 mm
Bayside
566091
73.25 mm
66148
NA mm
Georges River
566047
43.5 mm
66181
45 mm
Botany Bay
Sutherland Shire
66058
71.6 mm
N
Study Area
Catchment Area
Daily Rainfall Gauges
Isohyets (5 mm)
Rainfall Depth (mm)
High : 100
Low : 30
0
0.5
1
1.5
2
4
km
DECEMBER 1993 EVENT
2 DAY EVENT
Accumulated totals are for the period from 9 AM 16/02/1993 to 9 AM 18/02/1993
J:\Jobs\118004\ArcMaps\FigureF09_HistoricalRainIsohyets_Feb93.mxd

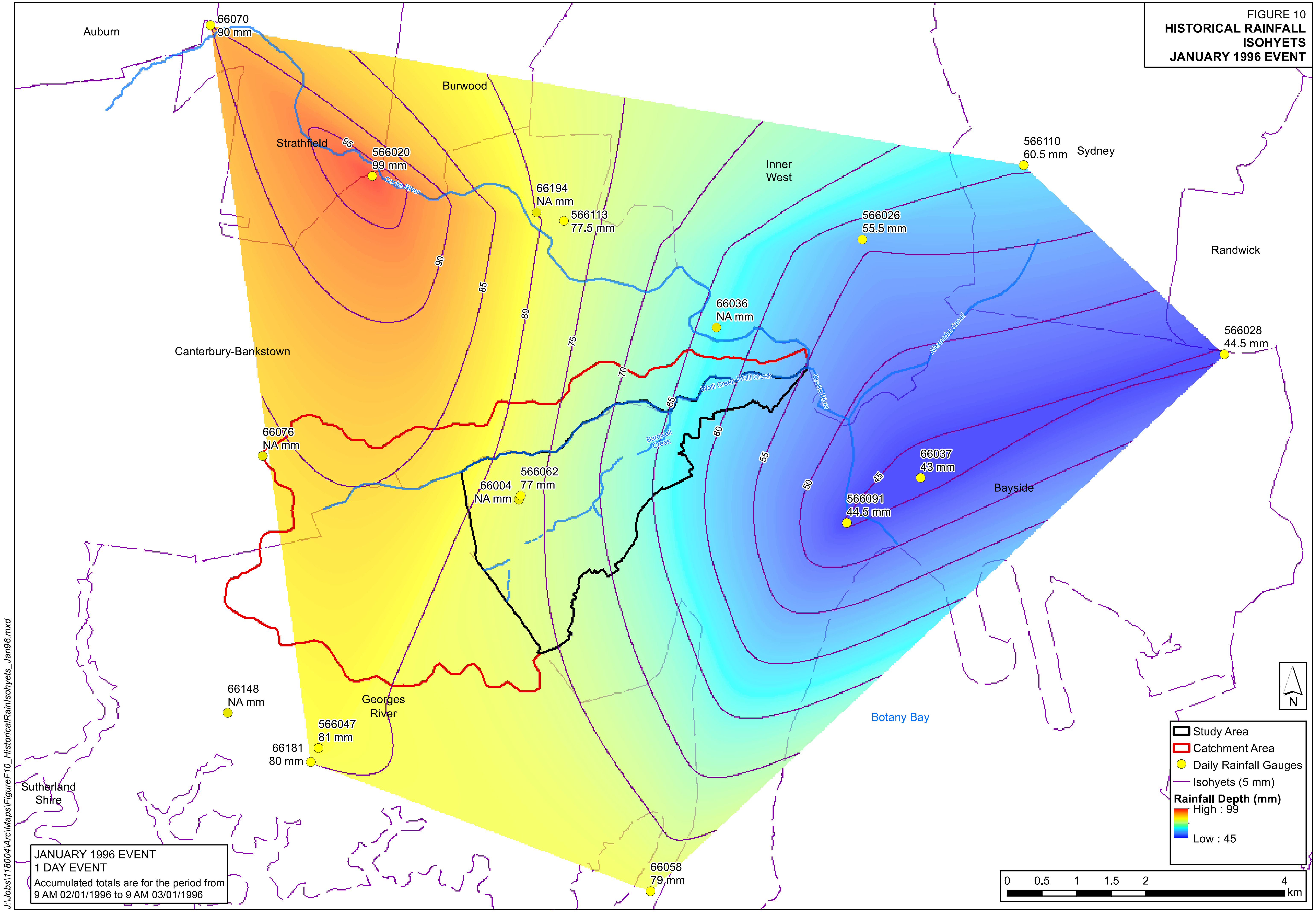


FIGURE 10
HISTORICAL RAINFALL ISOHYETS
JANUARY 1996 EVENT
Auburn
Burwood
Strathfield
Inner West
Sydney
Randwick
Canterbury-Bankstown
Bayside
Georges River
Sutherland Shire
Botany Bay
Cooks River
Wolli Creek
Bardwell Creek
Alexandra Canal
66070 90 mm
566020 99 mm
66194 NA mm
566113 77.5 mm
566110 60.5 mm
566026 55.5 mm
66036 NA mm
566028 44.5 mm
66076 NA mm
566062 77 mm
66004 NA mm
66037 43 mm
566091 44.5 mm
66148 NA mm
566047 81 mm
66181 80 mm
66058 79 mm
95
90
85
80
75
70
65
60
55
50
45
N
Study Area
Catchment Area
Daily Rainfall Gauges
Isohyets (5 mm)
Rainfall Depth (mm)
High : 99
Low : 45
0 0.5 1 1.5 2 4 km
JANUARY 1996 EVENT
1 DAY EVENT
Accumulated totals are for the period from 9 AM 02/01/1996 to 9 AM 03/01/1996
J:\Jobs\118004\ArcMaps\FigureF10_HistoricalRainIsohyets_Jan96.mxd

