Leichhardt Flood Study

FINAL REPORT

LJ2629

Prepared for Leichhardt Council

27 May 2015

Volume 1

Cardno (NSW/ACT) Pty Ltd
Trading as Cardno
ABN 95 001 145 035
The Forum
Level 9, 203 Pacific Highway
St Leonards NSW 2065
Australia
Telephone: 02 9496 7700
Facsimile: 02 9439 5170
International: +61 2 9496 7700
sydney@cardno.com.au
www.cardno.com.au

Document Control

Version	Status	Date	Author		Reviewer	
1	Working Draft	20 November 2009	Bala Kilaparty	BSK	Rhys Thomson	RST
2	Draft	10 February 2010	Rhys Thomson/ Bala Kilaparty	RST/ BSK	Louise Collier	LCC
3	Draft Final	7 June 2010	Rhys Thomson Bala Kilaparty	RST/ BSK	Louise Collier	LCC
4	Final	22 July 2014	Bala Kilaparty Emma Maratea	BSK / ERM	Rhys Thomson	RST
5	Revised Final	11 August 2014	Bala Kilaparty Emma Maratea	BSK / ERM	Heath Sommerville	HS
6	Final	7 November 2014	Heath Sommerville	HCS	David Paton	DP
7	Final	17 November 2014	Bala Kilaparty Heath Sommerville	BSK / HCS	David Paton	DP
8	Revised Final	27 May 2015	Emma Maratea	ERM	Emma Maratea	ERM

Front cover: Upper photographs: Features in the Leichhardt LGA Floodplain

Lower photographs: Historical flooding photographs in the Leichhardt area courtesy of Vera Nadile.

This document is produced by Cardno solely for the benefit and use by the client in accordance with the terms of the engagement. Cardno does not and shall not assume any responsibility or liability whatsoever to any third party arising out of any use or reliance by any third party on the content of this document.

© Cardno 2014. Copyright in the whole and every part of this document belongs to Cardno and may not be used, sold, transferred, copied or reproduced in whole or in part in any manner or form or in or on any media to any person other than by agreement with Cardno.

Foreword

The NSW Government's Flood Prone Lands Policy is directed towards providing solutions to existing flood problems in developed areas utilising ecologically positive methods wherever possible and ensuring that 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 prone land is the responsibility of Local Government. To achieve its primary objective, the policy provides for State Government financial assistance to Councils for actions to alleviate existing flooding problems. The policy also provides for State Government technical assistance to Councils to ensure that the management of flood prone land is consistent with the flood hazard and that future development does not create or increase flooding problems in flood prone areas.

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

1. Flood Study	Determines 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	Implementation of actions to manage flood risks for existing and new development.

The Leichhardt Flood Study is the first stage of the management process for the Leichhardt Local Government Area (LGA). The study, which has been prepared for Leichhardt Council by Cardno, defines flood behaviour for existing catchment conditions in the Leichhardt LGA floodplain.

Executive Summary

Cardno were commissioned by Leichhardt Council to undertake a flood study for the entire Leichhardt Local Government Area (LGA). The primary objective of the study is to define the flood behaviour in the Leichhardt LGA.

The Leichhardt LGA lies in Sydney's inner west and includes the suburbs of Annandale, Leichhardt, Lilyfield, Rozelle, Balmain and Balmain East. The LGA covers an area of approximately 10.7 square kilometres. The study area is roughly bounded by Parramatta Road to the south, Sydney Harbour to the north, Johnstons Creek and the City of Sydney LGA to the east and Hawthorne Canal to the west. Major creek systems are located in the south of the LGA and include Whites Creek, Johnstons Creek and Hawthorne Canal. Localised drainage systems distributed through the LGA are either tributaries of these main creek systems or drain directly to Sydney Harbour.

An extensive data compilation and review was undertaken in the study. This included an extensive survey exercise which required the collection of data for over 3500 pits within the LGA, together with cross sections of stormwater channels and details of hydraulic structures such as culverts.

The data compilation also included a resident survey of approximately 22,000 property owners and occupiers. This survey targeted local residents' experience with flooding in the LGA and has been compiled into a GIS database for Council.

A detailed 1D/2D hydraulic model was established. This model incorporates pipes upwards of 225 millimetres in diameter and has a fine 2D resolution of 1 metre. Hydrological modelling was undertaken utilising a combination of Direct Rainfall within the study area and traditional hydrological modelling for catchments external to the study area.

The models were calibrated to three historical flood events; 1991, 1993 and 1998. The largest of these storm events was in 1993, and corresponds roughly to a 50 year ARI for a 30 minute duration storm and a 20 year ARI for a 2 hour duration storm, based on rainfall intensities. The models show a good agreement to the observed flood levels from these events.

Using the established models, the study has determined the flood behaviour for the 100 year, 50 year, 20 year, 10 year and 5 year ARI design floods and the Probable Maximum Flood (PMF). The primary flood characteristics reported for the design events considered include depths, levels, velocities and flow rates. The study has also defined the Provisional Flood Hazard for flood-affected areas.

The outcomes of this study can also be used for future studies to investigate various management and flood mitigation options for the existing catchment conditions and will assist in evaluating long term flood management strategies now that existing flood risks have been defined in this study.

Table of Contents

List of Tables

List of Figures

Volume 1

Volume 2

Appendices

Glossary*

Australian Height Datum (AHD)	A common national surface level datum approximately corresponding to mean sea level.
Average recurrence interval (ARI)	The long-term average number of years between the occurrence of a flood as big as or larger than the selected event. For example, floods with a discharge as great as or greater than the 20 year ARI flood event will occur on average once every 20 years. ARI is another way of expressing the likelihood of occurrence of a flood event.
Cadastre, cadastral base	Information in map or digital form showing the extent and usage of land, including streets, lot boundaries, water courses etc.
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.
Creek Rehabilitation	Rehabilitating the natural 'biophysical' (i.e. geomorphic and ecological) functions of the creek.
Creek Modification	Widening or altering the creek channel in an environmentally compatible manner (i.e. including weed removal and stabilisation with suitable native endemic vegetation) to allow for additional conveyance.
Design flood	A significant event to be considered in the design process; various works within the floodplain may have different design events, e.g. some roads may be designed to be overtopped in the 1 year ARI flood event.

Development	Is defined in Part 4 of the 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. Eg, the urban subdivision of an area previously used for rural purposes. New developments involve re-zoning 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. Eg, as urban areas age, it may become necessary to demolish and reconstruct buildings on a relatively large scale. Redevelopment generally does not require either re-zoning 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).
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 fringe	The remaining area of flood-prone land after floodway and flood storage areas have been defined.

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 provisional hazard categories are provided in Appendix L of the Floodplain Development Manual (NSW Government, 2005).
Flood-prone land	Land susceptible to inundation by the probable maximum flood (PMF) event, i.e. the maximum extent of flood liable land.
Floodplain	Area of land which is subject to inundation by floods up to the probable maximum flood event, i.e. 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.
Flood planning area	The area of land below the FPL and thus subject to flood related development controls.
Flood planning levels	Are the combinations of flood levels (derived from significant historical flood events or floods of specific ARIs) and freeboards selected for floodplain risk management purposes, as determined in management studies and incorporated in management plans.

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 flow, or a significant increase in flood levels.
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. (See Section K5). Freeboard is included in the flood planning level.

Geographical information systems (GIS)	A system of software and procedures designed to support the management, manipulation, analysis and display of spatially referenced data.
High hazard	Flood conditions that pose a possible danger to personal safety; evacuation by trucks difficult; able-bodied adults would have difficulty wading to safety; potential for significant structural damage to buildings.
Hydraulics	The term given to the study of water flow in a river, channel or pipe, in particular, the evaluation of flow parameters such as stage and velocity.
Hydrograph	A graph that shows how the discharge changes with time at any particular location.
Hydrology	The term given to the study of the rainfall and runoff process as it relates to the derivation of hydrographs for given floods.
Local overland flooding	Inundation by local runoff rather than overbank discharge from a stream, river, estuary, lake or dam.
Low hazard	Flood conditions such that should it be necessary, people and their possessions could be evacuated by trucks; able-bodied adults would have little difficulty wading to safety.
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 purposes 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 0.3m (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 flowpaths through developed areas outside of defined drainage reserves; and/or ▪ The potential to affect a number of buildings along the major flow path.
Management plan	A document including, as appropriate, both written and diagrammatic information describing how a particular area of land is to be used and managed to achieve defined objectives. With regard to flooding, the objective of the management plan is to minimise and mitigate the risk of flooding to the community. It may also include description and discussion of various issues, special features and values of the area, the specific management measures which are to apply and the means and timing by which the plan will be implemented.
Mathematical/computer models	The mathematical representation of the physical processes involved in runoff and stream flow. These models are often run on computers due to the complexity of the mathematical relationships. In this report, the models referred to are mainly involved with rainfall, runoff, pipe and overland stream flow.
NPER	National Professional Engineers Register. Maintained by the Institution of Engineers, Australia.
Peak discharge	The maximum discharge occurring during a flood event.

Probable maximum flood	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	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 frequency or occurrence of flooding.
Risk	Chance of something happening that will have an impact. It is measured in terms of consequences and likelihood. For this study, it is the likelihood of consequences arising from the interaction of floods, communities and the environment.
Runoff	The amount of rainfall that actually ends up as stream or pipe flow, also known as rainfall excess.
Stage	Equivalent to 'water level'. Both are measured with reference to a specified datum.
Stage hydrograph	A graph that shows how the water level changes with time. It must be referenced to a particular location and datum.
Stormwater flooding	Inundation by local runoff. Stormwater flooding can be caused by local runoff exceeding the capacity of an urban stormwater drainage system or by the backwater effects of mainstream flooding causing the urban stormwater drainage system to overflow.

Topography	A surface which defines the ground level of a chosen area.

* Many terms in this Glossary have been derived or adapted from the NSW Government *Floodplain Development Manual*, 2005.

List of Abbreviations

1D	One Dimensional
2D	Two Dimensional
AHD	Australian Height Datum
ARI	Average Recurrence Interval
BoM	Bureau of Meteorology
DECCW	Department of Environment, Climate Change & Water (formerly the Department of Environment and Climate Change)
FPL	Flood Planning Level
FRMP	Floodplain Risk Management Plan
FRMS	Floodplain Risk Management Study
km	kilometres
km^2	Square kilometres
LGA	Local Government Area
m	metre
m^2	Square metres
m^3	Cubic metres
mAHD	Metres to Australian Height Datum
mm	millimetres
m/s	metres per second
NSW	New South Wales
OSD	On-site Detention
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
SES	State Emergency Service
SWC	Sydney Water Corporation (previously known as the Water Board.

1 Introduction

Cardno were commissioned by Leichhardt Council to undertake a flood study for the entire Leichhardt Local Government Area (LGA). The primary objective of the study is to define the flood behaviour in the Leichhardt LGA. The study has been undertaken to determine flood behaviour for the 100 year, 50 year, 20 year, 10 year and 5 year ARI design floods and the Probable Maximum Flood (PMF). The primary flood characteristics reported for the design events considered include depths, levels, velocities and flow rates. The study has also defined the Provisional Flood Hazard and Hydraulic Categories for flood-affected areas.

The assessment of flooding in this report includes both:

- ‘mainstream’ flooding - flooding associated with catchment rainfall flowing to a creek, open channel or open canal and the capacity of the channel is generally exceeded; and,
- ‘overland’ flooding – including where catchment rainfall cannot enter the stormwater drainage system and flows ‘overland’, which can be through properties or down streets.

The method of assessment used for this study allows for both types of catchment flooding to be considered at the same time. The terms flooding, catchment flooding or overland flows can be used interchangeably in this report.

The various components of this flood study can be grouped together into three main stages, with community consultation undertaken throughout.

Firstly, all available data was compiled for the study. This involved the collection of available historical rainfall and flood level data. Secondly, a hydrologic investigation was carried out for the catchment using a hydrologic computer model to define the catchment flows (the conversion of rainfall to runoff). Thirdly, a hydraulic computer model of the study area was established to determine flood depths, velocities and extents.

These models can also be used for future studies to investigate various management and flood mitigation options for the existing catchment conditions and will assist in evaluating long term flood management strategies now that existing flood risks have been defined in this study.

1.1 Catchment Description

The Leichhardt LGA lies in Sydney’s inner west and includes the suburbs of Annandale, Leichhardt, Lilyfield, Rozelle, Balmain and Balmain East. The LGA covers an area of approximately 10.7 square kilometres. The study area is roughly bounded by Parramatta Road to the south, Sydney Harbour to the north, Johnstons Creek and the City of Sydney LGA to the east and Hawthorne Canal to the west.

The study area is shown in **Figure 1.1**.

Land-use in the Leichhardt LGA is predominantly categorised as urban residential (terrace style and medium density housing) with portions of industrial and commercial land uses located in the catchment. Other land uses in the catchment are roads, open space and special purposes (e.g. schools and the like).

Major creek systems are located in the south of the LGA and include Whites Creek, Johnstons Creek and Hawthorne Canal. Localised drainage systems distributed through the LGA are either tributaries of these main creek systems or drain directly to Sydney Harbour. The majority of the trunk drainage systems throughout the study area, including the three main creek systems, are owned and managed by Sydney Water Corporation (Sydney Water or SWC).

Records of flooding through the main waterways exist from as early as January 1938 to several events through the 1990's and 2000's. Flooding has also occurred in the localised drainage network on a regular basis.

1.2 Study Objectives

The objectives of this study are to:

- Investigate historical flooding in the Leichhardt LGA (**Sections 2 and 3**).
- Identify all the flood-related data by searching all relevant data sources (**Sections 2 and 3**).
- Determine the likely extent and nature of flooding and identify potential hydraulic controls by carrying out detailed site visits of the study area (**Section 2**).
- Develop a computer model that can be used to predict the magnitude and extent of future flood events (**Sections 4, 5 and 6**); and
- Provide Leichhardt Council with the necessary information to make effective investments in flood hazard management (**Sections 8, 9, 10, 11 and 12**).
- Define design flood levels, velocities and depths for the catchment (**Section 8**).
- Define the extent of flooding for the 100 year, 50 year, 20 year, 10 year and 5 year ARI floods and Probable Maximum Flood (PMF) for the catchment (**Section 8**).
- Define Provisional Flood Hazard for flood-affected areas (**Section 9**).
- Define the Hydraulic Categories for flood-affected areas (**Section 10**).

2 Available Data

Data has been obtained from a number of sources and includes information required for input to the hydrologic and hydraulic models, together with information required for calibration and validation of model results (**Section 7**) and the adequate representation and presentation of those results.

Data was obtained from the following sources:

- Rainfall data from the Bureau of Meteorology and Sydney Water;
- Previous reports prepared for related studies in the area (see **Section 2.1**);
- Ground survey and aerial survey information (see **Section 2.2**)
- Aerial photography; and
- General GIS information (such as cadastre, street names, and etc.) from Leichhardt Council.