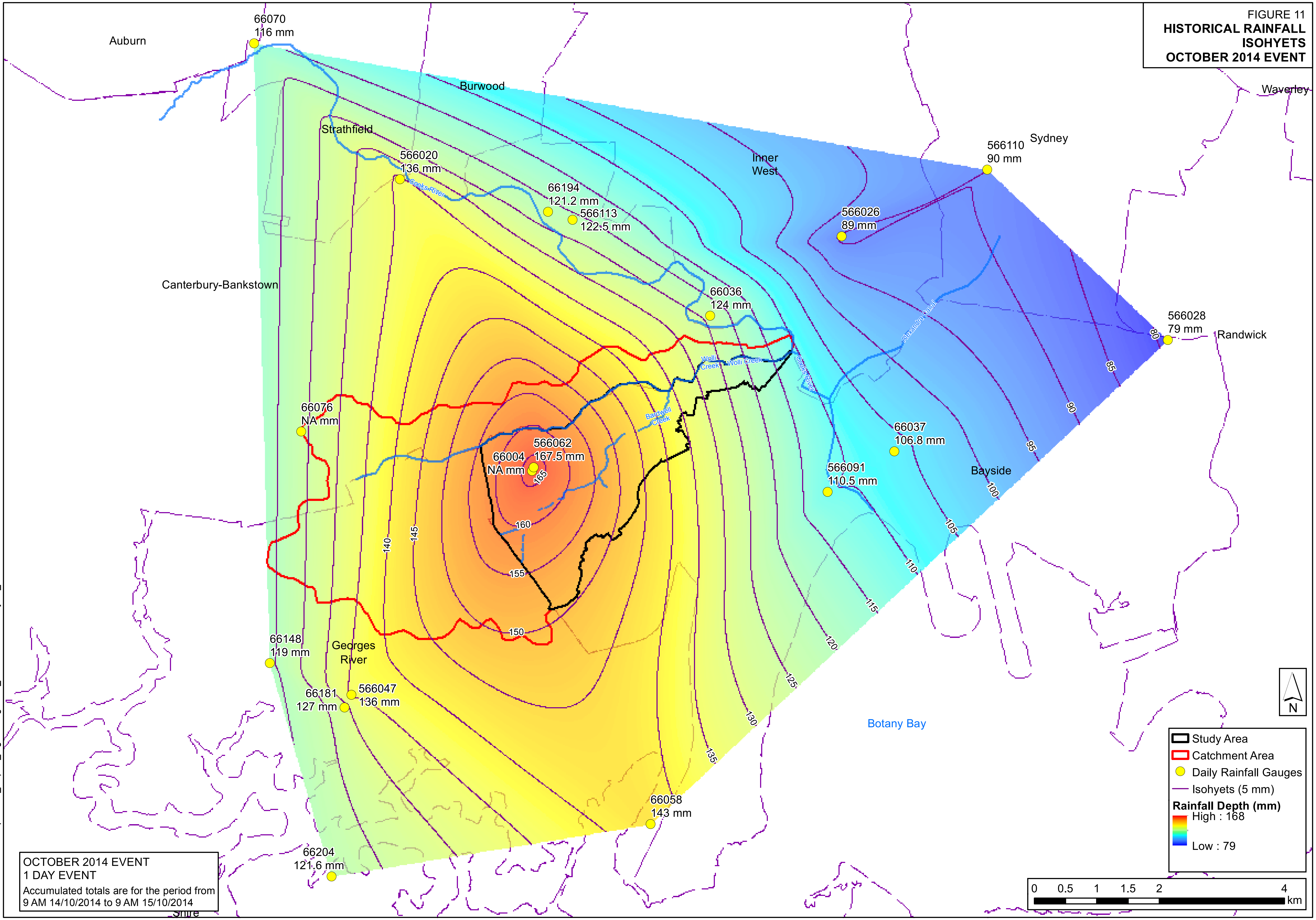


FIGURE 11
HISTORICAL RAINFALL ISOHYETS
OCTOBER 2014 EVENT
Auburn
Burwood
Strathfield
Inner West
Sydney
Waverley
Canterbury-Bankstown
Randwick
Bayside
Georges River
Botany Bay
Shire
66070 116 mm
566020 136 mm
66194 121.2 mm
566113 122.5 mm
566026 89 mm
566110 90 mm
66036 124 mm
566028 79 mm
66076 NA mm
66004 NA mm
566062 167.5 mm
66037 106.8 mm
566091 110.5 mm
66148 119 mm
66181 127 mm
566047 136 mm
66058 143 mm
66204 121.6 mm
Cooks River
Wolli Creek
Bardwell Creek
Alexandra Canal
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
155
160
165
N
Study Area
Catchment Area
Daily Rainfall Gauges
Isohyets (5 mm)
Rainfall Depth (mm)
High : 168
Low : 79
0 0.5 1 1.5 2 4 km
OCTOBER 2014 EVENT
1 DAY EVENT
Accumulated totals are for the period from 9 AM 14/10/2014 to 9 AM 15/10/2014
J:\Jobs\118004\ArcMaps\Main_Report_Figures\Figure11_HistoricalRainIsohyets_Oct14.mxd