2.1 Previous Studies and Reports

2.1.1 Sydney Water Flood Studies

Flood studies have been undertaken by Sydney Water (and its previous entity, the Water Board) for both Johnstons Creek and Whites Creek:

- Water Board (1990). Whites Creek SWC No: 95 Catchment Management Study, August.
- Water Board (1994). Whites Creek SWC No: 95 Detail Hydraulic Analysis, January.
- Sydney Water (1996). Johnstons Creek SWC No: 55 Flood Study, March.

These studies define the mainstream flooding behaviour for these two creek systems. Both of these studies are currently the governing documents for the determination of flood levels for Johnstons Creek and Whites Creek. Historical flood levels identified during these studies were collated and used in the present study for calibrating the model (**Section 7**).

2.1.2 Estuarine Planning Levels Study

It is important to note that some properties in the LGA may be affected by two types of flooding:

- Flooding from rainfall that becomes runoff (known as catchment flooding), and
- Flooding from inundation from Sydney Harbour (known as estuarine flooding).

Catchment flooding is addressed in this report (also referred to as overland flooding, or overland flow flooding). The *Leichhardt Estuarine Planning Level* Study is currently being undertaken by Cardno Lawson Treloar (*in prep*). The primary objective of the study is to define storm tide, wave run-up and overtopping effects on the Harbour water level around the foreshore areas of the Leichhardt LGA, so that consistent and informed development decisions can be made for the management of these areas. This report, to be released, will address estuarine flooding and will report water levels (designated as a ‘still water level’) and wave impacts (a short-term process) as may be generated by a range of storm events, including the 5, 10, 20, 50, 100 and 200 year average recurrence interval (ARI) design conditions.

In a manner similar to this Flood Study, the study has made use of numerical models, considering both hydrodynamic and nearshore wave process, to define the magnitude of various water level parameters along the Leichhardt Foreshore.

The study will provide a maximum level at each property, with simple adjustments to wave run-up that can be applied, depending on typical shoreline treatments, such as sloping embankments, beaches or vertical walls, and has been presented on a GIS layer for inclusion in Council's property database.

Where properties are affected by inundation from both mechanisms (catchment flooding and estuarine inundation), both water levels will be available from Council for planning and development purposes.

2.2 Survey Information

Council provided a substantial amount of the existing data of the study area. Additional survey was commissioned for the areas not covered by existing survey. Figure 2.1 provides details of the survey captured for different parts of the study area.

2.2.1 Existing Survey

Survey information was obtained from a number of sources. The following summarises the information received:

- Airborne Laser Scanning (ALS) – Council provided aerial survey across the entire catchment, captured on 26 August, 2006. This data was provided to Cardno on 19 November 2007. Generally, the accuracy of the ALS data is +/- 0.15m to one standard deviation on hard surfaces.
- Pit and Pipe Data – Data held by Council was provided by Council.
- Historical flood levels – historical levels identified as a part of the resident survey (**Section 3**) and from the previous Sydney Water studies (Water Board, 1994; Sydney Water, 1996).

2.2.2 Additional Survey

Additional ground survey was collected for parts of the study area where the existing survey did not exist or did not provide sufficient definition for the purposes of flood modelling. This survey was undertaken by Cardno's Survey Team and was completed on 18 November 2008.

The following survey details were obtained within the catchment:

- Pit and Pipe Field Survey – Council provided available stormwater drainage pit and pipe data in the study area. Cardno's Survey Team then completed a detailed field survey of all of the drainage system to update Council's information. More than 3500 pits and over 3000 pipes were surveyed over 2007 to 2008 (shown in **Figure 2.1**). This resulted in a 'pit and pipe database' which identifies the dimensions and locations of all Council's pit and pipes within the entire LGA. It should be noted that the inverts and surface levels of the pits were not measured directly. Instead, these were determined utilising Council's ALS data (refer **Section 2.2.1**). In addition, photographs were taken of every pit and this information is integrated within the pit and pipe database.

- Cross Sections and Culvert Dimensions – cross sections of the open channels and culvert dimensions within the study area were obtained (**Figure 2.1**). These details are generally not adequately defined in the aerial survey described in **Section 2.1.1** and were therefore obtained as supplementary information.
- Hydraulic Structures – details of all major hydraulic structures (such as culverts and bridges) were surveyed.
- Historical flood levels identified in the community consultation (**Section 3**) and from previous studies.

2.2.3 Sydney Water Pit and Pipe Data

Sydney Water provided GIS layers of pit and pipe data based on their records on 25 June 2007. This data was utilised to supplement the pit and pipe survey undertaken for the study, as discussed in **Section 2.2.2**. For example, where access to the underground drainage network was not available for the Cardno Survey Team (such as in the White Bay Power Station), the Sydney Water data was utilised to supplement the survey data.

2.3 Site Inspections

Detailed site inspections of the study area were conducted on 12/07/2007, 02/08/2007, 16/03/2009 and 30/04/2009. The site visits provided the opportunity to fine tune the modelling approach to capture various street drainage features which are common in the LGA, and to visually identify potential flooding hotspots in the catchment.

2.4 GIS Data

The following Geographic Information System (GIS) data was provided by Council for this study:

- Pit and Pipe data (also described in **Section 2.2.1**)
- Cadastre
- 2m Land Information Centre (LIC) contours
- Aerial photography (2006) captured by Council prior to the commencement of the current study.

2.5 Historical Rainfall Information

Three historical events (January 1991, February 1993, and April 1998) were identified through the community consultation (**Section 3**) and previous flood studies. Rainfall data was obtained for those events from Sydney Water. The Sydney Water rainfall gauge at Lilyfield is approximately at the centre of the study area, and was utilised in the model calibration process (**Section 7**).

Table 2.1 provides details on the gauge data that was obtained.

Table 2.1: Sydney Water Rain Gauge Information

Station No.	Station Name	Latitude (°S)	Longitude (°E)	Type
566065	Lilyfield (formerly Annandale)	32.1192 °S	151.1686 °E	Pluviometer (6 min interval)

Daily totals for each historical storm event are summarised in **Table 2.2 to Table 2.5**.

Table 2.2: Rainfall Totals for January 1991 Flood Event

Station No.	Station Name	Total Daily Rainfall (mm to 9am)
		26th January
566065	Lilyfield (formerly Annandale)	54

Table 2.3: Rainfall Totals for February 1993 Flood Event

Station No.	Station Name	Total Daily Rainfall (mm to 9am)
		17th February
566065	Lilyfield (formerly Annandale)	99.50

Table 2.4: Rainfall Totals for April 1998 Flood Event

Station No.	Station Name	Total Daily Rainfall (mm to 9am)	
		9th April	10th April
566065	Lilyfield (formerly Annandale)	109	185

NB: The storm event occurred between 9th and 10th April 1998.

Table 2.5: Approximate ARI of Historical Rainfall Events

Storm Event	Details	Duration				
		30 mins	60 mins	90 mins	2 hour	3 hour
January 1991	Intensity (mm/hr)	104	54.0	36	27	18
	Approx. ARI	*~20yr*	*5yr*	*2-5yr*	*2-5yr*	*1-2yr*
February 1993	Intensity (mm/hr)	116	72	55.33	43.50	32.67
	Approx. ARI	*~50yr*	*20yr*	*20yr*	*~20yr*	*10-20yr*
April 1998	Intensity (mm/hr)	88	48	38.67	32	26
	Approx. ARI	*10yr*	*2-5yr*	*2-5yr*	*~5yr*	*5yr*

2.6 Historical Flood Level Data

A number of historical flood levels were identified during community consultation (**Section 3**), and from the previous Sydney Water studies. This data was used in the calibration process (**Section 7**).

2.7 Design Rainfall

2.7.1 Standard Design Rainfall Information

Owing to the relatively small area of the catchment, uniform areal distribution of design storms was assumed for the hydrologic component of the analysis (**Section 5**). Design rainfall depths and temporal patterns for the 100 year, 50 year, 20 year, 10 year and 5 year ARI events were developed using standard techniques provided in *Australian Rainfall and Runoff* (AR&R) (Engineers Australia, 1999).

The design Intensity-Frequency-Duration (IFD) parameters obtained from Leichhardt Council for the catchment (centred on Latitude 33ºS, Longitude 151ºE) are presented in **Table 2.6**.

Table 2.6: Design IFD Parameters

Parameter	Value
2-Years ARI 1-hour Intensity	40
2-Years ARI 12-hours Intensity	8
2-Years ARI 72-hours Intensity	2.5
50-Years ARI 1-hour Intensity	85
50-Years ARI 12-hours Intensity	16
50-Years ARI 72-hours Intensity	5
Skew	0
F2	4.29
F50	15.8
Temporal Pattern Zone	1

Estimated design storm rainfall intensities for the full range of storm events and durations are presented in **Table 2.7**.

Table 2.7: Design Rainfall Intensities (mm/hr)

Frequency/ Duration	5 Year ARI	10 Year ARI	20 Year ARI	50 Year ARI	100 Year ARI
15 min	106	120	138	162	181
30 min	76	87	101	119	134
45 min	62	71	83	98	110
1h	53	61	71	85	95
1.5h	41	47.1	55	65	73
2h	34	38.9	45.3	54	60
3h	26	29.7	34.5	40.9	45.8
4.5h	19.9	22.7	26.3	31.1	34.7
6h	16.4	18.7	21.7	25.6	28.5
9h	12.6	14.3	16.5	19.4	21.7
12h	10.4	11.8	13.6	16	17.8
18h	8.11	9.20	10.6	12.5	13.9
24h	6.79	7.70	8.89	10.5	11.70
36h	5.25	5.95	6.87	8.08	9.01
48h	4.33	4.91	5.68	6.68	7.44
72h	3.24	3.86	4.25	5.00	5.57

2.7.2 Probable Maximum Precipitation

The Probable Maximum Precipitation (PMP) was estimated using the publication The Estimation of Probable Maximum Precipitation in Australia: Generalised Short - Duration Method (Bureau of Meteorology, 2003). The study effectively incorporates nine sub-catchments (as described in **Section 5**). If a study were undertaken separately for each one, then the PMP ellipses would be positioned differently than if they were located for the entire study area.

On this basis, the PMP ellipses were located individually for each of the main sub-catchments.

A weighted average of the PMP intensities was applied to the 2D portion of the model (**Section 6**). Table 2.8 shows the data for the PMP calculations. These PMP intensities are shown in **Table 2.9.**

The critical duration for the PMP event generally ranged from 15 minutes through to 2 hours.

Table 2.8: PMP Calculation Values

Zone	Parameter					
	PMP Ellipse	Area Enclosed	Area Between	Moisture Adjustment Factor	Elevation Adjustment Factor	Percentage Rough
A	A	1.0	1.0	0.70	1	0
IH	A	1.35	1.35	0.70	1	0
CD	A	1.48	1.48	0.70	1	0
BG	A	1.77	1.77	0.70	1	0
EFP	A	1.46	1.46	0.70	1	0
JK	A	1.43	1.43	0.70	1	0
ML Hawthorne Canal	A	2.60	2.60	0.70	1	0
	B	6.04	3.44	0.70	1	0
NO Whites Creek	A	1.93	1.93	0.70	1	0
	B	2.62	0.69	0.70	1	0
QR Johnstons Creek	A	2.6	2.6	0.70	1	0
	B	4.39	1.79	0.70	1	0

Table 2.9: PMP Rainfall Intensities (mm/hr)

Duration	Zone A	Zone IH	Zone CD	Zone BG	Zone EFP	Zone JK	Zone ML	Zone NO	Zone QR
15 min	680	680	680	680	680	680	600	640	640
30 min	500	480	480	480	480	480	460	480	460
45 min	413.3	413.3	400	400	400	400	386.7	400	386.7
1h	360	350	350	350	350	350	330	350	340
1.5h	273.3	273.3	273.3	266.7	273.3	273.3	253.3	260	260
2h	230	225	225	220	225	225	215	220	215
3h	170	170	166.7	166.7	166.7	166.6	160	163.3	160

3 Community Consultation

3.1 Overview

A questionnaire was sent out to selected community members to provide feedback on flood experience within the Leichhardt LGA. Community members that were selected to receive the questionnaire were those within a 20 metre buffer from main stormwater pipes or potential overland flow paths within the LGA. The questionnaires were sent in the post to residents in December 2007 and replies were received over the period January – March 2008. Approximately 22,000 residents were contacted, including owners and occupiers.

The questionnaire featured eight questions, which were directed at gaining understanding of community awareness of flooding as well as historical flood information against which the hydraulic model could be calibrated (**Section 7**). A copy of the questionnaire and associated figures are attached in **Appendix A**. The data received are summarised in this report, with a complete detailed list of responses provided to Council separately.

A summary of the responses to each question can be found in **Sections 3.3 – 3.8**.

3.2 Response Rate

A total of 902 responses were received, indicating a response rate of approximately 4%. This represents a mid-range response rate in comparison to similar studies undertaken by Cardno (as a guide a low return rate is 1% or less and a high return rate is around 15%).

3.3 Duration of Residence

The duration of residency reported by the respondents is shown in **Table 3.1** and **Figure 3.1**.

Table 3.1: Duration of Residence of Respondents

Period of Residence	Number of Respondents
Less than 1 year	68
1 to 2 years	68
2 to 5 years	149
5 to 10 years	166
10 to 20 years	196
20 to 30 years	137
30 to 40 Years	54
More than 40 Years	64
Total	902

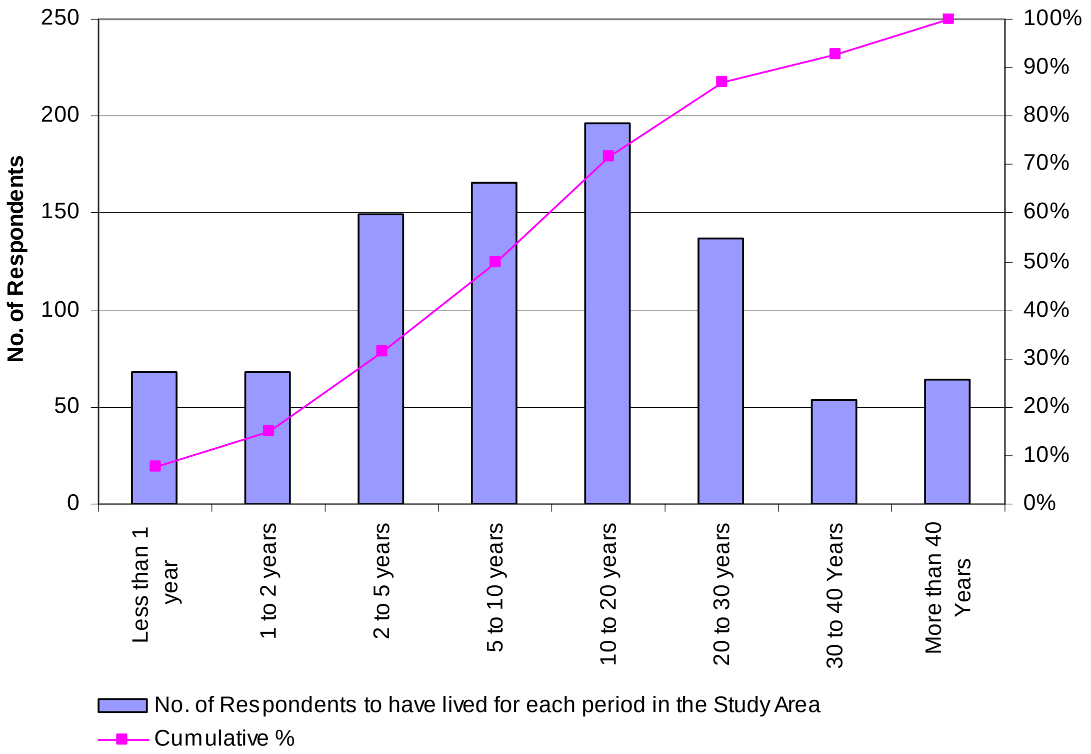

Figure 3.1: Duration of Residence of Respondents

Approximately 50 % of the respondents have lived in the study area for less than 10 years and 30 % for less than 5 years.