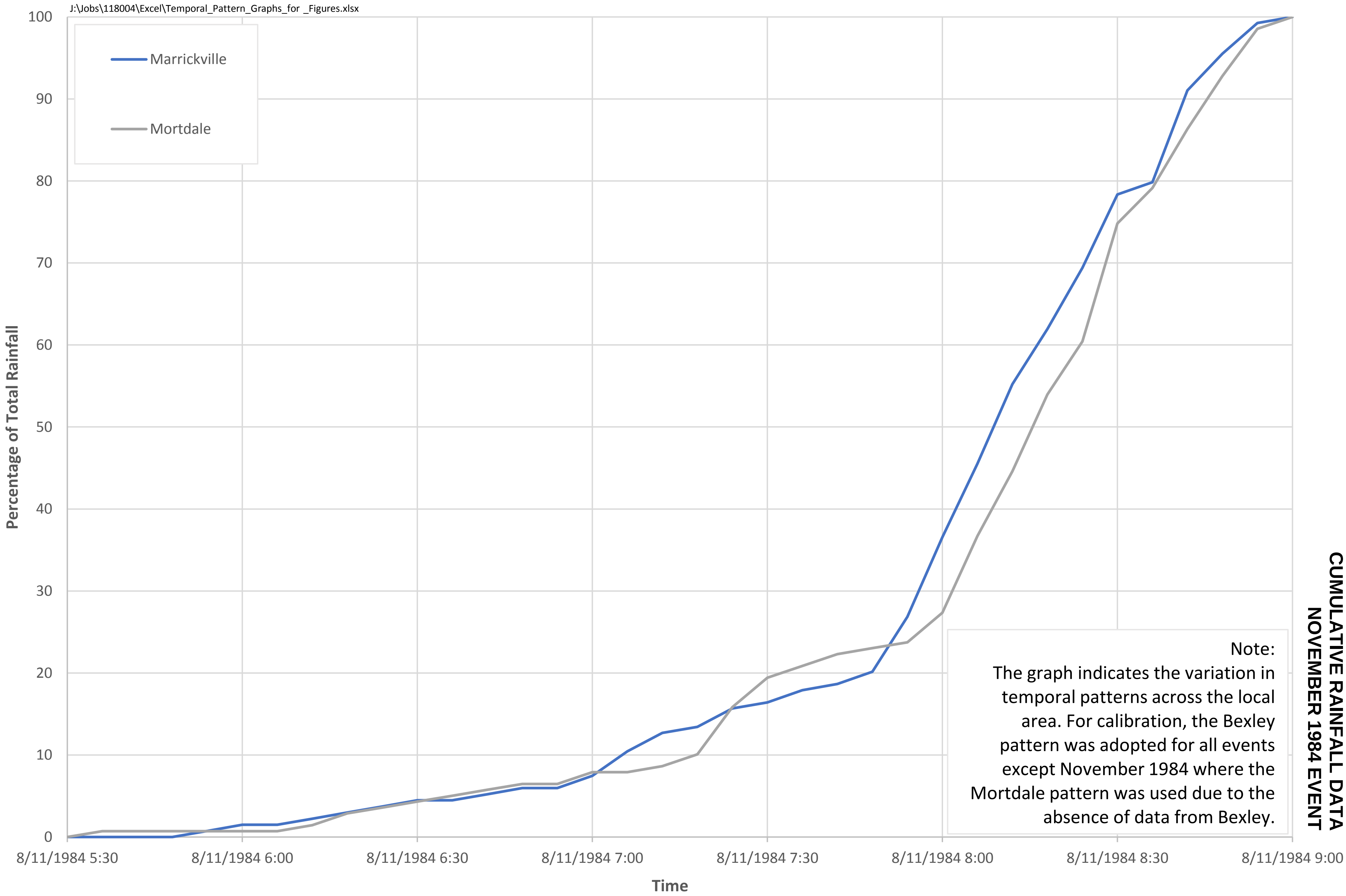


FIGURE 12
CUMULATIVE RAINFALL DATA
NOVEMBER 1984 EVENT

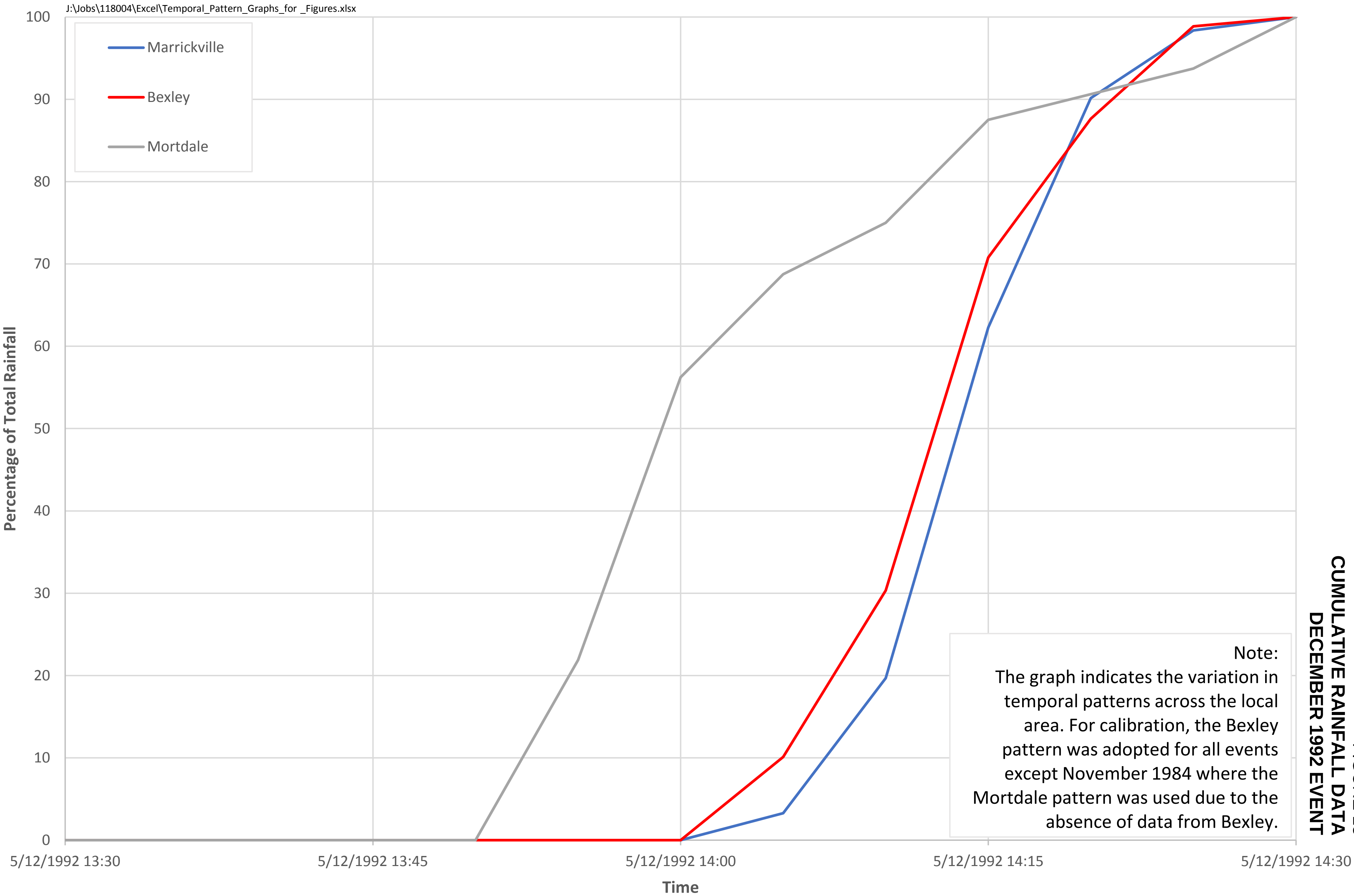


FIGURE 13
CUMULATIVE RAINFALL DATA
DECEMBER 1992 EVENT