3.4 Flood Awareness

There was generally high awareness of flooding amongst the respondents. A total of 605 of the 902 (approximately 67%) respondents indicated awareness or some knowledge of flooding in the study area. This does not necessarily indicate general awareness of flooding by the community as questionnaires were given to a select group that were more likely to be flood affected, and only 4 % of these questionnaires were returned.

Flood awareness amongst the respondents was found to increase mildly with the duration of residence. This distribution is depicted in **Table 3.2** and **Figure 3.2**.

Table 3.2: Flood Awareness of Respondents

Period of Residence	Number of Respondents	Flood Awareness (Percentages)	
		Aware or have some knowledge	Not aware
1 year or less	68	58%	42%
1 to 2 years	68	56%	44%
2 to 5 years	149	69%	31%
5 to 10 years	166	61%	39%
10 to 20 years	196	74%	26%
20 to 30 years	137	77%	22%
30 to 40 Years	54	72%	28%
More than 40 Years	64	67%	33%

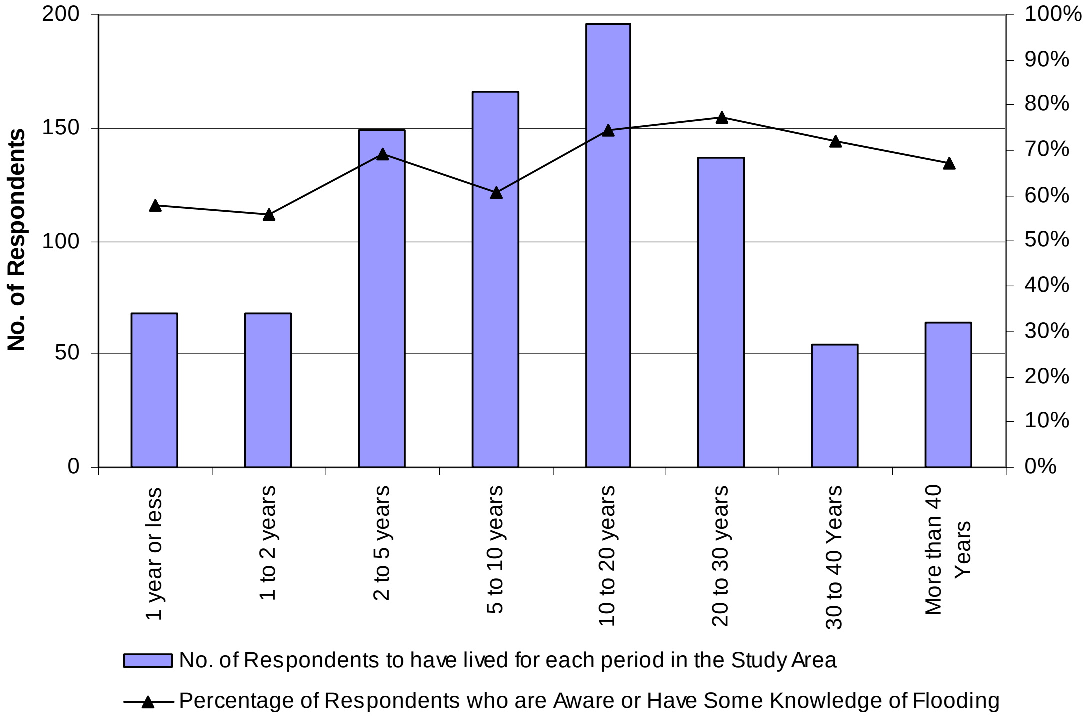

Figure 3.2: Flood Awareness and Time of Residence of Respondents

3.5 Flood Impacts

Although the majority of respondents indicated some awareness of flooding, only 41% of respondents (371) recorded being inconvenienced by flooding. The majority of the remaining respondents (58%) recorded not being inconvenienced by flooding, and 1 % did not state whether they had been inconvenienced.

A total of 26% of respondents indicated that their daily routine or access was affected by flooding in the past. Only a small number of respondents (4%) indicated that their safety had been threatened by flooding.

3.6 Events Experienced

A number of flooding events have been experienced in the study area in the past. It is expected that residents will be unlikely to recall the specific timing of all of these events, particularly the more distant events. More respondents will have experienced recent events whereas only longer term residents will have experienced more distant events. In short, the responses were skewed towards more recent events.

A summary of the classification of historical events used is presented in **Table 3.3**. The inferred (and approximate) representation of respondent's experience of these events is also shown.

Table 3.3: Inferred Flood Experience of Respondents Based on Time of Residency

Storm Events	Respondents that may have been present	
	Percentage	Number
1970's	15%	149
1980's	33%	303
1990's	50%	496
2000-2006	95%	868
Late May- Early June 2007	95%	869
End of November 2007	99%	891
Early December 2007	99%	891

3.7 Flood Damages

Properties

Residents were asked to state whether their property had been impacted by flooding in the past and, if so, when this had happened. The results are shown in **Table 3.4**.

A total of 690 of the 902 respondents (76%) stated that their property had not been impacted by floods during their period of residence. A lesser proportion of respondents (16%) stated that their land had been inundated or partially inundated, and 42 respondents (5%) stated that flooding on their property had been above the floor level of their residence. Some respondents (3%) did not answer this question.

Table 3.4: Flood Impacts Reported by Respondents

Storm Events	Not Present (Approximate)	No Damage	Property Flooded	Flooding above Floor Level	Not Stated
1970's	750	120	8	0	24
1980's	581	231	19	6	65
1990's	376	390	41	12	83
2000-2006	58	638	58	10	138
Late May- Early June 2007	22	668	73	10	129
End Of November 2007	3	686	66	9	138
Early December 2007	1	688	75	14	124

It should be noted that historical events would not have affected all parts of the LGA equally.

Regional

Residents were asked to identify other flood affected regions in the study area. Numerous areas were identified, although in many case these appeared to be related to spot flooding due to blocked drains. Two locations that were identified a number of times were the Catherine Street railway bridge, and the Thames Street ferry wharf. This is shown in **Figure 3.3**.

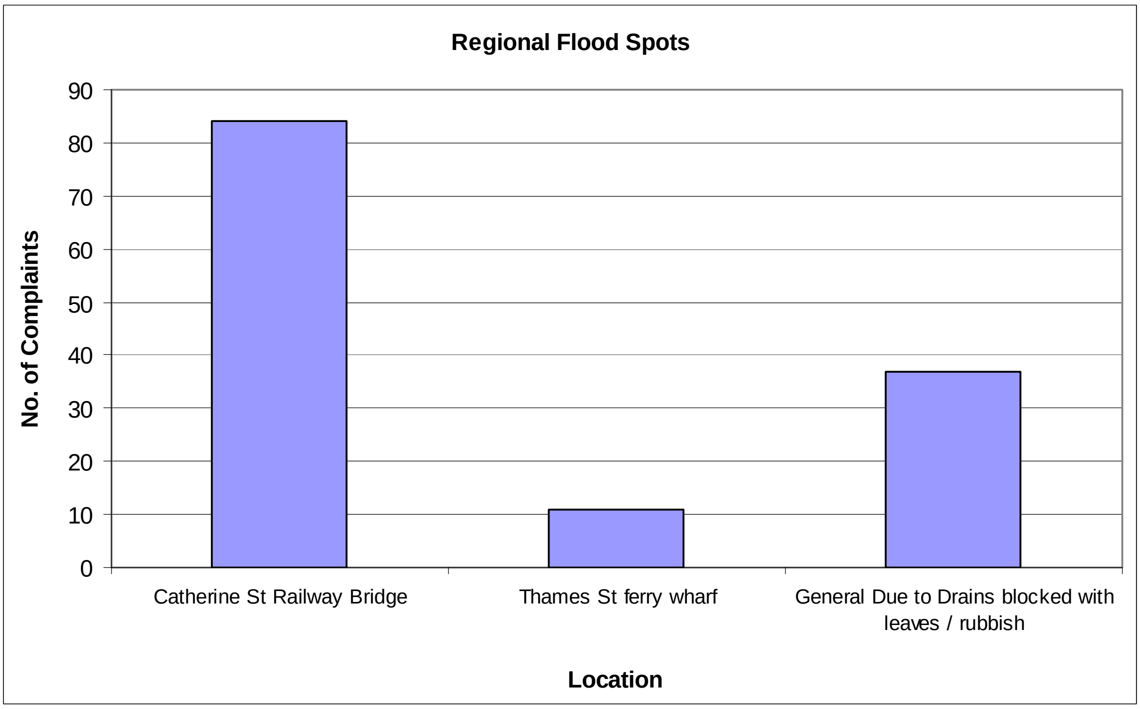

Figure 3.3: Reported Regional Flood Spots

3.8 Flood Levels

From ALS

Where respondents provided an estimate of the depth of flood water at a specific outdoor location, an estimate of the flood level could be made by considering the ALS data at that location (the ALS data is described in **Section 2.2.1**).

Residents that reported flooding were also contacted individually to obtain further data that would enable estimation of such levels.

In many cases, the respondent was describing typical flood conditions which occur regularly. In some instances the respondent could recall the specific event that the level was associated with. No respondent was able to provide multiple level estimates.

A summary of the flood level data obtained in this way is shown in **Table 3.5**. Addresses have been excluded from this table for privacy reasons.

Table 3.5: Flood Levels Estimated from ALS Using Data Reported by Respondents

Identifier	Estimated Flood Level (m/AHD)	General Flooding	1970's	1980's	1990's	2000-2006	Jun 07	Nov 07	Dec 07
98	15.9	Y	-	-	-	-	-	-	-
108	14.4	Y	-	-	-	-	-	-	-
117	28.9	Y	-	-	-	-	Y	-	-
121	21.2	Y	-	-	-	-	-	Y	-
173	22.2	Y	-	Y	-	-	-	-	-
184	14.8	Y	-	-	-	-	-	-	-
187	8.35	Y	-	-	-	-	-	Y	-
189	14.9	Y	-	-	-	-	-	-	-
204	21.85	Y	-	-	-	-	-	-	-
217	37.7	Y	-	-	Y	-	-	-	-
219	30	Y	-	-	-	Y	-	-	-
279	19.8	Y	-	-	-	-	-	-	-
315	2.9	Y	-	-	-	-	-	-	-
334	8.2	Y	-	Y	-	-	-	-	-
370	3.75	Y	-	-	-	-	-	-	-

Identifier	Estimated Flood Level (m/AHD)	General Flooding	1970's	1980's	1990's	2000-2006	Jun 07	Nov 07	Dec 07
439	12.2	Y	-	-	-	-	Y	Y	-
446	27.1	Y	-	-	-	-	Y	Y	Y
467	9.9	Y	-	-	-	-	-	-	-
589	25.15	Y	-	-	-	-	-	Y	Y
608	6.35	Y	-	-	-	-	-	-	-
620	13.2	Y	-	-	-	Y	Y	Y	Y
668	12.2	Y	-	-	-	Y	-	-	-
686	26.5	Y	-	-	-	-	-	-	-
756	24.5	Y	-	-	-	-	-	-	-
806	19.6	Y	-	Y	Y	-	-	-	-

Additional Observations

Additional key observations were available within the study area, and are shown in **Table 3.6**. These observations are useful in the determination of flood levels and estimation of flood extents within the study area. Addresses have been excluded from the table for privacy reasons.

Table 3.6: Additional Observations

Identifier	Property Damage	1970's	1980's	1990's	2000-2006	Jun-07	Nov-07	Dec-07	Comment from Respondent
58	Above Floor	-	-	Yes	Yes	Unlikely	Unlikely	Unlikely	During April 1998 & 2001.The water level was a few inches high and resulted in the back room being flooded.
62	Above Floor	-	-	-	-	-	-	-	The water pools in lower yard. Water rose up to level of rooms.
117	Property	-	-	-	Yes	Unlikely	Unlikely	Unlikely	The Garage was flooded 5 yrs ago. Floodwater rose to top of neighbours door step.
118	Above Floor	-	-	-	Yes	Likely	Likely	Likely	The living room was flooded. Our house sits on a sub-street level. Water travels over gutter and footpath into house.
272	Above Floor	-	-	Yes	Likely	Likely	Likely	Likely	Driveway, Backyard, Front yard, Garage, House.
302	Above Floor	-	-	-	-	-	-	-	Carpets were damaged.
335	Above Floor	-	-	Yes	-	-	-	-	Front yard. Water from street entered house & damaged carpet and furniture. Approx 1993.
370	Property	Likely	Likely	Likely	Likely	Likely	Likely	Likely	Driveway and backyard. Water marks on fence.
472	Above Floor	-	-	-	-	-	-	-	The neighbours uncontrolled stormwater node resulted in flooding of our property.
473	Above Floor	-	Likely	Likely	Likely	Likely	Likely	Likely	Flooding occurs during any rainfall [above floor level].
483	Above Floor	-	Yes	Unlikely	Unlikely	Unlikely	Unlikely	Unlikely	Backyard flooded building above floor level.
549	Above Floor	-	-	-	-	-	-	-	Water entered into house.
590	Above Floor	-	2	Unlikely	Unlikely	Unlikely	Unlikely	Unlikely	Carpets were damaged.
593	Above Floor	-	-	Yes	Unlikely	Unlikely	Unlikely	Unlikely	Easter 1998, floods caused damage to ground floor.
658	Above Floor	-	-	-	Unlikely	Yes	Unlikely	Unlikely	June 07- Water flowed into house since there were no drains.
675	Above Floor	-	-	-	-	Yes	Yes	Yes	Flooding in lower level room at ground floor.
710	Above Floor	-	-	-	-	-	Unlikely	Yes	Flooding in lower part of house-Dec 07. Water marks on walls.
734	Above Floor	-	-	Likely	Likely	Likely	Likely	Likely	After heavy rain.
747	Above Floor	-	Yes	Unlikely	Unlikely	Unlikely	Unlikely	Unlikely	1984 & June(?)1987 water was 1m deep hitting rear of house & rushing down side passage.
760	Above Floor	-	-	-	Unlikely	Unlikely	Unlikely	Yes	Backyard and Building.
763	Above Floor	-	-	-	Unlikely	Yes	Unlikely	Unlikely	Bathroom, kitchen & lounge (whole ground flood).
779	Above Floor	-	-	-	-	-	-	-	Backyard doesn't always process large volumes of water and it makes its way into the building.
792	Above Floor	-	-	-	Likely	Likely	Likely	Likely	During prolonged moderate to heavy rain and flash flooding.
806	Property	-	-	Likely	Likely	Likely	Likely	Likely	The garage gets flooded. Building below floor level.
828	Above Floor	-	-	-	Unlikely	Unlikely	Unlikely	Yes	Dec 07 water down Ford St, crossed Curtis Rd and flowed down Clayton Street. Flow was rapid and 20-30cm deep, passing over kerb and front step, flooding interior of property and shed and building.
830	Above Floor	-	Unlikely	Yes	Unlikely	Unlikely	Unlikely	Unlikely	Late 1998/early 1999 Carpets Damaged.
833	Above Floor	Unlikely	-	Unlikely	Unlikely	Yes	Unlikely	Yes	Flooding starts at rear then comes thru to garage, side lane in thru garden & house.
838	Above Floor	-	-	Unlikely	Unlikely	Unlikely	Unlikely	Yes	Rear of building.
851	Above Floor	-	Likely	Likely	Likely	Likely	Likely	Likely	When heavy down pour occurs street floods. Water comes inside - stock and carpet damaged.
861	Above Floor	-	Likely	Likely	Likely	Likely	Likely	Likely	
866	Above Floor	-	-	Likely	Likely	Likely	Likely	Likely	Ground floor laundry & bathroom flood in heavy rain.
Online 2	Above Floor	-	Likely	Likely	Likely	Likely	Likely	Yes	Yes. Whenever there is heavy rain such as on 5/12/2007.