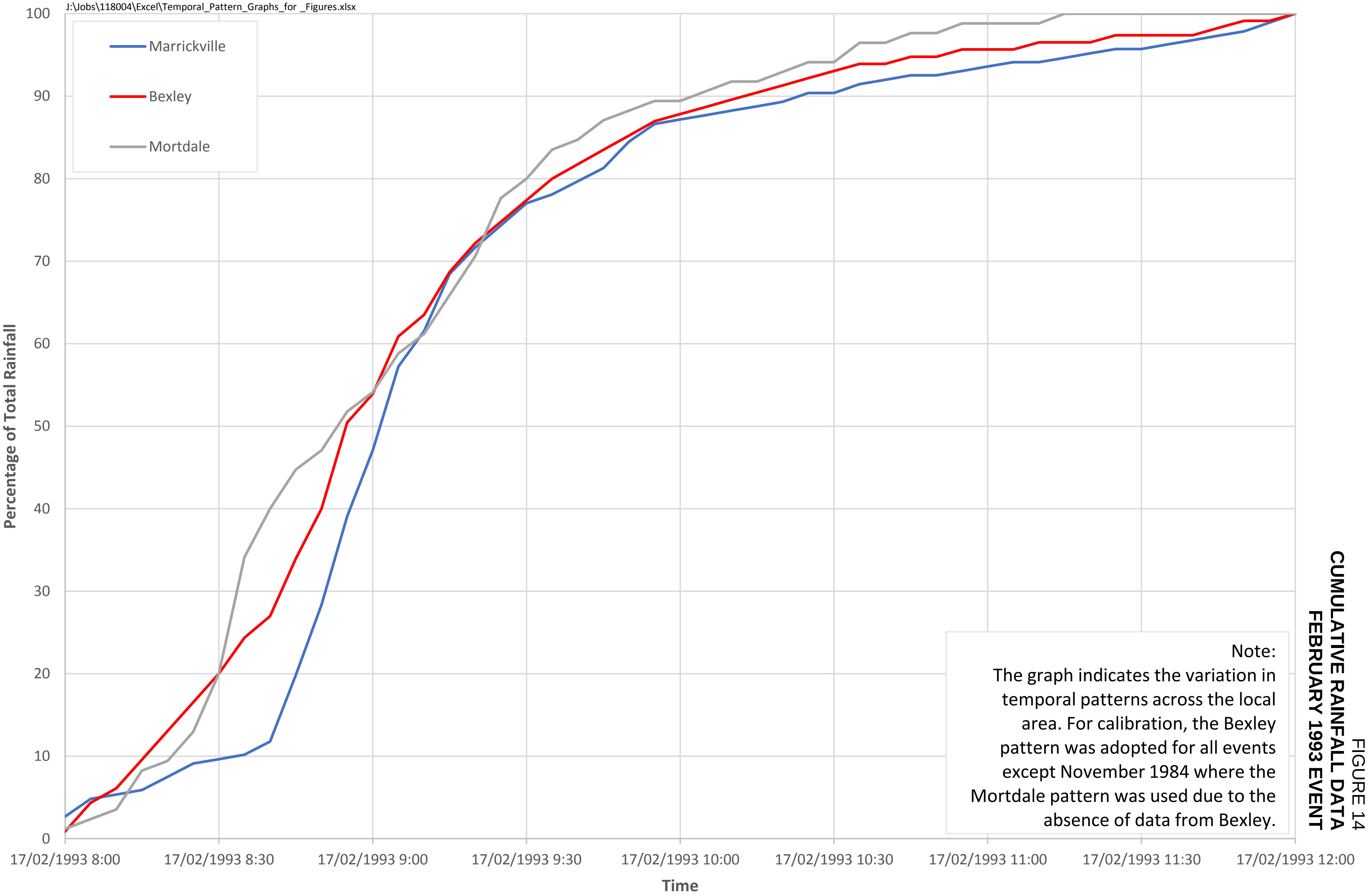


FIGURE 14

CUMULATIVE RAINFALL DATA

FEBRUARY 1993 EVENT

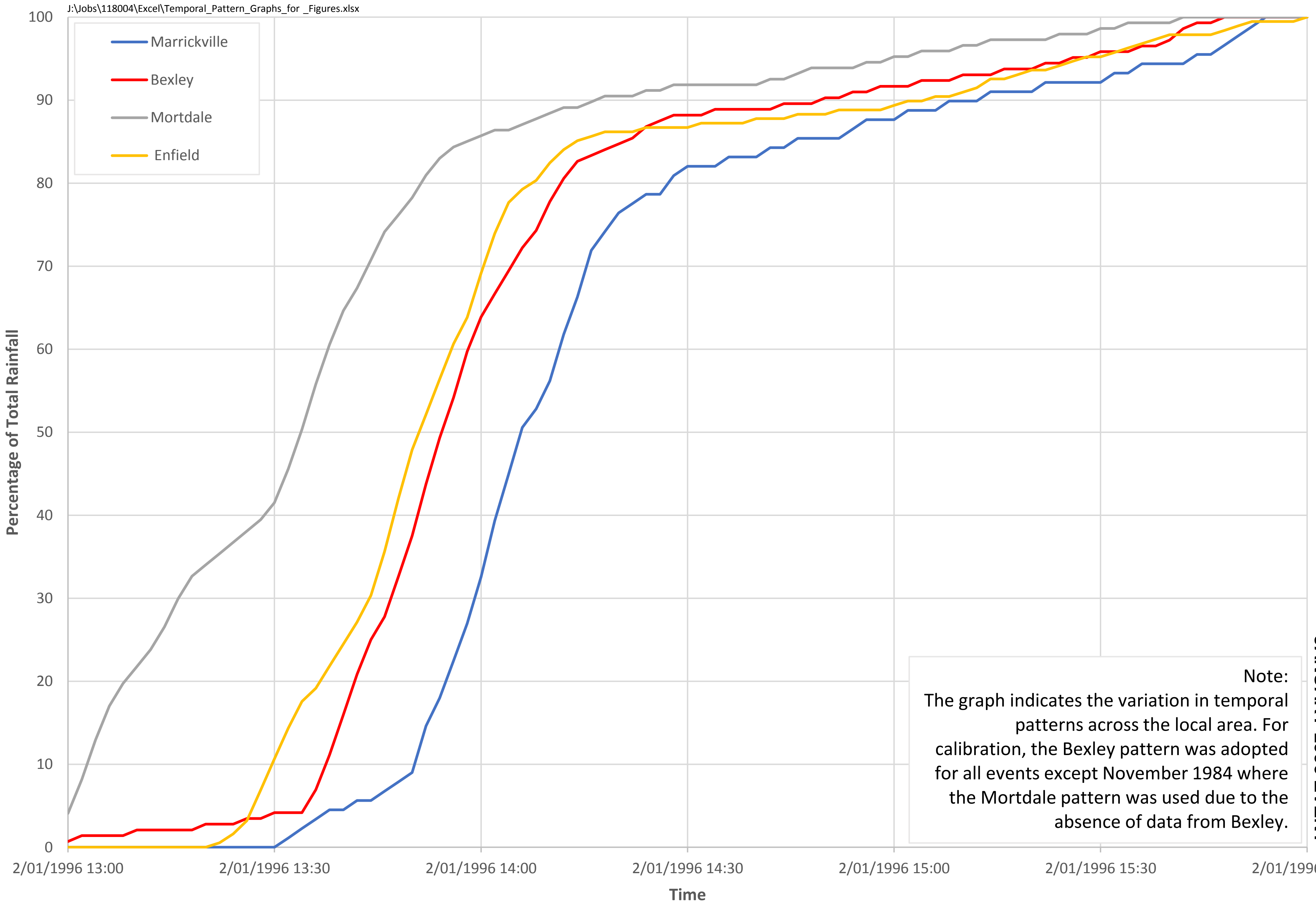
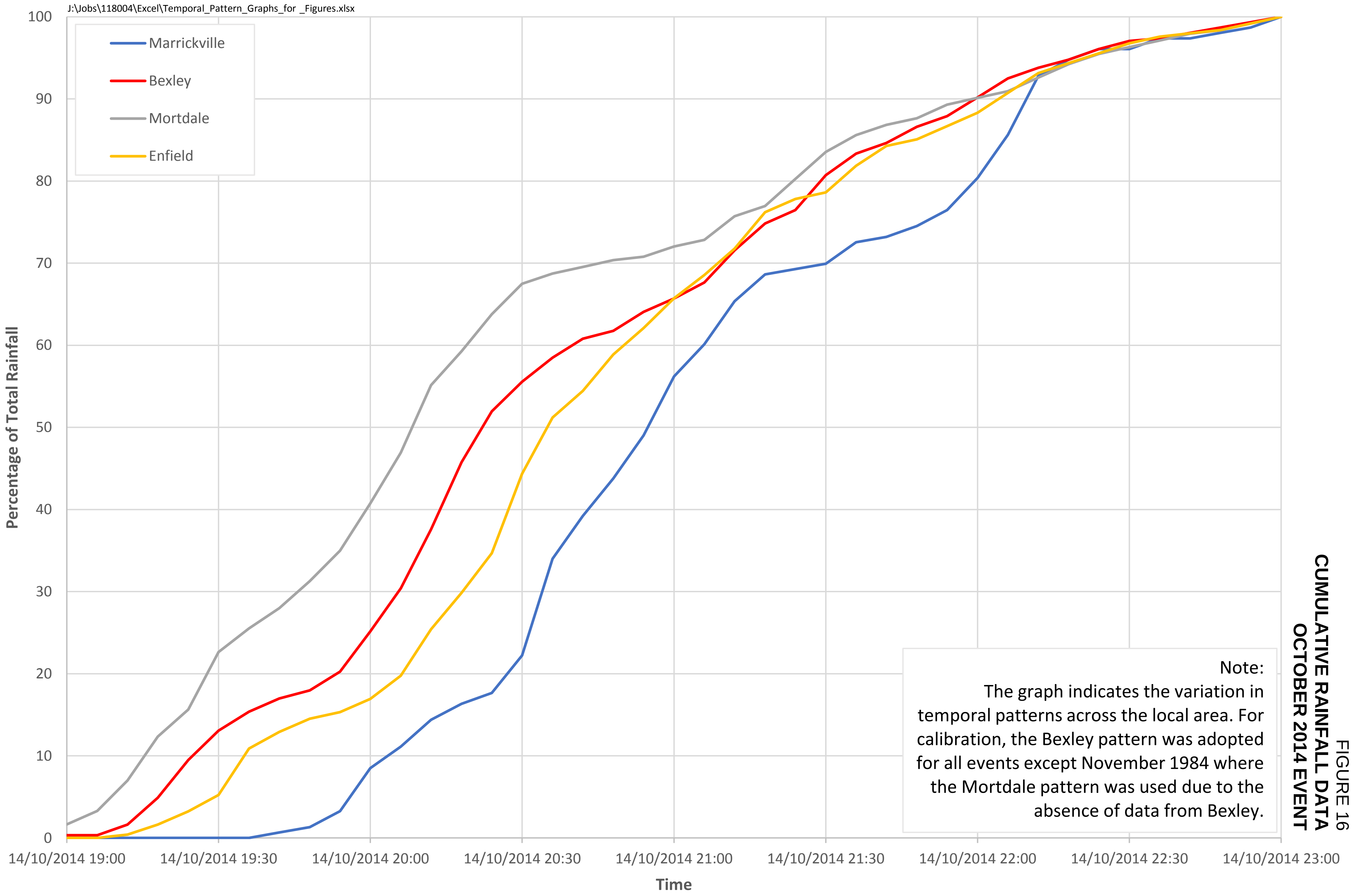


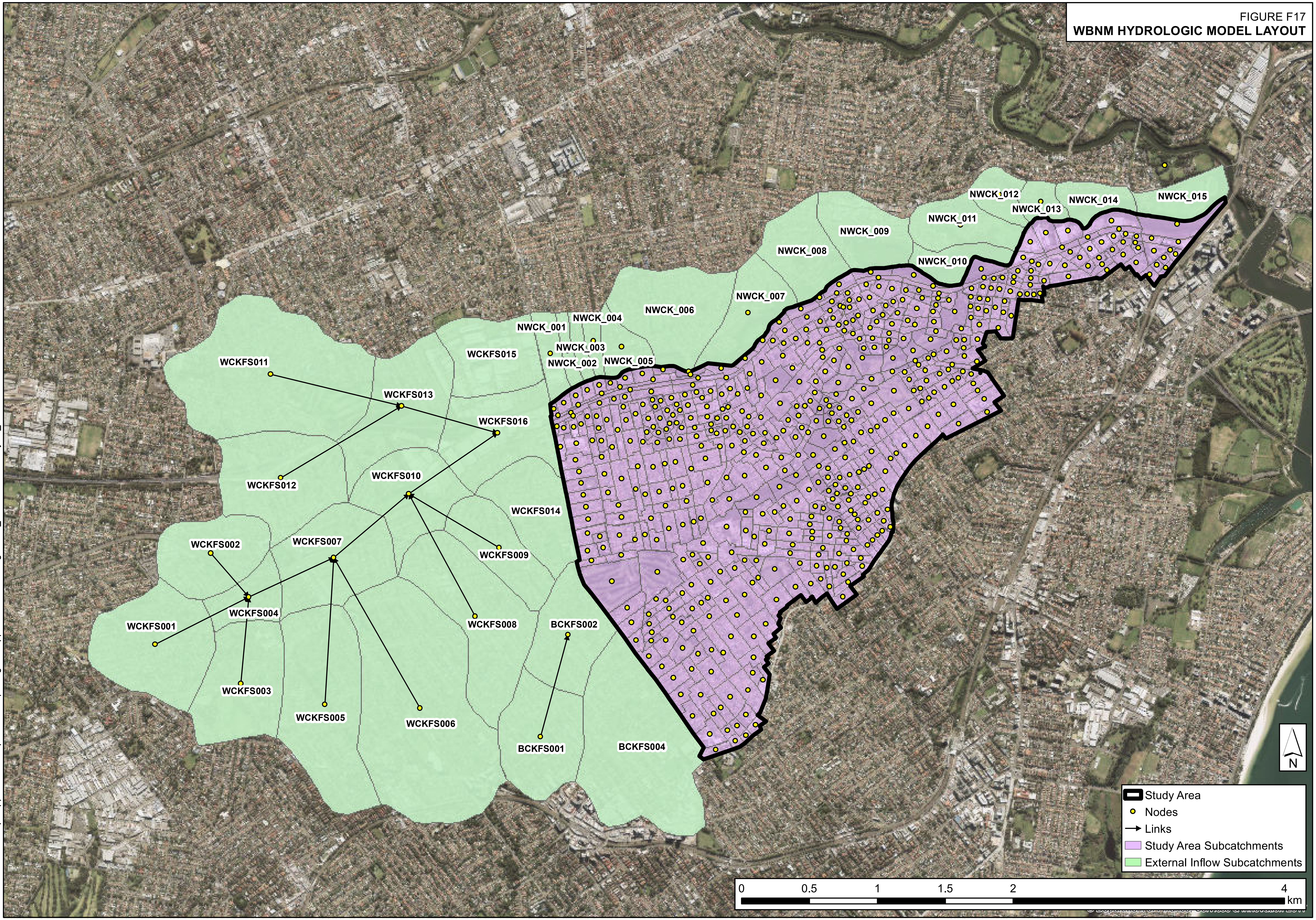
FIGURE 15
CUMULATIVE RAINFALL DATA
JANUARY 1996 EVENT



Note:
The graph indicates the variation in temporal patterns across the local area. For calibration, the Bexley pattern was adopted for all events except November 1984 where the Mortdale pattern was used due to the absence of data from Bexley.

FIGURE 16
CUMULATIVE RAINFALL DATA
OCTOBER 2014 EVENT

FIGURE F17
WBNM HYDROLOGIC MODEL LAYOUT



J:\Jobs\118004\Arc\Maps\AppendixF\A3\Updated Hotspot Figures\Appendix F - Other\FigureF11_HistoricalRainIsohyets_Oct14.mxd