3.9 Exhibition of Report and Information Sessions

The final draft (version 3) of this document was displayed on public exhibition in 2010. The exhibition of this document also involved the exhibition of a draft amendment of the flood control lot mapping contained in the Sustainable Water and Risk Management section of *Leichhardt Development Control Plan 2000.*

Given the fact that there were a number of new properties affected by the updated flood control lot mapping, the public consultation phase was split into two distinct components. Firstly, Council wrote to the owners of all new affected properties inviting them to information sessions on the Flood Study and the Draft Sustainable Water & Risk Management DCP and generally assist them to understand the consequences of the Studies and Draft DCP.

Following consultation with newly affected property owners, Council then gave public notice of the usual 28 day exhibition of the Flood Study. Public exhibition of the document was undertaken in September 2010.

As part of the consultation undertaken during the public exhibition process, specific review of the flood control lot mapping was undertaken.

4 Methodology

Two numerical modelling tools were utilised to assess flood behaviour in the LGA:

- Hydrological model (XP-RAFTS)
- Hydraulic model (SOBEK).

Both models are described in general below, and in detail in **Sections 6** and **7** respectively.

4.1 Hydrological Model

A hydrologic model combines rainfall information with local catchment characteristics to estimate a runoff hydrograph. For this study, the 'Direct Rainfall' method (also known as "rainfall on the grid") was used for areas within the 2D Domain and XP-RAFTS was used for the external catchments. The Direct Rainfall method was verified using results from a more traditional hydrological modelling approach using XP-RAFTS.

4.2 Hydraulic Model

A hydraulic model converts runoff (traditionally from a hydrological model) into water levels and velocities throughout the major drainage/creek systems in the study area (known as the model 'domain', which includes the definition of both terrain and roughness). The model simulates the hydraulic behaviour of the water within the study area by accounting for flow in the major channels as well as potential flow paths, which develop when the capacity of the channels is exceeded. It relies on boundary conditions, which include the runoff hydrographs produced by the hydrologic model and the appropriate downstream boundary.

A 1D/2D fully dynamic hydraulic model was established for the study area. SOBEK 1D/2D, a dynamic hydraulic modelling system developed by WL|Delft Hydraulics (now Deltares) of the Netherlands was used in this study. The system is used world-wide and has been shown to provide reliable, robust simulation of flood behaviour in urban and rural areas through a vast number of applications. The model allows addition of a 2 dimensional (2D) domain (representing the study area topography) to a one dimensional (1D) network (representing the channels in the study area) with the two components dynamically coupled and solved simultaneously using the robust 'Delft Scheme'.

An important feature of the model is the ability to model the hydraulic structures in the 1D component rather than in the 2D domain. The benefit of this approach is that structure hydraulics are modelled more precisely than the approximate representation possible in a 2D domain.

Stormwater drainage pits, pipes and channels are represented in the model as one-dimensional elements which are dynamically linked to the water conveyed across the elevation grid.

5 Hydrological Modelling

Hydrological modelling was undertaken using two methods:

- Traditional Hydrological modelling using XP-RAFTS - The hydrological modelling was undertaken to develop catchment runoff hydrographs for areas outside of the 2D model domain. These hydrographs were then used as inflow boundaries for the hydraulic modelling.
- Direct Rainfall Method, where rainfall is applied directly to the 2D hydraulic model grid and routing occurs within the hydraulic model.

Details of hydrological modelling are provided below.

5.1 Traditional Hydrological Modelling (XP-RAFTS)

An XP-RAFTS hydrological model was established for the upstream area of the catchment, outside of the Leichhardt LGA. The land use within the catchment is highly urbanised with predominantly residential areas and some light industrial / commercial areas. The following attributes were considered in the hydrological analysis of the catchment:

- Rainfall intensity-frequency-duration (IFD) relationships
- Sub-catchment divisions
- Slopes and overland flowpath lengths, and
- Land use (pervious and impervious areas).

5.1.1 Sub-Catchments

The catchments were defined based on the topographic features (using the 2-metre contour data), the likely flowpaths, location of pits and pipes and the requirements of hydraulic model. The catchment area outside of the LGA was divided into 20 sub-catchments. The sub-catchment areas and layout are shown in **Figure 5.1** and the characteristics of the sub-catchments are provided in **Table 5.1**.

For urban areas, an impervious percentage of the catchment of 60% was assumed. Higher density residential areas (such as apartments) were assigned an impervious percentage of 70%. However, the majority of the residential areas in the catchment are not high density, and were therefore assigned a 60% imperviousness. This assumption was based on site inspection and previous studies.

Using the above categories, the impervious and pervious areas for each of the sub-catchments were determined.

Table 5.1: Sub-Catchment Details

Sub-Catchment (ID)*	Sub-Catchment Area (ha)	Catchment Slope (%)	Impervious Area (ha)	Pervious Area (ha)
C1	18.4	3.6	11.0	7.4
C2	4.8	6.4	2.9	1.9
C3	45.9	2.0	27.5	18.4
C4	90.0	2.0	54.0	36.0
C5	12.2	2.2	7.3	4.9
C6	74.9	1.6	45.0	30.0
C7	14.5	3.4	8.7	5.8
C8	5.9	3.0	3.6	2.4
C9	49.2	3.5	29.5	19.7
C10	70.0	1.9	42.0	28.0
C11	31.3	2.7	18.8	12.5
C12	48.9	2.4	29.4	19.6
C13	8.6	3.0	5.1	3.4
C14	16.6	3.8	9.9	6.6
C15	69.1	2.0	41.4	27.6
C16	120.2	1.6	72.1	48.1
C17	47.7	2.7	28.6	19.1
C18	26.4	2.7	15.8	10.6
C19	32.7	3.1	19.6	13.1
C20	33.4	2.0	20.0	13.4

**See Figure 5.1 for the location of each sub-catchment.*

5.1.2 Hydrological Model Parameters

Important parameters used in the development of the XP-RAFTS model are provided in **Table 5.2**.

Table 5.2: XP-RAFTS Model Parameters

RAFTS Parameter	Urban Pervious Area	Urban Impervious Area
Manning's n for sub-catchments	0.1	0.015
Storage delay for parameter (B)	1.0	1.0
Hydrograph Routing Lag	Based on Kinematic Wave Equation, Manning's Equation and past experience	

5.1.3 Rainfall Losses

Design rainfall losses were adopted in accordance with AR&R (Engineers Australia, 1999). The loss values are provided in **Table 5.3**.

Table 5.3: Design Rainfall Losses used in RAFTS

Catchment Type	Initial Loss (mm)	Continuing Loss (mm/hr)
Impervious	1.5	0
Pervious	10	2.5

5.1.4 Runoff Hydrology

The RAFTS model was used to produce the runoff hydrographs for input into the SOBEK hydraulic model (**Section 7**). The model runs were carried out for historic (actual floods) as well as for design flood events.

Historic Events

Rainfall data (**Section 2.5**) for the January 1991, February 1993 and April 1998 flood events was processed for input to the model. The rainfall was incorporated in the model and the model hydrographs generated for use in the hydraulic model. **Figure 5.2** provides location of catchments which formed boundaries for the hydraulic model for the historic flood events for Hawthorne Canal, Whites Creek and Johnstons Creek.

Design Events

Due to the relatively small area of the catchment, uniform areal distribution of design storms has been assumed in the hydrologic analysis. The estimated design rainfalls (**Section 2.7**) were applied to the hydrologic model in order to predict design runoff hydrographs. Design flows were obtained for the 15min, 30min, 1hr, 1.5hr, 2hr, 3hr, 4.5hr, 6hr and 9hr duration storm events. **Table 5.4** provides the peak flows and critical durations determined from the XP-RAFTS model for the catchments directly upstream of the hydraulic model (i.e. catchments C4, C6, D2, C7, C8, C9, D1, shown in **Figure 5.2**).

Table 5.4: Peak Flows and Critical Durations from the XP-RAFTS Model

Design Event	C4		C6		D2		C7		C8		C9		D1	
	Qp*	CD*	Qp*	CD*	Qp*	CD*	Qp*	CD*	Qp*	CD*	Qp*	CD*	Qp*	CD*
PMF	153.25	0.25	127.83	0.25	199.92	0.25	24.41	0.25	10.10	0.25	81.60	0.25	247.50	0.75
100yr	38.40	1	32.21	1	51.64	1	6.63	1	2.74	1	22.27	1	73.36	1
50yr	34.06	1	28.66	1	45.81	1	5.83	1	2.44	1	19.88	1	64.90	1
20yr	30.48	1	25.75	1	41.01	1	5.15	1	2.17	1	17.74	2	55.90	1
10yr	26.14	1	21.93	0.5	34.86	1	4.41	2	1.82	1	15.14	2	47.94	1
5yr	22.75	1	19.28	0.5	30.82	0.5	3.88	2	1.58	0.5	13.27	2	41.18	1
Jan 1991	25.73	N/A	21.32	N/A	34.6	N/A	4.33	N/A	1.75	N/A	14.7	N/A	40.34	N/A
Feb 1993	23.48	N/A	19.79	N/A	31.62	N/A	3.86	N/A	1.59	N/A	13.38	N/A	36.73	N/A
April 1998	26.07	N/A	21.85	N/A	34.90	N/A	4.28	N/A	1.77	N/A	14.89	N/A	40.72	N/A

*Qp=Peak Discharge (m^3/s), CD = Critical Duration (hours)

5.1.5 Calibration of Hydrological Model

As is common for most urban areas, there are no flow gauges in the study area (i.e. gauges that measure actual water flows, commonly in a channel) and hence the hydrological model could not be calibrated directly. A combined hydrology/ hydraulics approach was adopted, where the hydraulic model was calibrated with input from the hydrologic model, thus indirectly validating the results of the hydrologic model. The January 1991, February 1993 and April 1998 storm events were used for this purpose. This process is described in **Section 7**.

5.2 Direct Rainfall

In the application of rainfall directly on the 2D grid ('Direct Rainfall' method), the hydrology and the hydraulics is undertaken in the same modelling package, using the hydraulics function only. In the model, rainfall is applied directly to the 2D terrain, and the hydraulic model automatically routes the flow using the same computation process that controls the routing of all other flows through the model. This means that catchment outlets do not have to be predefined, and flowpaths are identified by the model, rather than being assumed.

In this approach, the entire catchment is represented in the 2D terrain. This approach allows for overland flow paths to be revealed which would not otherwise be represented using traditional hydrologic and hydraulic approaches.

There are a number of advantages of the modelling approach, particularly given the nature of the Leichhardt Local Government Area. In flat areas, overland flow paths are not always obvious. Furthermore, additional and unexpected 'cross-catchment' flows may activate in larger events. The rainfall on the grid approach overcomes these issues, as the model will automatically divert flood waters along different flowpaths (based on the terrain and the roughness) during high flow events.

When there are a large number of stormwater pits and pipes, such as in the Leichhardt LGA, it can be difficult to determine the catchment that applies to a particular pit in using a traditional hydrological modelling approach. With the Direct Rainfall method, flows are automatically routed to the pit. This can provide a significant saving in time, as well as reduce potential errors in the application of flow.

5.2.1 Rainfall Losses

Currently it is not possible to incorporate varying rainfall losses or intensities within the model using the rainfall on the grid process. This is not considered to be a significant issue given the small sizes of the catchments in the Leichhardt LGA and the relative uniformity of the impervious area.

5.2.2 Calibration

As outlined in **Section 5.1.5**, there are no flow gauges in the study area and hence the hydrological model could not be calibrated directly. In the same manner as for the hydrologic model calibration, a combined hydrology/ hydraulics approach was adopted, where the hydraulic model was calibrated with input from the hydrology model, thus indirectly validating the results of the hydrology model.

5.2.3 Verification to XP-RAFTS Hydrological Modelling

A detailed discussion on the verification of the Direct Rainfall method to the results of the XP_RAFTS hydrological modelling is discussed in **Section 7.2**.

6 Hydraulic Modelling

The analysis of overland flow is a complex task in an urban environment. In many developed areas, the natural creek systems have been replaced with underground pipe drainage, which has a limited capacity. The overland flow resulting from a major rainfall event may affect areas that are different to those that would have otherwise been affected if the system were in its natural state. This is due to the complexity of overland flowpaths that are created as a result of the development of the area. A reasonably accurate assessment of flooding in such areas requires a two-dimensional approach in modelling the flood behaviour.

6.1 Model Schematisation

A fully dynamic one and two dimensional (1D/2D) hydraulic model was developed for the study area using the SOBEK modelling system. Smaller channels (up to the top of bank) have been modelled as a one-dimensional (1D) element with cross-sections defining the channel geometry (**Figure 2.1**). Once the channel capacity is exceeded, flow is able to spill into the two-dimensional (2D) overland flow grid, which overlies the 1D elements in the model. As flood waters recede, flow is also generally able to drain from the overland areas back into the defined channels. For larger channels (such as Hawthorne Canal), the channel has been represented in the 1D portion of the model.

Stormwater drainage pits and pipes (from 225 mm in diameter), shown in **Figure 2.1** have also been incorporated into the model as 1D elements. Once the pipe capacity is exceeded, excess flow spills into the 2D domain via the pits. Similarly, overland flow is able to enter the pipe network through the relevant pit when the drainage system at that location is not at capacity.

6.2 1D Model Set-up

For the 1D components of the model, the channel cross sections were located such that all flow controls were captured, and so that the cross sections adequately represented variations in the channel definition. Details of structures within the study area (such as bridges and culverts) were also gathered, and included in the model.

The details of the majority of 1D cross sections and structures were based on survey data captured by Cardno's surveyors (July 2008) and from Sydney Water (**Section 2**).

The 1D component of the model includes a number of drainage channels, stormwater drainage culverts at the concrete bridge and foot bridges in the study area. Pits and Pipes in the model, as defined in Council's GIS layer (**Section 2.4**) were incorporated into the 1D domain.

Larger channels within the study area were incorporated into the 2D portion of the model. These include Hawthorne Canal, Whites Creek and Johnstons Creek.

The layout of the channels and stormwater drainage incorporated in the model is shown in **Figure 6.1**.

6.3 Piped Drainage Systems

Piped drainage systems are incorporated into the SOBEK model as distinct 1D elements connected to the terrain grid. Detailed field survey by Cardno's surveyors (**Section 2.2.2**) was primarily utilised for the modelling. This data was supplemented by pit and pipe data supplied by Sydney Water (**Section 2.2.3**).

The different size of the inlet pit openings was included in the model as orifice-links of the same size to represent the restriction of the flow in the piped system. An orifice-link was included between pipeline reaches to model the energy losses at pits and between conduits.

Figure 6.1 shows the pipe and channel systems incorporated in the model. About 75 kilometres of pipes and 5 kilometres of channel systems are modelled.

6.4 2D Model Set-up

Two-dimensional (2D) hydraulic modelling was carried out to determine the flood behaviour for the entire catchment. The majority of the input to the hydraulic modelling was not based on traditional methods of hydrological analysis. Rather, design rainfall time-series were applied directly on the model domain as input, which resulted in the generation of overland flow. Appropriate rainfall losses were subtracted from the design rainfall (**Section 2.7**) to derive rainfall-excess hyetographs (see **Section 5.2**).

A fine grid size (1m x 1m) was deemed necessary to define the overland flowpaths through the developed areas of the LGA. This resulted in approximately 23 million grid cells for the model domain. However, due to current computer limitations (speed and memory), it was not possible to establish a single detailed model grid for the entire study area. To overcome this limitation, the study area was divided into nine model zones.

As described in **Section 6.2**, culverts/bridges in the study area were included as one-dimensional (1D) components within the fine grid.

The 1D component of the model primarily covers the in-bank portion of the smaller channels as well as pits and pipes in the study area. All other major flowpaths including the overland flow in the study area were modelled as part of the 2D model component.

The model grid was developed from the survey data (**Section 2**). The civil and surveying package 12D was used to generate a detailed 3D surface (digital terrain model) of the study area. Important hydraulic controls such as bridges were represented at the correct levels in the topographical grid.

6.5 Model Terrain

A terrain grid (also referred to as a 'topographic' grid) was developed to represent ground elevations based on aerial laser scanning data provided by Council (**Section 2**), with some modifications based on the cross-section ground survey. The model zones are shown in the **Figure 6.2**.

The details of elevation grids for each of the model zones are listed in **Table 6.1**.

Table 6.1: Model Zones

Zone	Area (ha)	Grid Origin Coordinates (GDA 94)	Grid Resolution	Number of Grid Cells
A	86	330547, 6252167	1mx1m	2,246,400
IH	134	331294, 6251649	1mx1m	2,496,860
CD	148	329072, 6250395	1mx1m	3,715,159
BG	177	330732, 6250802	1mx1m	2,556,072
EFP	146	329655, 6249914	1mx1m	2,593,848
JK	143	328346, 6249218	1mx1m	2,445,378
ML	153	328271, 6248389	1mx1m	1,969,335
NO	188	329401, 6248563	1mx1m	3,587,874
QR	129	330469, 6248660	1mx1m	2,157,562

6.6 Buildings

All buildings within the study area were conservatively assumed to completely block overland flow, and were modelled as raised blocks in the topographic grids. This was based on building outlines which were supplied by Council.

6.7 Hydraulic Roughness

The hydraulic roughness for the 1D cross sections and 2D model grid was determined using both aerial photography supplied by Council (**Section 2.2**) and site inspections carried out during the study (**Section 2.3**).

There is no standard reference that provides guidelines on estimating the hydraulic roughness for overland flow in 2D models in urban areas. Standard references such as Chow (1973) that provide roughness values for channels can provide an approximate estimate of 2D roughness. However, a better guide for 2D roughness is past experience in 2D model calibration. As such, the roughness values used in the 2D model grid have been based on past experience in model calibration in catchments of similar land use and topography.

The roughness values adopted for the 1D elements are listed in **Table 6.2.** The 2D roughness values adopted are shown in **Figure 6.3**.

Table 6.2: 1D Element Roughness Values

Component	Adopted Roughness Value
Pipe	0.018
Culvert	0.018
Open Channel	0.018

6.8 Estimation of Critical Duration

Due to the long computational run times, the model runs were carried out for critical durations only (the duration of rainfall over the catchment that will result in the greatest depth of flooding). The critical duration for each model zone was determined from preliminary modelling undertaken using a 5mx5m grid, excluding pipes. The PMF, 100 year, 50 year, 20 year, 10 year and the 5 year ARI design events were run for standard durations of 15, 30, 45 minutes and 1, 1.5, 2, 3, 4,5, 6, 9 and 12 hours. The results of this modelling were then used to establish the critical duration. **Table 6.3** provides the critical durations adopted for various model zones in the LGA.

Table 6.3: Critical Durations Adopted for Various Model Areas in the LGA

Zone*	100yr ARI	50yr ARI	20yr ARI	10yr ARI	5yr ARI	PMF
A	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	15m,30m, 45m
IH	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	15m,30m, 45m
CD	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	15m,30m, 45m
BG	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	15m,30m, 45m,90m
EFP	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	15m,30m, 45m,90m
JK	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	15m,30m, 90m,2hr
ML	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	15m,30m, 45m,60m, 90m,2hr
NO	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	30m,60m,2hr	15m,30m, 45m
QR	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	30m,60m,2hr, 9hr	15m,30m, 45m,90m,2hr

**See Figure 6.2 for model zone areas, m – minute, hr - hour*

6.9 Boundary Conditions

6.9.1 Model Inflows

Inputs to the upstream sections of the model were applied as hydrographs from the hydrological model (**Section 5.1**). Within the 2D domain, rainfall was applied directly to the grid. Thus rainfall-runoff routing for the modelled area was directly carried out in the hydraulic model (as described in **Section 5.2**).

This approach was used for both historical events (**Section 7**) and design conditions (**Section 8**).

6.9.2 Downstream Boundary

Overview

Sydney Harbour water levels affect the driving head available for discharge of flood flows into the Harbour.

Calibration Boundary Conditions

A synthetic tidal boundary was derived for the historical events of January 1991, February 1993 and April 1998 based on Fort Denison tidal constants. This approach assumes no tidal anomalies occurred at the time of the event (e.g. no effects of storm surge from ocean storm events, often referred to as 'storm tides'). As the majority of observations were not near the foreshore, this approach was considered reasonable and appropriate.

Design Flood Boundary Conditions

The following logic was adopted to determine the design Harbour levels.

The critical duration of flood events in Leichhardt is in the order of one to three hours, and peak Harbour levels, which are dominated by the astronomical tide, have a similar duration around peak water level (a normal tidal cycle in Sydney from low to high to the next low tide is approximately 12 hours). Therefore extreme Harbour storm tides are not likely to occur at the same time as urban floods of this type. Ocean storms may cause elevated Harbour water levels for periods of up to four days. Nevertheless, the normal astronomical tide will cause high and low water levels and the likelihood of a flood event occurring at the same time as peak ocean high water level is small.

Analyses of long term rainfall and measured water levels at Newcastle (for the Hunter River) have shown virtually no correlation. From a probability perspective, the most likely Harbour water level occurring jointly with a local flood event is mean sea level (MSL), with some minor hint of increased elevation caused by low atmospheric pressure. Therefore 0m AHD could be adopted as the most likely or expected ocean level. However, it is recommended that a more conservative risk-based approach is adopted whereby the Harbour boundary water level is to be that level which is only equalled or exceeded for 1% of the time. This level is 1.0m AHD in the Sydney region. This approach, originally developed for Newcastle City Council, has subsequently been adopted for various other studies and is suitable for this site also. The level excludes wave set-up which is not unreasonable for the study area. It should be noted that this approach is not appropriate for major river floods, but is suitable for short duration floods in urban catchments. Further discussion of the approach can be found in Howells *et al*, (2005).

Based on the above reasoning, the design water level for Sydney Harbour was adopted to be 1.0 mAHD for all design flood events. Thus for each design event in the catchment there is 99% chance that the Harbour level of 1.0 mAHD will not be exceeded during that event. This is based on the assumption that the Harbour water levels and catchment flooding are independent events.

An analysis of the impact of an alternate Harbour level to that assumed above is provided in the sensitivity analysis in **Section 12**.

As outlined in **Section 2.1.2**, it should also be noted that this study represents flooding from the catchment only and therefore this is why the approach outlined above has been adopted. Reference should be made to the *Estuarine Planning Levels* Study for more information on estuarine inundation flooding from the Harbour (Cardno Lawson Treloar, *in prep*).

7 Model Calibration and Validation

The calibration and validation of the model was undertaken through three stages:

- Calibration and validation to historical flood events;
- Verification to previous Sydney Water Studies; and,
- Verification of Direct Rainfall Method with xp-rafts.

7.1 Historical Flood Events

The storm events of January 1991, February 1993 and April 1998 were selected for calibration and validation of the SOBEK hydraulic model. Calibration and validation of models is undertaken to show that the models can reproduce conditions similar to actual historical events, which then gives confidence in the reliability of the results of design flood assessments.

The resident questionnaire detailed in **Section 4** indicated most respondents recalled January 1991, February 1993 and April 1998 events. The data required to calibrate the SOBEK model to particular events includes recorded water levels in the floodplain (**Section 7.1**), event rainfall data (**Section 2.5**), and tidal boundary conditions (**Section 6.9.2**). Data was available for the three events, thus the model could be both calibrated and validated.

7.1.1 Calibration and Validation Results

The hydraulic model was calibrated using the February 1993 flood event (approximately a 50 year ARI rainfall event, **Section 2.5**) and validated using the January 1991 (approximately a 20 year ARI rainfall event, **Section 2.5**) event and April 1998 event (approximately a 10 year ARI rainfall event, **Section 2.5**).

There were a number of observed flood levels and other anecdotal advice for each event. **Figures 7.1, 7.2 and 7.3** display the location of historic flood level information for the 1991, 1993 and 1998 events respectively.

Results from the model were compared against the recorded water levels and observed flow behaviour within the study area. **Table 7.1, Table 7.2 and Table 7.3** show the comparison between the observed and modelled flood levels.

7.1.2 Calibration and Validation Conclusions

The results of the calibration and validation (**Table 7.1, Table 7.2 and Table 7.3**) show that the hydraulic model is capable of reproducing the observations from the historical storm events. The majority of peak water level comparisons show that the model reproduces results generally within +/- 0.10 metres. Larger discrepancies are observed at a few locations, but these are generally expected to be due to measurement and observation errors. In addition to the peak water level comparisons, observations of flood behaviour noted by residents (**Section 4**) agree well with the flooding behaviour in the model.

On this basis, the models are considered reliable for the purposes of design flood event assessments.

Table 7.1: Validation Details - 21 January 1991 Event

Location ID#	Description	Source*	Observed Flood Depth (m AHD)	Observed Flood Level (m AHD)	Modelled Flood Level (m AHD)	Difference between Observed Level and Modelled Level		Comments
						Difference (m)	Based on (D= Depth, WL= Water Level)	
A	Property surrounded by water. Did not enter house.	SW	NA	5.98	6.0	0.02	WL	Excellent comparison between observed and modelled level.
B	No specific description available.	SW	NA	5.95	5.96	-0.01	WL	- Excellent comparison between observed and modelled level.
C	No specific description available.	SW	NA	5.47	5.47	0	WL	Excellent comparison between observed and modelled level.

*#See Figure 7.1; * SW – Sydney Water, NA – Not available, only level observed.*

Table 7.2: Calibration Details - 17 February 1993 Event

Location ID#	Description	Source*	Observed Flood Depth (m AHD)	Observed Flood Level (m AHD)	Modelled Flood Level/Depth (m AHD)/(m)	Difference between Observed Level and Modelled Level		Comments
						Difference (m)	Based on (D= Depth, WL= Water Level)	
A	No specific description available.	SW	0.5	4.2	WL=5.28m(AHD), Depth=0.5m	0	D	GL=4.78m(AHD) Excellent comparison between observed and modelled depth.
B	No specific description available.	SW	0.3	NA	Depth=0.35m	0.05	D	Good comparison between observed and modelled level.
C	No specific description available.	SW	0.3	2.44	WL=2.45m(AHD), Depth=0.32m	0.01	WL	Excellent comparison between observed and modelled depth.
D	No specific description available.	SW	0.3	2.1	WL=2.12m(AHD), Depth=0.28m	0.02	WL	Excellent comparison between observed and modelled depth.
E	About 0.25m above footpath at No. 3	SW	-	-	-	-	-	Exact location of observed level is uncertain.
F	No specific description available.	SW	0.45	2.91	WL=2.96m(AHD), Depth=0.49m	0.05	WL	Good comparison between observed and modelled level.
G	No specific description available.	SW	0.45	2.75	-	-	-	Exact location of observed level is uncertain.
H	No specific description available.	SW	0.3	1.84	WL=1.82m(AHD), Depth=0.31m	-0.02	WL	Excellent comparison between observed and modelled depth.
I	No visible flood mark.	SW	-	-	-	-	-	No reliable survey level could be obtained for this location.