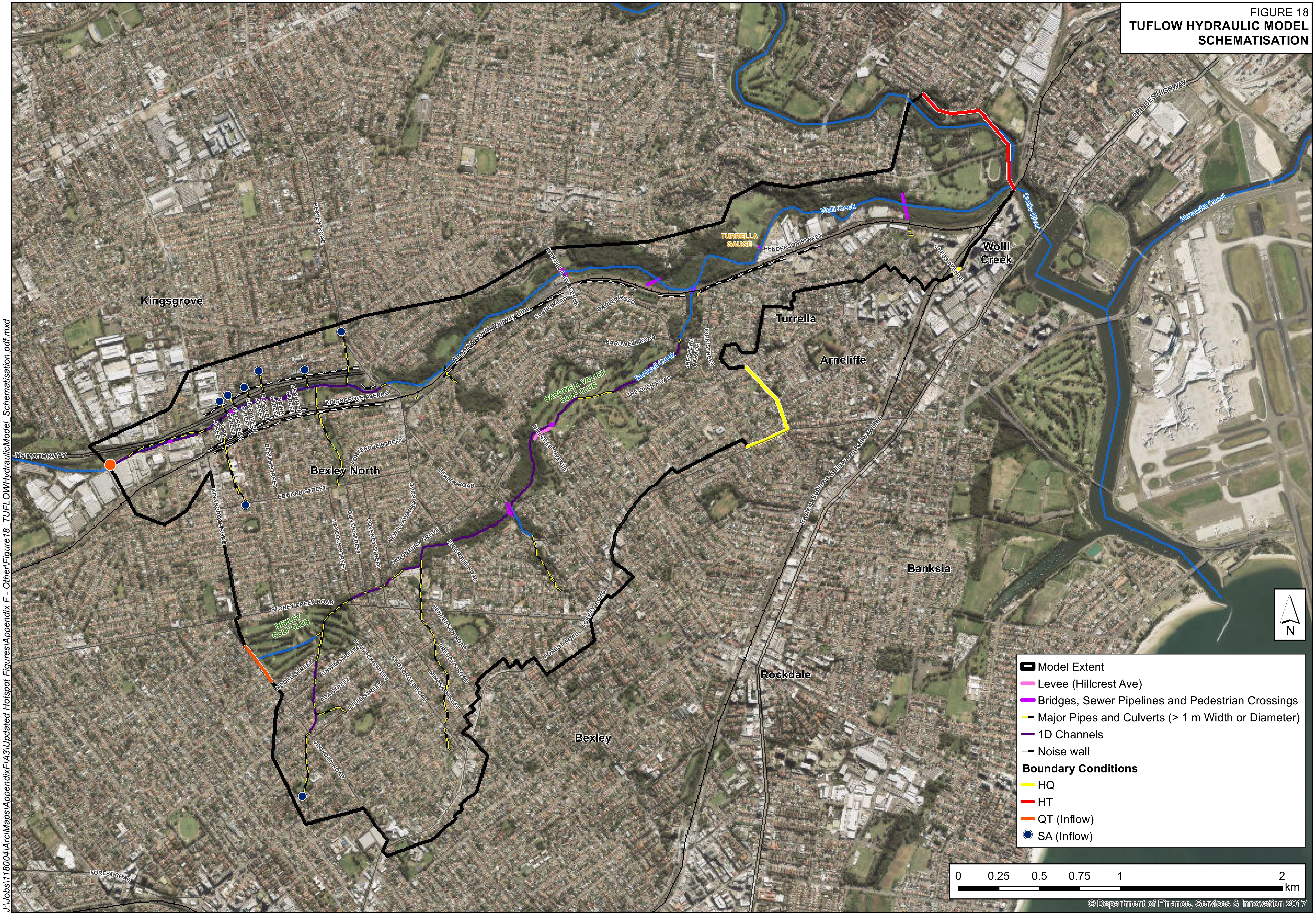
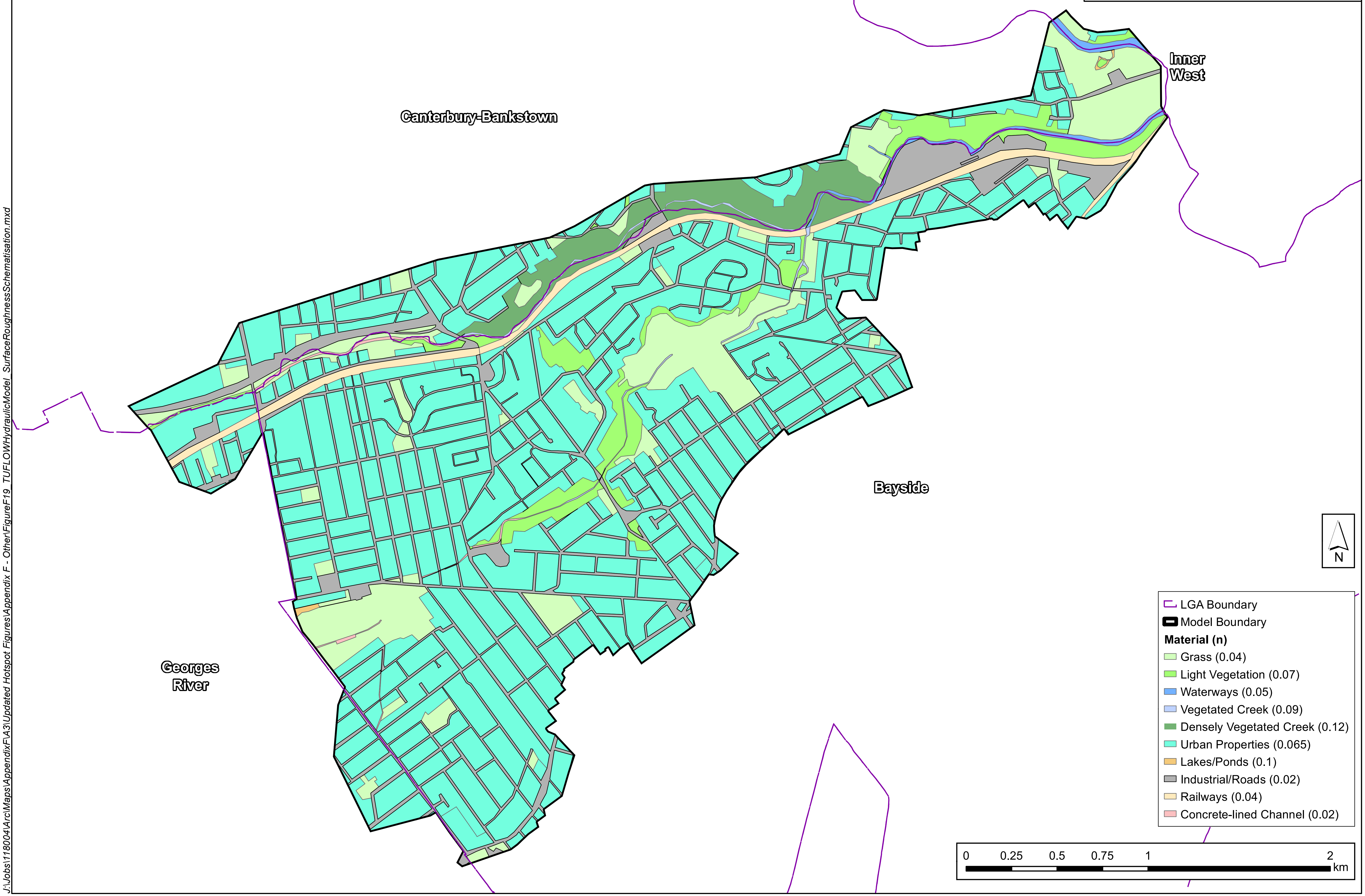


FIGURE 18
TUFLOW HYDRAULIC MODEL SCHEMATISATION

J:\Jobs\118004\ArcMaps\AppendixF\A3\Updated Hotspot Figures\Appendix F - Other\Figure18_TUFLOWHydraulicModel_Schematisation.pdf.mxd

FIGURE 19
TUFLOW HYDRAULIC MODEL
SURFACE ROUGHNESS SCHEMATISATION



J:\Jobs\118004\ArcMaps\AppendixF\A3\Updated Hotspot Figures\Appendix F - Other\FigureF19_TUFLOWHydraulicModel_SurfaceRoughnessSchematisation.mxd

FIGURE 20
WATERCOURSE AND PIT/PIPE STORMWATER NETWORK

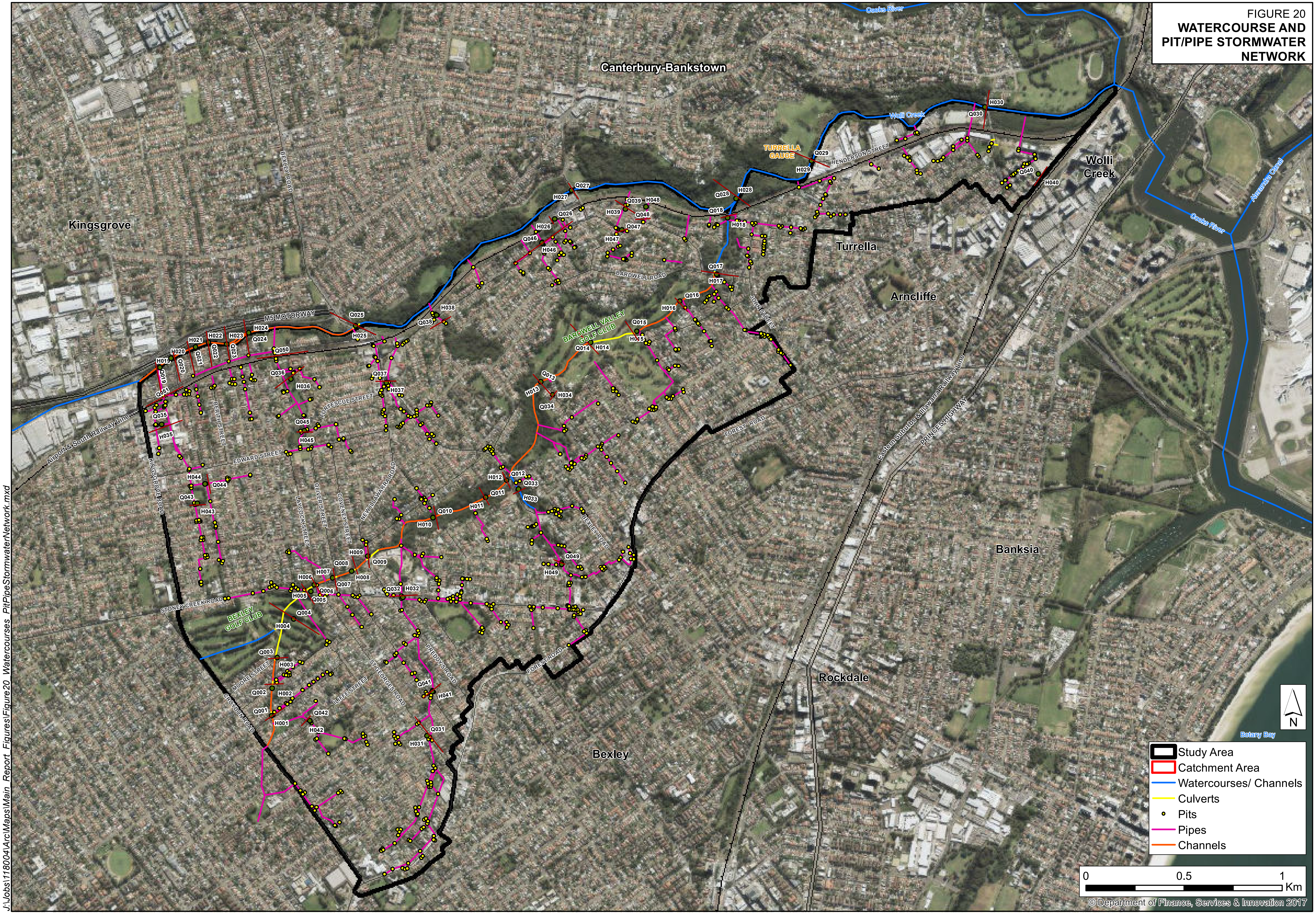


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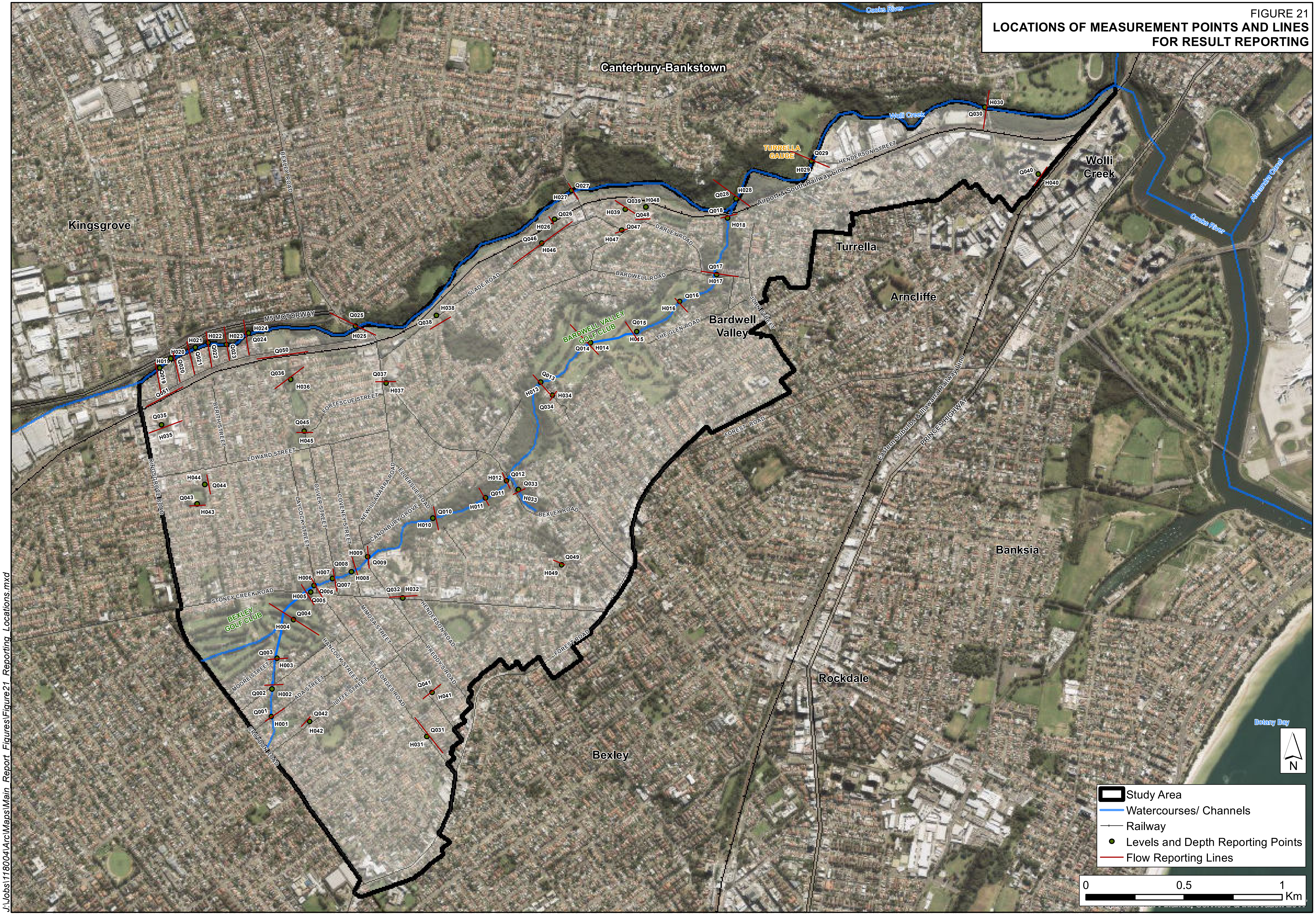
FIGURE 21
LOCATIONS OF MEASUREMENT POINTS AND LINES FOR RESULT REPORTING



J:\Jobs\118004\ArcMaps\Main_Report_Figures\Figure21_Reporting_Locations.mxd

APPENDIX A. ARR2016 Metadata

Appendix A

Australian Rainfall & Runoff Data Hub - Results

Input Data

Longitude	151.103
Latitude	-33.94
Selected Regions	
ARF Parameters	
Storm Losses	
Temporal Patterns	

Region Information

Data Category	Region
River Region	Sydney Coast-Georges River
ARF Parameters	SE Coast
Temporal Patterns	East Coast South

Data

ARF Parameters

Long Duration ARF

$$Areal\ reduction\ factor = Min\left\{1, \left[1 - a\left(Area^{b} - c\log_{10}Duration\right)Duration^{-d} + eArea^{f}Duration^{g}\left(0.3 + \log_{10}AEP\right) + h10^{iArea\frac{Duration}{1440}}\left(0.3 + \log_{10}AEP\right)\right]\right\}$$

Zone	SE Coast
a	0.06
b	0.361
c	0.0
d	0.317
e	8.11e-05
f	0.651
g	0.0
h	0.0
i	0.0
per_intersect	1.0

Short Duration ARF

$$ARF = Min\left[1, 1 - 0.287\left(Area^{0.265} - 0.439\log_{10}(Duration)\right).Duration^{-0.36} + 2.26 \text{ x } 10^{-3} \text{ x } Area^{0.226}.Duration^{0.125}\left(0.3 + \log_{10}(AEP)\right) + 0.0141 \text{ x } Area^{0.213} \text{ x } 10^{-0.021\frac{(Duration-180)^{2}}{1440}}\left(0.3 + \log_{10}(AEP)\right)\right]$$