Location ID#	Description	Source*	Observed Flood Depth (m AHD)	Observed Flood Level (m AHD)	Modelled Flood Level/Depth (m AHD)/(m)	Difference between Observed Level and Modelled Level		Comments
						Difference (m)	Based on (D= Depth, WL= Water Level)	
J	No specific description available.	SW	0.65	9.63	WL=12.48m(AHD) ,Depth=0.62m	-0.03	D	GL=11.86m(AHD) Good comparison between observed and modelled level.
K	No specific description available.	SW	0.65	9.64	WL=12.42m(AHD) ,Depth=0.66m	0.01	D	GL=11.76m(AHD) Excellent comparison between observed and modelled depth.
L	‘Just full’ (See comment).	SW	NA	NA	WL=4.2m(AHD), Depth=0.49m	-	-	It is assumed that the description refers to the channel. The model shows that the channel is full and just overflowing and the water flows over top of the culvert. The WL and flood depth refers to the side of the property near the channel.
M	Flood level 380mm above loading dock level.	F	NA	10.52	11.10m(AHD)	-	-	GL=10.3 m(AHD). The height of the loading dock is 0.38m above G.L, and the flood level is 380mm above the loading dock. (10.3+0.38+0.38=11.06m AHD)
N	Flood level at end entrance ramp.	F	NA	7.93	9.2m(AHD)	-	-	GL=8.15 m(AHD). The ground level is higher than the recorded flood level.
O	No specific description available.	F	NA	2.09	-	-	-	Exact location of observed level is uncertain.
P	No specific description available.	F	NA	2.56	WL=2.52m(AHD)	-0.04	WL	Good comparison between observed and modelled level.

Location ID#	**Description**	**Source***	**Observed Flood Depth (m AHD)**	**Observed Flood Level (m AHD)**	**Modelled Flood Level/Depth (m AHD)/(m)**	**Difference between Observed Level and Modelled Level**		**Comments**
						Difference (m)	**Based on (D= Depth, WL= Water Level)**	
Q	No specific description available.	F	NA	5.84	WL=5.88m(AHD)	0.04	WL	Good comparison between observed and modelled level.
R	No specific description available.	F	NA	5.8	WL=5.86m(AHD)	0.06	WL	Reasonable comparison between observed and modelled level.
S	No specific description available.	F	NA	5.4	WL=5.42m(AHD)	0.02	WL	Excellent comparison between observed and modelled level.

*#See Figure 7.2; * Source – SW – Sydney Water Studies, F= Information contained within LMC File No. 225419F1; NA – Not available, only level observed, GL – Ground Level.*

Table 7.3: Validation Details - 9 - 10 April 1998 Event

Location ID#	Description	Source*	Observed Flood Depth (m AHD)	Observed Flood Level (m AHD)	Modelled Flood Level (m AHD)	Difference between Observed Level and Modelled Level		Comments
						Difference (m)	Based on (D= Depth, WL= Water Level)	
A	Water through retaining wall to lower terrace.	SW	NA	NA	WL=5.88m(AHD),Depth=0.55m	-	-	Model shows that the backyard of the property is flooded. Water flows over the covered channel.
B	Over covering of main channel	SW	0.6	NA	WL=9.10m(AHD),Depth=0.62m	0.02	D	Model shows that the water flows over the covered channel. Excellent comparison between observed and modelled level.
C	Flood waters entered property to above floor level	SW	NA	NA	WL=7.25m(AHD),Depth=0.45m	-	-	The ground level is approximately 6.80m (AHD).The model shows that the backyard of the property is flooded. The WL and flood depth refers to the backyard of the property near the channel.
D	Above footway at fence in The Crescent opposite Trafalgar St	SW	0.3		WL=2.75m(AHD),Depth=0.33m	0.03	D	Good comparison between observed and modelled level.
E	Minor bank overflow in park	RS	NA	NA	WL=1.68m(AHD), Depth=0.17m	-	-	The model result shows that the WL is 0.15m above coping level in the channel.

Location ID#	Description	Source*	Observed Flood Depth (m AHD)	Observed Flood Level (m AHD)	Modelled Flood Level (m AHD)	Difference between Observed Level and Modelled Level		Comments
						Difference (m)	Based on (D= Depth, WL= Water Level)	
F	Water coming off Parramatta Rd, Young St and Ferris St	RS	NA	NA	WL=19.65m(AHD), Depth=0.30m	-	-	The ground level is approximately 19.35m (AHD).Model shows that water flows from Parramatta Rd to Ferris street. The WL and flood depth refers near the entrance of the property.
G	Flood water above floor level	RS	NA	NA	WL=20.48m(AHD), Depth=0.35m	-	-	Floor Level is approximately 20.30 to 20.35m (AHD). The WL and flood depth refers near the entrance of the property.
H	2 major floods in backyard. Water over 1 metre in backyard. Basement area flooded as was War Memorial Park. Happened twice over 15 years ago.	RS	NA	NA	WL=19.70m(AHD), Depth=1.43m	-	-	In all the three events (1991, 1993, 1998) the models show that the backyard of the property is flooded. The flood depth at the backyard of the property in all the three events is greater that 1m as noted by the resident.

Location ID#	**Description**	**Source***	**Observed Flood Depth (m AHD)**	**Observed Flood Level (m AHD)**	**Modelled Flood Level (m AHD)**	**Difference between Observed Level and Modelled Level**		**Comments**
						Difference (m)	**Based on (D= Depth, WL= Water Level)**	
I	During April 98 .The water level was a few inches high and resulted in the backroom being flooded.	RS	NA	NA	WL=12.40m(AHD), Depth=0.3m	-	-	The model shows the backyard of the property flooded. The WL and flood depth refers to the backyard of the property.
J	Carpet damaged in front hall, front yard flooded.	RS	NA	NA	WL=13.9m(AHD), Depth=0.2m	-	-	The Ground Level is approximately 13.70m (AHD).The model shows the entrance of the property flooded. The WL and flood depth refers near the front of the property. Property entrance is below street level, and is expected to be inundated by this depth of water.

*#See Figure 7.3; * Source – SW – Sydney Water Studies, RS – Resident Survey, NA – Not available, only level observed, GL – Ground Level.*

7.2 Verification with Sydney Water Studies

Sydney Water has undertaken flood studies for both Johnstons Creek and Whites Creek, as detailed in **Section 2.1.1**. A comparison was undertaken between the modelled levels from the Sydney Water studies and the levels from the current study for the 100 year ARI event. This comparison is shown in **Table 7.4** for Whites Creek and

Table 7.5 for Johnstons Creek. The locations of the points in this table are shown in **Figure 7.4** and **7.5**.

In general, it would be expected to find some differences in the models. The approach adopted in this study utilises a more detailed and refined model. In addition, more survey data, including aerial survey, was available for this study compared with the Sydney Water study.

Nonetheless, the comparison of the two sets of models shows a good agreement between the levels. In general, the peak water levels from the Sydney Water study are within +/-0.1 metres of the current study for the upper reaches of Whites Creek, while large differences are observed at the downstream open channel. Higher levels are expected downstream in the Sydney Water Study because HEC 2 model was used and that significant localised depression storages, would not be accounted in this model.

The peal water levels are in the order of +/- 0.1 to 0.2 metres for Johnstons Creek. The largest differences are observed at locations D, E, and F. However, it is noted for these two locations that the depths are close in both models, and therefore it is suspected that the survey data from the Sydney Water studies may not be incorrect or superseded.

Table 7.4 Sydney Water 100 year ARI Verification - Whites Creek

Location ID	Sydney Water Reference	Observed Flood Depth (m AHD)	Observed Flood Level (m AHD)	Modelled Flood Depth	Modelled Flood Level (m AHD)	Difference between Observed Depth and Modelled Depth (m)	Difference between Observed Level and Modelled Level (m)	Comments
A	2302	0.54	22.73	0.54	23.23	0	-0.5	Satisfactory comparison to observed flood depth
B	2268	0.38	21.61	0.38	21.71	0	-0.1	Satisfactory comparison to observed flood depth
C	2215	0.43	20.76	0.4	21.22	0.03	-0.46	Satisfactory comparison to observed flood depth
D	2174	0.67	20.3	0.64	19.96	0.03	0.34	Satisfactory comparison to observed flood depth
E	2126	0.85	19.79	0.76	19.5	0.09	0.29	Satisfactory comparison to observed flood depth

Location ID	Sydney Water Reference	Observed Flood Depth (m AHD)	Observed Flood Level (m AHD)	Modelled Flood Depth	Modelled Flood Level (m AHD)	Difference between Observed Depth and Modelled Depth (m)	Difference between Observed Level and Modelled Level (m)	Comments
F	2067	0.67	18.87	0.66	18.8	0.01	0.07	Satisfactory comparison to observed flood depth
G	2010	0.75	18.19	0.5	18.18	0.25	0.01	
H	1873	0.68	16.46	0.59	16.42	0.09	0.04	
I	1702	0.89	13.55	0.91	13.57	-0.02	-0.02	
J	1570	1.3	12.52	1.25	12.45	0.05	0.07	
K	1397	0.8	9.78	0.8	10.03	0	-0.25	Satisfactory comparison to observed flood depth
L	1219	1.89	7.19	1.83	7.26	0.06	-0.07	
M	1203	1.38	6.56	1.52	6.51	-0.14	0.05	
N	1075	1.48	4.58	1.38	4.43	0.1	0.15	
O	976.5	3.8	4.69	3.35	4.26	0.45	0.43	OPEN CHANNEL
P	894.1	3.78	4.55	3.5	4.3	0.28	0.25	OPEN CHANNEL
Q	877.4	3.82	4.56	3.1	3.83	0.72	0.73	OPEN CHANNEL
R	598.9	3.67	4.13	3.18	3.63	0.49	0.5	OPEN CHANNEL
S	519	3.77	4.13	3.33	3.7	0.44	0.43	OPEN CHANNEL
T	493.9	3.56	3.88	2.92	3.2	0.64	0.68	OPEN CHANNEL
U	401.4	3.32	3.58	2.92	3.12	0.4	0.46	OPEN CHANNEL
V	313.1	3.38	3.56	2.9	3.08	0.48	0.48	OPEN CHANNEL
W	46.3	2.33	1.63	2.3	1.63	0.03	0	OPEN CHANNEL

Table 7.5 Sydney Water 100 year ARI Verification - Johnstons Creek

Location ID	Sydney Water Reference	Observed Flood Level (m AHD)	Modelled Flood Level (m AHD)	Difference between Observed Level and Modelled Level (m)	Comments
A	P	9	9.01	-0.01	
B	O	8.19	8.21	-0.02	
C	N	7.47	7.46	0.01	
D	M	4.56	4.99	-0.43	
E	L	4.26	4.92	-0.66	
F	K	3.68	4.40	-0.72	
G	J	3.64	3.83	-0.19	
H	H	3.33	3.55	-0.22	
I	G	3.15	3.19	-0.04	OPEN CHANNEL
J	F	3.02	3.12	-0.10	
K	E	2.71	2.83	-0.12	
L	D2	2.47	2.60	-0.13	
M	LNO	2.27	2.40	-0.13	OPEN CHANNEL
N	C	2.15	2.37	-0.22	OPEN CHANNEL
O	B	2.04	2.22	-0.18	
P	A2	1.8	1.94	-0.14	
Q	A1	1.67	1.60	0.07	
R	A	1.4	1.22	0.18	OPEN CHANNEL

7.3 Verification of Direct Rainfall Model to XP-RAFTS Model

As the Direct Rainfall (rainfall on the grid) methodology is still relatively new to the industry, it was verified against a traditional hydrological model. The verification was undertaken by comparing the results from a 100 Year ARI event for the Direct Rainfall Model with the results from a traditional hydrological model (XP- RAFTS). It is not always expected that the two models will exactly match (in fact, two separate traditional hydrological models with similar parameters can produce significantly different results). However, where there are differences some interpretation of the results can be made, and the models can be checked as to why this is the case.

The comparison was undertaken on relatively small sub-catchments, as the larger the sub-catchment, the more likely significant hydraulic controls, such as culverts, would not be included in the hydrological model. In addition, the primary aim of this comparison is to ensure that the timing and peak flows from the direct rainfall hydraulic model (SOBEK) are reasonable, with the focus on the runoff areas rather than the mainstream areas.

The sub-catchments modelled for this comparison are shown in **Figure 7.5** and modelled results are listed in **Table 7.4**. The comparison is for sample sub-catchments near the Whites Creek (Zone N and Zone O) study areas for the February 1993 historical event and in Birchgrove (Zone A) for 100yr 90mins.

Table 7.6: Verification of Direct Rainfall Model (SOBEK) to XP-RAFTS Model

Location	Details	XP-RAFTS Peak Flow (m^3/s)	XP-RAFTS Volume (m^3)	SOBEK Peak Flow (m^3/s)	SOBEK Volume (m^3)
ZONE - N0 (N)	February 1993	7.20	4538	6.55	3645
ZONE - N0 (O)	February 1993	7.79	4027	7.48	3768
ZONE - A	Design Event (100yr 90mins)	3.22	6350	3.09	5434

Table 7.4 indicates that the comparison shows a reasonable match between the Direct Rainfall (SOBEK) and the XP-RAFTS model. The overall volume of runoff is marginally higher in the RAFTS model than in the SOBEK model. This is a function of the storages which are available in the detailed SOBEK model (particularly within the property, blockages from buildings etc). By comparison, there is no storage available in the RAFTS model other than indirectly through the rainfall losses.

8 Design Flood Modelling Results

8.1 Design Flood Modelling

Design flood modelling was undertaken for the 5, 10, 20, 50, 100 year ARI and PMF design flood events.

The modelling was undertaken for a number of critical durations for each model zone (**Table 6.3**). An envelope of the different durations was taken to determine the peak water level, depth, and velocity for each 1x1 m grid cell in the study area.

The results for the 5 year ARI, 100 year ARI and PMF events are presented in Volume 2 of this report:

- Flood extents and depths are shown in **Figure 8.1** to **8.3**; and
- Flood velocities are shown in **Figure 8.4** to **8.6**.

As described in **Sections 5.2 and 6.4**, rainfall was applied directly to the 2D domain, using the 'Direct Rainfall' approach. This approach effectively results in every 2D cell being inundated with some flood depth. In order to create model extents and provide reasonable results, a filter is applied to separate what is normal catchment runoff and what is flooding. The flood extents were drawn only for depths greater than 0.15m or where the velocity-depth product exceeded 0.1 m^2/s, together with some manual manipulation to remove small isolated areas of ponding. The filtered results are presented only within the flood extents.

For flooding within individual properties, the flood extents and results have not been provided in detail. Within individual properties, small modifications to the property, or the presence of local obstructions such as bins and cars, can alter the results locally. Therefore, an outline of the inundated areas has been provided instead.

Note that these figures are exclusive of the 1D results, which include some of the smaller drainage channels in the study area.

8.2 Flood Discharges

Flood discharges were obtained from the 2D results at suitable locations within the model. The method of extraction involved the measurement of discharge perpendicular to a specified line within the model. Due to the number of locations where this information is available, the information has been provided electronically to Council.

The data is provided as GIS lines with the measured peak flow from the model.

8.3 Effect of Stormwater Pit Blockages

Stormwater pits can potentially block through a number of factors, including the build up of leaf litter, parked cars and garbage bins. A number of Councils in NSW adopt a 'blockage policy' in undertaking design flood analysis. While these policies vary, a common policy is to adopt a minimum 50% blockage of stormwater pits, which is consistent with the recommendations for the design of stormwater systems outlined in AR&R (Engineers, 1999). Leichhardt Council has not adopted a specific policy to date.