Layer Info

Time Accessed	25 October 2018 03:03PM
Version	2016_v1

Storm Losses

Note: Burst Loss = Storm Loss - Preburst

Note: These losses are only for rural use and are NOT FOR USE in urban areas

Storm Initial Losses (mm)	32.0
Storm Continuing Losses (mm/h)	2.1

Layer Info

Time Accessed	25 October 2018 03:03PM
Version	2016_v1

Temporal Patterns

code	ECsouth
Label	East Coast South
per_intersect	1.0

Layer Info

Time Accessed	25 October 2018 03:03PM
Version	2016_v2

Median Preburst Depths and Ratios

Values are of the format depth (ratio) with depth in mm

min (h)\AEP(%)	50	20	10	5	2	1
60 (1.0)	7.5 (0.249)	4.8 (0.123)	3.0 (0.066)	1.2 (0.024)	2.1 (0.037)	2.8 (0.044)
90 (1.5)	10.4 (0.299)	7.4 (0.165)	5.4 (0.104)	3.4 (0.059)	2.3 (0.035)	1.5 (0.020)
120 (2.0)	10.6 (0.276)	8.2 (0.165)	6.5 (0.114)	5.0 (0.077)	3.2 (0.043)	1.9 (0.023)
180 (3.0)	8.0 (0.180)	6.8 (0.118)	6.0 (0.089)	5.2 (0.068)	4.6 (0.052)	4.2 (0.043)
360 (6.0)	7.8 (0.133)	12.4 (0.160)	15.4 (0.170)	18.2 (0.177)	13.8 (0.114)	10.5 (0.078)
720 (12.0)	3.7 (0.047)	9.7 (0.091)	13.7 (0.108)	17.5 (0.120)	20.0 (0.116)	22.0 (0.113)
1080 (18.0)	3.5 (0.037)	10.1 (0.078)	14.5 (0.094)	18.7 (0.104)	22.8 (0.107)	25.9 (0.108)
1440 (24.0)	1.9 (0.018)	6.6 (0.044)	9.7 (0.055)	12.7 (0.062)	17.1 (0.069)	20.4 (0.073)
2160 (36.0)	0.3 (0.002)	2.4 (0.014)	3.8 (0.018)	5.1 (0.021)	5.2 (0.017)	5.2 (0.016)
2880 (48.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	1.6 (0.005)	2.7 (0.007)
4320 (72.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)

Layer Info

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Version	2018_v1
Note	Preburst interpolation methods for catchment wide preburst has been slightly altered. Point values remain unchanged.

10% Preburst Depths

min (h)\AEP(%)	50	20	10	5	2	1
60 (1.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
90 (1.5)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
120 (2.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
180 (3.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
360 (6.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
720 (12.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
1080 (18.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
1440 (24.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
2160 (36.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
2880 (48.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
4320 (72.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)

Layer Info

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Note	Preburst interpolation methods for catchment wide preburst has been slightly altered. Point values remain unchanged.

25% Preburst Depths

min (h)\AEP(%)	50	20	10	5	2	1
60 (1.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
90 (1.5)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
120 (2.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
180 (3.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
360 (6.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
720 (12.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
1080 (18.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.5 (0.003)	1.0 (0.004)
1440 (24.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.1 (0.001)	0.2 (0.001)
2160 (36.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
2880 (48.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)
4320 (72.0)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)	0.0 (0.000)

Layer Info

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75% Preburst Depths

min (h)\AEP(%)	50	20	10	5	2	1
60 (1.0)	46.8 (1.547)	34.2 (0.877)	25.8 (0.576)	17.8 (0.352)	24.1 (0.416)	28.8 (0.453)
90 (1.5)	41.1 (1.180)	41.6 (0.928)	41.8 (0.812)	42.1 (0.724)	30.6 (0.458)	22.0 (0.299)
120 (2.0)	45.9 (1.189)	42.5 (0.857)	40.3 (0.705)	38.2 (0.591)	35.5 (0.477)	33.5 (0.408)
180 (3.0)	42.0 (0.937)	43.2 (0.748)	44.1 (0.660)	44.9 (0.592)	47.9 (0.546)	50.2 (0.517)
360 (6.0)	46.0 (0.779)	54.7 (0.707)	60.5 (0.670)	66.0 (0.640)	70.5 (0.584)	73.9 (0.548)
720 (12.0)	28.2 (0.354)	37.9 (0.354)	44.3 (0.351)	50.5 (0.346)	60.9 (0.353)	68.7 (0.354)
1080 (18.0)	33.6 (0.353)	42.6 (0.328)	48.6 (0.315)	54.4 (0.303)	66.7 (0.313)	76.0 (0.316)
1440 (24.0)	22.1 (0.206)	33.0 (0.222)	40.2 (0.227)	47.1 (0.228)	54.6 (0.222)	60.3 (0.217)
2160 (36.0)	12.4 (0.098)	22.7 (0.128)	29.5 (0.139)	36.1 (0.146)	38.6 (0.130)	40.5 (0.121)
2880 (48.0)	1.9 (0.014)	6.6 (0.033)	9.7 (0.041)	12.7 (0.046)	24.0 (0.072)	32.5 (0.087)
4320 (72.0)	0.0 (0.000)	0.7 (0.003)	1.1 (0.004)	1.5 (0.005)	14.1 (0.037)	23.4 (0.056)

Layer Info

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90% Preburst Depths

min (h)\AEP(%)	50	20	10	5	2	1
60 (1.0)	112.8 (3.729)	89.5 (2.297)	74.0 (1.652)	59.2 (1.172)	69.5 (1.200)	77.3 (1.215)
90 (1.5)	106.0 (3.042)	125.7 (2.808)	138.8 (2.693)	151.3 (2.602)	106.4 (1.590)	72.8 (0.988)
120 (2.0)	84.6 (2.194)	106.5 (2.148)	121.0 (2.118)	134.9 (2.089)	129.1 (1.731)	124.7 (1.516)
180 (3.0)	82.9 (1.851)	106.8 (1.848)	122.6 (1.835)	137.7 (1.818)	123.8 (1.410)	113.3 (1.166)
360 (6.0)	75.8 (1.285)	89.2 (1.152)	98.0 (1.086)	106.5 (1.031)	128.4 (1.063)	144.9 (1.076)
720 (12.0)	60.1 (0.755)	80.9 (0.756)	94.7 (0.750)	108.0 (0.740)	111.9 (0.649)	114.9 (0.593)
1080 (18.0)	74.2 (0.781)	87.4 (0.672)	96.1 (0.622)	104.5 (0.583)	127.3 (0.597)	144.4 (0.601)
1440 (24.0)	45.0 (0.419)	63.5 (0.427)	75.8 (0.427)	87.6 (0.425)	115.2 (0.468)	135.9 (0.489)
2160 (36.0)	36.9 (0.293)	49.1 (0.277)	57.1 (0.269)	64.9 (0.262)	87.0 (0.294)	103.7 (0.310)
2880 (48.0)	17.3 (0.123)	35.3 (0.178)	47.3 (0.199)	58.7 (0.212)	81.0 (0.244)	97.6 (0.261)
4320 (72.0)	6.2 (0.039)	15.0 (0.067)	20.8 (0.077)	26.3 (0.084)	52.0 (0.139)	71.2 (0.169)

Layer Info

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APPENDIX B. Photographs of Hydraulic Structures

Bardwell Creek


Image 1: Ada Street Culverts


Image 2: Unwin Street Culverts


Image 3: Moore Street Culverts


Image 4: Bexley Golf Course Culvert


Image 5: Laycock Street Culverts


Image 6: Oliver Street Culverts

Image 7: Preddys Road (looking downstream from road)

Image 8: Bexley Road Bridge

Image 9: Bardwell Golf Course Culverts

Image 10: Bardwell Road Culverts

Wolli Creek

Image 11: Noise Walls (East Hills Railway Line)

Image 13: Culverts Under Noise Walls (Kingsgrove and Bexley North Community Centre)

Image 12: Pedestrian Crossing (Kooreela Street)

Image 14: GPT on Wolli Creek

Image 15: Bexley Road Culverts

Image 16: Harthill Law Avenue Bridge

Image 17: Turrella Weir

Image 18: Turrella Footbridge