An analysis of the effect of stormwater pit blockages on flood behaviour was undertaken for the 100 year ARI by assuming that all pits within the Leichhardt LGA were blocked by 50%. Due to the age of the infrastructure in the LGA and the prevalence of street parking, this is considered to be a reasonable representation of potential blockages.

The results of this analysis are shown in **Figure 8.7** comparing the peak water levels from the blockage modelling with the 100 year ARI levels without blockage.

8.4 Effect of Culvert and Bridge Blockages

The culverts and bridges within the study area are primarily limited to Johnstons Creek, Whites Creek and Hawthorne Canal, as well as the culverts under the rail line adjacent to Hawthorne Canal. Blockages of these structures can occur by the accumulation of debris washed down from upstream. This debris, from historical observations in other similar catchments, can include vegetation and trees, cars and garbage bins.

The likely blockage of culverts can be difficult to predict. However, Wollongong Council have developed a Conduit Blockage Policy (Wollongong City Council, 2002) based on historical observations during major flooding in the urbanised portions of Wollogong in 1998 and 1999. This research behind this policy is probably the most complete to have been undertaken in NSW.

In summary, the Wollongong City Council Conduit Blockage Policy (Wollongong City Council, 2002) adopts the following blockages:

- 100% blockage for structures with a major diagonal opening width of less than 6 metres;
- 25% bottom up blockage for structures with a major diagonal opening width of greater than 6 metres;
- 100% blockage for handrails over structures in both (i) and (ii) when overtopping occurs.

These same criteria have been applied to undertake a culvert and bridge blockage analysis and the effects on flood behaviour. This analysis was undertaken for the 100 year ARI, and has been compared with the 100 year ARI with no blockage. The results of this analysis are presented in **Figure 8.8**.

9 Provisional Flood Hazard

9.1 General

Flood hazard can be defined as the risk to life and limb caused by a flood. The hazard caused by a flood varies both in time and place across the floodplain.

The *Floodplain Development Manual* (NSW Government, 2005) describes various factors to be considered in determining the degree of hazard. These factors are:

- Size of the flood
- Depth and velocity of floodwaters
- Effective warning time
- Flood awareness
- Rate of rise of floodwaters
- Duration of flooding
- Evacuation problems
- Access.

Hazard categorisation based on all the above factors is often referred to as ‘true hazard’. The scope of the present study calls for determination of ‘provisional’ flood hazards only. The provisional flood hazard is generally considered in conjunction with the above listed factors as part of the Floodplain Risk Management Study (the next stage of the Floodplain Risk Management process after the Flood Study) to provide a comprehensive analysis of the overall flood hazard.

9.2 Provisional Flood Hazard

Provisional flood hazard is determined through a relationship developed between the depth and velocity of floodwaters (Figure L2, NSW Government, 2005). The Floodplain Development Manual (2005) defines two categories for provisional hazard - High and Low.

The model results were processed using an in-house developed program, which utilises the model results of flood level and velocity to determine hazard. Provisional flood hazard was prepared for four design events, namely PMF, 100 year, 20 year and 5 year ARI design events. The provisional hazard is based on the envelope of the hazard at each location for each ARI.

Flood hazard for the 5 year ARI, 100 year ARI and PMF events is shown in **Figure 9.1** to **9.3**.

10 Discussion

10.1 Flooding Behaviour

The defined creek and channel systems within the LGA are primarily Hawthorne Canal, Whites Creek and Johnstons Creek. Mainstream flooding occurs along these systems when the channel capacity is exceeded.

A large majority of the flooding within the LGA occurs outside of the main creek systems, when the capacity of stormwater pits and pipes are exceeded. When this occurs, overland flows proceed down roads and through properties.

At a number of locations within the study area, historical development has occurred perpendicular to the overland flow paths, across existing depressions and low points. Therefore, rather than follow the roads, the overland flows tend to proceed through properties rather than down streets or via designated flowpaths. In addition, the density of development across the LGA, such as townhouses and terrace housing, can result in a complete obstruction to overland flow and the only overland flowpath available is directly through actual dwellings.

For the purposes of discussion of flooding behaviour, the LGA has been broken into the following areas:

- Hawthorne Canal Catchment
- Whites Creek Catchment
- Johnstons Creek Catchment
- Central LGA – roughly bound by City West Link in the south and Victoria Road in the north.
- Northern LGA – areas north of Victoria Road.

These areas are discussed in more detail in the following sections.

10.1.1 Hawthorne Canal

The catchment for Hawthorne Canal is in the order of 670 hectares in size, and is the single largest catchment in the Leichhardt LGA. A large portion of the catchment, greater than 400 hectares, is located outside of the LGA.

The majority of the flooding issues within the Hawthorne Canal catchment occur upstream of the rail line that runs generally parallel to the canal. In this area, there are no formalised creeks or channels, and when the capacity of the existing pipe system is exceeded overland flow proceeds down streets and through properties.

There are a number of tributaries of the Canal in this area, the largest of which originates from upstream of Parramatta Road in Marrickville.

The rail line itself forms a major hydraulic control in the study area, and significant ponding occurs upstream of this location. The ponding is largely influenced by the capacity of the culverts under the rail line connecting to Hawthorne Canal. The high hazard classification in this area is depth governed.

Flooding from the main Canal itself is limited to the west of the rail line, and does not affect a significant number of properties within the Leichhardt LGA. However, flood levels within the Canal can affect the conveyance of flows from the culverts originating on the eastern side of the rail line.

10.1.2 Whites Creek

The Whites Creek catchment rises in the south of the Leichhardt LGA within the Marrickville LGA. The southern portion of the Creek is actually a box culvert and Whites Creek Lane follows the majority of the length of this culvert. The culvert discharges into an open channel between Booth Street and Piper Street, and eventually discharges into Rozelle Bay to the east of The Crescent.

Flooding in the area occurs along both the Creek itself and a number of overland flow tributaries that connect with the creek. The Whites Creek culvert tends to flow full in a 5 year ARI event. While the flowpath tends to follow Whites Creek Lane, the flooding does extend to the adjacent properties.

Downstream of the culvert section of Whites Creek, the creek is followed by parkland on both sides for the majority of the length. Flooding is primarily limited to the parkland, although a number of adjacent properties are affected.

A number of properties are impacted by overland flooding from tributaries to the main Whites Creek flowpath.

10.1.3 Johnstons Creek

Johnstons Creek also originates from the south of the Leichhardt LGA. A large portion of Johnstons Creek is also located within the City of Sydney LGA, including all areas north of The Crescent. A short section of the creek within the LGA, from Parramatta Road to approximately Water Street, is a covered channel. The remainder is an open concrete lined channel.

The majority of the length of the main creek is followed by parkland, which limits flood impacts on adjacent properties. However, a number of tributaries to the main creek result in overland flooding of properties in these areas.

10.1.4 Central LGA

Overland flowpaths to the north of Balmain Road and Perry Street are primarily contained within Leichhardt Park, Rozelle Hospital and King George Park. The overland flow in these areas does impact on existing infrastructure, such as the buildings within the hospital grounds. Furthermore, significant ponding occurs around the electrical substation to the south east of King George Park, and may have implications on the operation of this substation during a significant flood event. A small section of the King George Park tributary also affects properties south of Victoria Road.

In the areas south of Balmain Road and Perry Street, the majority of the catchment drains towards the old rail yards. Significant ponding occurs in the rail yards, with the flood levels controlled by the centreline of the City West Link.

10.1.5 Northern LGA

The two main flowpaths in the northern LGA discharge to Whites Bay. In both cases, properties have historically been constructed across the flowpaths resulting in significant obstruction to overland flows and associated ponding of water in streets and properties. In some cases, this obstruction to flow also results in an effective detention basin with a flood benefit to the properties downstream (as the obstruction from the properties slows and holds back the water, reducing the potential flooding downstream).

In the downstream portion of both of these flowpaths, flood levels are controlled by the culverts under Robert Street and the port at White Bay and the ability for flows to overtop the port area. In addition, a long section of the port is obstructed by a high level fence which has been constructed. The combination of these factors results in significant ponding of water in this location.

Smaller overland flowpaths are also located to the north of Darling Street. In a number of cases, the streets in this area are aligned such that the majority of the overland flow proceeds along them, rather than directly through the houses. Significant ponding does occur on Birchgrove Oval, due to the low grades in this area.

10.2 Major Access Road Flooding

There are a number of major arterial roads which pass through Leichhardt LGA, including Parramatta Road, Victoria Road, City West Link and The Crescent. These roads form some of the main road corridor linkages between the City and the Western Suburbs. Should these roads become non-trafficable due to flooding, then this can represent a significant impact to the Sydney road network as a whole. Furthermore, it can prevent or hinder the access of emergency vehicles using the road network in the area.

A summary of major access road flooding is provided in **Table 10.1**, with the locations shown in **Figure 10.1**. This table provides indicative flood depths at a number of locations. It should be noted that, in general, the critical duration for flooding in the Leichhardt LGA ranges from 15 minutes to 2 hours, and therefore road inundation would generally only occur over a relatively short timeframe.

Table 10.1: Major Access Road Flooding - Indicative Depths (metres)

Location ID	Description	PMF	100 year	50 year	20 year	10 year	5 year
A	Parramatta Rd/ Flood St	3.29	1.71	1.55	1.42	1.28	1.20
B	Parramatta Rd	1.40	0.69	0.63	0.58	0.52	0.47
C	Parramatta Rd	0.73	0.55	0.53	0.51	0.48	0.46
D	Parramatta Rd	2.60	0.50	0.42	0.39	0.36	0.32
E	The Crescent/ Trafalgar St	1.53	0.70	0.67	0.62	0.56	0.51
F	The Crescent/ City West Link	1.32	0.71	0.61	0.47	0.38	0.32

10.3 Pit Blockages

The methodology for pit blockages is discussed in detail in **Section 8.3**.

In general, the impacts of pit blockages throughout the LGA are within +/- 0.1 metres in the 100 year ARI event. This is due to the limited capacity of the stormwater system.

Larger increases are observed in some locations. These tend to be in trapped low points, where minimal or no overland flow paths exist downstream and the only way for water to drain is via the stormwater system.

10.4 Culvert and Bridge Blockages

The methodology for culvert and bridge blockage is discussed in **Section 8.4**.

As expected, culvert and bridge blockages tend to affect the major creek systems within the study area. Increases of up to 0.3 metres are observed on Whites Creek downstream of Piper Street, while the increases are not as pronounced further upstream

On Johnstons Creek, increases of up to 0.4 metres are observed near Piper Street. The blockage of the bridge near Harold Park results in lower flood levels for the area near Trafalga Street and The Crescent. Increases of over 1 metre are observed at Parramatta Road due to the blockage of the Johnstons Creek Culvert.

The major impact on Hawthorne Canal is due to the blockage of the culverts under the rail line. This causes impacts in the order of 0.5 metres on the area upstream of the rail line.

10.5 Estuarine Inundation

The design model runs were undertaken for an assumed Harbour Level of 1m AHD (refer **Section 6.9.2**). This assumes that an estuarine inundation event is not occurring at the same time as a local catchment event. In using the model results, it is important to consider the implications of an estuarine event occurring, and that the levels from an estuarine event may be higher in some locations than local catchment flooding. Therefore, in determining appropriate flood levels for different locations within the study area, the maximum of the estuarine inundation level and the level from this flood study should be adopted. A separate study regarding estuarine inundation is currently in progress and is discussed further in **Section 2.1.2**.

A comparison of the flood levels from the local catchment and the estuarine flood levels (sourced from Cardno Lawson Treloar, *in* prep) are provided in **Figure 10.2**. This figure provides an indication of where the estuarine inundation levels are higher than the flood levels from the local catchment for the Johnstons Creek, Whites Creek and Hawthorne Canal floodplains. This is based on the 100 year ARI estuarine still water levels, which are summarised in **Table 10.2** and are discussed in detail in Cardno Lawson Treloar (*in prep*). The climate change estuarine levels have been based on a predicted sea level rise of 0.9 metres, in accordance with the NSW State Policy on Sea Level Rise (NSW Government, 2009).

Under existing climatic conditions, the 100 year ARI catchment flood level generally governs over the estuarine level for all three creek systems, except for a portion of Hawthorne Canal. Under a climate change scenario, estuarine levels govern for Hawthorne Canal to nearly the Marion Street crossing. On Whites Creek, the estuarine levels govern to approximately the Brenan Street crossing. For Johnstons Creek, the catchment flood levels govern over the estuarine levels within the Leichhardt LGA.

It is recommended that all locations be checked individually against both the flood study and the estuarine planning levels study, as the exact level can depend on the level of wave setup, the location within the catchment and other factors.

Table 10.2: 100 year ARI Estuarine Still Water Levels

Estuarine Planning Levels Study Location ID	Location Description	100 year ARI Estuarine Still Water Level (m AHD)*	100 year ARI + Climate Change Estuarine Still Water Level (m AHD)
1	Hawthorne Canal	1.56	2.46
101	Whites Creek Outlet	1.50	2.40
105	Johnstons Creek Outlet	1.50	2.40

*Still water only, excludes wave setup and climate change

11 Sensitivity Analysis

Sensitivity analysis allows for the testing of some of the key assumptions of the modelling. Sensitivity was undertaken on some of the key variables of the modelling, namely:

- Hydraulic Roughness – increase and decrease by 20%, shown in **Figure 11.1** and **11.2**.
- Model Inflows – increase and decrease in rainfall by 20%, shown in **Figure 11.3** and **11.4**.

Due to the long run times of the models, the sensitivity analysis was undertaken using a preliminary 3x3 metre grid cell model. This model allows for a reasonable assessment of the impact in modification of the model parameters.

The results of the analysis are discussed in the following sections.

11.1 Hydraulic Roughness

Increases in hydraulic roughness of 20% have a relatively minor impact on the predicted flood levels in the 100 year ARI event, with the majority of the increases in peak water levels lower than 0.05 metres.

Decreases in roughness of 20% result in changes in peak water levels in the 100 year ARI event typically within +/- 0.1 metres. The majority of changes result in a decrease in levels. The exception is in downstream areas, where the decreased roughness results in floodwaters arriving at these locations earlier.

11.2 Model Inflows

An analysis of the sensitivity of the model to rainfall is also an indication of the sensitivity of the study area to potential impacts for climate change. The 20% increase in rainfall assessed here is in the middle of the recommended DECCW climate change guidelines of 10 – 30% rainfall increases.

Peak flood levels were more significantly impacted by the 20% changes to rainfall intensities than by a 20% change in model roughness.

An increase in peak rainfall of 20% results in a general increase in peak water levels throughout the study area. For the majority of the overland flow areas, these increases are typically less than 0.1 metres. Along the main creeks, the increases are typically less than 0.2 metres, with the exception of the downstream end of Whites Creek, where increases up to 0.5 metres are observed.

A reduction in peak rainfall of 20% results in reductions in peak flood levels generally within 0 to 0.2 metres. However, there are a number of locations, particularly in downstream areas, where decreases of between 0.2 to 0.5 metres are observed. These areas are primarily in the downstream areas of Whites Creek, near the rail line adjacent to Hawthorne Canal and in the northern part of the study area draining towards Whites Bay.

11.2.1 Peer Review

A peer review was undertaken in 2011 of this Flood Study. Two components of the methodology were identified for further review.

- The modification to the initial loss values that were adopted for the SOBEK model; and
- The adoption of the embedded storm approach.

In response to the peer review, discussion is provided below and sensitivity analysis was undertaken to further understand the impacts of the selected approaches on the outcomes of the study.

11.2.1.1 Initial Loss Values in Modelling

The reviewer raised some comments in regards to the Direct Rainfall methodology. In particular, referring to the xp-rafts verification in the Flood Study, the reviewer identified that the volumes generated in the SOBEK model are consistently below those generated in the xp-rafts model (although the peak flows are generally similar).

The difference in volume of runoff can be attributed to what might be called localised depression storages within the “catchment”, and storages along the actual overland flow paths. There is no real demarcation of these two, but they have been separated for discussion purposes.

If the modelling in this Flood Study had been undertaken using traditional hydrology, and it still defined the overland flow paths, then numerous small subcatchments would be required across the study area. This would overcome any issues from “catchment” depression storages, but would not overcome the overland flow path storages, which may be caused by road sag points, backyards, fences etc. The key point is that the initial loss issue is not entirely a Direct Rainfall issue as it is a scale issue for the detailed level of the modelling that was undertaking.

Furthermore, it should be kept in mind that the xp-rafts model will assume that all of the rainfall excess will be converted to runoff and arrive at the catchment outlet. Given the number of obstructions and storages along the flowpaths, this may not be entirely representative of what occurs in reality. The key point here is that the xp-rafts model is not necessarily a correct representation either, and therefore the verification of the model to the xp-rafts model should be treated with caution.

Regardless of this, the point that the reviewer raises is that the initial loss applied in the model should potentially be lower than what would be incorporated normally. This is because the initial loss accounts for depression storages in the upper catchment which are incorporated to some degree in the hydraulic model. We would regard this to be due to a combination of the Direct Rainfall model and the scale that the model has been developed to.

11.2.1.2 Embedded Storm Method

The embedded storm method involves placing the design storm within an historical storm event. This attempts to replicate the fact that the design storms will be part of larger rainfall events. We understand that this is the likely direction that the update for Australian Rainfall and Runoff is currently taking.

To date, this method is currently not widespread throughout the NSW flood industry. To our knowledge, it is primarily limited to one or two consultants.

We have encountered challenges with this approach in some situations. For example, the embedded storm method may result in a number of sag points and storages within a catchment or floodplain being either filled or partially filled at the start of the design storm burst. This can result in higher peak water levels that from those using a more traditional initial loss/ continuing loss methodology.

It is important to note that we are not suggesting that either method is flawed, but merely that they are two alternatives to approaching the same problem.

11.2.1.3 Sensitivity Analysis

A sensitivity analysis has been undertaken to determine the potential impacts of the initial loss assumption and an embedded storm style method on the peak water levels in the study. This analysis was undertaken by lowering the initial loss applied to the models to 0mm. In effect, this results in additional rainfall falling at the start of the storm in comparison the methodology adopted for the design storm modelling, which results in some of the storages and depressions filling prior to the more intense portion of the storm.

This approach does not exactly replicate the embedded storm method, but it provides an indication of the likely sensitivity of the model to these alternative approaches.

The analysis was undertaken for the 5 year ARI and 100 year ARI. In the both cases, the change in levels is generally less than 0.05 metres. There are lower impacts in the upper catchment (where there are shallower flows) and higher impacts towards the downstream end of the catchment where there are higher depths of flows. Therefore, while you get towards 0.1 metres near the bottom of the model, this needs to be viewed in light of the depths in that area.

These increases are generally within the same order as the sensitivity analysis on the roughness and the input flows. Our recommendation is that this is within the error bounds of the various assumptions for the modelling. Therefore, the impact of adopting alternative initial loss values for the modelling, or adopting the embedded storm method approach, should not have a significant impact on the results.

12 Flood Control Lots

Flood control lots are those properties within the LGA that should be referred to Council's development controls because of their potential to be flood affected. This does not necessarily mean that the properties are flood affected, simply that they have the potential to be flood affected.

Typically, flood control lots may experience one or more of the following types of flooding:

- Mainstream flooding;
- Flooding by overland flows; and/ or,
- Estuarine inundation and wave impact.

Mainstream flooding is generally defined as overflow along Whites Creek and Johnstons Creek in Annandale and Hawthorne Canal in Leichhardt. Flooding by overland flows generates the majority of the flood control lots within the Leichhardt Local Government Area and is generally defined as flooding that occurs within natural depressions and along surface flowpaths along the streets or through properties.

Estuarine inundation and wave impact is associated storm tide, wave run-up and overtopping effects on water level for the foreshore areas of the Leichhardt Council LGA.

12.1 Background Reports

Flood control lots have been identified on the basis of the following hydraulic assessments of flooding and estuarine inundation:

- Leichhardt Flood Study (Cardno, 2014) (this document):
    - Mainstream flooding; and
    - Overland flows.
- Estuarine Planning Levels Study – Foreshore Region of Leichhardt Local Government Area (Cardno, 2010):
    - Estuarine inundation and wave impact.

12.2 Flood Control Lot Mapping

The mapping of flood control lots was undertaken in two components:

- *Flood Control Lot Mapping* of properties at risk of mainstream flooding and flooding by overland flows; and,
- *Foreshore Flood Control Lot Mapping* of properties at risk of potential inundation and wave action from the harbour during storm events.

12.2.1 Flood Control Lot Mapping

The flood control lot mapping identifies properties potentially affected by mainstream flooding and flooding due to overland flows. It has been undertaken based on the following criteria:

- The property contains, or is in the vicinity of, a stormwater pipeline, and therefore is potentially at risk of inundation due to surcharge or blockage of the pipeline or associated pits; or,
- The property is identified in the Leichhardt Flood Study (Cardno Lawson Treloar, 2014) (this document) as being partially or completely located within the zone defined as the Flood Planning Area.

Properties Affected by a Stormwater Drainage Pipeline

Flood related development controls potentially apply to properties which have a stormwater pipeline that traverses the cadastral block or that are immediately adjacent to a property that includes a pipeline. Stormwater drainage systems have a limited capacity and are prone to blockage and will surcharge during major storms leading to potential inundation of properties. Therefore, those properties which included a stormwater pipeline within or in close proximity to their cadastral block were included in the mapping.

A comprehensive pit and pipe database was established as a part of this Flood Study. Properties were flagged based on the following criteria:

- A stormwater pipeline traverses a portion of a cadastral block; or,
- The cadastral block is within 3 metres of a stormwater pipeline traversing another property.

It should be noted that:

- The 3 metre “buffer” was applied to both sides of each stormwater pipeline to allow for identification of neighbouring properties near to pipelines. The “buffer” also allows for potential error in the location of a pipeline with the pit and pipe database. The location of pipelines in the database was based on field inspection of pits, which are commonly within the road reserve. Therefore, the stormwater pipeline location through a property is an estimated alignment only.
- Stormwater pipelines within road reserves were not included in this analysis. A number of road reserves contain pipelines located within 3 metres of a property, but this does not necessarily mean that the property is at risk.

Properties Affected by Mainstream or Overland Flooding

Properties potentially affected by mainstream or overland flooding are those that are either partially or completely located within the Flood Planning Area.

The Flood Planning Area is defined by the NSW Government Floodplain Development Manual 2005 as the area of land below the Flood Planning Level and thus subject to flood related development controls. The Flood Planning Level is defined as the 100 year Average Recurrence Interval (ARI) flood level with a suitable freeboard allowance added. It is the minimum floor level to which Council requires new developments to be constructed. Council’s development controls are set out in the Water section of Council’s Development Control Plan (DCP2013) and the Flood Planning Level incorporates a freeboard allowance of 500mm.

Maps of the 100 year ARI flood and Probable Maximum Flood (PMF) (**Section 8**) were used to determine the extent of the Flood Planning Area.

The Flood Planning Area was established through the following steps:

- The Flood Planning Area includes all properties where any part of the property is overlapped by the 100 year ARI flood extent, as mapped in the 2014 Leichhardt Flood Study;
- At the low points in roads or where the direction of the flood flow was generally perpendicular to the alignment of a road, the Flood Planning Area extends to the extent of the PMF level, or to the extent defined by a level 500mm above the 100 year ARI flood level, whichever was the lesser extent;
- Where flow proceeds through properties, the Flood Planning Area extends to the PMF level, or the extent defined by a level 500mm above the 100 year ARI flood level, whichever was the lesser extent;
- For Whites Creek, Johnstons Creek and Hawthorne Canal, the Flood Planning Area was determined by the extent defined by a level 500mm above the 100 year ARI flood level
- It should be noted that properties were not included where the flows are generated only from within the property itself and/or from upstream private properties.

12.2.2 Foreshore Flood Control Lot Mapping

Design water levels for properties located along the foreshore of the Leichhardt Local Government Area will be affected by elevated water levels in Port Jackson that occur during severe ocean storms. Those high water levels may be accompanied by local sea wave activity that then causes wave set-up and run-up.

The 100 Year ARI design event from the *Leichhardt Estuarine Planning Levels Study* (Cardno Lawson Treloar, 2010) have been utilised to produce the flood control lot mapping. This mapping is based on the following criteria:

- Properties inundated by the 100 year ARI design still water level.
- Properties within 20m of the foreshore edge that are potentially affected by wave run-up over the foreshore area.

The design still water level is comprised of:

- Storm Tide Level at Fort Denison.
- Wind Set-up Adjustment.
- Wave Set-up, a function of edge treatment and incident waves.
- Mean sea level rise allowance of 0.9m.
- No freeboard has been included in this assessment.

Wave run-up depends upon edge treatment and surface roughness and is irregular in its character. Five idealised edge treatment cases have been addressed in this study:

- 1 in 20 natural slope
- 1 in 10 beach face

- 1 in 5 embankment
- 1 in 2 seawall
- Vertical wall

At the foreshore edge wave run-up may penetrate some distance inland, but is attenuated by percolation and friction. This landward reduction of wave inundation was based on observational experience and it is assumed that wave run-up diminishes to zero at a point 20m inland from the edge structure. To this end all properties within 20m of the foreshore edge have been included in the foreshore extent mapping.

12.2.3 Public Exhibition and Review

As a part of the exhibition period of the Flood Study (**Section 3.9**), Council received a number of submissions from the community relating to the flood control lot mapping. While the majority of these comments were addressed directly by Council, Council requested that Cardno review in more detail some of the responses. For each of these submissions, the following tasks were undertaken:

- A review of the Leichhardt Flood Study results.
- A review of the pit and pipe locations in the area.
- A review of the foreshore control lot mapping.
- A site inspection, where appropriate, to verify the results of the flood control lot mapping.

Based on these reviews several properties were removed from the flood control lot mapping for various reasons including:

- Identification of local features during site inspections affecting overland flow (such as brick walls and non-standard kerb heights) that were not able to be identified in the Airborne Laser Scanning (ALS) data or aerial photography.
- Site inspections identified erroneous ground levels recorded by ALS (this may be due to tree coverage, structure or cars blocking the survey).

Where no change was made to the flood control lot mapping, this was based on one or more of the following reasons:

- Site inspections confirmed ground levels recorded by the ALS.
- Site inspections confirmed likely flow paths identified in the hydraulic modelling (**Section 8**).
- Observations recorded in the resident surveys (**Section 3**) confirmed modelled flood behaviour.

12.2.4 Results

The resulting maps are provided in **Figures 12.1 to 12.5**. A GIS mapping layer has been also provided to Council which includes information on these properties.

13 Conclusions

A detailed investigation on the flooding behaviour has been undertaken for the entire Leichhardt LGA.

An extensive data compilation and review was undertaken in the study. This included an extensive survey exercise which required the collection of data for over 3500 pits within the LGA, together with cross sections of stormwater channels and details of hydraulic structures such as culverts.

The data compilation also included a resident survey of approximately 20,000 property owners and occupiers. This survey targeted local residents' experience with flooding in the LGA and has been compiled into a GIS database for Council.

A detailed 1D/2D hydraulic model was established. This model incorporates pipes upwards to 225 millimetres in diameter and has a fine 2D resolution of 1 metre. Hydrological modelling was undertaken utilising a combination of Direct Rainfall within the study area and traditional hydrological modelling for catchments external to the study area.

The models were calibrated to three historical flood events; 1991, 1993 and 1998. The largest of these storm events was in 1993, and corresponds roughly to a 50 year ARI for a 30 minute duration and a 20 year ARI for a 2 hour duration storm, based on rainfall intensities. The models show a good agreement to the observed flood levels from these events.

Using the established models, the study has determined the flood behaviour for the 100 year, 50 year, 20 year, 10 year and 5 year ARI design floods and the Probable Maximum Flood (PMF). The primary flood characteristics reported for the design events considered include depths, levels, velocities and flow rates. The study has also defined the Provisional Flood Hazard for flood-affected areas.

The outcomes of this study can also be used for future studies to investigate various management and flood mitigation options for the existing catchment conditions and will assist in evaluating long term flood management strategies now that existing flood risks have been defined in this study.

14 References

Bureau of Meteorology (2003) *The Estimation of Probable Maximum Precipitation in Australia: Generalised Short-Duration Method*, June.

Cardno Lawson Treloar (2010) *Leichhardt Estuarine Planning Level Study.* Prepared for Leichhardt Council.

Chow (1973) *Open-Channel Hydraulics*, McGraw-Hill Book Co., New York.

Department of Environment and Climate Change (2007) *Practical Considerations of Climate Change*, October, Version 1.0, Final.

Engineers Australia (1999) *Australia Rainfall and Runoff* [AR&R].

Howells L., McLuckie D., Collings G. & Lawson N. (2003) *Defining the Floodway – Can One Size Fit All?* Proceedings of 43rd Floodplain Management Authority of New South Wales Annual Conference, Forbes, 25-28 February 2003.

Howells L, Treloar D & Lawson N (2005) *Downstream Boundary Conditions for Flood Studies in Coastal Environments to Effectively Manage Risk and Uncertainty*, Proceedings of 45th Floodplain Management Authority of New South Wales Annual Conference, Lismore, 28 February – 2 March 2005.

NSW Government (2005) *Floodplain Development Manual – The Management of Food-Liable Land.*

NSW Government (2009) *Draft Sea Level Rise Policy Statement*, February.

Sydney Water (1996) *Johnstons Creek SWC No: 55 Flood Study,* March.

Wollongong City Council (2002) *Conduit Blockage Policy*, adopted by Council November 2002, Minute No 492, Policy 3.1Water Board (1994) *Whites Creek SWC No: 95 Detail Hydraulic Analysis*, January.